IAEA-TECDOC-1515

Development of Specifications for Radioactive Waste Packages

IAEA
International Atomic Energy Agency

October 2006

IAEA-TECDOC-1515

Development of Specifications for Radioactive Waste Packages

IAEA
International Atomic Energy Agency

October 2006

The originating Section of this publication in the IAEA was:

Waste Technology Section
International Atomic Energy Agency
Wagramer Strasse 5
P.O. Box 100
A-1400 Vienna, Austria

DEVELOPMENT OF SPECIFICATIONS FOR
RADIOACTIVE WASTE PACKAGES
IAEA, VIENNA, 2006
IAEA-TECDOC-1515
ISBN 92–0–109206–7
ISSN 1011–4289

Printed by the IAEA in Austria
October 2006

FOREWORD

The main objective of radioactive waste management is to protect people and their environment from the potential harmful effects of radioactive waste and to minimize the burden for future generations. Safe disposal of conditioned radioactive waste is considered the final step of waste management. Waste acceptance requirements, consistent with a disposal concept, should be defined either by national authorities or repository operators with the aim of meeting the safety goal of radioactive waste disposal.

An important task for waste management organizations is to translate general waste acceptance requirements into detailed waste package specifications. Waste package specifications should be individually prepared and implemented for each type of radioactive waste package produced (considering both waste form and waste container) and should reflect specific characteristics of the waste package. Such specifications allow simpler and more accessible control and verification methods to be applied directly by the waste generators and disposal facility operators. Waste package specifications can also be directly implemented in quality assurance and quality control systems during waste processing and waste package control.

A waste package is designed as an engineered component for ensuring the safe management of radioactive waste. It represents a principal unit used as a reference for controlling information and making decisions with due consideration to interdependencies of various steps in radioactive waste management. Converting waste acceptance requirements into waste package specifications is, therefore, an important but complicated procedure with great effects and consequences that may involve latent risks and problems. Recognizing this fact, the IAEA prepared a publication addressing development and implementation of waste package specifications. Detailing these specifications is important because waste acceptance requirements may be available but in some cases may not yet be defined. Moreover, the scope of this information is not adequately addressed in a comprehensive manner in other IAEA publications, although such publications address related quality assurance requirements and record keeping.

This report was prepared by experts from various countries with corresponding knowledge and skills in regulatory as well as technological aspects of radioactive waste management. The IAEA wishes to acknowledge the work of the experts, in particular, the contribution made by P. Brennecke of Germany, who took systematic care of the report from the beginning and I. Vovk of Ukraine, who made revisions to the report updating it to 2005. A final consultant review was performed in March 2006, and it was determined that the TECDOC remains current and relevant. The IAEA officer responsible for the initial period of this work was R. Burcl, who was succeeded in finalization of the report by J. L. Gonzalez Gomez and J.J. Kelly, all of whom were from the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The overall objective of radioactive waste management is to deal with radioactive waste in a manner that protects human health and the environment, now and in the future, and without imposing undue burdens on future generations [1]. Radioactive waste management covers all administrative and operational activities that are involved in the arising, handling, treatment, conditioning, transportation, interim storage, and disposal of the various types of waste. Thus, a national framework for radioactive waste management that includes a policy and strategy for managing waste in accordance with safety objectives and principles must be established. A strategy to implement this policy is also needed. The safety standards to be applied are set out in the IAEA publications [2–9] and the legally binding treaty on the safety of spent fuel management and radioactive waste management (Joint Convention) is presented in Ref. [10].

In the management of radioactive waste, a waste package is designed as the major engineered component for ensuring containment and providing safety functions. It also represents a principal unit used as a reference for controlling information, record keeping, and making decisions with due considerations of the interdependencies, impacts and information needs at various stages in radioactive waste management.

According to the IAEA terminology used in this publication [11], a waste package is the product of conditioning that includes the waste form and any container prepared in accordance with requirements for handling, transport, storage and disposal. Due to their multiple functions and the great importance of waste packages, there has been considerable activity including research and development (R&D) projects, during the past few decades in the IAEA and different Member States covering such aspects as waste package design, fabrication, inspection and testing, quality assurance, maintenance of records, etc. This has resulted in a significant number of reports on the topic, both within and outside the IAEA's radioactive waste management programme (References [12–22]).

Given that disposal is considered a final step of safe waste management, developing and implementing requirements for safe disposal of waste packages is an unavoidable prerequisite for the entire waste management system. The definition and quantification of waste acceptance requirements for disposal should be made or approved by national authorities with an eye toward international standards, best practices, and recommendations [7, 8, 23–38]. There is an important, direct relationship between the disposal waste acceptance requirements and the waste package specifications: Package specifications must reflect and comply with the applicable disposal waste acceptance requirements.

The waste acceptance requirements are either specified by the regulatory body or developed by the repository operator on the basis of safety assessments, considering radiological criteria, the conditions of operation, the planned duration of active institutional control and the characteristics of natural and engineered systems [7]. To assist Member States, the IAEA has provided guidelines on the definition, development and establishment of waste acceptance requirements [23, 25, 26]. Sometimes, in the absence of a national disposal facility or disposal concept, adequate waste acceptance requirements may not exist. Nevertheless, radioactive waste still needs proper packaging as a basic safety requirement for waste conditioning, interim storage and transportation.

Whether a package is intended to be stored or disposed of, the development of waste package specifications is recommended. This should cover the radionuclide content in the waste, other radiation safety parameters, and quality parameters for each kind of waste package. This should include the mechanical, chemical and physical properties of the waste form, waste container and the entire waste package. Waste package specifications (in contrast to general waste acceptance requirements) can be directly implemented in quality assurance (QA) requirements for waste packages. Waste package specifications might be used as a guideline in an application of simple, efficient and accessible control and verification methods by waste producers and disposal facility operators. And finally, waste package specifications are an efficient way to demonstrate compliance of each particular waste package with safety requirements for transportation, storage or disposal. If the national waste acceptance requirements for disposal are absent, or in situations where only general guidelines exist, the development and implementation of generic waste package specifications is a primary tool to assure compliance with the safety requirements for predisposal of radioactive waste [4].

In this way, the entire cycle from defining waste acceptance requirements for storage and disposal, through controlling waste processing, to demonstrating that waste packages comply with requirements could be completed in a manner that is both efficient and accessible for waste package producers and disposal site operators.

1.2. OBJECTIVE

The main objective of this publication is to provide guidelines for development of waste package specifications that comply with waste acceptance requirements for storage and disposal of radioactive waste. It will assist waste generators and waste package producers in selecting the most significant parameters and in developing and implementing specifications for each individual type of waste and waste package. This publication also identifies and reviews the activities and technical provisions that are necessary to meet safety requirements; in particular, selection of the significant safety parameters and preparation of specifications for waste forms, waste containers and waste packages using proven approaches, methods and technologies.

This publication is addressed primarily to waste generators, conditioners (waste package producers) and disposal site operators. It can also be a valuable source of information for other involved organizations in the Member States that require information on the subject for regulatory and operational purposes.

1.3. SCOPE

This publication covers development and implementation of waste package specifications for various types of waste and various kinds of waste packages. The emphasis is on selection of proper waste package characteristics, including content of radionuclides in the waste and other radiation safety parameters, physical and chemical properties of the solidified waste forms and canisters, and materials technology. Near surface and deep geological disposal options are also covered as they relate to waste package specifications.

The discussion of appropriate quality assurance systems and maintenance of records for waste packages are covered in detail in an earlier IAEA publication [13] and in a recently published companion publication. [31] However, for the sake of completeness, a special section has been devoted in this publication summarizing the main issues of quality assurance in the development of waste package specifications and the maintenance of records by waste generators, conditioners and repository operators.

Mining and milling wastes and other non-packaged wastes are beyond the scope of this publication. Spent fuel directed for disposal is also not addressed,

1.4. STRUCTURE

This publication is structured in seven sections. Section 2 includes a review of basic organizational and technical issues of radioactive waste management. Section 3 provides a description of waste package characteristics, and Section 4 addresses waste acceptance requirements.

Section 5 describes the key elements and procedures for the development of waste package specifications in greater detail. It includes a description of activities and procedural arrangements for approval and implementation of waste package specifications, the content of waste package specifications for near surface disposal, and the content and detailed aspects of waste package specifications for a deep geological repository.

Section 6 addresses quality assurance in the development of waste package specifications, and record keeping by waste generators, conditioners and repository operators. As addressed above in the Scope, this information is provided in References [13, 31]. The main issues are summarized herein for completeness.

Section 7 presents a summary and the overall conclusions of the report.

2. BASIC ORGANIZATIONAL AND TECHNICAL ISSUES OF RADIOACTIVE WASTE MANAGEMENT AS RELATED TO WASTE PACKAGE SPECIFICATIONS

Radioactive waste needs to be safely managed in a regulated manner, compatible with internationally agreed principles and standards [1–10]. Implementing a proper radioactive waste management system needs organizational and administrative arrangements that define competencies, responsibilities and activities of the institutions involved [3, 4, 7]. The conditioning and disposal method chosen for the waste should be commensurate with the hazard and longevity of the radionuclides. Near surface disposal and disposal in deep geological formations are options already used by many countries addressing radioactive waste [7, 28, 33–38]. Although the waste package is an integral part of the overall engineered barrier system, it is considered separately because of its direct bearing on the repository safety case and the necessity to accommodate other waste disposal issues, including quality assurance, record maintenance, and any waste retrieval requirements.

2.1. COMPETENCIES AND RESPONSIBILITIES LINKED TO WASTE PACKAGE SPECIFICATION

Member States

The Member States (Governments) are responsible for defining a national policy on radioactive waste management and for establishing a national regulatory framework addressing the respective competencies and responsibilities. This framework must be in line with national and international laws. In compliance with the national legal framework, each national regulatory body is responsible for implementing the national programme and a strategy for its realization, for defining safety principles and criteria, and for establishing applicable regulations. The national regulatory body is also responsible for licensing and controlling radioactive waste management facilities, which may include the selection of a disposal site. These regulatory responsibilities include the regulation and oversight of waste package specifications and requirements.

Waste generators and conditioners

The waste generator and conditioner is responsible for establishing appropriate waste package specifications, taking into account the national regulations, available conditioning techniques, transport regulations, requirements for interim storage of waste packages, and waste acceptance requirements related to existing disposal facilities (repositories). Responsibility for developing waste package specifications should be assigned even if waste acceptance requirements have not been defined. Such specifications should be approved by the competent national authority or the operator of a repository, and always in agreement with national regulations.

The waste generators and conditioners must implement adequate technical, organizational and administrative measures and demonstrate fulfilment of waste package specifications to the competent national authority. In the case of an existing or anticipated repository, the waste generators and conditioners have to demonstrate the fulfilment of waste acceptance requirements to the operator of a repository and provide all necessary (duly documented) information requested by the operator of the disposal facility.

Repository operators

The operator of a repository is responsible for the design, construction, operation and post-closure arrangements necessary to comply with national regulatory requirements, particularly with respect to safety issues. The operator should prepare waste acceptance requirements based on the results of a site specific safety assessment. In addition, he should verify that waste packages to be disposed of comply with the waste acceptance requirements (i.e. waste package specification which are incorporated into the waste acceptance requirements). With respect to possible deviations, the operator of a repository should implement appropriate measures and procedures for dealing with non-conformities The competent authority should approve these measures. Records on the disposal of radioactive waste shall be maintained in compliance with national regulations.

Waste classification and categorization

Radioactive waste is generated as a consequence of human activity in different kinds of facilities and comes in a variety of physical and chemical forms. The main activities that generate radioactive waste include nuclear power plant operations, reprocessing and other nuclear fuel cycle activities, nuclear research activities, and medical, research and industrial applications of radioactive materials.

Classification systems for radioactive waste may address safety related aspects, engineering demands, or regulatory issues. The classic approach is to focus on the safety related aspects, given the high risk potential that radioactive waste has to humans.

The appropriate waste classification scheme should be established according to national programmes and requirements. However, it would be desirable if an international consensus could be reached on this matter.

Some natural classification systems exist, e.g. the differentiation of radioactive waste according to the physical state, i.e. solid, liquid, gaseous. It is also possible to group the radioactive waste in terms of its origin. These classifications, however, do not reflect the clear linkage to safety aspects in radioactive waste management.

The IAEA waste classification system [26] emphasizes that waste allocated for disposal in near surface disposal facilities is primarily short lived low and intermediate level waste (LILW-SL) containing low concentrations of long lived radionuclides. Some residual long lived (LL) nuclides are acceptable. Institutional, decommissioning waste, and much of nuclear power plant (NPP) operational trash (paper, gloves, clothes, etc.) contaminated with low levels of long lived radionuclides fall into this category. Generic waste acceptance criteria and the current practice for near surface disposal in various countries limit activity concentration of long lived alpha emitters to 4000 Bq/g in individual waste packages and to an overall average of 400 Bq/g per waste package [32]. However, these limits cannot be applied rigidly. It is possible that disposing of larger volumes of waste will result in lowering concentrations not only of alpha emitters but also of long lived radionuclides on the basis of a safety assessment.

Radioactive waste should be categorized in terms of its physical, chemical, radiological and biological properties in order to facilitate its management into an acceptable form for disposal and to assure that the waste package will meet the waste acceptance requirements. The specification of each arising waste stream should start from its generation and consider interdependencies among pre-treatment, treatment, conditioning, storage and disposal steps, with conditioning being the principal waste package fabricating step. The specification of waste streams is important to facilitate the tracking and surveillance of each waste category by producers and operators of radioactive waste management facilities and to provide required information to the regulatory body.

2.2. RELATIONSHIP BETWEEN WASTE PACKAGE SPECIFICATION AND WASTE CONDITIONING

Conditioning of radioactive waste involves those operations that transform radioactive waste into a form suitable for handling, transportation, storage and disposal. The operation may include placing the waste into containers, immobilization of radioactive waste, and providing secondary packaging. The main objective of waste conditioning is to limit the potential for dispersion of the waste and to reduce the voids within the container, thus providing overall integrity and stability to the package.

