Deliverable 2.7
Guidance on formulating generic waste acceptance criteria

Date 26.4.2024 version Final

Public

Attila Baksay
Ferenc Takáts
TS ENERCON Ltd.
1027 Budapest, Csalogány str. 23-33.
Hungary

baksay@tsenercon.hu
takats@tsenercon.hu
tel +36 30 5027026

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Project acronym PREDIS	Project title PRE-DISposal management of radioactive waste		Grant agreement No. 945098
Deliverable No. D2.7	Deliverable title Guidance on formulating generic waste acceptance criteria		Version Final
Type Report	Dissemination level Public		Due date M44
Lead beneficiary TS ENERCON			WP No. 2
Main authors Attila Baksay and Ferenc Takáts, TS ENERCON	Reviewed by Liz Harvey, GSL and Shivangi Prasad, GSL; Lumir Nachmilner, CVRez	Accepted by Athony Banford, NNL, WP2 Leader and Maria Oksa, VTT, Coordinator	
Contributing author(s) T 2.3 Partners: • Liz Harvey, GSL (UK) • Timothy Schatz, VTT (FIN) • Lumir Nachmilner, Ing. Hana Vojtěchová, SÚRO (CZ), • Mignore Raio, SOGIN (IT) • Lucie Karaskova, CV Rez (CZ)			Pages 74

Abstract

There are situations when managing radioactive waste, that specific requirements cannot be derived. This can be due to a lack of governing, legislative background, waste processing, storage capacity, or a final disposal solution. However, there is still a need to define compliance criteria, in order to maintain the safe management of the waste.

Generic waste acceptance criteria (GWAC) can provide a solution for the situations where there are gaps in the waste management system. This approach tries to give safety related criteria without relying on site specific features, which in many cases are not known.

The aim of this Guidance is to provide help to the different radioactive waste management programmes, that have different limited possibilities. The information gathered in this document can help in the process of how to build up a waste acceptance system from the collecting of the baseline information, through definition of the scope of the waste acceptance criteria and to the possible GWAC parameters.

Keywords

WAC, waste acceptance criteria, GWAC, generic waste acceptance criteria, waste acceptance system, radioactive waste management

Coordinator contact

Maria Oksa
VTT Technical Research Centre of Finland Ltd
Kivimiehentie 3, Espoo / P.O. Box 1000, 02044 VTT, Finland
E-mail: maria.oksa.@vtt.fi
Tel: +358 50 5365 844

Acknowledgement

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 945098.

Table of Content

1 INTRODUCTION 7
2 DEFINITION AND ROLE OF GENERIC WASTE ACCEPTANCE CRITERIA 7
2.1 What do we mean by 'generic WAC'? 7
2.1.1 Examples of generic WAC in national programmes 7
2.1.2 Examples of generic WAC that have been developed collaboratively 9
2.1.3 Distinguishing between generic WAC and related terms 9
2.2 Why are generic WAC useful? 10
2.3 Interpretation of 'generic WAC' applicable in this report 11
3 STEPS FOR BUILDING UP GENERIC WASTE ACCEPTANCE CRITERIA 11
3.1 Development of criteria 12
3.2 Baseline for building up GWAC 12
3.3 Understanding the needs of the waste management system 16
3.4 General approach to derive safety related criteria 19
3.5 Methodology for GWAC derivation 26
4 MOST COMMON WASTE TYPES AND THEIR MANAGEMENT 26
4.1 Classification of radioactive waste 27
4.1.1 Waste classification by activity content 27
4.1.2 Waste types by physical form 29
4.1.3 Waste classification by origin 31
4.2 Characterization of radioactive waste 32
4.2.1 Radiological characterization 33
4.2.2 Physical and chemical characterization 33
4.3 Processing of radioactive waste 34
4.3.1 Processing of solid radioactive waste 34
4.3.2 Processing of liquid radioactive waste 35
5 STORAGE AND DISPOSAL OF RADIOACTIVE WASTE 37
5.1 Storage of radioactive waste 37
5.1.1 Types of Radioactive Waste Storage 37
5.1.2 Storage Aspects of Waste Acceptance Criteria 39
5.2 Final Disposal of Radioactive Waste 41
5.2.1 Types of Disposal 41
5.2.2 Disposal Aspects of Waste Acceptance Criteria 43
6 DERIVATION METHODS FOR RADIOLOGICAL CRITERIA 44
6.1 General view on radiological criteria 44
6.2 Description of the specific criteria elements 46

6.2.1 Heat generation 46
6.2.2 Dose rate 46
6.2.3 Surface contamination 47
6.2.4 Criticality – Fissile Content 47
6.2.5 Isotopic Content 47
6.3 Accident Scenarios for the operating phase of the waste management facilities 48
6.3.1 Fire case scenario 48
6.3.2 Drop and crush scenario 49
6.4 Intrusion scenarios for the Post Institutional Control phase 49
6.4.1 Description of the well drilling scenario 50
6.4.2 Description of the Excavation for house construction scenario 51
6.4.3 Description of the Excavation for road construction scenario 51
7 DERIVATION OF NON-RADIOLOGICAL CRITERIA 52
7.1 General view of non-radiological criteria 52
7.2 Specific considerations for derivation of non-radiological WAC 54
7.2.1 Physical characteristics and configuration of the packages 54
7.2.2 Mechanical stability of the Waste Form 55
7.2.3 Mechanical stability of the waste package 57
7.2.4 Fire and explosion hazard 57
7.2.5 Other dangerous characteristics 57
7.2.6 Durability of waste form 59
8 FORMULATION/DERIVATION OF GWAC 60
8.1 No policy or no plans for radioactive waste management. 62
8.1.1 Collecting the baseline information 62
8.1.2 Defining the scope of GWAC and selection of the derivation methodologies 63
8.1.3 Derivation of GWAC 63
8.2 No adequate facilities for waste management 63
8.2.1 Collecting the baseline information 64
8.2.2 Defining the scope of GWAC and selection of the derivation methodologies 64
8.2.3 Derivation of GWAC 64
8.3 Waste processing is available but there is no storage option 65
8.3.1 Collecting the baseline information 65
8.3.2 Defining the scope of GWAC and selection of the derivation methodologies 65
8.3.3 Derivation of GWAC 65
8.4 Storage available and no disposal option 66
8.4.1 Collecting the baseline information 66
8.4.2 Defining the scope of GWAC and selection of the derivation methodologies 66
8.4.3 Derivation of GWAC 67

8.5 New waste type for existing disposal option 68
8.5.1 Collecting the baseline information 69
8.5.2 Defining the scope of GWAC and selection of the derivation methodologies 69
8.5.3 Derivation of GWAC 69
9 UPGRADE OF GWAC TO WAC 71
9.1 Description of the conditions when it is required to turn GWAC into WAC 71
9.2 Steps for turning GWAC to WAC 72

1 Introduction

A necessary part of safety measures required while commissioning a disposal facility is the formulation of limits and conditions for its operation. These include a set of waste acceptance criteria used for verifying the compliance of waste packages delivered by waste producers to the safety, technical and administrative requirements of the disposal facility. However, even if a disposal infrastructure is missing, producers still need some instructions for the selection and application of waste conditioning technologies for waste streams to be disposed of in future: these instructions can be formulated as generic waste acceptance criteria (GWAC). GWAC can be applied in situations where insufficient information about a waste management facility, its anticipated technologies, and its host geological formation do not allow for formulating fully tailored waste acceptance criteria.

This Guidance was produced in the framework of PREDIS Subtask 2.3. The overall objective of Task 2.3 is to provide a critical review of waste acceptance systems and conditioned waste characterization methods, including non-radiological methods, and to compile guidance documents (i) for the qualification of conditioned waste forms for disposal, and (ii) on generic waste acceptance criteria and their derivation based on proven practices.

The task places a focus on the application of this knowledge to small inventory and developing disposal programmes, however, its findings might also be considered while updating the WAC of more advanced radioactive waste management (RWM) programmes.

In this document five different stages of development of RWM programmes were defined. The intention is to provide guidance on how to build up a waste acceptance system from the collecting of the baseline information, through definition of the scope of the waste acceptance criteria and to possible GWAC parameters.

The rest of this document has following structure: Chapter 2 provides a description of generic WAC, giving examples and defining the situations described in the current document. Chapter 3 gives the generic considerations behind the derivation of the GWAC, how development of the criteria was carried out, what baseline was needed for the derivation and gives the generic approach to derive safety related criteria. Chapter 4 gives an overview of the types of waste and waste processing techniques that can be accounted for in the GWAC derivation. Whilst Chapter 5 gives an overview of storage and disposal options, Chapter 6 and 7 describe the derivation of radiological and non-radiological criteria, respectively. Chapter 8 gives the approach for strategy options for GWAC criteria derivation. Finally, Chapter 9 provides information about the upgrade of GWAC to site specific WAC.

2 Definition and role of generic waste acceptance criteria

This section discusses the meaning and interpretation of the term 'generic WAC' and outlines why generic WAC can provide such a useful enabling tool for the progression of waste management activities. It draws on national responses to a survey conducted under the auspices of the EURAD ROUTES Work Package, which collected information on the use of generic WAC in Member States, as reflected in various ROUTES reports [1; 2]. Reference has also been made to PREDIS Deliverable D2.4 on international approaches to establishing a waste acceptance system [3], supplemented with updates by the authors of the present report.

2.1 What do we mean by 'generic WAC'?

2.1.1 Examples of generic WAC in national programmes

Put simply, generic WAC are not specific to any particular waste, site or facility. However, within this broad definition, there is quite some variation in the interpretation of what 'generic WAC' constitute and their application within national waste management programmes.

In various countries, generic WAC have been developed as precursors to site- or facility-specific WAC, and have been, or will be, superseded when details of the site or facility are known. For example:

- In Belgium, generic surface disposal facility characteristics were considered until facility-specific characteristics for the Dessel repository were available, in order to establish initial WAC. The resulting generic WAC for the disposal of short-lived LILW (Category A) waste in Belgium are now superseded and no longer in use.
- In Moldova, generic WAC have been formulated for a centralized long-term storage facility, the site and design of which have not yet been determined.
- In Slovenia, generic WAC were developed for the disposal of LLW before the site for LLW disposal was identified. These are now superseded by preliminary WAC for the Vrbina facility. In Slovenia, the proper term for such WAC is considered to be ‘very preliminary WAC’.
- In Ukraine, the regulatory document “Recommendations for establishment of WAC for conditioned radioactive waste for disposal in near-surface disposal facilities” makes provisions for the development and application of generic WAC for near-surface disposal facilities. Moreover, generic WAC were established for the proposed geological disposal concepts developed in the framework of the INSC project, taking account of the possibility for disposal in various geological formations. Once a specific facility is being designed, facility-specific WAC must be established.
- In the United Kingdom, an extensive system of generic waste package specifications (WPS) has been developed that are integral to the management of higher activity waste (HAW) destined for geological disposal. These provide a baseline against which the suitability of waste producers’ proposals to package waste for geological disposal can be assessed prior to identifying the disposal site. The WPS are generic in the sense that they make no assumptions regarding the geographical location of the disposal facility, the geological environment in which it will be constructed or the specific disposal concept which could be adopted. Accordingly, the generic WPS are defined so that they would be bounding of the eventual WAC for an operational GDF.
- Australia and Croatia have also developed generic WAC for LLW and ILW waste packages to aid facility design. These will be developed further once a specific site is selected and then iterated throughout site / facility operations.

However, other countries interpret the term differently and regard generic WAC as having a more enduring role. For example:

- In Cyprus, legal obligations for storage of radioactive waste (originating primarily from medical applications) prior to discharge to the environment are generic in the sense that they must be applied by all sites handling such waste.
- In France, overarching Generic Basic Safety Rules have been laid down by the French regulator (ASN) at a national level and are applicable at all facilities for LLW. These are applied alongside site-specific regulatory requirements (within national licenses) and site-specific WAC (specified by the Waste Management Organization (WMO - Andra) and approved by ASN) for individual disposal facilities such as the Centre de Stockage de l'Aube (CSA) at Aube.
- In The Netherlands, the term ‘generic WAC’ is used to refer to WAC that are facility specific but are applicable to a range of waste types, for example dose rate limits applicable to particular waste storage facilities for various categories of LLW or ILW.A similar approach is followed in other countries (such as Spain), but the term ‘generic WAC’ is not used elsewhere.

Many other countries do not deploy any form of generic WAC in an official capacity, and some of the above countries only apply generic WAC to certain waste classifications. The latter is true in France, where only facility-specific WAC are defined for the disposal of long-lived ILW and HLW at the planned Cigéo geological repository, and in the UK, where only facility-specific WAC are applicable for the disposal of waste at the Low Level Waste Repository (LLWR) in West Cumbria.

2.1.2 Examples of generic WAC that have been developed collaboratively

Various suites of generic WAC or generic disposability criteria have been developed collaboratively, for example, within EC projects. Typically, these are applicable to specific waste categories, but are independent of the national context for waste management (i.e., factors such as national waste classification approaches and other national regulations; specific inventory characteristics; details of treatment approaches linked with particular facilities; and specific disposal routes). For example:

- A suite of generic disposability criteria applicable to thermally treated wastes was developed in the EC THERAMIN project. These criteria could be used to evaluate any form of waste product, from any form of thermal treatment, for disposal in any type of facility [4, 5].
- The ERDO working group, which was established to support the development of shared radioactive waste management and disposal solutions for small inventory countries, conducted a task to identify 'minimum WAC' for near-surface disposal of VLLW and LLW, as part of its Legacy Waste Characterization (LWC) project [6].
- Related evaluations of waste product disposability and WAC development have been conducted in other PREDIS tasks for different waste types.

The guidance on formulating generic WAC set out in this report can be regarded as building on such initiatives by synthesizing the process(es) that have been followed elsewhere to develop generic WAC targeted at evaluating the disposability of wastes subjected to particular treatment and/or conditioning routes and defining a method that applies these approaches more generally.

2.1.3 Distinguishing between generic WAC and related terms

The term 'final' WAC denotes WAC that are formally approved and in use for waste acceptance. Final WAC are generally waste and facility specific, but not always, as is the case for storage 'WAC' applicable in Cyprus. It is also important to recognize that such WAC may be subject to revisions, for example, to reduce conservatisms in light of improved waste characterization, or if the design of the associated facility is adapted. As such, the term 'final' WAC is, in some ways, overstated.

'Preliminary' WAC are recognized to be WAC that are under development, and likely to undergo significant updates before relevant waste management facilities become operational. This term is often (although not always) used to indicate early versions of WAC for a specific site or facility. Updates are expected to reflect developments in understanding as planning and implementation of the associated waste management facility progresses.

As noted above, generic WAC are sometimes (but not always) developed as precursors to WAC for a specific facility or disposal site. Where this is the case, they can also be regarded as preliminary WAC. Indeed, in the UK, the WMO's generic Disposal System Specification notes that the current generic WPS "*act as preliminary WAC for the geological disposal facility*" [7]. But on the other hand, generic WAC are sometimes intended to be an independent or overarching set of general requirements applicable to multiple facilities, which will continue to be relevant even if / when facility-specific (or waste-specific) WAC are available. In such cases, preliminary and generic WAC are quite distinct in their nature and purpose.

Figure 1 illustrates the relationship between the different types of WAC discussed above.