Before packaging into a container, the volume of waste is often reduced by compaction, incineration, sedimentation or melting. For example, combustible low level waste, such as contaminated clothing, plastics, paper, wood or any other organic matter, is usually incinerated, and the ashes are incorporated in a stabilizing matrix material. Different types of conditioning materials are available. Cement is often used; bitumen and polymers have also been used. The main immobilization method for high level liquid radioactive waste is vitrification in a glass matrix, although ceramic matrices are also suitable.

The current waste conditioning and packaging technologies are relatively well advanced, although they still benefit from continuing research and development activities, They are described in a number of IAEA publications [12–19]. Considering the length of time that both near surface and geological repositories require for their development, an additional element of the waste conditioning process should be devising suitable arrangements for reviewing and updating waste conditioning and packaging technologies as well as quality assurance controls.

2.3. RELATIONSHIP BETWEEN WASTE PACKAGE SPECIFICATION AND INTERIM AND LONG TERM STORAGE

Storage of radioactive waste has long been practiced for various technical, economic or policy reasons. Storage is by definition an interim measure [11]. The term ‘interim storage’, as used in this publication, refers to comparatively short term (temporary) storage, consistent with Ref. [16]. Long term storage of waste is becoming an increasingly important and topical issue, given that several Member States have encountered difficulties in the development of complete disposal processes for various waste types. Therefore, some Member States plan to put such wastes in storage facilities for longer periods before disposal systems and facilities are designed and constructed. It must be recognized that the expected duration of the storage period will impact on waste package specifications. Longer term storage indicates a need for more robust waste package specifications. The operator of the interim storage facility can be the waste generator or conditioner or a separate organization. The operator is responsible for defining appropriate acceptance requirements on the waste package to be stored in his facility. These requirements should be developed in coordination with both the storage facility operator and repository operator in order to take into account the known waste acceptance requirements, if they are available.

In some instances, waste containers have experienced significant degradation while in storage. Therefore, waste packages must be kept under appropriate conditions during the period of storage in order to ensure that they will be suitable for handling and transport to a repository. In addition, a set of provisions must be implemented in case reworking of packages (e.g. repackaging) is needed, in particular, with respect to long term storage.

2.4. RELATIONSHIP BETWEEN WASTE PACKAGE SPECIFICATION AND WASTE DISPOSAL OPTIONS

Safe management of radioactive waste can be achieved by adhering to the basic principles of radiation protection, proper planning, and the adoption of appropriate methods for conditioning, handling, transportation, storage, and disposal of radioactive waste. A widely held view is that short lived low and intermediate level radioactive waste can be conditioned into proper waste packages and disposed near the surface. High level and long lived radioactive wastes require a higher degree of isolation and should be disposed predominantly in deep geological formations. The following paragraphs briefly describe these two options.

2.4.1. Near surface disposal

Near surface disposal facilities are used in several countries for short lived (usually with a half-life shorter than 30 years) low and intermediate level wastes. Such disposal facilities consist of concrete vaults at shallow depths or rock caverns and boreholes at the depth of tens of meters. Near surface disposal facilities can provide the required isolation of radioactive substances for hundreds of years. The required duration of repository institutional control will impact package specifications, with more robust packaging required for longer disposal.

Near surface disposal consists of isolating the waste by engineered or natural barriers. Engineered barriers can include the waste package (including the waste form and the waste container) and other manmade features, such as vaults, covers, linings, grouts and backfill material, which are intended to prevent or delay radionuclide migration from the disposal facility into the surroundings. For very low level waste, near surface disposal with simplified engineered barriers or landfill type repositories may be adopted.

Near surface disposal facilities are generally suitable for solid and solidified radioactive waste. Liquid wastes should be conditioned by cementation or with other materials such as polymers or bitumen, as described in Section 5.4.3.

Conditioning (solidification or immobilization) and waste packaging are typically carried out before transport to the repository site. For some types of waste, these operations may be carried out at the disposal facilities.

After closure of the repository, site surveillance, within a predefined period of institutional control, is generally implemented. Site monitoring and surveillance may include such operations as restriction of access, maintenance, documentation and remedial actions including waste retrieval and repackaging.

For more details on near surface disposal, refer to [7, 8, 28, 33–38] and Section 5.4.

2.5.2. Geological disposal

Radioactive waste containing significant amounts of radionuclides with long half-lives (i.e. long lived nuclides) require long periods of confinement. Longer disposal periods and the conditions of disposal impact on waste package specifications. These wastes include intermediate and high level waste originating from reprocessing of spent fuel elements, spent fuel when declared as waste and long lived alpha bearing waste. Deep geological formations of very low permeability or formations covered by overburdens of very low permeability (e.g. thick clayish layers) offer the greatest potential for long term isolation of such waste. A national waste management strategy may require that long lived waste and all other types of radioactive waste be emplaced in a geological repository, bypassing the near surface disposal option.

Many disposal concepts are possible in different host rocks such as granite, clay, tuff or salt with a minimum depth of a few hundred meters. In the design of geological repositories, the characteristics of the site, host rock, and the properties of the waste packages should be taken into account. Geological repository design is an iterative process and the design may be modified as new data about the site are generated during the above ground and underground characterization.

By definition, disposal means that there is no intention to retrieve the disposed waste. Nevertheless, retrievable disposal concepts may also be considered (e.g. in order to enhance public acceptance or to provide for unforeseen developments). Retrieval has implications on the design of waste packages and the repository.

Geological disposal programmes are in progress in various countries. Technological capability for the construction of geological repositories based on current drilling, tunnelling, backfilling and sealing technology is available. Experiences are being gained in underground laboratories and pilot facilities.

For the status and details on geological disposal, see Refs [27, 29, 30, 33, 34] and Section 5.5.

3. WASTE PACKAGE CHARACTERISTICS

A radioactive waste package is the product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner) prepared according to requirements for handling, transport, storage and/or disposal. The waste package can be characterized by its radiochemical, chemical, physical, and mechanical properties, which arise from the package contents and the packaging process. Some of these properties can be determined by direct measurement; others must be inferred on the basis of compliance with quality assurance (QA) and quality control (QC) systems, supported by development work. These properties can be used to describe and control the nature and content of the waste packages and thus provide assurance of package quality. Methods for determining the radiochemical and other properties of the waste packages must be approved by the national authorities to ensure that the waste package meets requirements for safe storage, handling, transport and eventual disposal.

3.1. WASTE FORMS

The "waste form" refers to the waste in its physical and chemical form after treatment and conditioning, resulting in a solid product prior to packaging. The primary safety requirement applied to the waste form is to confine and retain the radioactivity in the waste, which usually requires processing or immobilization of the waste items (e.g. producing sludge by chemical co-precipitation). However, freely packed loose waste may be acceptable, particularly when radioactivity is immobilized by the nature of the waste.

Waste forms can be homogeneous or heterogeneous, consisting of various materials and objects. They may be in the solid state originally or solidified by using conditioning technologies. A heterogeneous waste form is more difficult to characterize than a homogeneous waste form. It requires a more conservative approach in safety assessment, and requires an advanced package design.

Below is a description of the radiochemical, chemical, physical and mechanical properties that may be used to characterize and specify the waste form. It also includes information about the conditioning process with reference to practical control methods.

3.1.1. Waste form development

The waste form contributes to the waste package specification. The selection of a suitable waste form typically requires extensive development work. This work is largely to ensure physical and chemical compatibility between the waste and the immobilizing materials or the suitability of other treatments such as dewatering, drying or compaction. Another important objective of such work is to confirm, as far as possible, the ability of the waste form to perform adequately in handling, transport, storage and disposal environments. The results of such work may be used to evaluate the waste package design against waste acceptance requirements for any new waste package productions. Additional reworking on existing waste packages may be required depending on any deviations or discrepancies and their potential impact on the operational and long term safety of the repository.

The radionuclide release mechanisms for a variety of waste products, especially those containing heterogeneous waste and organic matrices, are not well understood. For this reason, although there is a significant amount of leaching data, the available information is challenging to model and predict waste form behaviour over the long term. In this respect, more research and development work is needed to generate and interpret data on radionuclide release from such waste forms.

It is important to test the durability of waste forms under conditions likely to be encountered in a repository setting both during operation and after closure (immersion testing, freeze-thaw cycles, compressive strength, etc.). Furthermore, as changes in waste form properties over time are likely to affect long term leaching behaviour. In order to predict waste form performance, it is important to establish the degradation-induced changes in leaching mechanisms, rates of changes, and mass transport properties of the degraded waste forms.

Chemical and mechanical stability of the waste form is important for the overall integrity of the waste package. For example, the waste form, together with the container, must have sufficient long term mechanical strength to withstand the load due to stacking of containers and backfill. Loss of waste package integrity can, in turn, contribute to instability of the disposal module and cover. Impact resistance and compressive strength are important properties that are tested to ensure that waste forms and packaging possess sufficient physical strength to maintain structural integrity under anticipated repository conditions [19, 28].

In summary, typical research and development work includes the following:

- composition selection tests for immobilizing and coating materials;
- strength testing (e.g. tension, compression and impact);
- confinement properties (e.g. leach testing);
- thermal tests (e.g. freeze/thaw cycling and fire performance);
- gas generation (radioactive and/or inactive) and dispersion analysis (e.g. cracking trials);
- degradation tests (e.g. corrosion, microbial activity, radiation damage).

3.1.2. Conditioning process

The waste conditioning technique applied to achieving the final waste form commonly impacts on waste package design (e.g. dewatering laterals and fill head connections for dewatered wastes. The conditioning process will be implemented and inspected according to national regulations and quality assurance (QA) and quality control (QC) programmes (see Section 6). For specific wastes, pre-treatment may be needed before conditioning (e.g. chemical adjustment).

Detailed consideration of the entire conditioning process should facilitate identification of all significant properties of waste forms and contribute to the definition of waste package specifications. The following aspects of the conditioning process are of interest:

- The origin and form of the raw waste, together with any preconditioning processes and blending of waste streams;
- Sampling and analysis of the raw waste for use in the further conditioning of the waste or for determining information to be entered into the conditioned waste data records;
- Composition limits on the waste feeds including solids content and any excluded materials;

- The process conditions including any limits on physical properties of feed materials (e.g. temperature, fluidity);
- Acceptable ranges of components to produce an acceptable waste form, including ratios of waste to immobilization matrix, and components of the immobilization matrix;
- The mode of feeding the raw waste into the conditioning process (e.g. batch or continuous) together with batch sizes and flow rates;
- A description of the conditioning process flow sheet and equipment used;
- The physical and chemical processes that the waste undergoes in reaching the final waste form, including technological operations, data on materials (formulations), and operating parameters;
- Raw materials to be used (e.g. glass frit, cement, sand, aggregates, water, additives);
- Secondary wastes and recycled material such as off-gas or decontamination liquors;
- Container filling techniques, including the addition of non-active material such as capping grout (grout added to top off a container to eliminate or minimize void space);
- Arrangements for temporary storage (e.g. to allow the package to cool or cement to set) and container closure;
- Heat generation due to source term or conditioning processes; and
- Combustibility, pyrophoricity or other properties of waste form materials to mitigate the potential impacts of fire.

Based on an analysis of all aspects of the conditioning process, a description of the in-process monitoring, measurements, checks and controls should be prepared. A flow chart may well display the main process steps and identify any production hold points, quality assurance checks, measurement points, and the release point for completed waste products. These factors have the potential to affect waste package properties. Such a flow chart would help identify the key control parameters and uncertainties for inclusion in formal QA and QC documentation. They should be updated in light of operational experience, especially if this experience results in developments to the process.

3.1.3. Radiochemical parameters

Radiochemical parameters impact on waste package design and specification. The principal waste acceptance requirement states that authorized limits must be established on radionuclide inventories and concentrations for individual waste packages and the repository as a whole. External dose rates and surface contamination of the waste packages must comply with transport requirements and with any other values derived in relation to radiation protection of workers at the waste repository [7].

The selection of radiochemical parameters to meet the acceptance requirements depends strongly on the waste type and disposal concept; however, in the first place, it is directly related to safety significance (handling, transport, storage and disposal). In all cases the total activity of the waste package would normally be required, with contributions from alpha and beta/gamma activity separately identified. Further radiochemical parameters may be defined for a number of reasons. For example, it may be necessary to limit the external dose rate in order to conform to package activity limits, to minimize impact on overall facility capacity, to control fissile material content to avoid nuclear criticality, or to comply with restrictions on the release of active gases (e.g. ^{222}Rn).

Generally, control of particular radionuclides is required for the following reasons:

– *Handling considerations*
  - high energy gamma emitters that require shielding;
  - high concentrations of alpha emitters that require tight containment;
  - spontaneous neutron emitters or materials that result in neutron release.

– *Storage considerations*
  Issues similar to those required for handling with the addition of radioactivity accumulation, which may result in additional shielding or containment requirements.

– *Disposal considerations*
  The radionuclides relevant to handling and storage remain important for the operational phase of the repository. In addition, long lived radionuclides, such as ^{36}Cl and ^{129}I, will become important after closure, given that they can dominate the assessed long term safety of a disposal facility.

The control of radionuclide concentration and of radiochemical parameters can be achieved by established methods. They are based on nuclear instrumentation consisting of a radiation detector and associated electronic equipment. A general overview and description of the analytical application of nuclear techniques is provided in a recent IAEA publication [39].

For wastes which are essentially identical in terms of radionuclide concentration (e.g. multiple containers of combustible waste from similar plant areas or multiple batches of spent ion exchange resin arising from the same demineralizer under similar operating conditions), a single comprehensive analysis of radionuclide ratios may be used in the determination of long-lived nuclides within other batches or containers. This is accomplished by developing and applying scaling factors (also called “fingerprints”) which correlate the ratios of easy to measure, predominant radionuclides to difficult to measure (DTM) radionuclides.

Measurements also can be performed at various points during the conditioning and packaging process. These range from analysis of the raw waste through in-process assay to dose measurement techniques on the completed waste package, the results of which can be interpreted in terms of radionuclide spectra. The accuracy of measuring instruments and statistical variations in processes can be combined to determine the variance of the determined values for each parameter.

3.1.4. Chemical and biological parameters

The chemical and biological parameters may be crucial for stability and containment characteristics of the waste package and surrounding barriers. (Consider, for example, chemical or microbial generation of gas and/or heat, corrosion, etc.) They would normally include a description of the organic and inorganic components of the waste, its acidity or alkalinity, its corrosiveness, and its potential interaction on processing (e.g. retardation of setting/hardening, exothermic reactions, gas release). Control or limitation of such parameters may be achieved by additional chemical treatment of the raw waste (e.g. neutralization) or by destruction of unwanted compounds (e.g. by incineration). These operations are normally required to be performed prior to immobilization. In addition to controlling these overall chemical and biological properties, consideration should be given, in particular, to the following:

- The free liquid content may need to be limited, so dewatering or drying may be required before conditioning or final packaging;
- Certain organic substances may need to be excluded or destroyed in order to prevent their microbial degradation or because of their chelating action;
- A proper formulation for the waste form composition shall be determined in order to ensure its physical, mechanical and chemical stability during handling, transport, interim storage and the operational phase of the repository. Furthermore, the waste form shall be compatible with the environment prevailing under disposal conditions. For this purpose, restriction on the content of certain reactive materials (e.g. some non-ferrous metals, unhydrated oxides, ion exchange resins) may apply;
- Hazardous materials (e.g. explosive or combustible materials) may need to be treated or made safe;
- The chemical toxicity of waste components might be significant (e.g. cadmium, lead, mercury, benzene); so the total inventory should be determined and limited, as appropriate;
- The potential generation and release of noxious or poisonous gas should be controlled, especially where human contact is possible.

The need for control of the package content for these and other prohibited materials and chemical and biological processes will need to be examined on a case-by-case basis, making use of results from the waste form development work and assessments of their significance for safety.

3.1.5. Physical and mechanical parameters

These package parameters relate to the mechanical stability of the waste form and to its ability to be handled, stored and disposed of in an appropriate manner. The selection of key parameters will depend on the waste type, treatment and conditioning processes, intended final waste form, and national disposal concept. The following parameters may be relevant, depending on the national programme:

- Mass (kg);
- Density (g/cm^3);
- Heat output (W/package);
- Compressive strength (stack ability and impact) (MPa);
- Tensile strength (MPa);
- Microscopic porosity (%);
- Macroscopic voidage (%);
- Thermal conductivity (W/m.°K);
- Heat capacity (J/kg. °K);
- Radiochemical and chemical homogeneity;
- Water permeability (saturated) (m/sec);
- Gas permeability (dry) (m/sec);

- Diffusivity (m^2/sec);
- Dimensional stability (%);
- Gas (radioactive and/or inactive) generation rate (m^3/yr);
- Leach rate (g/cm^2.day);
- Surface area (after cooling) (m^2/package);
- Thermal expansion (1/°K);
- Softening point (°C);
- Flash point (°C);
- Setting time (hrs);
- Swelling (m^3/year);
- Ageing (days or years);
- Volatility (g/cm^2.day);
- Young's modulus (N/m^2);
- Transformation temperature range (ºC);
- Liquidus temperature range (ºC);
- Devitrification (volume percentage).

These parameters are measured and controlled by established conventional methods. As indicated for the radiochemical parameters, similar statistical techniques will be required to establish variance and to include it in the determined values.

3.2. WASTE CONTAINERS

The waste container is designed to contain, physically protect, and/or radiologically shield the waste form during the various activities involved during the period from conditioning until emplacement and closure of a disposal facility. In some cases the container also plays a role in the near field containment of the radionuclides for a certain period after closure. The main parameters and control methods are the following:

Materials of construction

Typical container (packaging) materials are metals, fibre and concrete or some combination of these. Plastics, such as high density polyethylene (HDPE), are some of the other materials being considered or currently in use for high integrity containers (HICs) fabrication. In order to prevent or limit the rate of release of radionuclides and other contaminants, some packages in the process of conditioning are provided with additional internal barriers (for example, absorbing materials and liners). For the purposes of transportation, storage and disposal, they may be provided with an additional canister or an overpack. Materials of construction are normally selected using established engineering design techniques. Testing and development work is also necessary to verify the selection. This can range from simple strength testing through corrosion simulation to long term integrity and durability tests, such as creep testing. Specific tests of radionuclide release properties might be implemented if the container is also designed for additional (barrier) containment purposes.

Geometric shape and dimensions

Geometric shape and dimensions are designed taking account of the prime purpose of the container and the environmental conditions to which it will be subjected. A range of standard shapes and sizes of containers can be developed, although cylindrical drums and rectangular (often cubes) boxes are most common. Advice is available on the design of waste containers for particular uses in References [12, 16, 36]. The wall thickness can vary significantly to suit the intended use and performance objectives (e.g. corrosion resistance, corrosion allowance, radiological shielding), but manufacturing tolerances must be respected, especially for handling features. The shape and dimensions of handling features should be controlled, especially in remote environments where human intervention is undesirable or impossible.

Design and operation of internal features

Waste containers may be designed for in-package mixing of waste and the immobilization matrix (e.g. with a paddle), for grouting of buoyant materials (e.g. requiring hold-down apparatus), for receiving inner container (e.g. in polyethylene), or for internal guides to centralize the wastes. These package ‘internals’ should be selected for compatibility with the waste form and the container materials.

Lifting arrangements

The containers will need lifting features to be compatible with the existing and expected equipment used at the waste generation, interim storage, and repository sites. High dose rate packages will require distance handling considerations (e.g. easy lifting grapples and cables).

Container internal corrosion

Internal protection may be required e.g. to avoid galvanic corrosion or in case of production of corrosive agents (due to radiolysis or chemical interactions between different components of the waste form). The application of an internal protection should be addressed, particularly in the frame of long term storage.

Container strength and stackability

The container is often designed to be stacked directly, either during storage or in the disposal facility. The packages should normally be designed to support the maximum expected load induced in such a stack, without support from the waste form. Note that in a disposal repository, the expected load may include multiple containers plus the closure cap and overburden.

Selection of surface coating and texture

Selection of surface coating and texture is particularly important in the control of surface contamination. It is also a controlling factor for internal and external galvanic (corrosion) action. Specially developed paints may be used to inhibit corrosion and extend container life, depending on the application.

Design and operation of closure features

All containers will need to be closed for storage, transport and disposal. Closure can be engineered (e.g. bolts or clamps) or permanent (e.g. welded). Packages may be sealed or vented depending upon the gas generating characteristics of the waste being contained. Where venting is necessary to avoid over pressurizing of the container and the accumulation of potentially explosive gases, filtered vents should be used.

Resistance to environmental conditions

Containers should be designed to withstand all anticipated environmental impacts during their required service life. These include long term accumulated radiological dose (alpha, beta/gamma and neutron), thermal impact, and chemical or corrosive attack.

3.3. WASTE PACKAGES

The waste package should be produced under an appropriate QA and QC system, which would specify compliance testing for some key package parameters at the time of waste packaging (see Section 6.3). Nevertheless, the waste packager or disposal organization may decide to perform some further regular or random measurements. These would focus on parameters of special interest that can be determined for a complete package or that might be required by national or international frameworks (e.g. transport regulations).

Package marking

Each packaging represented as manufactured to a given national specification or a UN standard must be marked on a non-removable component of the packaging with specification markings conforming to the applicable specification. Such markings should appear in an unobstructed area, with letters and numerals identifying the standards or specification (e.g. UN 1A1, DOT 4B240ET, etc.). The markings must be stamped, embossed, burned, printed or otherwise marked on the packaging to provide adequate accessibility, permanency, contrast, and legibility so as to be readily apparent and understood.

A United Nations (UN) standard packaging may be marked with the UN symbol and other specification markings in conformance with national regulations. The marking must include the name and address or symbol of the packaging manufacturer or, where specifically authorized, the symbol of the approval agency certifying compliance with a UN standard. Symbols, if used, must be registered with the appropriate national authority.

Waste package mass

The gross mass can be confirmed after completion of the package. It is an important parameter for both handling and stacking in a storage or disposal facility. A gross weight restriction will apply to packages with respect to transport and handling at the storage and repository sites. This, in turn, will determine a band of acceptable weights on individual waste containers. Mass is also taken into account because waste acceptance requirements often define radionuclide limits in term of specific activities.

Radionuclide inventory

Depending on the type and content of radionuclides in the waste and the conditioning process chosen, the radionuclide inventory can be determined either by analysis of the raw waste or by direct measurement of the waste package. Some radionuclides are difficult to measure, thus it is of value to develop radionuclide ratios (scaling factors “fingerprints”) between difficult and easy to measure radionuclides. Where the fingerprint of the waste is known, the detection of some radionuclides may be sufficient to infer the presence of many others.

Dose rate

The waste packager should confirm the external radiation dose from the waste package and transport package (if different), in accordance with Reference [9] and as may be modified by national requirements.

Surface contamination

The waste packager should check the external surface of the waste package for alpha and beta/gamma contamination, usually in accordance with Reference [9] but sometimes modified by national requirements. The detection of external contamination may indicate a loss of package integrity.

Heat output

The waste conditioner should provide information on the heat output of the complete waste package. For packages with high heat output, this may be measurable directly; in most cases, it will need to be calculated on the basis of the radionuclide inventory, taking account of an appropriate period of radioactive decay.

The contribution of other sources of heat (e.g. resulting from the completion of cement hydration) remains marginal and will not, therefore, be further considered.

4. WASTE ACCEPTANCE REQUIREMENTS

4.1. INTERDEPENDENCIES AMONG WASTE ACCEPTANCE REQUIREMENTS AND WASTE PACKAGE SPECIFICATIONS

In order to achieve the overall objective of radioactive waste disposal, it is essential to have proper planning for all necessary steps in radioactive waste management. It is important to notice that there are interdependencies among and between various steps, and decisions made at one step may affect subsequent steps or foreclose viable alternatives. It is therefore of great importance to manage radioactive waste within the chosen system, avoiding conflicting requirements that could compromise safety. Given that disposal is the last step in radioactive waste management, it should also be taken into account when any other upstream radioactive waste management activity is being considered. In addition to predisposal processing activities (e.g. pre-treatment, treatment or conditioning of radioactive waste), transport and storage-related activities represent interdependencies that may influence, and may be influenced by disposal-related activities.

The establishment of radioactive waste disposal facilities depends on the national nuclear energy programme and the status of its realization and implementation. Member States might have to face the problem that a repository is not yet available. Thus, disposal of radioactive waste may only be carried out in the future, and situations may occur where decisions (e.g. on radioactive waste conditioning) must be made before all radioactive waste management activities are finally established. Despite such deficiencies, radioactive waste arisings must be dealt with, requiring guidance with respect to conditioning, handling, transport, interim storage and disposal. Such circumstances underscore the importance of preparing waste package specifications — even in a preliminary form — and the need to gain their approval by the competent national authority. Providing such guidance at an early stage contributes to fostering the stepwise implementation of an overall radioactive waste management system.

Waste package specifications may either cover a broad range of different waste packages or be established for individual waste package types. Specification development should focus on assessing or controlling the radiological, physical and chemical properties of waste packages in order to be accepted for storage and disposal. Waste package specifications are usually oriented toward the performance or control of specific conditioning processes. It is therefore expected that they will address all relevant parameters of the waste forms and the waste container known prior to conditioning as well as any additional requirements originating from the facility. In addition, the specifications should consider the intended storage facility and the transport regulations and incorporate any relevant parameters from waste acceptance requirements, if available.

In response to further development of the national programme, such waste package specifications might be introduced into the planning work for a near surface or geological repository, depending on the national strategy. Thus, they might serve as input data for the site specific safety assessment of a repository and be further developed in accordance with the results.

For countries that have a repository already available or anticipated, a site specific safety assessment should already have been performed. The assessment results should form the basis for the preparation of quantitative waste acceptance requirements. Depending on the national strategy, waste acceptance requirements may constitute a flexible system of requirements, tailored to the radioactive waste generated and that allows improvements and future developments in waste conditioning techniques. Such a flexible system may include different options for the waste packages to be disposed of, all of which ensure the required level of safety for the repository in the operational and post-closure phases. The waste generators and conditioners thus have the possibility of applying and fulfilling those requirements that are specifically applicable to the radioactive waste packages they produce and intend for disposal. Naturally, such a flexible system of requirements would be considerably complex. However, the advantages offered to the waste generators and conditioners may well outweigh this apparent disadvantage.

In addition to existing or anticipated waste acceptance requirements, it may be necessary to prepare and implement waste package specifications. Such specifications identify, for each requirement, the respective waste package characteristics or the operational parameters of an appropriate conditioning process (waste processing and packaging). In addition, the waste package specifications may contain supplementary data, thus further demonstrating compliance with the repository-related waste acceptance requirements.

According to the national programme and strategy, the waste package specifications, as well as the waste acceptance requirements and the waste package acceptance process, should be periodically reviewed and revised, if necessary. This may be the case if safety related assessments are re-examined and adapted to new findings, results or experiences. Thus, waste package specifications and waste acceptance requirements will remain consistent with revised safety assessments and safety related issues.

Whether or not a repository is available, it is likely that radioactive waste will be transported and stored prior to disposal. Transportation and storage require the fulfilment of safety related issues. Thus as noted previously, the development and preparation of waste package specifications — as well as waste acceptance requirements — should address disposal related issues, as well as transport and storage related issues.