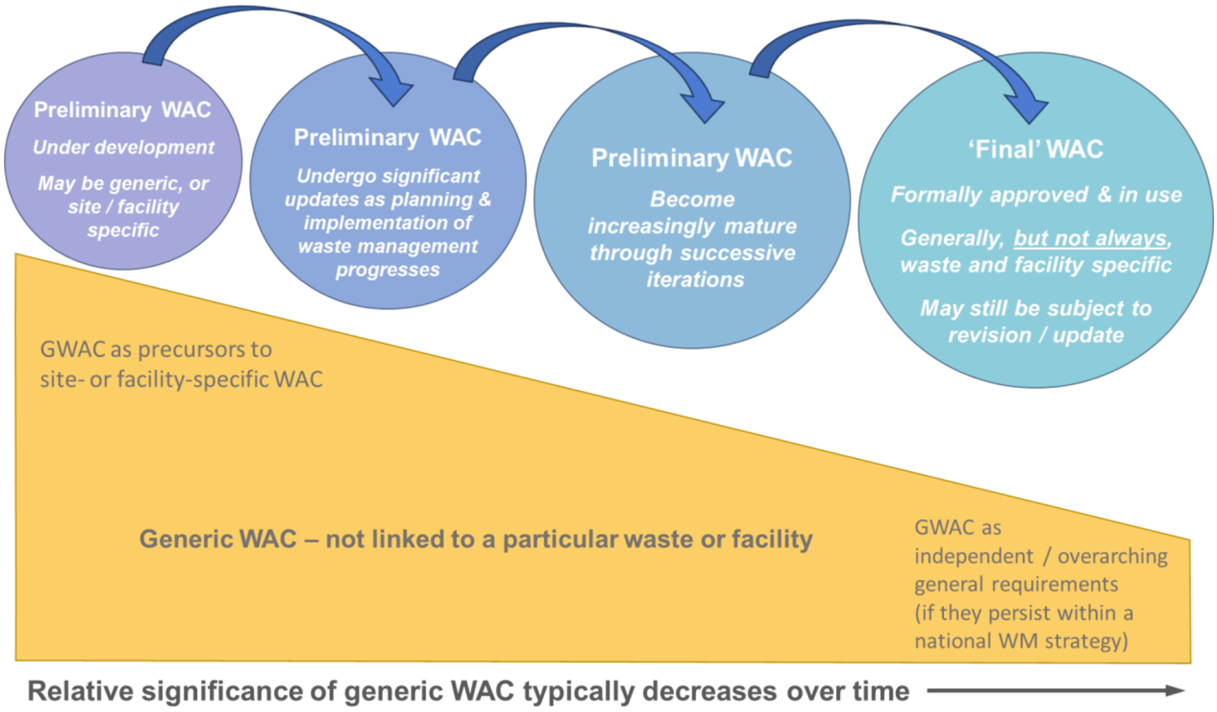

Figure 1. Schematic illustration of the relationship between different types of WAC, and how this may change over time.

It is also important to bear in mind that requirements effectively corresponding to WAC are not always defined explicitly as 'WAC', particularly where they apply to upstream stages in the waste management lifecycle, i.e., pre-storage and predisposal. Other related terms may be employed instead, such as: conditions for acceptance, requirements, procedures, policies, decrees, criteria, regulations, or specifications. This is particularly the case for the receipt of waste at a facility where there is no transfer of ownership or liability, for example, where waste producers are responsible for conditioning or storing their own waste. Such waste acceptance systems are, nevertheless, useful to inform waste management planning and development of WAC where they are not yet available.

2.2 Why are generic WAC useful?

There are situations when the overarching waste management strategy, or elements thereof, are unclear. Associated uncertainties risk impeding predisposal waste management, owing to concerns that any such activities may constrain options for downstream waste management, reduce flexibility and/or increase lifecycle waste management costs. Such situations, if not addressed, can lead to unacceptable delays in the decommissioning of nuclear facilities and/or the processing of wastes for safe interim storage and disposal. Examples of such situations include:

- Early-stage national programmes that have no policy for waste management and/or detailed plans for waste management systems or route(s) to disposal.
- National programmes that have policies and plans for waste management systems in place, but where the available options or equipment for waste processing 'on the ground' are limited.
- Programmes where waste processing options are available but there is no available option for storage of the resulting waste, either for the short or long term.
- Programmes where waste processing and storage options are available, but the route to disposal is not known (or no specific disposal facility has been identified).

The above situations may be applicable to a national radioactive waste inventory or to parts thereof, for example, certain wastes whose properties are particularly challenging to manage or dispose of, that are poorly characterized, or that are difficult to retrieve from redundant equipment (sometimes referred to as problematic or orphan wastes).

There is also the situation of existing waste management options being in place, but needing to be adapted to accommodate newly identified waste types (for example revising storage or disposal WAC to be applicable to conditioned wastes arising from a new processing facility).

In such situations, generic WAC offer an important tool to enable waste management planning to progress despite ongoing uncertainties. Application of generic WAC that have been developed collaboratively, or that are benchmarked against established systems deployed elsewhere gives confidence in the completeness of general requirements being established in a new situation, and in the adoption of best practice.

This is particularly valuable when there is an extended period of uncertainty over a management route, which can often be the case with regard to the formulation of a national disposal strategy for radioactive waste and the identification of candidate disposal sites and development of disposal facility designs, all of which have a significant influence on the scope of WAC required to ensure safety. Indeed, the IAEA noted in 2000 that "*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*" [8]. In this context, one must recognize that treatment and conditioning of radioactive waste has to be carried out in a way that considers the safety and stability of waste packages for the long time period relevant to interim storage and eventual disposal. Where storage or disposal routes are uncertain, flexible or reversible processes (e.g. packaging without deploying a conditioning matrix) are preferred, to avoid foreclosing future options, or requiring significant re-working to meet facility-specific WAC in due course. It is noted that the EURAD ROUTES WP considered various case studies of waste management with and without WAC being available and made recommendations for so-called 'no regret' waste management measures that offer flexible or reversible predisposal options, to reduce the short-term risks associated with raw waste, and to facilitate decommissioning of facilities, without closing off options for storage and disposal [9].

2.3 Interpretation of 'generic WAC' applicable in this report

Bearing in mind the range in interpretations of the term 'generic WAC' that is evident from the discussion above, it is crucial to give a clear explanation of how this term is being interpreted in each particular context. For the purposes of this report, the term 'generic' WAC (GWAC) is taken to mean:

"WAC put in place to facilitate predisposal waste management planning or processing activities in the face of ongoing uncertainty over downstream management strategies (such as storage or disposal routes) and, hence, over detailed site- or facility-specific requirements."

This definition allows for GWAC to be waste-specific or waste-independent, as appropriate, and to consider, or omit, details of waste management routes to a variable extent depending on what is appropriate (i.e., known or uncertain) in a particular context. It also encompasses the possibilities for GWAC to be either:

- precursors to site- or facility-specific WAC that, in time, are superseded; or
- general high-level requirements of an enduring nature that are retained and applicable to multiple wastes or facilities.

The choice of which of the above approaches is most appropriate would need to be made by those involved in applying the methodology set out in this report within a particular waste management context or national programme.

3 Steps for building up generic Waste Acceptance Criteria

The general methodology to build up the GWAC includes the same steps which are necessary in case of specific WAC [10], but the context and the details of the steps may differ.

At the time period typically relevant to development of GWAC, there is a lack of verified information provided by the site-specific safety assessment on final disposal solution, or even on storage for the waste arisen. Therefore, the scope and extent of surveys and analyses should be wider, while the range and uncertainty of GWAC parameters would be higher than in case of well-known waste management routes.

The steps of the methodology to build up GWAC can be grouped into four phases:

1. Collecting the baseline information and making decisions necessary for building up the GWAC
2. Defining the scope of GWAC and selection of the derivation methodologies
3. Performing safety calculations, according to the criteria derivation methodologies
4. Determination of quality management procedures suitable to check the compliance with the criteria

This Chapter proposes guidance to conduct the first two phases of the criteria development.

3.1 Development of criteria

In the process of developing criteria, a hierarchy of criteria must be defined before detailed GWAC can be properly considered. The hierarchy has the following steps: [11]

1. Basic health and safety criteria. (Criteria established by national regulatory authorities, based on international recommendations and guidelines)
2. Generic criteria for waste storage and disposal. (Generic criteria addressing the entire storage and/or disposal system in the context of the site, the storage facility and/or repository and waste package.)
3. Site specific criteria. (Same type as the general criteria but applied to a specific site.)
4. Technical criteria and economic considerations. (Assessment of the technical feasibility of the various conditioning options and their costs.)

3.2 Baseline for building up GWAC

There are several prerequisites that must be fulfilled regarding radioactive waste management, before starting the development of GWAC

WAC – whether specific, generic or preliminary – are an essential part of the overall waste management system. In some cases, preliminary WAC shall be defined before the determination of further details of waste management processes, in other cases the development of specific WAC shall be done in parallel with the design of technical procedures. However before deriving any – even generic – WAC, waste management policies and strategies shall be defined.

The line separating policy from strategy is not always sharp and sometimes an issue should be discussed both in policy and strategy. [12] However, the prerequisites for development of policy and strategy are very similar:

A. Identification of the status of the radioactive waste management system:
    a. Identification of waste streams already existing or anticipated
        i. Inventory of spent fuel and radioactive waste
        ii. Waste classification
        iii. Waste characterization
    b. Description of legal and institutional framework
        i. Present the national legal framework (existing regulatory regime)
        ii. Applicable international conventions
        iii. Present national policies and strategies affecting radioactive waste management

            iv. Present the institutional structure and existing waste management facilities
B. Decision on radioactive waste management policy
    a. Determination of endpoints and other key aspects of waste management system
    b. Restrictions and opportunities of development
        i. Waste management policies and strategies in other countries
        ii. Availability of resources
        iii. Concerned parties' expectations and interests
C. Elaboration of radioactive waste management strategy or strategies

The safety, technical and economic considerations for the development of national policy end strategies are detailed int the relevant IAEA guideline. [12]

In this section, the information which is relevant from a technical viewpoint for development of GWAC is discussed in detail.

A. Identification of waste streams (radionuclide inventory)
    a. Description of waste arisings:
        i. Origin of waste:
            1. waste from nuclear power plant
            2. waste from research reactors
            3. waste from reprocessing plants
            4. waste from fuel fabrication plants
            5. waste from Naturally Occurring Radioactive Materials (NORM) industries
            6. waste from research institutions and from education
            7. waste from medical application
            8. waste from industrial application
            9. waste from other application
            10. waste from emergency response
            11. waste from management of existing exposure situation
            12. legacy waste
            13. orphan sources
        ii. Description of waste material
            1. Radiological characteristics
                a. radionuclide composition,
                b. level of activity concentration or surface contamination
                c. heat generation
                d. radionuclide distribution: surface contamination, surface layer activation, deep penetration, homogeneous distribution, inhomogeneous distribution
            2. Non-radiological characteristics
                a. physical form, materials, density, etc.
                b. chemical characteristics, chemical components,
                c. non-radiological hazards
            3. Packaging for collection that remains during the further waste management process (so becomes part of the waste)
                a. type (bag, drum, box, canister, etc.)
                b. material (plastic, metal. wood, composite, etc.)
                c. characteristics (thickness, density, physical and chemical properties, mass, loading mass)
                d. sealing, if any

iii. Information on technology:
    1. Circumstances of waste generation: approved practice, nuclear emergency, NORM, liquidation, orphan sources, etc.
    2. Identification of the technology
    3. Aspects having impact on the uncertainty of waste characteristics:
        a. description of the method of identification and collection of waste at the workplaces
        b. characterization methodology of waste at the workplaces (for example measurements of representative samples or a certain amount of waste, activity estimation via surface contamination, material balance analyses, scaling-factor calculation, etc.)
        c. record keeping and archiving system

b. Volume of waste generation
    i. Amount of waste items or waste packages
        1. small amount
        2. moderate amount
        3. bulky waste
    ii. Overall volume per period: total activity, mass, volume
    iii. Generation tendency: increasing or decreasing volume, occasional

B. Waste processing technologies at the workplaces/practices
    a. pre-treatment processes
        i. collection
        ii. segregation
        iii. chemical adjustment
        iv. partial decontamination
    b. treatment processes
        i. volume reduction (typically mechanical compaction, incineration, and evaporation.)
        ii. activity removal
        iii. change of composition
        iv. type of liquid waste treatment:
            1. chemical treatments: pH adjustment, flocculation, precipitation, etc.
            2. mechanical processes: filtering, concentration, evaporation, embedding, etc.
        v. type of solid waste treatment
            1. chemical treatments: dissolution in liquid and treatment as liquid
            2. mechanical processes: compressing, embedding, etc.
    c. conditioning process
        i. immobilization (solidification, embedding or encapsulation)
        ii. packaging (enclosure of the waste in a container suitable for safe handling, transport, storage and/or disposal)
        iii. overpack (use of secondary (or additional) outer container for one or more waste packages, used for handling, transport, storage and/or disposal.)
    d. technical parameters of processing
        i. technology description
        ii. technology parameters (solidification matrix specification, etc.)

C. Information about the waste package prepared at the workplaces/practices
    a. Waste form description:

            i. consistency of waste form: solid, liquid, disused sealed radioactive sources (DSRS),
            ii. radiological characteristics of waste form
            iii. non-radiological characteristics of waste form
    b. Packaging of waste form:
            i. type (bag, drum, box, canister, etc.)
            ii. material (plastic, metal, wood, composite, etc.)
            iii. characteristics (thickness, density, physical and chemical properties, mass, loading mass)
            iv. sealing
    c. Waste package description:
            i. identification (any kind of name and codes)
            ii. waste class: VLLW, LLW, SL-ILW, LL-ILW, HLW (waste classification described in 4.1)
            iii. radiological characteristics of waste package
                1. dose rate (gamma and neutron)
                2. surface contamination (in case of large items without packaging)
            iv. non-radiological characteristics of waste package

D. Present steps of waste management carried out outside the workplaces
    a. Existing requirements for safe handling, transport, and (short or long term) storage
            i. Status of legislation
            ii. Legal requirements
            iii. Technical requirements (determined in legal documents, regulations or technical instructions)
    b. Present waste management steps
            i. Description of input waste
            ii. Description of present WAC
            iii. Description of the technology
            iv. Description of output waste

E. Approaches to development of waste management according to national policies and strategies
    a. Feasibility studies of options for predisposal management and for disposal
            i. Identification of potential disposal options based on the country's geological and geographical characteristics
            ii. Identification of potential legal solutions and technical procedures for returning the DSRSs to the producer and for reprocessing the spent fuel (with or without residual waste to be disposed).
            iii. Identification of potential legal solutions and technical procedures for treatment and conditioning of waste outside the country.
            iv. Identification of capacity building perspectives for treatment and conditioning of radioactive waste in the country.
            v. Identification of necessary storage options concerning the schedule of potential disposal options or reprocessing
    b. Preliminary gap analyses between the present and required status / characteristics of waste packages
            i. Concerning the safety requirements for handling, transport and available (short or long term) storage relevant for the waste forms, are further treatment or immobilization (conditioning) techniques required?
            ii. Concerning the existing safety requirements for handling, transport and available (short or long term) storage, are other packaging or further overpacking methods required?

        iii. Legislative issues
    c. Components of the development of the radioactive waste management system
        i. Changes in the legal environment
        ii. Need for third party services (including export/import of radioactive waste)
        iii. Development of disposal solutions (selection of technical solutions)
        iv. Development of storage options (selection of technical solutions)
        v. Enhancing treatment, conditioning and storage capabilities
    d. Survey of available expertise to perform safety calculations, assessments

3.3 Understanding the needs of the waste management system

In order to ease the development of GWAC, the predisposal management, storage and disposal situations are categorized. GWAC for waste treatment, conditioning techniques, storage and disposal can be adopted to the specific categories of the waste management situation. Instead of a rigid formulation and list of criteria, this method provides flexibility to the GWAC, focusing on the important characteristics and parameters.

The categories of the waste management situation shall be consistent with the existing approaches for radioactive waste management system.

As previously mentioned, one of the prerequisites of the development of the GWAC is the elaboration of national policy and related waste management strategies. The waste management strategy defines the actions for achieving the goals and requirements set out in the national policy for the safe management of spent fuel and radioactive waste and is normally established by the relevant waste owner or operator, which is either a governmental agency or a private entity. The national policy may be elaborated across several different strategies. The individual strategies may address different types of waste (e.g. reactor waste, decommissioning waste, institutional waste, etc.) or waste belonging to different owners. [12]

Existing policies and strategies may need to be updated from time to time.

The predisposal management, storage, and disposal situations relevant for a certain type of waste stream are outlined by the relevant waste management strategy. Waste management categories supporting the development of GWAC should be related to the waste management strategies or sub-strategies.

Waste management strategies and the range of technical options for managing the various types of radioactive waste are discussed with respect to a proposed IAEA waste classification scheme. The IAEA safety guide on classification of radioactive waste [13], together with other IAEA safety standards on radioactive waste, intends to assist in the development and implementation of appropriate waste management strategies. Advantages in using the waste classification system are detailed in the appendix of the relevant IAEA document [13]. Although IAEA proposes a waste classification system, the national classification system may differ, e.g., adopting waste classes defined by the U.S. Nuclear Regulatory Commission (NRC). In general, the waste classification system establishes a generic linkage between the different classes of waste and disposal options, considering the required time period and level of containment and isolation.

Additionally, the waste classification system generally reflects on the radiation level, non-radiological hazards and other particular – even security – characteristics of the waste. Hence the waste class determines the key characteristics of the waste which should be taken into account during processing, storage and disposal of radioactive waste.

Therefore, waste management categories supporting the development of GWAC could be linked to the waste classes defined in waste management strategies.

Basic waste management situations considered in the development of GWAC are:

1. **Having Very Short-Lived Waste (VSLW):** Goal is storage for decay. Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge. This class includes waste containing primarily radionuclides with very short half-lives often used for research and medical purposes. The containment during storage should be maintained for a shorter period of time. Activity can be varied in wide range, it may require additional shielding.
2. **Having Very Low Level Waste (VLLW):** It often exists in large volumes and is mainly generated during the operational, decommissioning, and dismantling stages of a nuclear facility. Examples of typical VLLW are concrete, soil and rubble. The volume of VLLW can be reduced by appropriate characterization to separate those components that may be released as cleared waste. Generally, VLLW is stored at the site of its generation until transport to a suitable disposal facility. During storage, a simple shelter or temporary cover may be appropriate to provide protection from atmospheric influences (precipitation, wind). VLLW can be disposed of in purpose-built disposal facilities, in the form of earthen trenches with engineered covers. Sometimes it is disposed of with other waste types, e.g., low level waste (LLW).
3. **Having Low Level Waste (LLW):** Contains limited concentration of long-lived radionuclides. It requires isolation from the biosphere for periods of up to a few hundred years. LLW is generated in most facilities involved in nuclear power production, nuclear research, and nuclear medicine. The processing of LLW consists of treatment and conditioning to prepare for transport, storage and disposal. Concerning treatment, the volume reduction of solid waste is common practice, while the treatment processes for liquid LLW are directed towards volume reduction and the removal of radionuclides from the bulk of the waste, resulting in a concentrated waste stream. Conditioning produces a more stable physical or chemical form. Cementation and bituminization are the most typical solidification technologies used for liquid LLW. Processed or unprocessed LLW may also be placed into high integrity containers capable of providing containment for long periods of time. Steel, plastic or concrete containers have been developed for this purpose. Waste packages should be housed within a suitable storage structure that provides a sheltered, non-corrosive environment, which is physically secure. Storage may last from days to decades. It is common practice to dispose of LLW in engineered near-surface or sub-surface facilities.
4. **Having Intermediate Level Waste (ILW):** ILW has a higher concentration of radionuclides, especially long-lived radionuclides, than LLW; it may require additional shielding to provide adequate protection for workers and greater provisions to ensure its isolation from the biosphere. However, ILW needs no or only limited provision for heat dissipation during its storage and disposal. ILW typically comprises metals which have been irradiated in reactor cores, graphite waste, ion exchange resins and fuel cladding waste resulting from spent fuel reprocessing. Concerning processing and storage of ILW, all methods used for LLW are also acceptable for ILW. An important factor to be considered in choosing the processing option is the radiation resistance required of the waste form. To provide for long term safety, disposal at greater depths than for LLW is normally considered to be appropriate (at least several tens of meters). While repositories specifically for ILW exist in some countries, in others, co-disposal with spent fuel and high-level waste (HLW) is being considered.
5. **Having spent fuel and High Level Waste (HLW):** The waste management strategy for spent fuel and HLW is affected by the nuclear fuel cycle policies adopted by a State. Two distinct nuclear fuel cycles are employed:
    a. Open fuel cycle: Spent fuel is considered to be HLW;
    b. Closed fuel cycle: Spent fuel is reprocessed to recover unused uranium and the plutonium generated by nuclear fission, with the production of HLW.

    Spent fuel and HLW are highly radioactive and heat generating and need to be cooled and shielded. After removal from a reactor, spent fuel requires shielding and heat removal. After several years of cooling, the fuel is transferred to a separate storage facility. The eventual need to retrieve and transport the spent fuel to a disposal facility or for reprocessing has to be considered when designing the storage facilities. Processing of liquid HLW involves chemical treatment and evaporation followed by conditioning by vitrification into a glass or ceramic matrix and packaging in stainless steel canisters. HLW has to be stored until disposal facilities become available. Disposal in deep geological repositories is generally considered to be the best way to provide a permanent management solution for spent fuel and HLW. While most countries with spent fuel and HLW are working towards national solutions, others, for mainly economic reasons, have indicated an interest in developing multinational disposal facilities.

6. **Having disused sealed radioactive sources (DSRS):** The preferred option for the management of DSRSs is to return them to their supplier for reuse or disposal. Sometimes this is not possible, especially for older sources where the supplier is not known, or is no longer in business. Alternative solutions need to be found. Methods for DSRS processing include metal matrix immobilization (for highly active sealed radiation sources) and encapsulation in stainless steel casings. They may further be grouted in steel drums or other suitable overpack. Disused sealed radioactive sources containing short-lived radionuclides may be stored for decay in an appropriate container or package and then be released from control (cleared) when their radioactive contents have decayed sufficiently. Capsules containing conditioned DSRSs are stored in an appropriately designed shielded container until appropriate disposal arrangements are available. Provisions to ensure physical security are necessary for some types of high activity source stores. Disposal options for disused sealed radioactive sources vary depending on the activity levels and types of radionuclides in the sources. Near surface repositories may be suitable for low activity, short-lived sources. For long-lived disused sources with activity levels exceeding the criteria for disposal in a near surface repository, underground disposal is the preferred option.
7. **Having Naturally Occurring Radioactive Materials (NORM)**: NORM occurs as a by-product, residue or waste from activities such as uranium mining and milling; coal burning; oil and gas extraction; tin, iron, niobium and non-metal mining; and milling and water treatment. NORM contains radionuclides of the uranium and thorium decay chains and is characterized by very large volumes. NORM often contains other toxic substances such as heavy metals and, for this reason, both radiological and non-radiological aspects have to be taken into account for its management. In some countries, NORM is regulated as a radioactive waste and in others as a chemically toxic waste. Processing consists of pile stabilization by various processes in order to increase the safety of storage and disposal sites. Solid, large pieces of NORM waste, such as pipes from the oil industry, are fragmented for handling and transport purposes. Liquid NORM waste is treated to reduce its radionuclide content and mobility. Decontamination and recycling may be effective options for reducing the volume of this waste. NORM waste is generally deposited in consolidated and over-covered piles or sludge beds, or purpose designed repositories with lined cells and protective capping. As it is not feasible to move such large amounts of material, the waste tends to be disposed of on the site of its generation. Capping and some engineered structures may be used to prevent erosion and to limit the leakage of radioactive gases. In some cases, the waste has been disposed of by using it to backfill disused underground mines.

Other waste classes or waste types may be considered according to their particular characteristics, such as:

- Uranium Mining and Mill Tailings – special by-product materials
- Transuranic Waste – contains elements with atomic numbers greater than that of Uranium (92), where half-lives of transuranic elements exceed 20 years and have concentrations higher than 3,7 kBq/g (100 nCi/g).
- Medical waste – also infectious waste
- Nuclear power plant waste – application of scaling factors
- Emergency waste – preparedness for managing it, but hopefully it does not arise
- Legacy waste – uncertainty of waste characteristics, unacceptable conditioning.

The status of waste management system can be evaluated from the viewpoint of existing waste management strategies, based on waste classes as below:

a) Category VSLW
b) Category VLLW
c) Category LLW
d) Category ILW
e) Category HLW
f) Category DSRS
g) Category NORM
h) Category Country-specific waste (legacy waste, uranium milling waste, transuranic waste, etc.).

Besides the waste classes, the waste management policy and strategy define the status of the waste management system, including the proven practice and the future development. It is necessary to determine for all waste types / waste classes, what waste management activities are conducted by proven technical solutions - where specific WAC already exist -, and which waste management activities are under development – where the development of GWAC are needed. Radioactive waste management activities are specified in the IAEA Safety Glossary [14].

The status of a waste management system can be evaluated in the viewpoint of the missing and existing waste acceptance criteria based on waste management activities:

A. Category P: Criteria for pre-treatment procedures shall be developed (waste from emergency exposure situation, legacy waste. etc.)
B. Category T: Criteria for treatment procedures shall be developed
C. Category C: Criteria for conditioning procedures shall be developed
D. Category S: Criteria for storage procedures shall be developed
E. Category D: Criteria for disposal procedures shall be developed.

Criteria for transport procedures are developed and determined by transport regulations based on IAEA Safety Standards SSR-6 [15]. Hence the development of criteria for transport is out of scope of the document.

In summary, concerning the existing approaches for waste management systems, the waste management situation in a country relative to the need for GWAC development can be categorized by:

a) waste classes to be managed via the waste management strategies, and
b) capacity development demand of one or more waste management activities.

Example of waste management categories for application of GWAC:

- VSLW – S
- VLLW – D
- LLW –D
- LLW – C+S+D
- ILW – T+C+D
- HLW – P+T+C+S+D

3.4 General approach to derive safety related criteria

The safety related concerns for the general waste management, storage and disposal options shall be defined to determine the GWAC as well as the potential criteria derivation methodologies.

The basic safety function relevant for nuclear power plants – namely (a) Control of reactivity; (b) Cooling of radioactive material; (c) Confinement of radioactive material – could be adopted for radioactive waste management activities as well. From those, the confinement function is applicable for all waste types, while the risk of criticality and the heat generation should be considered in the case of HLW, spent fuels and TRU.

The confinement function shall be assessed for both radionuclides and other hazardous materials.

The confinement function can be achieved by containment. The level of containment is relevant for the retention capability and the period of time required.

During processing, storage and transport activities, the confinement function is provided by the waste form and the packaging.

During disposal the confinement (isolation) function is provided by the waste package, the engineered barriers and host environment.

For the protection of workers, the shielding against direct and scattered radiation and protection against non-radiological hazards shall be considered.

The short description of waste classes presented in [12] and section 3.3 shows, that – due to the derivation method of waste classes – different level of shielding and containment are considered for each waste class. These considerations can be associated with the safety functions mentioned above:

- level of shielding during waste processing, storage and transport
- confinement viewpoints:
  - containment level of the radionuclides during waste processing, storage and transport
  - non-radiological hazards associated to the waste form
  - robustness of packaging
  - level of isolation (containment of waste package and capability of host environment) of the radionuclides after disposal
- possibility of heat generation
- industrial safety aspects of technical solutions.

Safety related criteria concerning WAC in radioactive waste management:

- Radiological criteria for
  - radiation protection of the workers
  - radiation protection of the public (present generation)
  - radiation protection of the future generation
- Occupational health and safety criteria for
  - protection of workers and
  - protection of the public.

Since the different waste classes represent different levels of risk and safety issues, the required level of shielding and containment for the different waste class would be different during each step of waste management. The performance of the shielding and the containment functions is strongly influenced by the safety issues. The performance level of the safety functions can be set by the GWAC.

However, the relevance and importance of criteria may be different in the different waste management steps (pre-treatment, treatment, conditioning, storage, transport and disposal). For example, the content of fine particles could pose a safety issue during processing the waste both in normal operation and accident conditions, while only accident conditions are relevant during storage or disposal.

The general methodology of deriving scenarios and safety calculations for a selected waste management step are shown in Table 1.

The criteria cited as an example in the last column in Table 1 are described in Chapter 5 and 6.

After development of the GWAC, the criteria might be structured in other ways to communicate to users of as follows [8].

1. Basic requirements on radioactive waste to be disposed:
    a. Prohibition of mixing non-radioactive waste with radioactive waste
    b. Compliance with the requirements of the site-specific safety assessment
2. General requirements on waste packages:
    a. Surface dose rate
    b. Surface contamination
    c. Hazardous substances content limitation
    d. Absence of overpressure
    e. Waste package mass
3. Requirements on waste forms:
    a. Basic requirements (e.g., only solid or solidified waste, no free liquid)
    b. Specific requirements (e.g., stabilization (dispersion inhibition), heterogeneity, chemical restrictions)
    c. With immobilization binder (e.g., bitumen, polymer or cement)
    d. Without immobilization binder (e.g., radioactivity and radionuclide restrictions).
4. Requirements on waste containers:
    a. Basic requirements (e.g., geometric shape and dimensions, stackability)
    b. Specific requirements (e.g., mechanical stability, thermal resistance, leak tightness, shielding function)
    c. Inner containers (e.g., surface coating, seals, vents, void space restrictions).
5. Limitations of activity:
    a. Permissible activities for individual radionuclides
    b. Permissible total activity per waste package
    c. Permissible total alpha and beta/gamma emitter activity
    d. Declaration of radionuclide-specific activities/total activities per waste package.
6. Delivery of waste packages:
    a. Compliance with transport regulations
    b. Permits/documentation including record keeping
    c. Marking of waste packages
    d. Requirements on transport containers.

Table 1. General methodology of deriving scenarios and safety calculations for a selected waste management step.

Safety concern	Scenario	Example	Effects	Safety function associated	Associated Criteria (examples) parameters
Radiation protection of the worker	Planned exposure situation (normal operation)	• Pre-treatment, treatment, conditioning, storage of radioactive waste • Operation of disposal facility	Exposure to direct radiation	Shielding	Levels of ambient dose rate (gamma, neutron, beta bremsstrahlung)
			Inhalation and ingestion of radioactive isotopes	Containment of radionuclides by the waste form	• Activity, activity-concentration • Gas release (including volatile nuclides) • Content of fine particles • Content of liquid
			Contamination of skin or eye	Containment of radionuclides by packaging	• Level of surface contamination • Loading weight • Retention capability of packaging • Sealing of packaging • Resistance against heat generation • Resistance against ionization radiation
	Emergency exposure situation (Accident scenarios)	• Pre-treatment, treatment, conditioning, storage of radioactive waste • Operation of disposal facility	Exposure to direct radiation	Shielding	• Levels of ambient dose rate (gamma, neutron, beta bremsstrahlung) • Fire resistance of shielding
				Containment of radionuclides by the waste form	• Content of fine particles • Radionuclides released in case of fire • Content of liquid
				Containment of radionuclides by packaging	• Levels of ambient dose rate (gamma, neutron, beta bremsstrahlung) • Level of surface contamination

Safety concern	Scenario	Example	Effects	Safety function associated	Associated Criteria (examples) parameters
					• Fire resistance of packaging
Radiation protection of the public	Planned exposure situation (normal operation)	• Discharges during pre-treatment, treatment, conditioning or storage of radioactive waste • Discharges from operation of disposal facility	Inhalation and ingestion of radioactive isotopes	Containment of radionuclides by the waste form	• Activity, activity-concentration • Gas release (including volatile nuclides) • Content of fine particles
				Containment of radionuclides by packaging	• Resistance against environmental conditions (humidity, temperature, mechanical effects) • Resistance against waste form (chemical compatibility, basics, acids) • Sealing of packaging
	Emergency exposure situation (Accident scenarios)	• Discharges during pre-treatment, treatment, conditioning or storage of radioactive waste • Discharges from disposal facility	• Inhalation and ingestion of radioactive isotopes • Contamination of skin or eye	Containment of radionuclides by the waste form	• Content of fine particles • Radionuclides released in case of fire
				Containment of radionuclides by packaging	Fire resistance of packaging
Radiation protection of the future generation	Normal evolution scenario	Discharges from disposal facility	Intake of radioactive isotopes via food and water	Long term containment of radionuclides by waste package	• Stability of waste form (leaching, dispersion) • Resistance against environmental conditions (humidity, temperature, mechanical effects) • Resistance against waste form (chemical compatibility, basics, acids, biological agents) • Resistance against heat generation

Safety concern	Scenario	Example	Effects	Safety function associated	Associated Criteria (examples) parameters
					• Resistance against ionization radiation
				Long term containment of radionuclides by engineered barrier system	• Stability of barriers • Compatibility or barriers with waste form
	Alternative evolution scenario	• Discharges from disposal facility • Intrusion	Exposure to direct radiation (to DSRS)	Shielding	• Levels of ambient dose rate (gamma, neutron, beta bremsstrahlung) • Activity
			• Intake of radioactive isotopes via food and water • Inhalation and ingestion of radioactive isotopes • Contamination of skin or eye	Long term containment of radionuclides by waste package	• Stability of waste form (leaching, dispersion) • Resistance against environmental conditions (humidity, temperature, mechanical effects) • Resistance against waste form (chemical compatibility, basics, acids) • Resistance against heat generation • Resistance against ionization radiation
				Long term containment of radionuclides by barriers	• Stability of barriers • Compatibility or barriers with waste form
Occupational health and safety criteria for	Normal operation	Discharges from pre-treatment, treatment, conditioning or	• Inhalation of hazardous materials	Containment of hazardous material by the waste form	Content of toxic materials, basics,

Safety concern	Scenario	Example	Effects	Safety function associated	Associated Criteria (examples) parameters
protection of workers		storage of radioactive waste Discharges from operation of disposal facility	• Ingestion of hazardous materials • Mechanical injuries due to handling waste packages • Other health risks	Containment of hazardous material by packaging	• Environmental conditions (humidity, temperature, mechanical effects) • Resistance against waste form (chemical compatibility, basics, acids)
				Design of technology	• Package design for loading and stacking • Special technological criteria (antistatic packaging, handling biological waste, etc.)
Health and safety criteria for protection of workers and public	• Industrial incidents ○ fire ○ explosion ○ degradation of waste form characteristics ○ degradation of packaging characteristics	• Discharges during pre-treatment, treatment, conditioning or storage of radioactive waste • Discharges from disposal facility	• Inhalation of hazardous materials • Ingestion of hazardous materials • Mechanical injuries due to handling waste packages • Other health risks	Inherent stability of waste form	• Content of explosives, self-ignition materials • Gas generation
				Work safety functions of packaging	• Fire resistance of packaging • Loading and stacking capacity in case of operational incidents, or fire, earthquake,
				Design of technology	• Characteristics degrading the technology

3.5 Methodology for GWAC derivation

In the previous chapters the prerequisites to develop the methodology to GWAC derivation and its basic components were outlined.