4.2. DEVELOPMENT OF REQUIREMENTS

Waste acceptance requirements are quantitative criteria or qualitative guidelines specified by the regulatory body that determine whether a waste package is acceptable for disposal or storage [11]. These criteria serve as a benchmark for repository operators who accept radioactive waste for disposal and for operators who accept waste for storage. The acceptability of waste packages can be judged in relation to the specific conditions of a given waste management step [23–26].

The development of requirements for radioactive waste disposal might be performed with respect to international safety standards and recommendations presented in Refs [2, 7, 8 23–36, 40–47]. According to these publications, reasonable assurance for the safety of each individual disposal system can be provided in a stepwise approach, based on site specific safety assessments of the operational and post-closure phases. The following three stages can be distinguished with an interaction between waste package characteristics and repository design:

(1) First, generic requirements are defined (a) on the basis of the national radioactive waste disposal policy; (b) on general information on the types and quantities of waste expected to be generated; and (c) on the availability of potential sites.
(2) Site selection and site characterization follow to determine the characteristics of the disposal site.
(3) Finally, specific waste acceptance requirements are established.

Depending upon the specific national situation, the development of waste acceptance requirements must encompass disposal of all types of radioactive waste. In their preliminary form, they may qualitatively specify the measures to be taken to achieve the protection objective of disposal and define the principles by which it must be demonstrated that this objective will be reached, i.e. technical measures and methods or procedures are to be adjusted to one another. They shall emphasize the importance of site selection, the system consisting of geology/repository/waste packages, the multibarrier concept, and the use of state-of-the-art technology. These requirements should result from a site specific safety (performance) assessment of the operational and post-closure phases of a repository.

Requirements for disposal may address relevant waste package parameters as well as any additional requirements imposed by the licensing and supervising authorities. They may either cover a broad range of different waste packages or be established for individual types of waste packages.

Naturally, the waste acceptance requirements permit some freedom of judgement and approaches. The uncertainties gradually diminish in fostering the national radioactive waste management and disposal concept or in the realization of a repository project. This may be determined by a site specific safety assessment, within the scope of which the required safety of the repository in its operational and post-closure phases must be evaluated quantitatively, including the derivation of requirements on the design of the disposal facility, as well as on the waste packages.

In any case, the protection objective of disposal can only be achieved within an iterative process drawing together more detailed information as the repository project progresses through its various phases of investigation, conceptual planning, detailed design, and performance assessment, consequently assuming more stable forms. Thus, the original qualitative waste acceptance requirements (guidelines) may assume a more quantitative character (criteria). Quantitative waste acceptance requirements for a near surface or geological repository can be defined at an advanced stage of development based on the results of a site specific safety assessment. Such an assessment should consider the geological situation, the technical concept/design of the repository, its scheduled mode of operation and the waste packages to be emplaced.

4.3. SITE SPECIFIC SAFETY ASSESSMENTS

A site specific safety assessment allows quantitative waste acceptance requirements to be established in a relevant and credible manner. Its key components are as follows [26]:

— the specification of the assessment context (Step 1);
— the description of the disposal system (Step 2);
— the development and justification of scenarios (Step 3);

— the formulation and implementation of models (Step 4); and
— the calculations and interpretation of results (Steps 5 and 6).

When developing an actual disposal system, iterations of these steps can be performed according to the expected waste package characteristics, and modifications may be introduced.

While carrying out safety assessments, the process for all stages of disposal must be carefully analyzed, potential radionuclide release pathways identified, and possible releases evaluated. Analysis must cover both the operational phase and the post-closure phase of a repository, including a surveillance phase if required.

The main criterion underlying the derivation of waste acceptance requirements is that the consequential risks to workers and to the public do not exceed the radiological protection criteria [2, 7, 27]. Thus, site specific safety assessments must cover the following aspects [8, 26, 40, 41]:

(1) Assessment of doses or risks to the operating staff and to the vicinity of the repository resulting from direct and scattered radiation as well as from radiation due to radioactive substances released from the waste packages and being discharged (normal operation);

(2) Assessment of doses or risks to the operating staff and to the vicinity resulting from radiation due to radioactive substances released as a result of mechanical or other plausible failures of waste packages in the operational phase (assumed accidents);

(3) Assessment of doses or risks resulting from radiation within the site and its surroundings in the post-closure phase, including radiological effects due to radionuclide migration through the geosphere and/or due to inadvertent intrusion (post-closure safety).

In the case of disposal of waste packages containing considerable amounts of long lived radionuclides (alpha emitter bearing waste) or heat generating waste such as vitrified fission product solutions originating from reprocessing of spent nuclear fuel or spent nuclear fuel itself (when declared to be a waste), performance assessments have to be extended to include these issues:

(4) Nuclear criticality safety in the operational and post-closure phase (criticality safety);

(5) Decay heat of the radionuclides contained in the waste packages (thermal impact upon the engineered barriers and the host rock in the near field and far field).

In assessing the safety of the normal operation of a repository, volatile radionuclides such as ^{3}H, ^{14}C or ^{129}I are of special importance. With respect to assumed accidents, scenarios involving the release of radionuclides due to mechanical or thermal loads, fire, etc., must be investigated and radiological consequences determined. Thus, possible containment properties of the waste form and the waste container could be defined.

Ensuring post-closure safety is of utmost importance. In the case of a waste repository (i.e. in near surface or deep geological formations), these issues must be addressed:

(i) possible release scenarios and release paths must be identified (including the potential for inadvertent human intrusion);

(ii) the migration of radionuclides through the geosphere to the biosphere must be investigated considering the oxidation state of the radionuclides, their sorption and desorption behaviour, and any other physiochemical interactions in the near field and far field; and

(iii) attention has to be paid to chemical reactions that may occur, e.g. gas generation due to aerobic and anaerobic corrosion of metals and metallic compounds, microbial activities, and radiolysis.

The data and information on waste package characteristics (see Section 3) needed for the site specific safety assessment should be supplied by the waste generators or conditioners or should be determined by research and development programmes. This information will serve as input data for a particular iteration of the repository safety assessment and can be further detailed in accordance with the results of the assessment.

4.4. REQUIREMENTS ON WASTE PACKAGES

Waste acceptance requirements might be prepared in such a way that they either define the safety related envelope for the waste intended for disposal or focus on specific requirements on individually characterized radioactive wastes.

Waste acceptance requirements might first describe the general disposal related aspects and requirements of the waste packages and then develop into more specific requirements on the waste forms, the waste containers, on individual radionuclides and activity, on documentation and record keeping, and finally on the delivery of waste packages. Thus, depending upon the near surface or geological repository, waste acceptance requirements might be structured as follows:

(1) Basic requirements on radioactive waste to be disposed:

— Prohibition of mixing non-radioactive waste with radioactive waste
— Compliance with the requirements of the site specific safety assessment

(2) General requirements on waste packages:

— Surface dose rate
— Surface contamination
— Hazardous substances content limitation
— Absence of overpressure
— Waste package mass

(3) Requirements on waste forms:

— Basic requirements (e.g. only solid or solidified waste, no free liquid)
— Specific requirements (e.g. stabilization (dispersion inhibition), heterogeneity, chemical restrictions)
— With immobilization binder (e.g. bitumen, polymer or cement)
— Without immobilization binder (e.g. radioactivity and radionuclide restrictions)

(4) Requirements on waste containers:

- — Basic requirements (e.g. geometric shape and dimensions, stackability)
- — Specific requirements (e.g. mechanical stability, thermal resistance, leak tightness, shielding function)
- — Inner containers (e.g. surface coating, seals, vents, void space restrictions)

(5) Limitations of activity:

- — Permissible activities for individual radionuclides
- — Permissible total activity per waste package
- — Permissible total alpha and beta/gamma emitter activity
- — Declaration of radionuclide-specific activities/total activities per waste package

(6) Delivery of waste packages:

- — Compliance with transport regulations
- — Permits/documentation including record keeping
- — Marking of waste packages
- — Requirements on transport containers

Regardless of the requirements for a near surface or geological repository, the regulations on transporting dangerous goods and waste packages with fissile material must be followed.

5. WASTE PACKAGE SPECIFICATIONS

5.1. GENERAL APPROACH

Waste package specifications consist of a quantitative description of waste packages prepared for disposal. As noted in previous sections of this report, separate waste package specifications should be developed for each type of waste package. The intention is to demonstrate that the waste packages will meet the waste acceptance requirements for disposal facilities. Typically, waste package specifications will describe the nature, content and performance of each type of waste package and provide a link between the supporting research and development (R&D) and package production.

It is important that all parties involved in the development, approval and implementation of the waste package specifications are consulted at the earliest opportunity. This will allow a cross-fertilization of ideas and promote smooth progress during the development, approval and implementation phases. It will, in particular, allow those involved to understand and reach a consensus on what can reasonably be expected within the specifications and on what can actually be provided.

Depending on the national legislation, a formal statement on the approval and acceptance of waste package specifications should be done by the regulatory authority and in agreement with the operator of the repository or disposal facility. In the case of waste package specifications dealing with waste to be returned from foreign countries, official statements between the authorities of those countries are to be exchanged.

In compliance with a given regulatory context, contractual negotiations on waste processing and waste disposal provide an ideal opportunity to clarify waste acceptance requirements and to define waste package specifications that must be followed. Important contractual relationships will exist between the waste generator and conditioner on the one side and the operator of the repository on the other side, even if such a facility is not yet available. Close consultation between the waste generator and the repository operator will help take account of any aspects of the wastes that are not the concern of the generators when they operate their facilities. For example, long lived activation products do not influence operation of a power plant but can be very significant for disposal.

As with any interactive project, the preparation, approval and implementation of waste package specifications require careful definition of the task, realistic programming and appropriate allocation of resources to ensure efficient progress. This will allow cost benefits to be realized, especially through avoidance of backfitting, (both of equipment and control measures) to comply with requirements that existed but were earlier ignored

Waste package specifications must be reviewed regularly and updated as required (in accordance with the quality assurance system) to ensure that they continue to define the characteristics of the waste package. New versions of waste package specifications must be issued when significant changes to the requirements have occurred. It is imperative that waste package records reflect the waste package specifications in place at the time of package design and construction, including any subsequent modifications or upgrades.

5.2. DEVELOPMENT OF SPECIFICATIONS

The development of waste package specifications is a highly interactive process involving several disciplines and organizations, with regulatory requirements being the key component for developing effective package specifications. The main duties and responsibilities of regulators, designers, users, etc. are outlined in Section 2. These bodies will be involved to different extents depending upon the stage of development reached. For each stage of package design and construction, any contractual constraints must be taken into account. If not, a list of subjects to be included in the contracts must be considered. It is important to note that reference to the waste package specifications must not be too prescriptive but concentrate on the main requirements. For example, the contract should identify whether suitability for transport, storage and disposal is required, list the main legal constraints and requirements, and suggest a time frame for the preparation, submission and approval of the specifications. In the case of international transfers of waste, compliance with any intergovernmental agreements will also be required [10].

The waste generator is the first to be involved, in order to characterize the raw waste and identify options for conditioning of the waste (see Section 3). At this point consultation with experts will be required to extract the results of technical assessments and the relevant R&D work. Additional R&D may need to be commissioned, and the design of the conditioning process, control system, measurement system and the container may need to be modified. Conditioning plant designers need to be consulted early in order to avoid expensive backfitting in the future.

Consultation with experts is an acknowledged methodology to reduce uncertainty and confer added confidence [13, 42]. Although expert review could be regarded as part of quality assurance, it has its own scientific and technical value. Confidence in the validity of results depends to a great extent on the outcome of the expert review process. Therefore, it is reasonable that evaluation activities and results relevant to the development of waste package specifications are subject to an expert review process. Evaluation results should be published so that they become available for detailed scrutiny by other experts active in the field.

Adopting the expert review process for developing waste package specifications may include forms other than the typical expert review of scientific publications. National radioactive waste management programmes normally have provisions for technical review of important activities. In some cases, the waste generator or conditioner may be required to organize critical reviews by independent bodies. Such reviews can additionally make use of the expertise of various specialists and can be effective in raising the level of confidence in the results of technical assessments and the R&D work.

While it is possible for local experts involved in the national radioactive waste management and radioactive source control programmes to do this, experience has shown that it is very helpful if external experts are involved, because a broader expertise is obtained, and blind spots are identified better. Also, while developing waste package specifications, account should be taken of the world’s best practices in this area in relation to both technology and radiation and nuclear safety. Issues of transport modelling and technologies to evaluate characteristics of radioactive waste — essential components to developing waste acceptance requirements and waste package specifications — have reached a high level of complexity. In order to ensure consistency with best practices internationally, external expertise could be of great value, especially to developing countries.

When the waste form and package concept have been decided upon, all relevant parameters should be quantified in terms of ranges that may be achieved in producing the waste package. Maximum values for each parameter and factors of safety can then be determined. Such upper limits must then be compared with quantitative requirements and reconciled either by additional constraints on the waste package content or, if possible, by relaxing the requirements. The process may require modelling of the waste production process. If a number of waste streams are combined prior to conditioning, this also should be modelled.

The specifications may be split into a number of sections. A suitable structure would cover the following items:

- general introduction;
- waste container and associated items;
- waste composition and inactive feed materials;
- formulation envelope, process description and conditions;
- waste product storage conditions;
- guaranteed parameters of the conditioning process;
- summary of the supporting R&D, identifying parameters that show the waste package is consistent with waste acceptance requirements;
- QA and QC arrangements;
- additional or supplementary information;
- figures and diagrams.

Each of these items should be developed interactively to ensure consistency. As in many other areas of the nuclear industry, experience has shown that many drafts may be needed before a formal version of the specifications is ready for issue.

During the development of the specifications it is likely that further detailed information will be required on, for example, the waste conditioning process, QA and QC arrangements, methods of determination and accuracy of parameters, the numbers of packages, and a time frame to be followed. Such information would best be provided in separate documentation so that the specifications would not become too large and cumbersome.