These prerequisites were to set the baseline for building up the GWAC:

i. Identification of the status of radioactive waste management system, including identification of waste streams
ii. Decision on radioactive waste management policy
iii. Elaboration of radioactive waste management strategy or strategies.

Having the baseline, the needs for the enhancement of the waste management systems shall be determined. In this context the scope of the development of GWAC shall be defined by analyses and categorization of the waste management situation.

The waste management situation can be characterized by:

a) waste classes to be managed via the waste management strategies, and
b) capacity development demand of one or more waste management activities.

Based on the waste classes to be managed and the waste management activities demanded, the waste management routes can be clearly defined, and the scope of the development of GWAC can be determined. To formalise this process, categories of waste management situation were defined in Chapter 3.3.

One of the objectives of the GWAC is to ensure the compliance with safety requirements via implementation of basic safety functions. The essence of the methodology for the development of GWAC is the association of the criteria to the safety functions of each waste management step in both normal and emergency scenarios, as shown in Chapter 3.4. By defining the link between the criteria and the safety function in selected scenarios, safety calculation for the quantification of criteria can be conducted.

The most common waste types, waste streams and associated waste classes, as well as associated waste management activities and methods are detailed in Chapter 4.

Typical storage and disposal solutions are presented in Chapter 5. The descriptions are structured according to waste management categories.

Derivation methods for radiological criteria, based on radiological safety concerns are detailed in Chapter 6. This section includes the safety functions to be fulfilled, the relevant scenarios, calculations and their application conditions.

Derivation methods for non-radiological criteria, based on industrial health and safety concerns are detailed in Chapter 7. The section includes the safety functions to be fulfilled, the relevant scenarios, calculations and their application conditions.

4 Most common waste types and their management

Nuclear power plants, industries, medical and nuclear research institutes, are the main sources of generation of radioactive wastes. The disposal of such radioactive wastes is one of the most critical issues which can lead to various hazards if not managed adequately.

The radioactive waste that is generated in all these activities is varied in form, activity concentration and type of contamination. It may be solid, liquid or gaseous. Levels of activity concentration range from very low levels associated with radioisotope applications in laboratories, hospitals, etc. to extremely high levels associated with spent fuel and residues from fuel reprocessing.

Equally broad is the spectrum of radionuclides and consequently of half-lives contained in the radioactive waste.

For this reason, waste is mainly classified according to its radioactivity level and its decay time. These two characteristics, together with waste material type and physical status principally influence the choice of the best method for waste treatment and its storage/disposal.

4.1 Classification of radioactive waste

Radioactive waste can be considered in different categories, according to the activity concentration, the physical form (state of aggregation) and the origin.

4.1.1 Waste classification by activity content

Distinction between waste types based on activity level is defined as follows

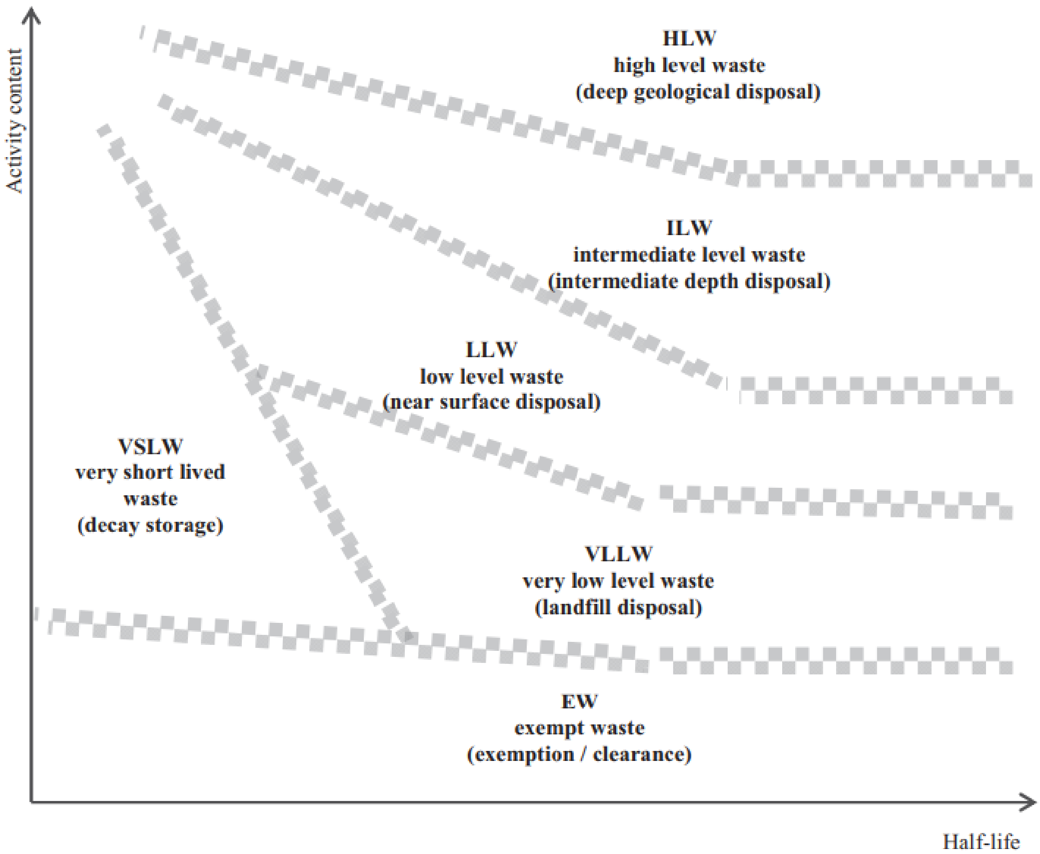

Figure 2. Waste classification according to IAEA GSG-1 [13].

Exempt Waste (EW)
Some radioactive wastes are considered exempt, because their levels of radioactivity fall below thresholds defined in state legislation and disposal of this waste does not require a radioactive substances' permit or authorization from the environmental regulators.

However, disposal of exempt waste may be subject to other environmental regulation because of its non-radiological properties.

Not all countries apply the exemption strategy in the waste management policy.

Very Short-Lived Waste (VSLW)
This category of the waste contains only very short-lived isotopes with the half lives in the magnitude of hours, days, or weeks. This property makes it possible, that its storage for a limited period of up

to a few years to allows its radioactivity content to reduce by radioactive decay to the exemption level.

This category of the waste may not be present in many waste management programmes and in these cases this type of waste than is dealt like VLLW or LLW.

Very Low Level Radioactive Waste (VLLW)
In this category there are wastes that for their type of radionuclides and activities do not meet the criteria of EW, but that do not need a high level of containment and isolation and, therefore, are suitable for disposal in near surface landfill type facilities with limited regulatory control. Such landfill type facilities may also contain other hazardous waste. Typical waste in this class includes soil and rubble with low levels of activity concentration. Concentrations of longer-lived radionuclides in VLLW are generally very limited.

Low Level Radioactive Waste (LLW)
Waste that is above VLLW levels, but with limited amounts of long-lived radionuclides (but more than VLLW). Such waste requires higher level of isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities. This class covers a very broad range of waste. LLW may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration.

This category usually includes a wide range of items that have become contaminated with radioactive material or have become radioactive through exposure to neutron radiation. A variety of industries, hospitals and medical institutions, educational and research institutions, private or government laboratories, and nuclear fuel cycle facilities generate LLW as part of their day-to-day use of radioactive materials. Some examples include radioactively contaminated protective shoe covers and clothing; cleaning rags, mops, filters, and reactor water treatment residues; equipment and tools; medical tubes, swabs, and hypodermic syringes; and carcasses and tissues from laboratory animals. The radioactivity in these wastes can range from just above VLLW levels to much higher levels, such as seen in parts from inside the reactor vessel in a nuclear power plant.

Most LLW arises from the operation of nuclear power stations and nuclear fuel reprocessing facilities, as well as the decommissioning and clean-up of nuclear licensed sites. Operational LLW is principally lightly contaminated miscellaneous waste arising from maintenance and monitoring, such as plastic, paper and metal. LLW from decommissioning is mainly soil, building materials and metal plant and equipment.

The waste is segregated, treated, conditioned, packaged, monitored and stored, as appropriate, before being transferred to a disposal facility.

Drying, incineration, evaporation, high pressure compaction, melting and cementing are common processes applied to the conditioning of LLW. Concrete containers, steel drums and steel boxes are commonly used for their packaging.

Intermediate-Level Radioactive Waste (ILW)
Waste that because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no or limited management for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, in particular alpha emitting radionuclides that will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore, waste in this class requires disposal at greater depths, of the order of tens of meters to a few hundred meters.

ILW arises mainly from the reprocessing of spent fuel and from general operations and maintenance at nuclear sites and can include metal items such as fuel cladding and reactor components, graphite from reactor cores, and sludge from the treatment of radioactive liquid effluents.

High-Level Radioactive Waste (HLW)
Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process, or waste with large amounts of long-lived radionuclides need to be considered in the design of a disposal facility. Disposal in deep, stable geological formations, usually several hundred meters or more below the surface is the generally recognized option for disposal of HLW, because heat generation has to be taken into account when designing storage and disposal facilities.

This category of waste includes:

- the liquid residue that contains most of the radioactivity from the reprocessing of spent nuclear fuel;
- this residue once it has been solidified; or
- any other waste with similar radiological characteristics.

4.1.2 Waste types by physical form

All nuclear activities generate various types and quantities of radioactive wastes. In addition to the radiological content and the type of radionuclides of such waste, it is important to consider the physical state for the choice of management and treatment options.

4.1.2.1 Solid Radioactive Waste

Solid radioactive waste can be:

- Plastic (bags, booties, gloves, sheets, clothing, etc.)
- Glass
- Paper/wood
- Metal
- Powder
- Debris/Rubble
- Disused sources (can also be liquid)
- Miscellaneous solidified liquid/wet wastes, such as sludges (inorganic and organic) and spent ion exchange resins (these can be considered as wet solid wastes).

Plastic/Glass/Paper/Wood
This kind of waste is produced in a wide variety of operations in nuclear industries, medicine and research. The main problem for these types of material is that they may have been in contact with the hazardous and radioactive materials and need some form of analysis or sorting/segregation. Thermal treatment for combustible materials can be used for this type of waste as well as compaction to reduce volumes of the final waste.

Metal
The variety of operations and practices in the nuclear industry, especially during decommissioning, can lead to the production of metal waste. If not adequately treated, this waste can be an issue especially due to the increase in costs and space required for disposal. Treatments of this type of waste can include decontamination with subsequent recycling, supercompaction or melting, to reduce volumes, followed by immobilization.

Powder
These wastes include the dried powders of concentrated wastes, various powdered wastes generated in the decommissioning process (crushed concrete, decontamination sludge, etc.), and fine radioactive soil, which is not easy to decontaminate. As these particulate wastes must be packaged so that they become non-dispersive, they can be compacted or can be solidified with solidification agents, such as cement and polymer. However, solidification methods can increase the volume of the final waste.

Debris/Rubble
The term is used to cover a broad category of discarded materials. These materials may have been in contact with the hazardous and radioactive materials used in the facility, and therefore become contaminated. They can also include steel and concrete from the operation and demolition of nuclear facilities or facilities related to radioactive material treatment.

At present, pre-treatment options for rubble include sorting of the waste to segregate different materials and contaminants. Treatment options include: organic material destruction, separation of contaminants by thermal desorption, and stabilization of treated residuals. All contaminants should be removed to such a level that they will not interfere with the stabilizing materials used to produce the final waste form, nor create an environmental hazard after disposal.

Disused Sealed Radioactive Sources
The preferred option for the management of DSRSs is to return them to their supplier for reuse or disposal. Sometimes this is not possible, especially for older sources where the supplier is not known or is no longer in business. Alternative solutions are, therefore, necessary.

Those containing short-lived radionuclides may be stored for decay in an appropriate container or package and then be released from control (cleared) when their radioactive contents have decayed sufficiently.

Capsules containing conditioned DSRSs are stored in an appropriately designed shielded container until appropriate disposal arrangements are available. Provisions to ensure physical security are necessary for some types of high activity source stores.

Methods for DSRS processing include metal matrix immobilization (for highly active sealed radiation sources) and encapsulation in stainless steel casings. They may further be grouted in steel drums or other suitable overpack.

Inorganic and organic sludges
Industrial operations involving radioactive materials produce a variety of relatively homogeneous sludges or similar wastes. These can be both organic and inorganic. These waste categories could also be called homogeneous or wet solids. Sludges may contain a very high percentage of water. However, their high content of dissolved solids makes them non fluid. They are generally difficult to pump, do not flow on their own or otherwise flow extremely slowly.

Organic sludges are heavy, highly viscous oils or grease, or may be comprised of organic liquids adsorbed onto inorganic materials such as vermiculite, clay or organic adsorbent materials.

The objective is to remove or destroy the organic material so that the remaining inorganics may be stabilized for disposal.

Spent ion exchange resins
Ion exchange resins are used in a wide variety of chemical decontamination or cleaning processes in the nuclear industry. For example, they can be used to control water system chemistry to minimize corrosion or the degradation of system components and to remove radioactive contaminants from liquids.

In many cases in the nuclear industry, spent ion-exchange resins (spent resins) are considered as a problematic solid waste and require special treatment and precautions to meet the WAC for a disposal site. Treatment options currently consist of immobilization and thermal treatments.

4.1.2.2 Liquid Radioactive Waste

Liquid Waste can be divided in Aqueous (or inorganic) and Organic categories:

- Aqueous
- Organic (Oils, Scintillation liquids, Solvent extraction liquids, Miscellaneous solvents, etc.)

Aqueous liquid waste
Aqueous liquid radioactive waste is mostly generated during nuclear reactor operations and during industrial and institutional application of radioisotopes. The chemical compositions and radioactivity levels of the generated wastes depend on the conducted operation. Aqueous wastes containing short-lived beta/gamma activity are kept in storage. After decay to exemption limit, if these wastes meet the regulatory requirements for chemical and biological hazards, they can be safely discharged into the environment. Aqueous wastes that have higher radioactivity content and/or long-lived radionuclides may be treated using ion exchange/sorption, chemical precipitation, evaporation, reverses osmosis, filtration and solvent extraction.

Treatment options for these wastes are based on conventional wastewater treatment processes.

The primary treatment provides removal of suspended solids and neutralization, if required, before further processing. Suspended solids may be separated and treated with inorganic sludges if they are expected to contain regulated contaminants.

Acidic or basic wastes are neutralized.

Evaporation may be used to concentrate the dissolved inorganic compounds before the residues are immobilized. High salt content wastes may be not amenable to stabilization in many common immobilization agents, such as Portland cement. These salt streams may be concentrated or dried and then stabilized with polymers or other salt tolerant media, such as glass or ceramic matrix. The immobilization process usually retains both the radionuclides and toxic inorganic materials.

Reactive chemicals in wastes, such as strong acids, bases, oxidizers, cyanides, etc. may be deactivated, which must be defined for each type of chemical compound.

Organic liquid wastes
Liquid organic radioactive wastes are generated from the use of radioisotopes in nuclear research and in medical and industrial applications.

A strategy for the effective management of these wastes is necessary in order to ensure their safe handling, processing, storage and disposal. Aqueous radioactive wastes may be discharged to the environment after the radioactivity has decayed or been removed.

By contrast, organic radioactive wastes require management steps that not only take account of their radioactivity, but also of their chemical content. This is because both the radioactivity and the organic chemical nature can have detrimental effects on health and the environment.

If present, some hazardous organic materials may be separated from liquid waste streams, purified, and recycled. Assuming that the recycling of such materials has been maximized, the remaining organic hazardous materials are best treated by a destruction technology, commonly by a thermal treatment. It is important to demonstrate that the thermal treatment process can destroy the hazardous organic material which may be present.

Some treatment strategies may also include homogeneous cementation, but this usually implies keeping the load of organic material in the cement matrix very low. New strategies under development also include absorption in polymer matrices or the use of geopolymers for conditioning.

4.1.3 Waste classification by origin

Radioactive wastes can be distinguished by their origin.

Nuclear industry
The largest volume of radioactive waste is generated in the nuclear industry. The operational and decommissioning waste from nuclear fuel cycle facilities is the biggest part of the world's inventory. The nuclear industry creates basically every kind of waste mentioned above, from exempt waste to high level waste, as well as numerous types of solid and liquid waste.

Institutional waste
Industry, healthcare, research and education use radioactive substances during routine operation. The wastes generated from these activities are handled as radioactive waste by the responsible organization.

Legacy waste
Legacy Waste is defined as radioactive waste generated during past activities (energy production, medicine, research, industry) which have been treated and conditioned according to the rules in force at the time or simply stored pending a suitable management solution. Such waste is often lacking sufficient physio-chemical-radiological characterization data for envisaging possible re-treatment/re-conditioning processes in line with current regulatory requirements and/or checking compliance with WAC of storage/disposal facilities.

NORM waste
Radioactive material containing no significant amounts of radionuclides other than naturally occurring radionuclides.

Orphan radioactive sources
A radioactive source which is not under regulatory control, either because it has never been under regulatory control or because it has been abandoned, lost, misplaced, stolen or otherwise transferred without proper authorization.

4.2 Characterization of radioactive waste

According to the IAEA Glossary, characterization is the determination of the physical, chemical and radiological properties of the waste to establish the need for further adjustment, treatment, conditioning, or its suitability for further handling, processing, storage or disposal.

Radioactive waste types fall into one of four subtypes, which are developed as a combination of two components depending upon the consistency and complexity of the waste properties (physical, radiological, chemical, etc.). The first component is due to the complexity of developing the nuclide vector or collection of properties, and the second component is due to the variability of vectors.

The first component is described as either simple or complex. This refers to the level of difficulty (and corresponding expense) to develop the list of properties. For example, simple waste streams do not require much effort or expense to develop the vector. More complex streams will require a great deal of expensive analysis to develop the fingerprint. Classification is presented in Table 2.

Table 2. Classification of waste streams by ease of measurement and sampling ability.

	Ease of Measurement and Sampling Ability			
Waste streams	**Simple and Stable**	**Complex and Stable**	**Simple and Variable**	**Complex and Variable**
NPP origin	X	X		
Institutional	X			
Nuclear Research Lab			X	
Reprocessing		X		
Enrichment, Conversion, Fuel Fabrication	X			
Decommissioning	*	*	*	*
Spent Sealed Sources	X			
Spent Fuel	X			
Final waste Form		X		
Legacy waste	**	**	**	**

*: Facility dependent

** May or may not include this subtype

The variability component refers to whether the properties remain relatively constant over time. For example, streams where the waste always comes from a consistent process will be stable, and wastes coming from varying or multiple processes are likely to be variable. [16]

4.2.1 Radiological characterization

International, national and state regulations determine the inventory and the parameters to be characterized for any facility and activity that involves radioactive waste management. Strategies in the field of radiological characterization need appropriate radio-analytical and radio-metrological support in order to determine the concentration of important nuclides within the relevant accuracy.
Measured radionuclides can be divided into two categories according to the analytical methodology to be applied: difficult to measure radionuclides (DTM), which cannot be characterized by direct measurement in the waste form, and easy to measure radionuclides (ETM), which can be determined by direct measurements.

The concentration of Difficult to Measure (DTM) nuclides (alpha, pure beta and X ray and low energy gamma emitters) is usually determined by destructive assay. These methods consist basically of the following:

- Sample dissolution
- Specific chemical separation process
- Radiometry depending on chemical and radioactive properties of the nuclides

High energy gamma emitting nuclides can be determined by direct measurement in an appropriate geometry by solid scintillation gamma spectrometry (low resolution). High resolution gamma spectrometry with semiconductor detectors may be applied when a complex mixture of gamma emitters is treated before separation or if the waste has a simple composition of gamma emitters by direct measurement of the dissolved sample.

The scaling factor methodology can determine the radioactivity of DTM radionuclides using correlations between them and key nuclides (KN) chosen among the Easy to Measure (ETM). Specifically, the DTM nuclides are predicted from a gamma nuclide easily measured by multiplying the concentration of this KN by the scaling factors calculated from the radioactivity of nuclides obtained through appropriate radiochemical analysis or through modeling code calculation, and which represent the average relationship of the DTM nuclide to the KN. [16]

4.2.2 Physical and chemical characterization

Determination of the physical and the chemical properties of the radioactive waste is important to ensure it is treated in an appropriate way. Physical properties are important in the design of the waste processing campaign and in the design of the radioactive waste packages, their size, durability, mechanical stability, etc.

The chemical characterization is a tool to determine the possible hazards related to the radioactive waste other than radiological risks.

Typical physical properties of the radioactive waste:

- Physical state (solid, liquid or gaseous)
- Size and weight
- Compactability
- Dispersibility
- Volatility
- Miscibility
- Free liquid content

Important features of the chemical composition of the radioactive waste:

- Solubility and chelating agents
- Potential chemical hazard
- Corrosion resistance/corrosiveness
- Organic content
- Combustibility and flammability
- Chemical reactivity and swelling potential
- Gas generation
- Sorption of radionuclides

4.3 Processing of radioactive waste

A very important step of the predisposal management of radioactive waste is the waste processing. The role of this procedure is to have the raw radioactive waste in a form that can be safely handled, stored for long period or even to finally dispose. The steps of the radioactive waste management process can be divided into the following sections:

- Pre-treatment of radioactive waste is the common expression for those operations prior to waste treatment, which serve as preparation for the further treatment.
- Treatment of radioactive waste is the collection of operations that are intended to benefit safety and/or economy by changing the characteristics of the waste.
- Conditioning of radioactive waste is the common name for those operations that produce a waste package suitable for handling, transport, storage and/or disposal.

4.3.1 Processing of solid radioactive waste

There are various technical options for the management of solid radioactive waste which may be applied.

4.3.1.1 Pre-treatment of solid radioactive waste

Collection
The first step of the waste processing is the segregate collection of the waste. The segregated way of collecting disused items or other material will help in the further steps, since there will be no need to segregate them for the later stages.

Segregation
Waste or materials (radioactive and exempt) are separated or are kept separate according to radiological, chemical and/or physical properties which will facilitate waste handling and/or processing. For example, it may be possible to segregate radioactive from exempt material and thus reduce the waste volume.

Decontamination
This process is the removal of contamination by a deliberate physical, chemical or biological process.

4.3.1.2 Treatment of solid radioactive waste

Compaction
It is aimed at reducing the volume and increasing the stability of solid waste for transport, storage and disposal. The volume reduction achievable depends on the nature of the waste and the equipment used, but it can be considerable. It is an economical technique due to moderate capital cost and low operation and maintenance cost. Operations being at room temperature are simple and the fire risk is relatively negligible. There is no multiple handling of the waste. Generation of airborne activity is also minimal, hence radiation exposure during operation is very low. Commercially available presses and compacting devices are frequently used in radioactive waste treatment after appropriate adaptation to the specific task.

Future reworking (reconditioning) of packages containing compacted wastes can be extremely difficult, risky and expensive. This is often needed for legacy waste already treated by compaction and that may no longer be compatible with the standards of treatment in a country.

Incineration
This method can be applied to both solid and liquid combustibles. It achieves the highest volume reduction as well as yielding a chemically stable form. The facility used for incineration should be designed to retain the radionuclides during the incineration process and must be approved by the regulatory body. After combustion, radionuclides from the waste are distributed between ash, the product from the cleaning of the exhaust gases and airborne particles contained in washing liquids, spent filters and stack discharges.

Thermal treatment technologies provide great solutions for volume reduction of nuclear waste and chemical waste stabilization. Nevertheless, most of the existing technologies still need large initial investments, are very expensive to operate and their cost increases exponentially with waste activity. Moreover, some technical issues, like gaseous effluent treatment, are still far from having been solved and the public acceptability of some thermal treatments (i.e. incineration) may be difficult.

Metal melting
This technique is applied to metallic (and sometimes polymeric) waste and may bring high volume reduction. The resulting waste form is compact (ingots, polymer blocks) and does not usually require packaging. However, secondary waste is also created (slag, filters etc.).

Pyrolysis
This process is the thermal decomposition of materials at elevated temperatures, often in an inert atmosphere. Pyrolysis is most commonly used for the treatment of organic materials.

4.3.1.3 Conditioning of solid radioactive waste

Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning is the enclosure of the waste in containers, and, if necessary, providing an overpack.

Immobilization
Conversion of waste into a waste form by solidification, embedding or encapsulation. The aim is to reduce the potential for migration or dispersion of radionuclides during handling, transport, storage and/or disposal.

Packaging
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.

Overpack
A secondary (or additional) outer container for one or more waste packages, used for handling, transport, storage or disposal.

4.3.2 Processing of liquid radioactive waste

The selection of a liquid waste processing system involves making decisions on a number of factors. These can be grouped into five main categories:

- Characterization and segregation of liquid waste,
- Discharge requirements for decontaminated liquors,
- Available technologies and their costs,
- Conditioning of the concentrates resulting from the treatment,

- Storage and disposal of the conditioned concentrates.

The processes available for treating liquid radioactive waste fall generally into three main categories: ion exchange/sorption, chemical precipitation and evaporation. [17]

4.3.2.1 Pre-treatment of liquid radioactive waste

Segregated collection of liquid waste

The most essential pre-treatment step is the segregated collection of the liquid radioactive waste. It is necessary to collect liquid waste not only by its state but by its origin as well: different collection is needed for residues, evaporates, etc.

Pre-filtering

Removal of large particles from the media in order to protect the later stages of filtering, further processing.

Chemical adjustment

Chemical oxidation is used in liquid waste treatments to reduce odour, decolorize, destroy organic matter to improve precipitation and flocculation, and oxidize ions such as iron and manganese to a higher valence state and thereby improve the removal of these elements by the precipitation treatment.

Reduction reactions are employed in waste treatments to convert a pollutant to a solid form, such as in the reductive recovery of metals or precipitation of an insoluble material.

4.3.2.2 Treatment of liquid radioactive waste

The treatment processes for liquid LLW are directed towards volume reduction and the removal of radionuclides from the bulk of the waste. They result in a concentrated waste stream (that must be further conditioned) and a supernatant/distillate which can often be cleared from regulatory control and directly released or released after additional treatment.

4.3.2.2.1 Chemical treatment

pH adjustment

Adjustment of the pH can be used to modify the ionic species present in the waste stream. This may influence the choice of precipitants and the operating conditions used in the treatment process.

The adjustment of solution pH can sometimes be advantageously employed in the treatment of waste containing metal ion complexes, in order to form an undissociated acid or base.

Precipitation

Precipitation using chemical compounds will result in a sludge that contains the bulk of radioactivity and will require conditioning.

Ion exchange

The use of ion exchange procedures in chemical processing, water and wastewater treatments was well developed by the time the technique was first applied in the nuclear industry. Extraction by selective ion exchange resins, can be both organic and inorganic.

The process involves the exchange of ionic species between a liquid solution and a solid matrix containing ionizable polar groups. When exchangers become fully loaded they are removed from service and treated as radioactive waste. Alternatively, many organic ion exchange materials may be regenerated by strong acids or bases, yielding radioactive liquid waste with a high salt and activity content. [17] The spent resin used will be the secondary waste created and must be subsequently treated.

4.3.2.2.2 Physical treatment

Filtering
The separation of solids from liquids or gases by passing the mixture through the interstices of a suitable medium, for example filter paper, cloth or glass wool. [14]

Evaporation
Evaporation of aqueous or organic solutions concentrates radionuclides and results in a very high waste volume reduction factor as well as a high decontamination factor. The resulting concentrate must be further conditioned.

4.3.2.3 Conditioning of liquid radioactive waste

Conditioning encompasses those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers, and, if necessary, providing an overpack.

5 Storage and Disposal of Radioactive Waste

Radioactive waste may be subject to storage at a number of stages during its management and, therefore, may be stored in processed and unprocessed forms for varying periods of time. [18] Storage is a temporary measure in which radioactive waste is held in a facility that provides for its containment, with the intention of retrieval. Extended storage periods are generally only required for radioactive waste for which no disposal option is yet available.

5.1 Storage of radioactive waste

5.1.1 Types of Radioactive Waste Storage

As discussed in Chapter 4, LILWs are commonly processed to produce volume-reduced, solid waste forms and the converted wastes are enclosed and/or over packed in containers. These resulting waste packages[1] are often stored in above-ground storage buildings or in shallow near-surface storage structures, and facility operators generally use a combination of engineering design features, operating procedures and monitoring programmes to achieve safe handling and storage. [19]

In order to provide common safety considerations for radioactive waste storage, the development of storage according to recommendations for passive safety, including the following is advised [18]:

a) The radioactive material should be immobile.
b) The waste form and its container should be physically and chemically stable.
c) Energy should be removed from the waste form.
d) A multibarrier approach should be adopted in ensuring containment.
e) The waste form and its container should be resistant to degradation.
f) The waste storage environment should optimize the lifetime of the waste package.
g) The need for active safety systems to ensure safety should be minimized.
h) The need for monitoring and maintenance to ensure safety should be minimized.
i) The need for human intervention to ensure safety should be minimized.
j) The waste storage building should be resistant to foreseeable hazards.
k) Access to the waste storage building should be provided for response to incidents.
l) There should be no need for prompt corrective action in the event of an incident.
m) The waste packages should be able to be inspected.

[1] As defined by the IAEA Glossary [14], the waste package is the product of conditioning that includes the waste form and any container(s) and internal barriers (e.g., absorbing materials and liners), prepared in accordance with the requirements for handling, transport, storage and/or disposal, the waste form is the waste in its physical and chemical form after processing (treatment and/or conditioning resulting in a solid product) and the container is the vessel into which the waste form is placed.

n) The waste packages should be retrievable for inspection or reworking.
o) The lifetime of the waste storage building should be appropriate for the storage period prior to disposal of the waste.
p) The waste storage facility should enable the retrieval of waste.
q) The waste package should be acceptable for final disposal of the waste.

While in storage, radioactive waste should be expected to retain its form and suitability for transport and disposal for a predetermined period of time without subsequent reconditioning [20]. This expectation is met through the interaction of three sets of criteria: the WAC, the waste form and container specifications, and the design and operating requirements of the storage facility.

Storage of LILW
The storage of the very low, low-and intermediate level waste can carried out by using different storage concepts. The safe enclosure of the radioactive waste can happen by using different means of package types, these can be:

- drums,
- steel or concrete molds,
- tanks,
- containers, ISO containers. [19]

A number of different types of materials have been used for the fabrication of waste containers. Examples of typical containers can be found in Figure 3. Detailed descriptions of containers for LILW are available in IAEA Technical Report Series 355 [21].

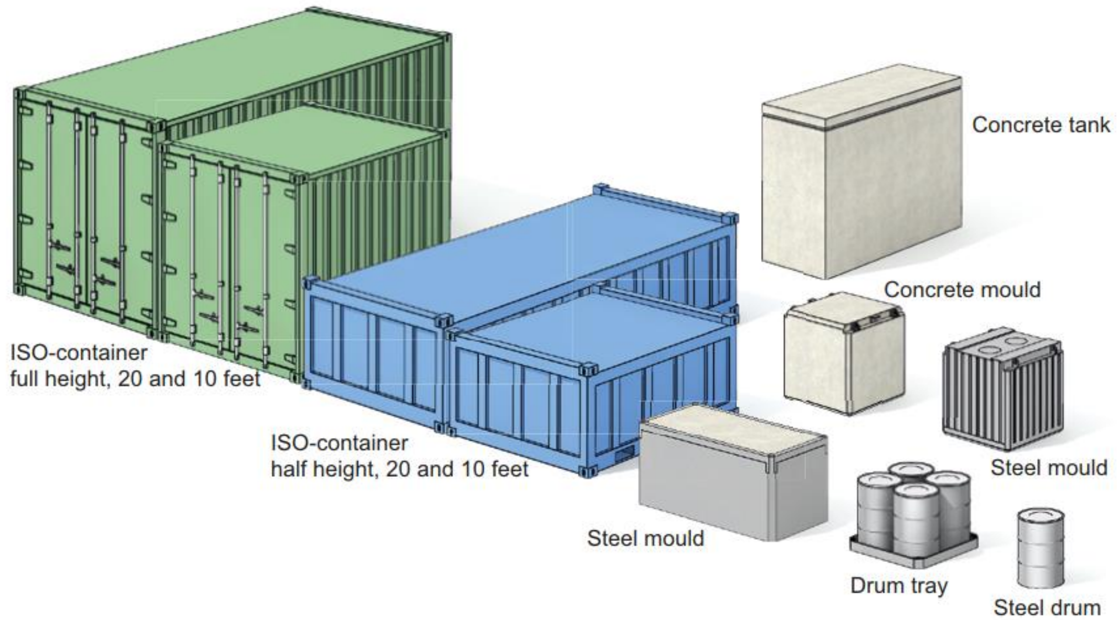

Figure 3. Standardized containers used for waste packaging in Sweden (Government Offices of Sweden, Ministry of the Environment, 2020).