5.3. APPROVAL AND IMPLEMENTATION

After waste package specifications are finalized, they should be submitted for approval by the competent authority. Premature submission could cause confusion and additional expenses if a series of updates were to be issued in short succession. Clearly, changes may be unavoidable if some unforeseen developments should occur but to issue, specifications formally when they are still under development can lead to extensions of the overall programme. The final version then has to be implemented by the waste generator and conditioner.

The operator of the repository will also be involved in accepting the waste package specifications. In agreement with the regulatory authority, all necessary examinations should be undertaken to check waste package specifications, to evaluate compliance with the waste acceptance requirements, and to assess the QA and QC measures and procedures necessary to verify the waste package characteristics and properties given in the specifications. For the approval of waste package specifications, the following procedural arrangements must be addressed:

- A clear understanding of the approval procedure is of primary importance. This approval procedure will operate within a defined legal framework, with clear responsibilities and duties for the various authorities and institutions involved and may require an independent expert review.
- In order to complete the approval procedure in an efficient manner, it is recommended that a target time frame be agreed upon at the start of the process.
- Depending on Member States, foreign waste generators or conditioners may also submit waste package specifications. This is of particular importance if the radioactive waste described in the specifications originates from foreign facilities and the resulting waste packages are to be returned for disposal. In such cases, international agreements and/or commitments relevant to radioactive waste must also be addressed.
- To avoid misunderstanding or mistakes, the formal approval process should only consider the latest revision of the waste package specifications and additional pertinent publications.
- The approval of waste package specifications may be based upon two assessment procedures: a formal assessment and a technical assessment. The formal assessment should address the feasibility of the processes described, the precision and consistency of data, process parameters, and waste package characteristics. The technical assessment should be performed in a more detailed and in-depth manner, focusing on conformance with waste acceptance requirements where these are available.
- Appropriate knowledge and experience should be used wherever it is necessary and available. To evaluate the technical content of waste package specifications, the operator of a repository may consult an expert for scientific and technical support. In addition, peer reviews or other involvement by scientific expert groups may assist the competent authorities.
- Finally, the implementation of the approved waste package specifications may occur on the basis of contractual agreements between the waste generator and the operator of the repository or disposal facility.

Once the waste package specifications have been implemented, modifications should be kept to a minimum. However, should these become necessary, modifications should be issued and approved in a properly controlled manner in accordance with the relevant QA and QC system.

5.4. WASTE PACKAGE SPECIFICATIONS FOR NEAR SURFACE DISPOSAL

In the development of waste package specifications for near surface and geological disposal, many similarities exist. They are identified and described in Sections 5.4 and 5.5, respectively, using the identical approach and description pattern, and consistent with that of Section 3. The cross-references to these sections are necessary; in some parts they overlap and in others they complement each other. It is important to note that all waste packages will have to comply during transport with IAEA Transport Regulations [9] with regard to activity content, radiation and package tests as required.

As noted previously, near surface disposal facilities are primarily intended for wastes containing relatively short lived radionuclides, some of which require substantial shielding. Therefore, the preparation of waste packages for disposal in a near surface repository requires careful waste segregation and appropriate container design. The wide range of materials that may exist in these wastes will also affect the design of the waste containers and waste forms to ensure compatibility and appropriate stability and longevity. Retrievability may also be an issue in some near surface disposal concepts. The development of waste package specifications for near surface disposal will therefore need to be supported by specific R&D work and a targeted QA and QC programme described in detail in various IAEA publications [13–19, 33–37, 43]. The QA and QC issues are further addressed in Section 6, which focuses on the content of waste package specifications for near surface disposal. Section 6 also addresses the waste container, raw waste composition, waste form production, and waste package characteristics.

5.4.1. Waste container

The waste container plays a key role in ensuring safety during several stages of a radioactive waste management system, from interim storage through transport to its final disposal. Waste containers are designed to provide radiation shielding and/or physical containment to restrict or prevent the spread of contamination (see Section 3.2 for general description). With respect to the disposal of short lived radionuclides in a near surface repository, the waste container may be designed either for a longer durability or for a relatively short life. In the latter case, the container can be classified as non-durable and may have a life of a few decades. The following container characteristics should be considered.

Dimensions and mass

The container dimensions and mass must be defined with associated compliance limits. These measurements should be compatible with the requirements of existing or anticipated handling and storage arrangements, transport systems and disposal facilities.

Qualification tests

To assure that the waste container and waste package meet the design requirements, qualification tests should include examining the material of fabrication and the container or its parts during manufacture. Extensive testing would be undertaken during the design phase, with more limited testing during routine waste processing. Definitions and examples of containment, mechanical and other tests for containers used in near surface disposal may be found in the IAEA Transport Regulations [9] and in Ref [19].

Radionuclide containment

It is essential that the completed waste packages contain radionuclides during the handling, storage and transport phases. In addition, the package containment may be a barrier preventing the release of radioactivity from the repository to the geosphere or biosphere. Containment tests for packages can be performed by immersing them in representative repository groundwater.

While performing material assessments, especially for containers required to maintain integrity in the long term storage facility or to serve as a confinement barrier for extended durations in the repository, the following list of possible materials should be considered:

Concrete:

- Chemical – including leaching, sulphate attack, acid attack (groundwater/acid rain), alkali aggregate reaction, and carbonation.

- Physical – including crystallization of salts, freeze-thaw action, abrasion/erosion, temperature cycling, vibration (fatigue), building movement and excessive loading (pressure).

Metals, reinforcing and post-tensioning steel:

- Chemical – corrosion, with rates enhanced by physical degradation, acidification, and chloride attack or migration (in concrete).

- Physicochemical – relaxation of tendons affecting the induced stresses (creep of concrete or steel).

Corrosion properties

To provide containment of the waste form during storage, transportation and the initial operational phase of the repository, the container must retain its integrity for a number of decades. It could be that the disposal concept considers the specifics of the container to be a barrier after the closure of the repository. In such a case, a metallic container must achieve a required corrosion resistance, which has to be determined experimentally in special corrosion tests.

Chemical durability

Chemical durability of waste containers is crucial in delaying contact of the waste form with water and thus releasing radionuclides. It also ensures sufficient time for the short lived radionuclides to decay to acceptable levels. For example, materials used to fabricate high integrity containers (HIC) include high density polyethylene (HDPE) (see Section 3.2). Plastic container materials (HDPE, etc.) are not susceptible to corrosion although they can be severely degraded by extended exposure to ultraviolet light present in sunlight. In addition, because of problems related to the mechanical stability of plastic containers, HDPE containers are often placed in concrete overpacks to provide additional containment and structural durability lasting for hundreds of years. Chemical durability of waste containers should be evaluated with account taken of the processes listed in the preceding paragraphs (see *Radionuclide containment*).

Compressive strength

Adequate compressive strength is required for the waste container to ensure that it meets stacking requirements during storage and disposal and to ensure that the waste package is robust for handling and transportation operations. Measurements can be made on materials representative of the components, scale models of the package, or the complete package. Preservation of assigned functions may require implementation of special design features in the container, waste package or engineered barriers; for example, using tailored packing or backfill material to retain a required configuration.

Resistance to mechanical impact

The resistance to mechanical impact is important in potential accident conditions. The container must be designed so that, in conjunction with handling systems, releases due to mechanical impact are limited to acceptable levels. This may be checked by means of standard tests applied to the container or the completed waste package.

Fire resistance and combustibility

Exposure to external fire in the event of handling, transportation, storage and disposal accidents is a credible accident scenario. Therefore, technical specifications for a waste container must contain combustibility and fire resistance provisions to mitigate the potential impacts of fire and reduce the propagation of fire between waste packages.

Radiation dose rates and radiation resistance

External radiation dose rates of conditioned waste packages must be in compliance with the limits for facilities and equipment at which they will be handled. Control may be established by limiting radionuclide inventories during conditioning or by providing supplemental shielding strength to the container. Radiation can affect the waste container, and qualification tests may be required. Generally, effects of irradiation are likely to be most severe for containers constructed from polymers, less for concrete containers, and the least for metal containers. For most near surface disposal systems, radiation resistance of containers is not expected to be a limiting criterion, provided the long term accumulated dose to the package does not exceed 10^6 Sieverts (at which point plastic packages may experience creep buckling).

Labelling

Each container should have a label that uniquely identifies it and allows it to be correctly recognized and recorded during waste management steps. The durability of the label should be assured at least until the waste package is emplaced in the repository.

5.4.2. Raw waste composition

Near surface disposal is primarily designed for short lived wastes, although some wastes may contain limited concentrations of long lived radionuclides. Therefore, it is necessary that the waste package specifications provide for appropriate control and segregation of raw wastes prior to treatment and conditioning for disposal. The characteristics of the raw wastes should be known with sufficient accuracy to ensure that the content of the waste packages will comply with the specifications. The following characteristics of raw waste should be considered.

Description of the waste – origin and history

A description of the origin and history of raw waste is important with respect to deciding on the necessary segregation, treatment and conditioning approaches. Knowledge of the waste generation process is necessary for understanding physical and chemical properties of the waste and for determining its radionuclide content.

Radionuclide content

Information on the radionuclide content of raw waste is required to ensure that waste packages are produced, which can safely support specific radionuclide activities and that they meet authorized limits where applicable. Radionuclides with high initial activity, high mobility, and high dose factors are likely to be of major concern (e.g. content of tritium and other mobile radionuclides, radium and plutonium isotopes, etc.). Methods of sampling and analysis used by the waste generator (including the methodology for the derivation of scaling factors where radionuclides are difficult to measure) should be appropriate.

Fissile content

The content of fissile radionuclides should be controlled to ensure that subcriticality is maintained under all conditions likely to be encountered during the waste management process. Considering such features as the origin of the waste and the unacceptably long half life of most fissile radionuclides, criticality is unlikely to be of significant concern for waste packages designed for near surface disposal.

Physical, chemical and biological properties

Information on the physical, chemical and biological properties of raw waste is required to ensure safety during waste processing and to produce waste packages consistent with the relevant safety standards, waste acceptance requirements, and supporting R&D evidence. A discussion of the potentially significant physical, chemical and biological properties of radioactive wastes can be found in Section 3.1.

5.4.3. Waste form production

An objective of waste form production is to obtain a stable product that is compatible with the disposal environment and meets safety requirements. Therefore, differences between waste forms for near surface and deep disposal are likely to be determined mostly by the nature of the waste materials. However, waste package specifications must identify those parameters that need to be controlled in order to ensure compliance. The following aspects of waste form production should be considered.

Formulation envelope

A major purpose of developing technical specifications and of supporting R&D activities related to waste form production is to define a formulation envelope. Limits should be defined for the ratio of waste to encapsulation materials and for the ratios of different encapsulation materials if blends are used. The raw materials, mixing formula, and associated parameters must be clearly indicated with relevant tolerances.

Qualification tests

To ensure that the waste form meets the design requirements, qualification tests should be performed. Procedures should specify the characteristics to be tested, methods to be employed, prerequisites for environmental conditions, requirements for instrumentation and calibration of equipment, and personal qualifications and acceptance criteria. Qualification tests might include leachability of the waste form, gas permeability tests and accelerated ageing. Extensive testing would be undertaken during the R&D phase.

Process control

A work process consists of a sequence of events that determines or modifies important properties of the waste package to comply with waste acceptance requirements. It may include any manual, physical or chemical process performed during any stage of the waste form production from waste collection to packaging. Adequate process control means that prerequisites including environmental conditions, equipment and personnel qualification requirements, are satisfied and the process variables are controlled according to acceptance criteria written into instructions and procedures.

Limits should be defined for key process parameters that influence product quality (e.g. the temperature of ingredients and the process environment, addition rate, mixing time, curing time). A detailed description of the arrangements for controlling them should be produced as part of the waste package specifications. For ease of communication, it is recommended that this also be developed in the form of flow charts.

Binder/Immobilization matrix

A detailed description of material parameters and their control according to the particular type of binder (e.g. bitumen, cement, polymer) is given in [14, 17, 19]. Typical parameters for each binder are as follows:

Bitumen: cold resistance, content of solids, density, homogeneity, penetration, plasticity, porosity, softening point, viscosity, water content.

Cement: weight and ratio of individual mix constituents such as Blust Furnace Slag (BFS) or Pulverized Fuel Ash (PFA), water, additives, powder addition rates, mixing time, free liquids quantity, grout fluidity, temperature and addition rate, container vibration frequency, amplitude and time, grout level, curing temperature, curing time.

Polymer: mixing time, gelation time, cure temperature, tensile strength, compressive strength, elongation, impact strength, hardness.

Whatever type of binder is used, the control of raw materials used to manufacture the binder must be defined in purchase specifications. These should include tests performed by subcontractors and receipt procedures.

Inactive feed materials

The waste package specifications should define limits on the physical and chemical composition of inactive components in the feed materials (e.g. water, cement powders, acids, additives). Where present, this may include capping grout.

5.4.4. Waste package characteristics

The completed waste package will have additional overall characteristics and performance requirements, which are defined by the container and waste form but are not realized until the manufacturing process is complete. As the completed waste product is intended for disposal, the waste package specifications should identify those characteristics that need to be controlled, from waste package production to its emplacement in the repository. This period of time may be short for near surface disposal, although after emplacement such packages will be subject to climatic variations and extremes that will not be experienced in a deep disposal facility. The following overall waste package characteristics should be considered.

Package lifetime history

An overall record should be established for each package, as discussed in Section 6. To demonstrate compliance with waste package specifications and requirements, all information relevant to the control of package production (as defined in Sections 5.4.1 to 5.4.3) must be retained. Records must cover any period of storage, including package movements (with information on place and time), to record clear responsibility in case of damage. Package records should also ensure compliance with national and international requirements.

Integrity under environmental conditions

It is important to demonstrate that waste package integrity will be maintained under various environmental conditions and extremes, particularly involving climate-driven cycling of temperature and humidity (e.g. freeze/thaw, desiccation, solar heating). The waste package may be subjected to a series of cycles as part of qualification testing [19, 28]. If the waste packages are exposed to natural light, it will be important to show that they are resistant to the effects of microbial growth (e.g. algae) or biodegradation processes.