Storage of HLW
The storage of HLW can happen by using similar waste packages as it was described in the case of the LILW. However in case of the storage of the HLW extra attention has to be paid to the radiation protection and the heat removal from the packages.

Well type storage installation can be found in several cases, for instance, in some NPPs. The purpose of the storage wells is to provide the extra radiation protection during the storage period. In this case it is not likely that the waste package is usable for the final disposal.

Storage of DSRS

Depending on the possibilities, the storage of the DSRS can vary. In some cases shielded drums or other shielded containers are used to store DSRS. These means of storage provide a transportable way of storage.

There are situations, where the storage of the DSRSs is done by using well type storage installations. In this case the wells are constructed in a storage facility and the wells are lowered beneath the floor level, so the radiation protection is provided by the soil beneath the wells.

While the portable solutions for the storage of DSRS might be used in the case of the disposal, in the case of the well storage the repackaging of the DSRS is very likely.

Figure 4. Potential storage solutions for the DSRSs. Left: cross section of a shielded drum [22], right: lowering source into a well type DSRS storage in Püspökszilágy, Hungary.

5.1.2 Storage Aspects of Waste Acceptance Criteria

WAC for storage are specific requirements defined to ensure waste consigned to a specific storage facility complies with applicable regulatory requirements [19]. They are parameters often specified in terms of the required physical form of the waste and the waste packages, maximum levels of radioactivity, dose rate, packaging requirements, etc., in order to provide reasonable assurance that the emplaced waste can be stored and retrieved safely at a storage facility within planned time frames. In some countries, storage WAC have been developed based on foreseeable conditions as identified in facility safety cases (e.g., the United Kingdom), while others do so with future disposal requirements or management strategies taken into account (e.g., Sweden).

Typical storage WAC address a wide range of physical, chemical and radiological criteria essential to the safe and effective performance of the waste package [20]. As a waste package consists of a waste form and a container, a specific set of technical requirements can be addressed to each of them separately and to the waste package as a whole. For a waste form, these criteria concern but are not limited to the following, depending on facility requirements:

- Waste composition,
- Chemical durability,
- Immobilization and/or stabilization,
- Structural stability,
- Respirable fraction,
- Distribution of activity.

WAC for waste containers may cover the following parameters:

- Internal pressure,
- Mechanical integrity,
- Properties affecting primary confinement,
- Venting,

- Compatibility with the waste form.

Each waste package must meet a general set of criteria in addition to requirements specific to the waste form and waste container. WAC applied for waste packages generally include the following:

- Seal integrity
- Free liquids
- Gas generation
- Flammability
- Radionuclide inventory
- Fissile mass
- Decay heat
- Radiation dose rate and surface contamination
- Configuration and weight
- Identification.

Waste packages may also be subject to additional constraints due to limitations or special conditions present at the storage facility that do not exist at a disposal site. [20] For instance, floor loading and entrance dimensions may limit the package size and weight permitted for storage. When a disposal site with WAC is available, the requirements between the storage and disposal facilities should be compared, and the most conservative set chosen for the waste packages. Waste packages that have been designed to comply with the WAC of an existing disposal facility are expected to comply with them both during and after the storage period. In situations when waste packages are produced in the absence of a disposal facility, they may be produced and characterized in accordance with international best practices and assumptions.

Overall, storage WAC are facility specific, often developed by facility operators and waste management agencies, with inputs from the facility designers to ensure that waste can be safely stored using robust storage technologies and under the planned storage conditions. [19] The main functions of the storage facility are to provide safe custody of the waste packages and to protect both operators and the public from any associated hazards. [20] The storage facility should be capable of maintaining the “as-received” integrity of the waste package until it is retrieved for disposal. The storage facility must protect the waste from environmental conditions, including extremes of humidity, heat and cold, or any other environmental condition which would degrade the waste form or container. Examples of LILW storage facilities can be found in Figure 5.

Figure 5. LILW storage in Germany (top left), Canada (top right), the UK (bottom left), the Netherlands (middle right) and Belgium (bottom right).Top images from [19] and others from [20].

5.2 Final Disposal of Radioactive Waste

5.2.1 Types of Disposal

Disposal represents the endpoint of a radioactive waste management programme and, ultimately, LILW packages will be transported from storage facilities to disposal facilities following a defined schedule. Similar to storage of LILW packages in storage facilities, all waste to be disposed of in disposal facilities must conform to predefined WAC. Disposal WAC concern general, radiological, chemical and physical as well as mechanical requirements.

The fundamental safety objective of radioactive waste management is to protect people and the environment from the harmful effects of ionizing radiation. This means that radioactive waste disposal facilities shall be designed to protect the people and the environment both now and in the future. In general, a disposal facility is designed to contain the radionuclides embedded in the radioactive waste, isolate them from the accessible biosphere and retard the dispersion of radionuclides in the geosphere and biosphere. The design of a disposal facility shall ensure that all reasonable measures are considered to prevent, inhibit and delay releases into the environment. The facility shall also provide isolation of the waste from phenomena that could degrade the integrity of the facility. The various elements of the disposal system, including physical components and control procedures, contribute to performing safety functions in different ways. [2, 23, 24]

According to [14], the term ‘disposal’ refers to the emplacement of waste into an appropriate facility without the intention of retrieval. However, some national waste management strategies include retrievability. Specific aims for disposal are: [23]

a) To contain the waste;
b) To isolate the waste from the accessible biosphere and to reduce substantially the likelihood of, and all possible consequences of, inadvertent human intrusion into the waste;
c) To inhibit, reduce and delay the migration of radionuclides at any time from the waste to the accessible biosphere;
d) To ensure that the amounts of radionuclides reaching the accessible biosphere due to any migration from the disposal facility are such that possible radiological consequences are acceptably low at all times.

Numerous design options for disposal facilities have been and are currently being developed, constructed and operated around the world: [23]

a) Specific landfill disposal: Disposal in a facility similar to conventional landfill facility for industrial refuse but which may incorporate measures to cover the waste. Such a facility may be designated as a disposal facility for very low-level radioactive waste (VLLW) with low concentrations or quantities of radioactive content. Typical waste disposed of in a facility of this type may include soil and rubble arising from decommissioning activities.
b) Near surface disposal: Disposal in a facility consisting of engineered trenches or vaults constructed on the ground surface or up to a few tens of meters below ground level. Such a facility may be designed as a disposal facility for low level radioactive waste (LLW).
c) Disposal for intermediate level waste: Depending on its characteristics, intermediate level radioactive waste (ILW) can be disposed of in different types of facilities. Disposal could be by emplacement in a facility constructed in caverns, vaults or silos at least a few tens of meters below ground level and up to a few hundred meters below ground level. It could include purpose-built facilities and facilities developed in or from existing mines. It could also include facilities developed by drift mining into mountainsides or hillsides, in which case the overlying cover could be more than 100 m deep.
d) Geological disposal: Disposal in a facility constructed in tunnels, vaults or silos in a particular geological formation (e.g., in terms of its long-term stability and its hydrogeological properties) at least a few hundred meters below ground level. Such a facility could be designed to receive high level radioactive waste (HLW), including spent fuel if it is to be treated as waste. However, with appropriate design, a geological disposal facility could receive all types of radioactive waste.
e) Borehole disposal: Disposal in a facility consisting of an array of boreholes, or a single borehole, which may be between a few tens of meters up to a few hundred meters deep. Such a borehole disposal facility is designed for the disposal of only relatively small volumes of waste, in particular disused sealed radioactive sources. A design option for very deep boreholes, several kilometers deep, has been examined for the disposal of solid high-level waste and spent fuel.
f) Disposal of mining and mineral processing waste: Disposed usually in or near ground surface, but the manner and the large volumes in which the waste arise, as well as its physicochemical form and its content of long-lived radionuclides of natural origin distinguish it from other radioactive waste. The waste is generally stabilized in situ and covered with various layers of rock and soil.

Selecting the disposal method and the design for the disposal facility for LILW depends on various factors, both technical and administrative. The national radioactive waste management policy, legislation and regulation, waste origin and inventory, climatic conditions, site characteristics and societal acceptability are some of the topics affecting the selection. [25]

5.2.2 Disposal Aspects of Waste Acceptance Criteria

All the above presented disposal facility design options, from near surface disposal to geological disposal, set the basis for requirements for the waste packages to be disposed. Waste acceptance requirements and criteria for disposal facilities ensure safe handling of waste packages and unpacked waste during normal operation and anticipated operational occurrences. Waste packages and unpacked waste accepted for disposal shall fulfil the criteria that are fully consistent with, and are derived from, the safety case. [23]

Waste acceptance criteria can be defined as quantitative or qualitative requirements that must be fulfilled in order for the waste to be accepted for final disposal. According to [26], the overlying requirement for waste is:

"The waste package, i.e., the waste form and packaging, should prevent radionuclide dispersion during handling and relay radionuclide migration during disposal. The waste package should protect workers and the environment from radiation. The waste package should be suitable for handling in the transport and disposal systems. Both the activity and the materials in the waste packages should be selected with regard to the technical barriers of the repository so that the repository is safe after closure. The above principles should be upheld by optimization from an ALARA perspective and the use of best available technologies (BAT). "

Waste acceptance criteria can be developed in stages based on the level of available information regarding waste packages, facility design and site characteristics [25]:

- Generic requirements are initially defined based on (i) the national radioactive waste disposal policy, (ii) general information on the type and quantities of waste packages expected to be generated, and (iii) the availability of certain sites.
- Site selection and site characterization follow, providing information on the characteristics of the potential disposal site.
- Once the actual characteristics of the entire disposal system has been identified, the formulation of specific waste acceptance requirements is completed.

A stepwise approach allows development of general requirements prior to having a waste storage or disposal facility design, and as the level of information increases, more detailed waste acceptance criteria can be specified. The more detailed waste acceptance criteria are based on the safety case and the safety functions for the disposal facility and set the basis for the waste packages, so that they can be accepted for disposal. In general, waste acceptance criteria are divided into general and qualitative (radiological, chemical and physical, and mechanical) requirements. The waste acceptance criteria must be quantified for all types of waste and as a result, there will be a set of criteria for each waste type. [27, 25]

Below are listed some examples of recognized topics for both general and qualitative waste acceptance criteria [28, 26]:

- General requirements
  - geometry
  - dimensions
  - weight
  - conditioning
  - labelling of waste packages

- Radiological requirements
  - radionuclide inventory
  - surface dose rate and dose rate at a certain distance
  - surface contamination
  - radiation effects of the waste and homogeneity

- Chemical and physical requirements, and
  - composition and structure
  - homogeneity
  - hydraulic properties
  - gas formation
  - liquids
  - fire resistance
  - chemical reactivity (complexing agents)
  - leaching
  - environmentally hazardous substances

- Mechanical requirements
  - robustness against external influences
  - internal stability
  - corrosion resistance

As some storage waste acceptance criteria have been developed considering existing or future disposal requirements, these can be quite similar to the criteria set for disposal waste acceptance criteria. According to [28], the defined waste acceptance criteria shall be measurable and verifiable. Due to this, waste packages intended for disposal must be characterized to ensure compliance with the waste acceptance criteria. If the requirements and criteria are not met, the generator of the waste or the operator of the disposal facility must confirm the needed corrective measures to be taken. There should be processes for handling waste packages that do not meet the acceptance criteria, either returning them to the waste generator or correcting the deviations at the disposal facility. [26]

Waste acceptance criteria are established to ensure adequate defense in depth and so that safety of the disposal facility is not dependent on a single element or control measure, such as verification of the inventory of waste packages, or dependent on the fulfilment of a single safety function or a single administrative procedure. [23]

It is difficult to set unambiguous waste acceptance criteria for LILW due to waste type differences, handling technologies and disposal concepts [29]. Generic waste acceptance criteria can be developed before a disposal facility exists, but more detailed WAC have to be derived from the safety case and the safety functions.

Both storage and disposal of waste should be undertaken within appropriate national legal frameworks that provide for clear allocations of responsibilities and ensure the effective regulatory control of facilities and activities.

6 Derivation methods for Radiological Criteria

Radiological criteria can only be derived from a preliminary assessment of dose consequences and nuclear safety calculations. This is because waste packages must meet criteria that guarantee the safety of workers and the general public in both the short and long term. The general approach to the derivation of the radiological criteria is presented in the next chapter, followed by the specific description of the criteria elements. Since the safety assessments are the key players in the derivation of radiological criteria, the incident scenarios for the operational phase of the waste management facilities and the intrusion scenarios of the post-closure period are highlighted.

6.1 General view on radiological criteria

By definition, the elements of the radiological criteria have some effect on the environment and the people that can have direct contact with it or can suffer from the consequences of incidents or accidents. The main elements of the radiological WACs are:

- heat generation
- contact dose rate and at a 1m distance;
- contamination;
- criticality, fissile content;
- isotope content.

Two approaches are considered related to the radiological criteria. One is based on the periods of the waste management cycle and the other one is based on safety functions.

The IAEA Guidance for Development of Waste Acceptance Criteria [11] makes distinction on functional considerations such as (i) handling and identification, (ii) operational period and (iii) post-closure period.

The safety function approach divides the elements of the radiological criteria into four groups: (i) level of shielding, (ii) heat generation, (iii) confinement and (iv) industrial safety.

For criteria the only derivation method for the radiation related criteria is the usage of safety assessments.

Table 3. Overview of the radiological criteria and their derivation and control methods.

Elements of the radiological criteria	IAEA-TECDOC-285 approach			Safety function approach				Derivation method	Control methods*
	handling	operational period	post-closure	level of shielding	heat generation	confinement	industrial safety		
HEAT GENERATION		X	X		X		X	SA	M, Ca
SURFACE DOSE	X	X		X				SA	M
CONTAMINATION	X	X		X			X	SA	M, S
CRITICALITY	X	X	X			X	X	SA	M, Ca
ISOTOPE CONTENT	X	X	X	X		X	X	SA	M, C, E

*Control methods:

- M – direct Measurement
- Ca - Calculation
- C - inspection of Certificate
- S – Sampling and measurement
- E – Estimation

As it can be seen, results of safety assessments are an important means for determining inventory and/or concentration limits for specific radionuclides in the waste and provide one way for developing waste acceptance requirements for waste management facilities. This approach can be used for both operational phase of any waste management facility and also for the post-closure periods of a disposal facility. [30]

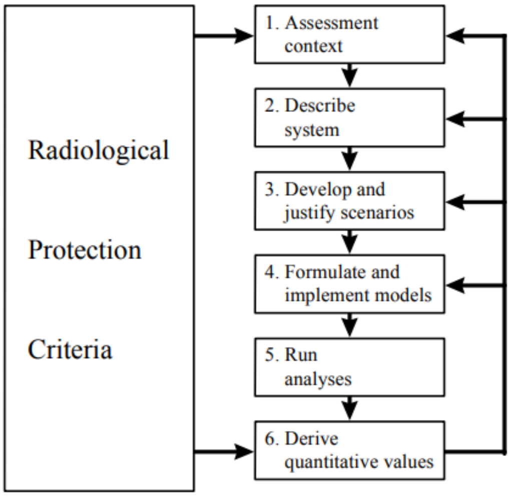

Figure 6. The approach used for deriving activity limits for operation and post-closure periods.