Gas permeability and release rate

Data on the release of gases from waste packages are required for safety assessment of waste disposal [28] and for radiological protection considerations during operations and transportation. Where the gas permeability of the container or waste form is too low, the venting of containers should be arranged to avoid over pressurization.

Waste package storage

The waste package specifications should define limits on the handling of packages and define the environmental conditions for storage of the completed waste packages. These may include temperature, humidity, airborne chloride levels, and stacking conditions (see also Section 5.5.4).

5.5. WASTE PACKAGE SPECIFICATIONS FOR GEOLOGICAL DISPOSAL

Deep geological disposal facilities can be used for disposal of all categories of radioactive waste; however, they are primarily intended for wastes containing long lived radionuclides. Although the disposal system will generally rely on the barrier properties of the host rock, the high level of fissile materials and the wide range of materials that may be anticipated in these wastes will also affect the design of the waste packages. Therefore, as in the case of near surface disposal, the development of waste package specifications for geological disposal will need to be supported by specific R&D work [19, 44–46] and a targeted QA and QC programme as described in Section 6.

5.5.1. Waste container

As noted previously, the waste container plays a key role in shielding ionizing radiation and containing contaminants, thus ensuring safety in various stages of a radioactive waste management system from interim storage through transport to its final disposal. High level waste (HLW) are generally placed in metallic (usually iron or steel) containers. Containers for long and intermediate level wastes (LILW) destined for geological disposal are normally made from mild or stainless steel, or concrete. Concrete containers may include reinforcements such as steel bars. Stainless steel is used to give long term stability during storage, thus avoiding the need for repackaging for shipment and disposal.

With respect to the disposal of long lived radionuclides in a deep geological repository, the container will likely provide a barrier within the repository. This may require the container to maintain its integrity for a period of at least several hundreds years. For a geological repository, its design may be important with regard to specific properties that may be suited for retrievability of waste packages. The following waste package characteristics should be considered.

Dimensions and mass

The container dimensions and mass must be defined with associated compliance limits. They should be compatible with the requirements of existing or anticipated handling and storage arrangements, transport systems, and disposal facilities. It is recommended that all constraints or functions of the container, including emplacement and potential retrievability provisions, through its different phases of life should be examined before choosing the material and the geometry of a container suitable for geological disposal.

Qualification tests

To ensure that the waste package meets the design requirements, qualification tests should be performed. These tests include examining the material of fabrication and the container or its parts during manufacture. Extensive testing would be undertaken during the design phase with more limited testing during routine waste processing. Factors specific for geological repositories that should be considered include the geochemical environment, the groundwater characteristics, the hydrostatic and lithostatic loads, and the thermomechanical properties of the host rock.

Radionuclide containment

It is essential that the waste package contain the radioactivity during the handling, storage and transport phases. In accordance with the multibarrier concept, the container (see Section 5.5.4) is likely to be a barrier preventing the release of radionuclides from the repository to the geosphere. After emplacement, a container can provide complete in situ containment of wastes for its physical life. For a certain period of time, after container failure, backfill materials surrounding the waste package may undertake the containment function by hindering or slowing down the release rate of radionuclides. This primary barrier containment function and interaction with the repository backfill may be an important issue in the container design for some disposal systems, thereby incorporating related waste package specifications within the waste acceptance requirements.

Corrosion properties

To contain the waste form during interim storage, transportation, the operational phase of the repository, and retrieval if necessary, the container must retain its integrity for several decades. To achieve this, a metallic container requires corrosion resistance, which has to be determined experimentally. Possible failure modes should be considered including general corrosion, local corrosion, stress corrosion cracking, and reactions that could alter material properties and cause early failures.

Chemical durability

Chemical durability is a key factor for long term containment. The duration of the containment function must be assessed and relevant tests or studies may be performed. These studies may include modelling of degradation of the binder or corrosion of the container. While durability of metallic containers is affected first by corrosion, performance and durability of nonmetallic containers under repository conditions can also be affected by degradation processes as a result of exposure to groundwater, waste constituents, and other chemicals present in the repository. Therefore in assessing chemical durability, it is necessary to consider chemical and physicochemical mechanisms in conjunction with plausible features, events and processes that may lead to container degradation.

Compressive strength

Adequate compressive strength is required for the waste container to allow it to meet stacking requirements during storage and disposal and to ensure the waste package is robust for handling and transportation operations. The complete waste packages have to maintain their physical dimensions and properties to the required degree under conditions of compressive loads, chemical reactions and biodegradation. Measurements can be made on materials representative of the components, scale models of the package, or the complete package.

The mechanical properties of standard containers, in particular metallic containers, may not be adequate to withstand the high pressures induced by solid rock and the tremendous overburden which can prevail at depths of several hundreds of meters. In such conditions, thick-walled overpacks will be needed to enhance the overall structural integrity of packages used in deep geological repositories.

Resistance to mechanical impact

The resistance to mechanical impact is important in potential accident conditions. Foreseeable accidents and their consequences must be identified. The physical stability of the container should be evaluated to determine if adequate containment is provided. It may be measured by means of standard tests applied to the container or the completed waste package. In particular, waste packages must be capable of sustaining a drop from a specified height and similar occurrences without breach.

Thermal resistance and combustibility

The resistance to thermal impact is important in potential accident conditions. The waste package must meet any fire protection requirements for handling, transport, storage and disposal. This can be achieved by performing tests on models of the packages and deriving, if necessary, limitations for introduction of combustible matters in waste. Qualification testing should include exposure to fires of an intensity credible for the facilities.

It also should be recognized that deep geological disposal of several hundreds of meters results in an increased geothermal gradient which may adversely impact some packaging. As a general guide, the temperature gradient increases at a rate of approximately 3 °C for every 100 meters depth.

Radiation resistance

Radiation can affect the waste container. Therefore, in addition to controlling external radiation dose rates, irradiation qualification tests on container material may be required. Such tests should ensure that radiation induced processes, which may cause degradation of material properties of the waste package, repository components and the host rock, do not occur to an unacceptable degree.

Labelling

Each container should have a label that uniquely identifies it and allows it to be correctly recognized and recorded during waste management steps. The durability of the label should be assured at least until the emplacement of the waste package in the repository.

5.5.2. Raw waste composition

A waste package specification for geological disposal must provide for the appropriate control of the raw waste composition, including the content of long lived radionuclides, prior to treatment and conditioning for disposal. The characteristics of the raw wastes (e.g. solid waste, liquid and wet waste, heat generating waste, non-heat-generating waste containing significant quantities of alpha bearing or other long lived radionuclides) should be known with sufficient accuracy to ensure that the specifications of the waste package will comply with waste acceptance requirements. The following characteristics of raw waste should be considered.

Description of the waste — origin and history

For near surface disposal, a description of the origin and history of raw waste is important with respect to deciding on any necessary segregation, treatment and conditioning approaches. Knowledge of the waste generation process is necessary, in particular for understanding the physical and chemical properties of the waste and for determining its radionuclide content. Given that wastes to be disposed in geological repositories arise mostly from nuclear fuel cycle activities, it is important to provide a detailed description of the expected fissile content in various waste streams (see below).

Radionuclide content

Information on the radionuclide inventory of raw waste is required to ensure that waste packages are produced with known radionuclide specific activity and that they meet authorized limits (where applicable). For example, the waste specifications may include upper limits on key radionuclides due to heat output or external dose constraints. Radionuclides with high initial activity, high mobility and high dose factors are likely to be of major concern. Methods of sampling and analysis to be used by the waste generator (including the methodology for the derivation of scaling factors where radionuclides are difficult to measure) should be appropriate and approved by the respective authority.

Fissile content

The content of fissile radionuclides should be controlled to ensure that subcriticality is maintained under all conditions likely to be encountered during the entire waste management process. As relatively large quantities of fissile radionuclides are expected to be present in some wastes prepared for geological disposal, this is likely to be of concern. Safety can be ensured by engineered controls, such as safe geometry, structural separation, shielding, and the use of neutron moderator and absorber materials (reactivity poisons). The waste package specifications should make cross-reference to any arrangements designed to ensure that fissile limits are not breached (compliance assurance).

Heat output

The decay heat output of waste packages is limited for the sake of their safe handling during predisposal and disposal operations. Due to the insulating properties of the host rock environment and package stability concerns, a maximum heat output may be specified for wastes intended for geological disposal. This will apply to vitrified fission product wastes (it would also apply if spent fuel is disposed as a waste), and to wastes in which the decay heat may contribute to the generation of explosive gases. The decay heat output may be derived from the radionuclide content of the waste packages. The specifications must indicate at which stage of the process the parameter is guaranteed: storage or retrieval from storage.

Physical, chemical and biological properties

Information on the physical, chemical and biological properties of raw waste is required to ensure safety during waste processing and to produce waste packages that are consistent with the relevant safety standards, waste acceptance requirements, and supporting R&D evidence. A discussion of the potentially significant physical, chemical and biological properties of radioactive wastes can be found in Section 3.1.

5.5.3. Waste form production

The common objective of waste form production is to obtain a stable product that is compatible with the disposal environment and meets safety requirements. As noted above, differences between waste forms for near surface and deep disposal are likely to be determined mostly by the nature of the waste materials (see Sections 5.4.2 and 5.5.2). The standard procedure for the solidification of HLW is dispersal in a glass matrix. However, alternative techniques are being investigated. For example, incorporation in a ceramic matrix is considered very promising. Both glass and ceramic forms of HLW, which result primarily from fuel reprocessing, require deep geological disposal. Cement and bitumen are standard matrices for LILW forms. The following aspects of waste form production should be considered.

Formulation envelope

A major purpose of the development of technical specifications and supporting R&D activities related to the waste form production is to define a formulation envelope. Limits should be defined for the ratio of waste to encapsulation materials and the ratio for different encapsulation materials if blends are used. The limits should accommodate potential variations in the waste composition (e.g. the quantity of free liquids, compressed gases, explosive and pyrophoric substances, toxic and corrosive materials). The raw materials, mixing formula and associated parameters must be clearly indicated with relevant tolerances.

Vitrified and ceramic waste forms

The development of vitrified and ceramic waste forms has focused on the production of fully or semi-homogeneous products in which the radionuclides are held in solid solution in glass or within the crystal structures of ceramic waste forms such as Synroc. Limits should be defined for the composition of the raw waste, the proportion of added waste, and various key process parameters (e.g. the temperature of the calciner, reaction time, cooling rate).

Qualification tests

To provide assurance that the waste form meets the design requirements, qualification tests should be performed. Qualification tests might include leachability of the waste form, gas permeability tests and accelerated ageing. Extensive testing would be undertaken during the R&D phase.

Process control

Waste form production processes should be adequately performed and controlled. Limits should be defined for key process parameters that influence product quality (e.g. the temperature of ingredients and the process environment, addition rate, mixing time, curing time). A detailed description of the arrangements for controlling them should be produced as part of the waste package specifications. For ease of communication, it is recommended that this be developed in the form of flow charts.

Binder / Immobilization matrix

A detailed definition of material parameters and their control according to the particular type of binder (e.g. cement and bitumen) is given in [14, 17, 19, 44]. Typical parameters for each binder and its definition valid for geological disposal have been summarized earlier (see Section 5.4.3). Whatever type of binder is used, the control of raw materials used to manufacture the binder must be defined in purchase specifications. These should include tests performed by subcontractors and receipt procedures.

Inactive feed materials

The waste package specifications should define limits on the physical and chemical composition of inactive components in the feed materials (e.g. water, cement powders, additives).

5.5.4. Waste package characteristics

The completed waste package will have additional overall characteristics and performance requirements that are defined by the container and waste form but are not realized until the manufacturing process is complete. As the completed waste product is intended for disposal, the waste package specifications should identify those characteristics that need to be controlled, from waste package production to its emplacement in the repository. This may include some additional arrangements. For example, depending on the disposal concept, high level waste could be placed first in a primary metallic (usually iron or steel) container that is then placed inside an overpack or canister.

The period of storage may be significant before the geological disposal facility comes into operation. If this situation should occur, the waste packages will need to be stored under carefully controlled conditions to provide assurance of their continued integrity and suitability for retrieval, handling and transport. The following overall waste package characteristics should be considered.

Package lifetime history

An overall record should be established and maintained for each package, as discussed in Section 6. To demonstrate compliance with waste package specifications and requirements, all information relevant to the control of package production must be retained (as defined in Sections 5.5.1 to 5.5.3). Records must cover any period of storage, including package movements (with information on place and time), in order to record clear responsibility in case of damage. Package records should also ensure compliance with national and international requirements.

Integrity under environmental conditions

It is important to demonstrate that waste package integrity will be maintained under the environmental conditions following emplacement in the disposal facility, either prior to sealing (closure) or during any period for which the waste packages must be retrievable or retain their containment capability.

The integrity of the waste package is related to its durability and the ability to perform long term primary barrier functions under normal environmental conditions. Typically, these matters are assigned to the waste container in conjunction with the overpack or canister. There could be two possible conceptual approaches: corrosion (degradation) allowance and corrosion resistance. The former uses readily corrodible (sacrificial) metals (mild steel, cast iron) or reinforced concrete with sufficient thickness to delay waste package failure for hundreds to thousands of years, i.e., until short lived fission products in the waste have decayed. Thereafter, the corrosion products may have some chemical barrier role. Corrosion resistant materials (copper, titanium alloys) prevent water access for much longer periods (up to 100,000 years), possibly until all mobile radionuclides have decayed and the waste hazardous component has declined to levels close to those of natural uranium ore [30].

The repository conditions may be the main challenging factors (elevated temperatures, high humidity, high groundwater salinity, high pH), but appropriate experimental tests may be designed as part of the R&D programme to provide evidence for long term behaviour of waste packages under such conditions [30, 44-46].

Gas generation, gas permeability and release rate

Due to the higher inventory of radionuclides and reactive metals in wastes intended for geological disposal, higher levels of gas generation may be expected [47]. Data on the release of gases from waste packages are required for safety assessments of waste disposal and for radiological protection considerations during operations and transportation. If the gas permeability of the container or waste form is too low, container venting should be arranged to avoid over pressurisation.

Waste package storage

Waste package specifications should define limits on the handling of packages and define the environmental variables, such as temperature, humidity, airborne chloride levels, and stacking conditions. Instrumentation and control systems important to waste package integrity and safety in the storage facility, including arrangements for surveillance and monitoring, should also be defined.

In the most critical cases, when failure of operational controls and interlocks could give rise to events of high consequences, stringent requirements in terms of redundancy and single failure criteria have to be met [48].

5.6. GUARANTEED PARAMETERS FOR WASTE PACKAGES

After identifying the key waste package parameters, they may be defined as ’guaranteed’ or ‘supplementary.’ Guaranteed parameters are limiting values (maximum or minimum) required by the waste disposal organization, usually linked to safety significance. It is the responsibility of the waste conditioner to comply with these values. Supplementary parameters are given to comply with other aspects of the specifications or as general supportive or indicative information. Ranges of values may also be provided for supplementary parameters as part of the definition of the waste package specifications. However, these parameters would tend to be for guidance and would not be subject to the same compliance requirements.

The definition of guaranteed parameters for the conditioning process (taking account of the range of uncertainties) will give indirect control of waste package characteristics. Demonstrating compliance with them will provide a strong basis for compliance with the requirements for handling, transport, storage and eventual disposal.

The accuracy of determining the measured values is an important aspect, particularly when the parameter is to be guaranteed below a required limit. If the parameter is to be guaranteed, the statistical variance should be estimated and may be added to the indicated value for comparison with the guaranteed limit (e.g. $\pm 2\sigma$). The guaranteed parameters are mainly determined during the conditioning process, in some cases by indirect methods, although some measurements will be made on the final package (see Sections 5.4.4 and 5.5.4).

It is recognized that much of the supplementary information will be derived from development work but will frequently be linked to adequate process controls, supported by a well managed QA and QC system. Examples of guaranteed and supplementary parameters for different waste types are given in Tables I and II.

TABLE I. EXAMPLES OF "GUARANTEED" PARAMETERS

Waste type	***Guaranteed parameter (unit)***	***Measurement***	***Safety significance***
HLW	• Chemical composition of glass (%) • Heat output (W/package)	• During the process • From the activity content	• Long term stability • Integrity of engineered barriers
LILW	• Total activity per waste package (Bq/m^3) • Actinide content (g/package) • Surface contamination (Bq/m^2) • External dose rate (Sv/h)	• On raw waste • On raw waste • On conditioned package • Direct on completed package	• Operational and post-closure safety • Criticality safety in the long term • Transport limits and operational safety • Operational safety

TABLE II. EXAMPLES OF "SUPPLEMENTARY" PARAMETERS

Waste type	***Supplementary parameter (unit)***	***Measurement***	***Significance***
HLW	• Container dimensions (m)	• During manufacture	• Handling, storage and transport
LILW	• Container dimensions (m) • Blend ratio for grout (%) • Package mass limit (kg) • No free liquid • Hazardous substance content	• During manufacture • Plant process control equipment • Direct on items for package • Control on raw waste • On raw waste	• Handling, storage and transport • Stability of product • Handling, storage and transport • Long term containment • Post-closure safety

6. QUALITY ASSURANCE AND MAINTENANCE OF RECORDS

6.1. INTRODUCTION

The waste generator or conditioner is responsible for providing reliable information in order to prove that the developed waste package specifications meet applicable standards as well as waste acceptance requirements (if available) and that waste packages produced comply with the waste package specifications. The necessary provisions are to be taken in accordance with the QA and QC programme and the system of documentation and maintenance of records, which the waste generator or conditioner must implement prior to operation of their facilities. The competent national authority performing the necessary audits and inspections to verify compliance should approve the QA and QC programme and record keeping procedures.

Establishing QA and QC and record keeping systems is an important requirement of the IAEA Safety Standards [49] and has been introduced in many areas of radioactive waste management. It has been further described in detail in Refs [5–7, 13, 18, 31, 43, 48–50].

6.2. QUALITY ASSURANCE FOR WASTE PACKAGE SPECIFICATIONS DEVELOPMENT

As a part of the comprehensive radioactive waste management quality assurance system, QA and QC programmes have to be established at an early stage for developing the waste package specifications in accordance with recognized standards, e.g. ISO 9000 series. A framework for managing the project is also needed at this early stage. At the same time, the rights and responsibilities of the various bodies involved should be defined. A working group containing experts from within or external to the generator's/conditioner's organization should be set up (see Section 5.2) and regular contact/meetings with customers and other integrated or relevant organizations arranged.

At this stage, the competent national authority and disposal organization (if relevant) should be informed and, if desired, presented with information on the specifications and their proposed development. This will be a timely opportunity for the regulators to clarify the criteria and requirements that relate to the waste package specifications when delivered for storage and/or disposal. In agreement with the regulatory authority, all necessary examinations should be undertaken to assess the QA and QC measures and procedures envisaged to check waste package specifications, to evaluate compliance with the waste acceptance requirements, and finally to verify the waste package characteristics and properties given in the specification.

6.3. VERIFICATION OF COMPLIANCE WITH WASTE PACKAGE SPECIFICATIONS

The waste generator must take all necessary care to ensure that radioactive waste will be treated and/or conditioned in an appropriate manner, i.e. that the waste package specifications will be met. Quality assurance and quality control are the main instruments for demonstrating compliance with these waste package specifications. The QA and QC programmes to be implemented by the waste generator need to take into account the waste acceptance requirements of a storage or disposal facility (if the latter is available).

Since appropriate QA and QC measures and procedures are quite well developed and introduced internationally (see Refs in Section 6.1), only the basic ideas and concepts of their application in waste package specification control are mentioned here. The general objective of QA and QC for waste packages is to provide adequate confidence of the fulfilment of waste package specifications. One possible way to demonstrate that the waste package specifications are fulfilled is the qualification of the conditioning process.

The qualification programme is intended to prove that the process will actually produce waste packages as specified. It is conducted on prototype packages, on non-radioactive packages or on specimen sample waste forms. The choice depends on the specific parameter that is investigated (e.g. for testing mechanical strength, a radioactive package is not required). But the package or the sample that is used must be a good representation of the packages that will be produced with regard to the investigated parameter. The qualification programme can also be based on studies, for instance, calculations for some parameters of the radioactive content. Experimental verification of the results of these studies must be performed.

The qualification programme should be submitted to the stakeholders of the specifications for acceptance including all involved waste management organizations.

During the qualification programme, the waste generator must identify the parameters that can be directly measured or controlled in the conditioning process to comply with specifications. The waste generator will introduce monitoring of these parameters in the QA and QC stage of the process, procedures or facility. Conditions in which qualification is performed must therefore be carefully chosen, particularly the range of values for parameters to be monitored.

Compliance with the waste package specifications can be proved in the following ways:

- examination of its design (comparison to design specifications);
- manufacturing controls (fabrication inspections and controls);
- test and control measures during waste conditioning (in-process control);
- tests or controls on the waste packages.

Instrumentation and control systems important to in-process control and tests or controls on the waste packages should be in place. In particular, consideration should be given to providing the following instrument functions in support of in-process and waste package controls:

- Radiation monitoring to check the contamination level;
- Gamma and neutron monitoring to confirm performance of the shielding;
- Negative pressure monitoring to confirm evacuation of the container before backfill with inert gas;
- Subsequent positive pressure monitoring to observe and control pressure of backfill gas;
- Inert gas (e.g. helium) leak detection to confirm integrity of the containment seals.

Guidance on instrument and control systems important to the safety of various radioactive waste management facilities has been provided in a recent report by the International Electrotechnical Commission [48].

6.4. ADDITIONAL CONTROLS

Checking compliance of the waste package specifications should be performed by the competent national authority or by an independent organization such as the operator of the disposal facility. These controls may, according to national programmes, deal with in-process controls and testing of waste packages, or surveillance audits of the organization performing verification.

After production (during interim or long term storage), periodic visual checking or other surveillance and monitoring of waste packages should be arranged with direct examination if possible (for low-level waste (LLW) packages) or with remote control equipment, such as video cameras, etc., when necessary (for intermediate level waste (ILW) and high level waste (HLW) packages). This would serve to confirm the integrity and operation of the store as a whole and provide an opportunity to examine the external package conditions. All required labels and markings should be confirmed and fixed to the container, in good condition for reading.

Evidence of waste package damage and closure defects, which can affect structural or containment stability, would prompt the implementation of remedial measures. Attention should be given to evidence of damage, such as dents (metallic containers); cracks (concrete containers); extensive corrosion or swelling (metallic containers); evidence of leakage; damaged waste package closure mechanisms and other devices (e.g. vents, tamper seals); and the presence of water on top of the package. Where swelling is anticipated, dimensional checking using indirect techniques may be implemented, taking account any predicted changes after production of the waste package. In the case of concrete containers, particular attention should be given to the grouted cap or junction.

6.5. NON-CONFORMANCES AND DEVIATIONS

Non-conformance of a completed waste package with the waste package specifications (or with waste acceptance requirements) can be identified during either waste package production or by inspection of the waste package upon receipt at the waste generator, storage or repository site. Non-conformances shall be dealt with according to well defined and approved procedures. The following issues shall be addressed according to the national programme:

- description of the non-conformance and identification of waste package;
- assessment of the impact of the non-conformance on the quality of the waste package, operational and long term safety of the waste management facility;
- methods or suggestions for correcting the non-conformance (i.e. corrective action);
- schedule for completing the corrective action; and
- implementation of corrective action.

The waste package may be accepted after it has been reworked or reconditioned to comply with specifications or after the deviation has been accepted, or the package may be rejected. After the corrective action is performed, the situation should be analysed and the result should be documented in the non-conformance report to prevent further production of waste packages that do not comply with the waste package specifications/waste acceptance requirements.

6.6. DOCUMENTATION AND MAINTENANCE OF RECORDS

6.6.1. Records system

In order to prove and declare compliance of waste packages with the waste package specifications, the waste generator and conditioner should establish a system of documentation and maintenance of records. Such a system would allow operators to record and track all relevant information from raw waste characteristics and waste containers, through changes related to waste processing, till final checking and verification of waste package parameters. Records on processing technologies, facilities operations and approved quality assurance systems should also be maintained. The system should provide for controlled approval, receipt, retention, retrieval, distribution and disposition of all records related to waste packages.

Depending on the type of radioactive waste to be processed and packaged and the conditioning facility, the appropriate documentation (e.g. testing and sampling results, analytical batch data reports, instrumental charts, checking certificates or lists, log books, computer files or printouts) must be registered and maintained. In addition, it must be organized in such a way that the information on the operation of the conditioning facility is guaranteed. This has to include possible malfunctions, also. The documentation system should include at least the following:

- the waste package specifications and different reviews and revisions, if any,
- the description of the radioactive waste to be conditioned,
- the conditioning process (any modifications that were performed must be recorded),
- the quality assurance/quality control measures to be applied.

For each waste package produced, a file must be issued and kept where the results of the different controls and measurements are recorded. In particular, the individual characteristics of each waste package must be included, thus allowing for a comparison with the characteristics laid down in the waste package specifications.

In comparison with reference values or with guaranteed parameters given in the specifications, the waste generator and conditioner must demonstrate compliance with required limitations or limiting values, such as absence of free liquids, compressive strength of cemented waste forms (if required), or permissible radionuclide specific activities per waste package. The certification of compliance for each waste package should finally be established and added to the documentation. At a minimum, information attached to each waste package must be on paper form.

6.6.2. Classification of records

The waste generator and the conditioner, as well as any other organization processing or possessing radioactive waste, should provide classification of records as either permanent or non-permanent records. In general, procedures are classified as non-permanent records, and results are classified as permanent records if the recorded results can be interpreted without recourse to the procedures. However, when interpretation of the results depends on knowledge of the procedures, both should be classified as permanent [49]. Examples of permanent records relevant to developing waste package specifications are as follows [31]:

- waste characterization data;
- documentation, supporting process knowledge;
- waste treatment and conditioning processes qualification records;
- treatment and conditioning process control records;
- waste container and transport container design documents and performance-based test qualification records;
- waste container qualification records (non-destructive assay, container radiography, visual examination, etc.);
- material certification and production records for containers required to maintain integrity as a confinement barrier for extended durations in the repository;
- assay records for individual containers, packages, and transport container payloads (original manufacturer's certification and decay calculations for sources);
- other data used for developing waste package specifications and required by safety or performance assessments such as critical parameters of the waste form, container, waste package, and transport container on an individual waste package and transport container payload basis;
- waste package specifications.

6.6.3. Responsibilities for record retention and transmittal

The organization responsible for certifying that waste is acceptable for disposal should ensure that records are retained and transmitted to all organizations involved. These records should be available any time for inspections and audits by the competent national authority in order to verify waste package specifications and to transmit this information to the follow-up organizations.

Keeping the records database permanently by the waste generator and conditioner is of essential importance with respect to verifying information about shipment of waste packages to storage and/or disposal facilities. This provides proof of compliance with transport regulations, storage acceptance criteria, or repository waste acceptance requirements if available. Such a database also serves as a source for retrieval of original data in case these are missing or have been lost. This may require the waste generator and conditioner to pass required documents along to the shipping company and to the operator of the storage or disposal facility.

The waste disposal operator is responsible for issuing a requirement describing the documentation to be permanently kept by the waste generator and conditioner. The registration and record keeping procedures have to be approved by the competent national authority.

6.6.4. Quality assurance on annex documents and cross-references

Waste package specifications must include, as an appendix, cross-references to the set of relevant documents used by the waste generator as to manufactured package, consistent with requirements of specification. That includes operational procedures relevant to conditioning and control, quality assurance, drawings and raw material specifications.