6.2 Description of the specific criteria elements

6.2.1 Heat generation

One of the major factors in the design of a high-level waste repository is heat generation in the waste packages. The high-level waste contains nearly all the heat-producing fission products that are present in radioactive waste and therefore generates significant levels of heat. Therefore, the high-level waste packages shall be designed and controlled to be thermally compatible with the repository. In terms of handling the waste packages, the level of decay heat output will be at a maximum at the time of conditioning. At this time, provisions shall be made to handle safely and store temporarily the heat generating waste packages until such time that they are transported to either long-term storage or disposal facilities.

The contents of the individual waste packages partially determine the maximum temperature of the waste form and of the geological medium adjacent to the waste packages. There are several ways of reducing this maximum temperature, examples of which are reducing waste concentration, allowing radioactive decay and increasing the surface area of the container. These options can be controlled by the waste producer or WMO. Whichever option or combination thereof is selected, the waste package must meet heat generation and size limitations established by the repository operator or regulatory authority.

Waste concentration reduction is achieved simply by putting less waste in a unit volume of container so that the container contains more matrix material and less actual waste.

Radioactive decay of the waste can be achieved during interim storage before and/or after conditioning the waste. One must, of course, respect regulations that may limit the period of storage of the waste before disposal.

The use of engineered barriers in the repository could affect the temperature of the entire waste package. The repository designer should have allowed for this when the maximum heat generation rate is specified for a waste package. [11]

6.2.2 Dose rate

These criteria can be derived from the regulation for transport. The purpose is to ensure the safety for operators and the population during transport and handling of the packages. The reference limits can be taken from regulations for ADR transport (European Agreement concerning the International Carriage of Dangerous Goods by Road) [31] and are:

Contact dose

- 2 mSv/h on contact;
- 0.1 mSv/h at 1 m distance from package surface.

A shield must be used if these limits are exceeded. It is recommended to take these limits into consideration when deriving limits for the activity levels.

6.2.3 Surface contamination

These criteria can be derived from the regulation for transport (ADR). Contamination means the presence of a radioactive substance on a surface in quantities in excess of 0.4 Bq/cm^2 for beta and gamma emitters and low toxicity alpha emitters, or 0.04 Bq/cm^2 for all other alpha emitters. [31] Non-fixed contamination means contamination that can be removed from a surface during routine conditions of carriage. Fixed contamination means contamination other than non-fixed contamination.

Removable Contamination:

- 4 Bq/cm^2 for Beta/Gamma radionuclides;
- 0.4 Bq/cm^2 for Alfa radionuclides.

6.2.4 Criticality – Fissile Content

Criticality can only occur if an unacceptably high level of fissionable material is immobilized with the waste. Maximum levels for these elements in the concentrated and immobilized waste should be established. In nearly all cases fissionable materials are not expected to be present in significant enough quantities to be a problem, so it is the non-routine or one-time occurrence that one should be guarding against. Analysis of waste batches of uncertain fissile content being introduced to the immobilization facility for fissionable materials will identify whether they are of concern. If fissionable materials are present in the waste, it might also be possible for these materials to be concentrated in one portion of the waste or in the waste package. This might be especially true if there are opportunities for precipitation of certain elements during immobilization. In the case of potential segregation in the waste, one should fully understand the operation of the process and identify any opportunities for this to happen. Proper process controls, as well as monitoring the waste form, will eliminate the possibility of this occurring.

Fissile material content in each package must be limited to exclude the possibility of critical events. In particular, it will be necessary to guarantee a criticality index (Criticality Safety Index - CSI) equal to zero for each package. [31]

6.2.5 Isotopic Content

The package for disposal must have a radiological content such as to ensure compliance with the dose limits prescribed for operators and the population in the different life phases of the repository and established by the safety authority.

Before disposing of the package in the repository, the requirement for the contact dose can be, if necessary, satisfied by the use of a shielding overpack.

The radiological limits are set based on the type of radionuclide both for waste package and for repository site, or just for waste package.

This criterion translates into limits on the maximum activity concentration for each radionuclide, expressed in terms of Bq/g, derived from the safety analyses carried out for the following scenarios:

1) incident scenarios for the repository operating phase;
2) intrusion scenarios for the post Institutional Control phase;
3) normal evolutionary scenario for the post Institutional Control phase.

In the absence of a definitive site for repository the value adopted for the maximum possible activity concentration of each radionuclide for a package, will be the lowest of those that will be derived from the first two scenarios; simulations can be done using generic conditions to determine preliminary radiological GWAC.

The normal evolution scenario will instead be used to establish the total radiological capacity of the repository system, to be compared with the total radiological spectrum of the waste to be disposed of and to determine (in synergy with the first scenarios) the average activity concentration for each radionuclide per package and which cannot be exceeded in the repository.

This last criterion can be defined at the end of Safety Assessment that will be carried out once the final repository site will be selected.

In the absence of a definitive Safety Assessment, i.e. a site for the repository, it is possible to start carrying out evaluations to determine the maximum possible concentration per package, doing simulations on accidental scenarios.

6.3 Accident Scenarios for the operating phase of the waste management facilities

Possible accidents that could occur during the repository operational phase must be established; the hypothesized scenarios are:

- Fire case
- Drop and crush of a package.

For these scenarios, once conditions have been established and validated by the safety authority, simulations will have to be carried out by means of calculation codes and, starting from the fixed dose limit, it will be possible to establish what the maximum concentration per package for every single radionuclide can be.

6.3.1 Fire case scenario

For the fire scenario, in the assessment the following features have to be considered:

- The modalities of the event (area in which it happens, number of drums involved etc.)
- Event duration
- Methods of intervention (number of operators who will intervene, exposure time)
- Effect on the public
- Maximum acceptable dose limit connected to the event for operators and the population (established by the safety authority).

The amount of waste or waste packages that can be affected by the fire must be specified. The behavior of the waste, such as if it contains any flammable, or explosive material must also be considered.

There must be a reasonable response time for the situation. It is important to know what the protocol is in the event of a fire in the waste management facility, in order to have a realistic view of the activity related to the fire fighting.

Where the anticipated fire case is located must also be accounted for, as a fire case that is anticipated on the road, during the transportation of the waste may require a longer response time. A waste management facility may have its own fire extinguishing system.

To assess the doses of the operators and the personnel involved in the intervention, both external irradiation dose and dose from inhalation/ingestion of radioactive substances have to be taken into account. Whether the smoke can reach inhabited areas should be considered, and if that is the case then an airborne contaminant transport calculation is needed to estimate the dose consequences for the public.

It is recommended to carry out the calculations using unit specific activities for each anticipated isotope, as this can simplify the calculations when the limits are derived from the dose limits of the effected group of people.

It is also recommended to use conservative but realistic estimations, to avoid the overestimation of the dose consequences.

6.3.2 Drop and crush scenario

Regarding the drop and crush incident, the following conditions must be considered:

- The modalities of the event (area in which it happens, height of fall, type of container breakage, number of containers involved, etc.);
- Event duration;
- Methods of intervention (number of operators who will intervene, exposure time);
- Effect on the public;
- Maximum acceptable dose limit connected to the event for operators and the population (established by the safety authority).

The amount of waste that can be involved in the calculations of the dose consequences of such scenarios must be defined. The physical properties of the waste are important to estimate the rate of package failure, amount of the spillage and ratio of the isotopes that can get airborne.

The knowledge of the existing protocols for accidental situations of the waste management facility is important, to avoid the creation of unrealistic scenarios.

Both external irradiation and inner doses have to be taken into account when assessing the doses of the personnel and the people involved in the intervention. The calculation of the airborne release offsite has to be considered if the amount of waste involved in the anticipated scenario, the distance of the inhabited area or any other factor makes it reasonable to do so.

As mentioned in the previous Chapter, the usage of unit specific activities is beneficial when dealing with the derivation of activity limits, to avoid the overestimation of the dose consequences.

6.4 Intrusion scenarios for the Post Institutional Control phase

The concept of the intrusion scenarios is presented in Figure 7. Three accidental scenarios of inadvertent human intrusion are currently being hypothesized:

- Well drilling
- Excavation for house construction
- Excavation for road construction.

For each scenario, the following conditions must be established and approved by the safety authority:

- Residence of the intruder on the site (intruder lives on the site or not)
- Rate / Quantity of excavated material (m^3)
- Area of cultivated land (m^2)
- Time of occupation on the ground (h / year)
- Water consumption
- Dose goal.

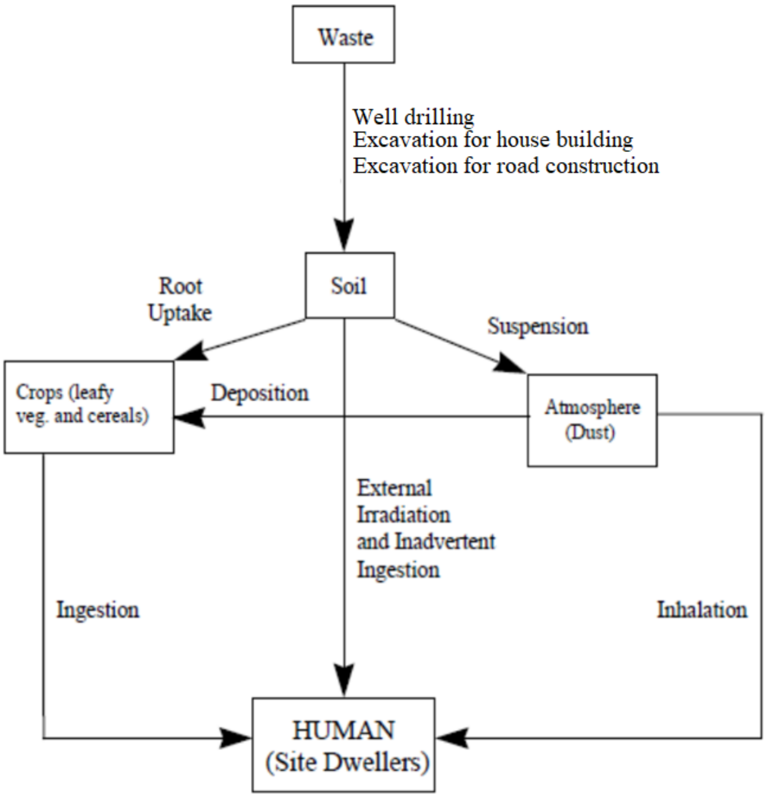

Figure 7. Conceptual model of human intrusion scenario.

6.4.1 Description of the well drilling scenario

The intruder digs a well through the repository structure and pours the excavated material onto the ground surface in the area around the repository (Figure 8).

This scenario affects the intruder, as a member of the population living in the area next to the repository. The exposure is permanent as a constant excavation rate over the period of a year is assumed. A contamination rate is therefore generated on the soil which feeds a local vegetable production line. The dose intake is due to external radiation, ingestion of sediments, inhalation of dust ingestion of contaminated water by human and by cattle, and ingestion of vegetables (leafy vegetables, fruit, tubers and cereals).

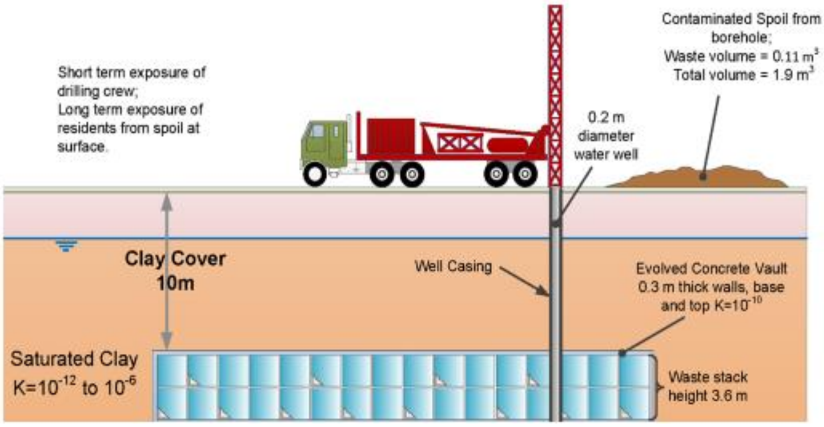

Figure 8. Concept of well drilling scenario.

Potential Transport and Exposure Pathways:

The primary transport pathways for the worker are likely to be direct exposure to the cuttings or drill core and inhalation of the dust. Other transport pathways could include ingestion of contaminated particles. The exposures for the worker are expected to be relatively short-term. The resident receptor could ingest contaminated food due to waste being mixed with surface soil (vegetables, milk or meat from cattle eating contaminated grain or grass) and may also ingest or inhale soil with radionuclide contamination and receive external exposures. There can also be exposures from drinking groundwater obtained from the aquifer that has been contaminated by previous releases from the disposal facility. Contaminated water may also be used for agriculture or livestock (ingestion). The exposure to the resident farmer is expected to be relatively long-term.

6.4.2 Description of the Excavation for house construction scenario

This intrusion event involves excavation into a near surface disposal facility to construct a residence. Radioactive materials are exposed at the surface during excavation and radioactive materials surround the basement foundation of the residential building (Figure 9). The primary worker receptor is likely to be an excavation worker. Other exposed workers could be the surveyors, field scientists, constructions workers building the residential building. The primary public receptor is likely to be the occupant of the residential building.

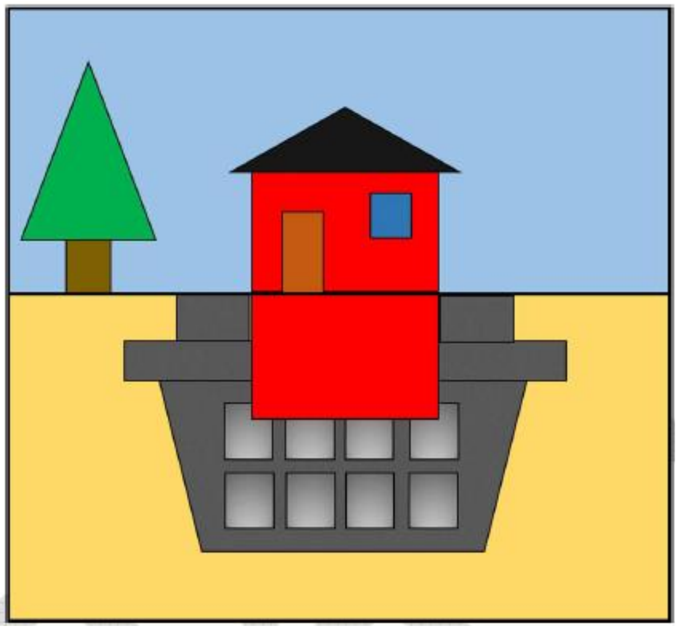

Figure 9. Concept of house building scenario.

Potential Transport and Exposure Pathways:
The primary exposure pathways for the workers are likely to be direct exposure to the radioactive material and inhalation of the dust, when working with the waste. Other transport pathways could include ingestion of contaminated particles. The exposures for the primary worker are expected to be relatively short term. The primary exposure pathways for the resident receptor would be similar to the drilling scenario but may also include exposures associated with the basement floor proximity to the waste and a mixture of excavated waste and soil that would be used as backfill around the basement walls (e.g., external exposure). Note that this scenario is often mitigated by including sufficient clean cover over the waste material to preclude a basement reaching the depth of the buried waste.

6.4.3 Description of the Excavation for road construction scenario

This intrusion event involves excavation into a near surface disposal facility to build a road and could also include other larger scale public works. Radioactive materials are exposed at the surface during excavation and materials on the roadside remain exposed after the road is constructed. The concept of this scenario is shown in Figure 10. The primary worker receptor is likely to be an excavation worker. Other exposed workers could be the surveyors, field scientists, constructions workers building the road, or any laboratory staff investigating the excavated material. The primary public receptor is likely to be the occupant of a nearby residential building. Note that scenarios like this involving major public works projects could potentially be considered less likely during the time frame that public records and permitting requirements are assumed to remain.

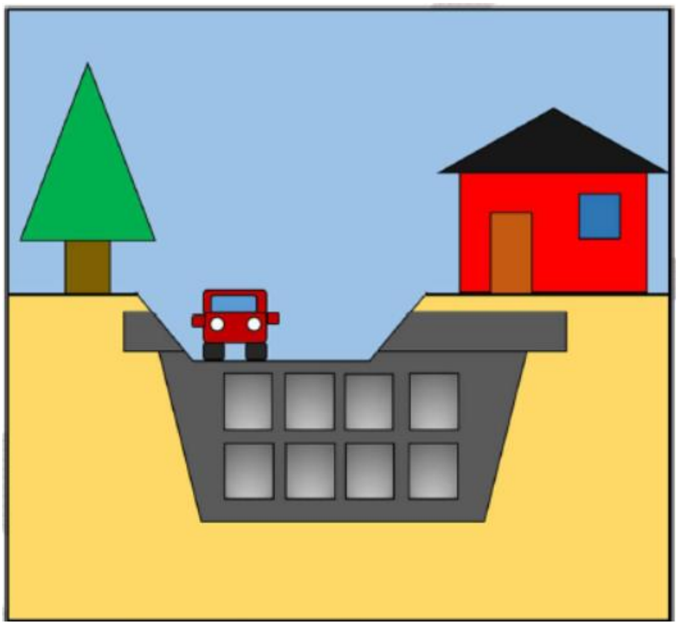

Figure 10. Concept of road construction scenario.