All annex documentations must be managed in an appropriate QA and QC manner in order to maintain good tracking of all necessary revisions of waste package specifications.

7. SUMMARY AND CONCLUSIONS

Radioactive waste is being generated in an increasing quantity in many countries as the demand for nuclear application in medicine, research and industry including nuclear power is continually increasing. Effective management of radioactive wastes includes, as a basic step on the way from waste generation to final disposal, the issues of conditioning and packaging. Disposal can largely be defined as emplacement of properly packaged wastes in a near surface or geological repository. Hence, an important task for waste management organizations is to translate general waste acceptance requirements for disposal into detailed waste package specifications.

The waste package is an important element of safely managing radioactive waste. It must be engineered according to requirements for handling, transport, storage and disposal. It represents a principal unit used as a basis for controlling information and making decisions with due consideration of the interdependencies, impacts and needs at various steps in radioactive waste management. There has been a great deal of interconnected activity during the past few decades in the IAEA and different Member States covering aspects of developing waste package specifications, fabricating actual waste packages, and developing systems and methods for maintaining records of waste packages during processing, transportation, storage and disposal.

This report provides guidance for developing waste package specifications by using a systematic stepped approach, integrating the technical, organizational and administrative factors that need to be considered at each step of planning and implementing waste package fabrication, approval and control. The report reflects the considerable experience and knowledge that has been accumulated in the Member States and is consistent with the current international requirements, principles, standards and guidance for the safe management of radioactive waste. Relevant IAEA publications covering specific issues, such as regulatory requirements, waste package design, characterization, inspection and testing, transportation and storage, as well as safety assessments, surveillance and monitoring of disposal facilities, QA and QC procedures, and requirements for records maintenance, are referenced to provide further details on the activities linked to the development of waste package specifications.

The approach to providing guidance in this report is meant to be generic, flexible and suitable for use in the various Member States, ranging from countries that have nuclear power plants to countries that have small inventories of radioactive waste from nuclear applications. It looks at the entire cycle of radioactive waste management. Consequently, it is relevant to all programme levels in the Member States, whether they are still in the planning stages, a mature operational level, or at a post-closure stage of a disposal facility. It is recognized, however, that some existing and former waste package specifications were developed, and they might not fully comply with the guidance provided here. The national authorities should review the safety implications of any deviations and decide whether improvements are necessary.

The implementation of each step in the development of waste package specifications is determined by a series of factors, which are identified and discussed in this report. While some of these factors are likely to be similar in many Member States, for example, the national policy and legal framework, and the scientific and technical basis, other factors may be very different, for example, the waste types or inventories, the site specific waste acceptance requirements, or socioeconomic conditions. Therefore, when applying the guidelines, it is recommended that responsible organizations in the Member States do so with full consideration of the influence of these country- specific factors.

While emphasizing that the development of waste package specifications is an indispensable part of a national radioactive waste management programme as a whole, the report discusses the specific technical issues related to the waste conditioning process and characteristics of raw wastes, waste forms, containers and assembled packages in more detail. The major conclusions and practical recommendations that could apply to waste generators and/or conditioners are as follows:

- design waste and site specific measurement and instrumentation plans;
- develop special tools and technologies;
- acquire and install instrumentation and monitoring systems;
- make in-process measurements and monitor system performance;
- sample waste forms, containers and assembled packages for testing;
- develop a performance database, quality assurance, and quality control programmes.

While developing waste package specifications, account should be taken of the world's best practices in this area in relation to technology, radiation and nuclear safety. The degree of sophistication, especially in terms of transport modelling, and the body of science and technologies relating to the evaluation and remediation of hazardous characteristics of radioactive waste, which are important elements for the development of both waste acceptance requirements and waste package specifications, have evolved considerably in the advanced countries and have reached a high level of complexity.

Consequently, it must be concluded that in order to ensure the efficiency of the waste package specifications system (treatment, conditioning and containment), significant effort will be required to provide adequate scientific and technical support levels and appropriate QA and QC to waste package specification activities, especially those related to analytical characterization of radioactive waste and modelling its potential release from a repository and mobility in the environment. Therefore, there must be a long term commitment by the Member States and international organizations to demonstrate and transfer suitable technology to support research and development, and to exchange scientific and technical information and expertise relevant for the development of waste package specifications.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, The Principles of Radioactive Waste Management, Safety Fundamentals, Safety Series No. 111-F, IAEA, Vienna (1995).

[2] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series No. 115, IAEA, Vienna (1996).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Legal and Governmental Infrastructure for Nuclear, Radiation, Radioactive Waste and Transport Safety, IAEA Safety Standards Series No. GS-R-1, IAEA, Vienna (2000).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, Including Decommissioning, IAEA Safety Standards Series No. WS-R-2, IAEA, Vienna (2000).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Low and Intermediate Level Radioactive Waste, IAEA Safety Standards Series No. WS-G-2.5, IAEA, Vienna (2003).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of High Level Radioactive Waste, Safety Standards Series No. WS-G-2.6, IAEA, Vienna (2003).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal of Radioactive Waste, IAEA Safety Standards Series WS-R-1, IAEA, Vienna (1999).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Near Surface Disposal of Radioactive Waste, IAEA Safety Standards Series No. WS-G-1.1, IAEA, Vienna (1999).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulations for the Safe Transport of Radioactive Materials 2005 Edition, IAEA Safety Standard Series No. TS-R-1, IAEA, Vienna (2005).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, IAEA, Vienna (1997).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Management Glossary, 2003 Edition, IAEA, Vienna (2003).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Containers for Packaging of Solid Low and Intermediate Level Radioactive Waste, Technical Reports Series No. 355, IAEA, Vienna (1993).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance for Radioactive Waste Packages, Technical Reports Series No. 376, IAEA, Vienna (1995).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Requirements and Methods for Low and Intermediate Level Waste Package Acceptability, IAEA-TECDOC-864, IAEA, Vienna (1996).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Characterization of Radioactive Waste Forms and Packages, Technical Reports Series No. 383, IAEA, Vienna (1997).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Interim Storage of Radioactive Waste Packages, Technical Reports Series No. 390, IAEA, Vienna (1998).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of the Factors Affecting the Selection and Implementation of Waste Management Technologies, IAEA-TECDOC-1096, IAEA, Vienna (1999).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Inspection and Verification of Waste Packages for Near Surface Disposal, IAEA-TECDOC-1129, IAEA, Vienna (2000).
[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Long Term Behaviour of Low and Intermediate Level Waste Packages Under Repository Conditions, IAEA-TECDOC-1397, IAEA, Vienna (2004).
[20] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY (SKB), Status Report, Canister Fabrication, SKB Technical Report TR-04-23, SKB, Stockholm (2004).
[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Waste Inventory Record Keeping Systems (WIRKS) for the Management and Disposal of Radioactive Waste, IAEA-TECDOC-1222, IAEA, Vienna (2001).
[22] INTERNATIONAL ATOMIC ENERGY AGENCY, Records for Radioactive Waste Management up to Repository Closure: Managing the Primary Level Information (PLI) Set, IAEA-TECDOC-1398, IAEA, Vienna (2004).
[23] INTERNATIONAL ATOMIC ENERGY AGENCY, Acceptance Criteria for Disposal of Radioactive Wastes in Shallow Ground and Rock Cavities, Safety Series No. 71, IAEA, Vienna (1985).
[24] OECD NUCLEAR ENERGY AGENCY, Shallow Land Disposal of Radioactive Waste: Reference Levels for the Acceptance of Long Lived Radionuclides, OECD, Paris (1987).
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Qualitative Acceptance Criteria for Radioactive Wastes to be Disposed of in Deep Geological Formations, IAEA-TECDOC-560, IAEA, Vienna (1990).
[26] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).
[27] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste, Publication 81, Pergamon Press, Oxford and New York (2000).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste, Technical Reports Series No. 412, IAEA, Vienna (2002).
[29] INTERNATIONAL ATOMIC ENERGY AGENCY, Issues Relating to Safety Standards on the Geological Disposal of Radioactive Waste (Proc. Specialist Meeting, Vienna, 2001), IAEA, Vienna (2002).
[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Scientific and Technical Basis for the Geological Disposal of Radioactive Waste, Technical Reports Series No. 413, IAEA, Vienna (2003).
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Methods for Maintaining a Record of Waste Packages during Processing and Storage, Technical Reports Series No. 434, IAEA, Vienna (2005).
[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Derivation of Activity Limits for the Disposal of Radioactive Waste in Near Surface Disposal Facilities, IAEA-TECDOC-1380, IAEA, Vienna (2004).
[33] INTERNATIONAL ATOMIC ENERGY AGENCY, Report on Radioactive Waste Disposal, Technical Reports Series No. 349, IAEA, Vienna (1993).
[34] INTERNATIONAL ATOMIC ENERGY AGENCY, Maintenance of Records for Radioactive Waste Disposal, IAEA-TECDOC-1097, IAEA, Vienna (1999).

[35] INTERNATIONAL ATOMIC ENERGY AGENCY, Considerations in the Development of Near Surface Repositories of Radioactive Waste, Technical Reports Series No. 417, IAEA, Vienna (2003).
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Considerations in the Disposal of Disused Sealed Radioactive Sources in Borehole Facilities, IAEA-TECDOC-1368, IAEA, Vienna (2003).
[37] INTERNATIONAL ATOMIC ENERGY AGENCY, Surveillance and Monitoring of Near Surface Disposal Facilities for Radioactive Waste, Safety Report Series No. 35, IAEA, Vienna (2004).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Safety Appraisal. An International Expert review of the Licence Application for the Australian Near Surface Radioactive Waste Disposal Facility. Report of the IAEA International Expert Review Team, IAEA, Vienna (2004).
[39] INTERNATIONAL ATOMIC ENERGY AGENCY, Analytical Application of Nuclear Techniques, IAEA, Vienna (2004).
[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a Coordinated Research Project, Vol. I: Review and Enhancement of Safety Assessment Approaches and Tools, IAEA-ISAM, IAEA, Vienna (2004).
[41] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a Coordinated Research Programme, Vol. II: Test Cases. IAEA-ISAM, IAEA, Vienna (2004).
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulatory Decision Making in the Presence of Uncertainty in the Context of the Disposal of Long Lived Radioactive Wastes, IAEA-TECDOC-975, IAEA, Vienna (1997).
[43] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Quality Assurance to Radioactive Waste Disposal Facilities, IAEA-TECDOC-895, IAEA, Vienna (1996).
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Performance of Engineered Barriers in Deep Geological Repositories, Technical Reports Series No. 342, IAEA, Vienna (1992).
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, The Use of Scientific and Technical Results from Underground Research Laboratory Investigations for the Geological Disposal of Radioactive Waste, IAEA-TECDOC-1243, IAEA, Vienna (2001).
[46] MATERIALS RESEARCH SOCIETY (MRS), Scientific Basis for Nuclear Waste Management XXIII (Proc. Symp. Boston, 1999), Vol. 608, MRS, Warrendale, PA (2000).
[47] EUROPEAN COMMISSION, Research into Gas Generation and Migration in Radioactive Waste Repository Systems (PROGRESS Project): Final report, EUR 19133 EN, Brussels (2000).
[48] REISCH, F. and KRISTENSSON, D., In Control of Radwaste. Nuclear Engineering International, November (2004), 22-24.
[49] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance for Safety in Nuclear Power Plants and Other Nuclear Installations, Code and Safety Guides Q1-Q14, Safety Series No. 50-C/SG-Q, Document Control and Records, Safety Guide Q3, IAEA, Vienna (1996).
[50] NEYAMA, A., ISHIHARA, Y., FUSAEDA, S., "Quality Assurance Program with Computer-Oriented Management System for Performance Assessment", In High-Level Radioactive Waste Management (Proc. Eighth Int. Conf. Las Vegas, 1998), American Nuclear Society, La Grange Park, IL (1998).

ABBREVIATIONS

BFS – Blast Furnace Slag

HDPE – High Density Polyethylene

HIC – High Integrity Container

HLW – High Level Radioactive Waste

ILW – Intermediate Level Radioactive Waste

LILW – Low and Intermediate Level Radioactive Wastes

LILW-LL – Low and Intermediate Level Radioactive Wastes — Long Lived

LILW-SL – Low and Intermediate Level Radioactive Wastes — Short Lived

LLW – Low Level Radioactive Waste

NPP – Nuclear Power Plant

PFA – Pulverized Fuel Ash

QA – Quality Assurance

QC – Quality Control

R&D – Research and Development

CONTRIBUTORS TO DRAFTING AND REVIEW

Brennecke, P.	P. Bundesamt fur Strahlenschutz, Germany
Burcl, R.	International Atomic Energy Agency
Carter, P.	BNFL, United Kingdom
Corcos, J.	ANDRA, France
Dutzer, M.	ANDRA, France
Gens, R.	ONDRAF/NIRAS, Belgium
Gonzalez Gomez, J. L.	International Atomic Energy Agency
Homola, J.	Nuclear Regulatory Authority of Slovak Rep., Slovak Republic
Kelly, J.	International Atomic Energy Agency
Konecny, L.	Nuclear Regulatory Authority of Slovak Rep., Slovak Republic
Konopaskova, S.	RAWRA, Czech Republic
Lagrange, M-H.	ANDRA, France
Miller, C.	Pacific Gas & Electric, United States of America
Ruokola, E.	Radiation and Nuclear Safety Authority, Finland
Skogsberg, M.	Swedish Nuclear Fuel and Waste Management Co., Sweden
Vovk, I.	Independent Consultant, Ukraine
Wisbey, S.	UK NIREX, United Kingdom

Consultants Meetings
Vienna, Austria: 22–26 June 1998, 19–23 February 2001,
28 December 2004 – 28 February 2005 (CSA),
Final Consultants Review 15–17 April 2006

Technical Meeting
Vienna, Austria: 19–23 June 2000