Potential Transport and Exposure Pathways:
The primary transport pathways for the primary worker are likely to be direct exposure to the radioactive materials and inhalation of the dust. Other transport pathways could include ingestion of contaminated particles. The exposures for the workers are expected to be relatively short-term. The potential exposure pathways for the resident receptor would be similar to those considered for the drilling scenario. The exposure to the public receptor either for the worker of the road construction or the driver, driving on the road is expected to be relatively long-term.

7 Derivation of non-radiological criteria

In radioactive waste management even the non-radiological properties of radioactive waste, that are important from safety point of view, must be considered. In the frame of development of waste acceptance criteria, either generic or specific, the non-radiological properties could be sorted into different groups based on the safety viewpoints.

7.1 General view of non-radiological criteria

The IAEA Guidance for Development of Waste Acceptance Criteria [11] makes distinction on bases of functional considerations such as (i) handling and identification, (ii) operational period and (iii) post-sealing period.

Keeping in mind the approach of IAEA-TECDOC-285, the kind of effect on the safety functions described in Section 3 of the document should be also considered. From those the confinement and the general industrial safety functions could be relevant.

Some of the non-radiological properties may have a direct link to the cause of an event affecting the non-radiological safety of the workers or, in the case of a serious accident, of the public. This kind of event could be relevant for the operational period of waste treatment and disposal facilities. These industrial safety related properties are, for example the toxic components of the waste, the content of explosive materials, or even the weight of the package.

Other non-radiological properties may not have any direct effect on non-radiological safety, but may pose a risk to weaken or negate confinement safety functions. These confinement related properties could be an indirect cause of events leading to the release of radionuclides above limits during the operational period and will have a significant effect during long term storage, or in the post-closure period.

There are non-radiological WAC, which have no relevance to waste package properties, but function rather as administrative requirements for tracking and record keeping to promote safety. An example of this kind of criteria is the identification and labelling of waste packages. However, the identification of packages is not discussed in this section since it is not a non-radiological specific issue.

Table 4. Overview of the non-radiological criteria and their derivation methods.

Non-radiological criteria	IAEA-TECDOC-285 approach			Safety function approach		Derivation method	Control methods*
	handling	operational period	post-closure period	industrial safety	confinement		
PHYSICAL CHARACTERISTICS AND THE CONFIGURATION OF THE PACKAGES							
Waste package shape and dimension	X	X		X		Design	M / C
Packaging properties / Durability of container							
material	X	X	X	X	X	Design	C
thickness	X	X	X	X	X	Design	C / M
sealing	X	X	X	X	X	Design	C
welding	X	X	X	X	X	Design	C
inside and outside coating	X	X	X	X	X	Design	C
design for active/passive cooling	X	X	X	X	X	Design	C
lifting method	X	X		X		Design	V / C
total and net weight	X	X		X		Design	M
MECHANICAL STABILITY OF WASTE FORM							
compressive strength		X	X		X	SA	T / QA
void space		X	X		X	SA	E / QA
homogeneity		X	X		X	SA	E / QA
content of fines		X	X	X	X	SA	E / QA
content of sludges		X	X		X	SA	E / QA
MECHANICAL STABILITY OF WASTE PACKAGE							
freeze/thaw cycle effect			X		X	SA	T
withstanding higher temperature and pressure		X	X	X	X	SA	T
retention against load test		X		X	X	Design	T
retention against dropping and other mechanical test		X		X	X	Design	T
FIRE AND EXPLOSION HAZARD							
content of combustible materials	X	X		X	X	SA	E/QA/S
content of flammable liquids	X	X		X	X	Exclusion	E/QA/S
content of flammable solids	X	X		X	X	Exclusion	E/QA/S
content of self-reactive substances		X		X	X	Exclusion	E/QA/S
content of pyrophoric substances		X		X	X	Exclusion	E/QA/S
content of self-heating substances		X	X	X	X	Exclusion	E/QA/S
content of substances which, in contact with water, emit flammable gases (see also gas generation)		X	X	X	X	Exclusion	E/QA/S
content of solid desensitized explosives		X	X	X	X	Exclusion	E/QA/S
content of explosives	X	X		X	X	Exclusion	E/QA/S

Non-radiological criteria	IAEA-TECDOC-285 approach			Safety function approach		Derivation method	Control methods*
	handling	operational period	post-closure period	industrial safety	confinement		
OTHER DANGEROUS CHARACTERISTICS							
Oxidizing substances		X		X		Exclusion	E/QA/S
Organic peroxides		X		X		Exclusion	E/QA/S
Toxic substances	X	X		X		SA	E/QA/S
Infectious substances	X	X		X		SA	E/QA/S
Corrosive substances		X	X	X	X	SA	E/QA/S
Miscellaneous dangerous substances and articles		X		X		SA	E/QA/S
OTHER MISCELLANEOUS CHARACTERISTICS							
Gas generation			X		X	SA	E/QA/S
Items with compressed gases			X		X	Exclusion	E/QA/S
Free liquids			X		X	SA	E/QA/S
Reactants			X		X	SA	E/QA/S
Complexing reagents			X		X	SA	E/QA/S
DURABILITY OF WASTE FORM							
Chemical parameters important for leaching under hydraulic or hydrothermal conditions (pH, Liquid-to-Solid Ratio, Redox Potential, Complexation, Desorption, Biological activity)			X		X	SA	T/QA/S
Physical parameters important for leaching under hydraulic or hydrothermal conditions (Particle Size, Permeability, Porosity, Geometry)			X		X	SA	T/QA/S
Waste form/container compatibility			X		X	SA	T/QA/S
Radiation stability (radiation damage, hydrolysis, volume change, waste form change)			X		X	SA	T/QA/S
OTHER							
Migration and sorption of the chemical form of released radionuclides			X		X	SA	T/QA/S
Reactivity with the environment			X		X	SA	T/QA/S

*Control methods:

- M – direct Measurement
- C - inspection of Certificate
- T – Testing specimens
- V – Visual inspection
- S – Sampling and measurement
- QA – Quality Assurance
- E – Estimation

7.2 Specific considerations for derivation of non-radiological WAC

7.2.1 Physical characteristics and configuration of the packages

Waste package shape and dimension:

- The shape and dimension of waste package contributes to the optimal space utilization of the storage or disposal area, which is restricted by financial considerations. However, the fabrication limits, transportation criteria, restrictions by the transfer routes (e.g. shafts, boreholes), manipulation methods and stress tests will also influence the design of packages.

Packaging properties / Durability of container:

- The packaging properties shall be designed to ensure, together with the waste form, the mechanical stability of the waste package and the capability of handling of packages during processing, transport, storage and disposal.
- The materials used for the container, closing end, and coatings are subject to qualitative criteria, while the thickness of those are quantitative criteria.
- The performance of welding and sealing shall be equivalent to that of the body of the container.
- The lifting method shall be designed to fit the package handling technology.
- The load capacity depends on the design of storage and disposal system.
- Waste packages shall be designed such that, in conjunction with handling systems, releases due to mechanical impact under foreseeable incidents are limited to acceptable values.
- The waste packages must be able to withstand stresses arising without any unacceptable deterioration in their ability to fulfill safety related functions. Stresses which must be withstood might arise from normal handling and transportation loads during the operational period, from internal pressure due to gas generation or release, from external pressure due to lithostatic and hydrostatic loads, and from temperature gradients.

7.2.2 Mechanical stability of the Waste Form

Compressive strength:

- The natural barriers, the engineering barriers and the waste package (packaging material and the waste form) together shall ensure that the disposal system does not collapse or sink due to its own weight and loading by machinery, infrastructure or buildings prognosed to the future. The structural stability of a waste package is essential for containing radioactive waste for the long term in a repository where there are no self-sustaining natural barriers above the waste pile.
- Compressive strength is a quantitative criterion.
- For deriving the initial compressive strength, the following shall be considered:
    - presence or absence of self-sustaining natural barriers above the waste
    - the mass (height and density) of the waste package pile
    - the mass (height and density) of the engineering barriers /cover above waste package pile
    - the long-term behavior of backfilling material on the self-sustaining property of the disposal system,
    - the effect of physical, chemical and biodegradation of waste material to its own compressive strength
    - potential loading due to natural (e.g. snow) or artificial effects (e.g. heavy machinery, building)
    - other criteria, such as free liquids, fines, etc.

Void space:

- Voids within the waste package might have to be filled in order to prevent collapse or deformation of the packing material.
- The usual definition for void is a large hole or empty space. In radioactive waste management a void might be defined as any open volume, or gas-filled parts of the waste matrix with a maximum dimension exceeding 5 cm.
- Although usually there are limits for the amount of void volume (e.g. 10%), it is a rather qualitative criterion.

Homogeneity:

- Homogeneity is important for storage and disposal to ensure that the assumptions and assessments made regarding behavior of the waste form will be valid.
- Within the waste form, the presence of strongly different properties – such as activity, activity concentration, density, chemical behavior, etc. – should be avoided, unless shielding or stabilization agents are necessary for conditioning.
- The presence of voids, liquids or gases in higher volumes, also point sources of radiation should be excluded, unless shielding or stabilizing the source cannot be solved otherwise.
- For solidified and embedded waste, efforts must be made to evenly distribute the waste in the solidifying material.
- If possible, the same types of waste should be put into the same waste form with the same conditioning procedure.

Content of fines:

- The safety importance of fines can be considered from different viewpoints based on their size and composition.
- Fines should be considered in the evaluation of the long-term stability and self-sustainability of the waste form. Small sized particles (fines and fine graded materials) in general reduce the stability of waste form and stabilization of this kind of waste form is required. However, from the viewpoint of radiation safety and industrial safety, the potential inhalation of these materials due to an incident is notable.
- Fine particles between 1 mm and 0.1 mm in size can be seen with the naked eye, however, particles smaller than 100 µm (< 0.1 mm) can only be seen with the help of technical means. Dust particles smaller than 1 µm (< 0.001 mm) never settle and remain constantly airborne. Particles smaller than 100 µm can be inhaled, but most of them are caught in the nose and mouth, possibly in the larynx, so they do not reach deeper into the airways. Particles smaller (airborne dust) than 10 microns pass the pharynx, and particles smaller than 4 microns enter the lungs (respirable fraction). Particles smaller than 2.5 µm are not cleared from the lungs at all, or only with great difficulty. Airborne dust is divided into different categories depending on the size of the particles (aerodynamic diameter): Coarse particles (PM10). have an aerodynamic diameter ranging from 2.5 to 10 µm; Fine particles have an aerodynamic diameter of 2.5 µm or less (PM2.5). Fine particles which are smaller than 0.1 µm are referred to as ultrafine particles (PM0.1).
- The content of fines in the waste package must be limited and kept to the lowest possible level considering the consequences of malfunctions that may occur during processing and handling of waste, or even in the case of unintended human intrusion.
- Both the radiological and other hazardous (toxicity, pathogenicity, corrosivity) properties must be considered. The acceptable limits should be based on safety assumptions considering:
    - potential incident and accident scenarios during processing of waste form and manipulation of waste packages
    - technical safety measures (e.g., ventilation)
    - protection level of PPEs.
- Example GWAC for storage and disposal might be that segregable materials with a particle size of less than 1 mm must be stabilized. The amount of dust, ash and similar micro-particles must be limited to a maximum of 1 m% for particles smaller than 10 µm, and a maximum of 10 m% for free dust smaller than 100 µm.

Content of sludges:

- Sludges, muds or other mixtures of solids and liquids (corrosion products from spent fuel ponds or materials from the treatment of aerial or liquid effluents) with similar viscosities should be excluded from the conditioned waste form, as such content reduces the stability of waste form and, due to the content of water, may facilitate the migration of radionuclides. The treatment process of this kind of waste has to focus on to convert sludges into a solid phase.

7.2.3 Mechanical stability of the waste package

Freeze/thaw cycle effect:

- Depending on the storage circumstances, the effects of single and repeated freezing and thawing cycles might affect the waste package integrity and lifetime. The behavior of the waste package shall be analyzed by testing or modelling for the entire storage period if the temperature control is not feasible.

Withstanding higher temperature and pressure:

- In the case of high-level waste or geological disposal, the behavior of the waste package against stresses of higher temperature and pressure shall be analysed.
- Retention against load during waste processing and possible accidental scenarios shall be tested.
- Waste containers must be capable of sustaining the total weight of the waste package during handling, lifting and transportation.
- The container integrity (including welding and lifting accessories) shall be tested for a higher weight than the total weight of one waste package.
- Retention against dropping and other mechanical tests.
- Waste containers must be capable of sustaining a drop of a specified height, and other similar likely occurrences, without breach. Foreseeable incidents and their consequences must be identified based on specific design features of storage, handling and disposal facilities.

7.2.4 Fire and explosion hazard

Content of combustible materials:

- The maximum content of combustible materials in the waste form may be limited to avoid industrial accidents during processing if there is a high risk of ignition by the processing technology.
- A minimum content of combustible materials may be required for volume reduction procedures by incineration or pyrolysis.
- Combustible material content can be defined by a quantitative criterion.

The content of flammable, self-reactive, pyrophoric, self-heating, explosive and desensitized explosive substances:

- Shall be excluded in the conditioned waste package to avoid damaging the integrity of the waste package by uncontrolled ignition or explosion.
- Shall be limited to very low levels tailored to the storage and processing technology for unconditioned waste acceptance for processing to avoid industrial accidents.
- The content of such substances is defined by qualitative criteria for conditioned waste packages.
- The content of such substances may be defined by quantitative criteria for waste processing and interim storage. Lower quantities defined in the transport regulations for exempted packages may be accepted without the application of special technology. For the processing of waste containing higher quantities of these kinds of substances, specialized technology may be required.

7.2.5 Other dangerous characteristics

Hazardous components such as oxidizing substances, organic peroxides, toxic substances, infectious substances, corrosive substances and others can present serious health risks for workers during waste processing, and for the public in case of alternative disposal scenarios. The amount of these materials shall be limited or excluded.

If the amount of hazardous components exceeds the limits for such materials (mixed waste), the safety requirements for hazardous components shall be considered for the relevant phases of waste processing (pre-treatment, treatment and conditioning), and for storage and disposal as well.

In special cases, waste packages containing hazardous substances exempted from the transport regulations for dangerous goods may be allowed for storage and disposal.

The limits for hazardous components shall be calculated by safety analyses, considering:

- parameters of waste conditioning (material flow can be managed by the technology, maximum ratio of hazardous materials and conditioning or neutralization agents)
- technical conditions and limits of procedures for waste processes (ventilation and filters suitable for hazardous materials, non-sparking and antistatic environment, corrosion resistant surfaces, etc.)
- personal protective equipment available for workers
- assumptions for alternative disposal scenarios.

Gas generation

- Decomposition of organic materials results in gas generation and volume loss. Rapidly decomposing, fermenting organic materials occurring in larger quantities can cause a large amount of gas generation (methane formation), overpressure, as well as cavity (void) formation, which must be avoided. Organic matter prone to rotting and fermentation, easy decomposition or compostable organic matter is not allowed in the waste.
- Due to the expected limited rate of decomposition of waste containing paper, textile and plastic enclosed in barrels, overpressures are not expected to reach the value of 0.5 bar, and the total amount of gases formed will remain below 0.05 v%. Therefore, this kind of waste does not need to be limited from the gas generation viewpoint.
- In special cases, if overpressure is anticipated, the waste package must either be designed to withstand it (for example, due to the decomposition of compressible waste or the formation of radon), or the package must be ventilated in such a way as to prevent the escape of radioactive material.
- Substances in the waste which, when in contact with water, emit flammable gases or which react with the packaging material or with the conditioning agents and generate gases should be excluded for storage and disposal. It has to be noted, that it is possible to encapsulate reactive metals (such as Magnox, aluminium or uranium),through the proper design and operation of a treatment process.
- The content of substances which, when in contact with water, emit flammable gases or which react with the packaging material or with the conditioning agents and generate gases, shall be considered for the planning of waste processing technology, to protect the workers.

Compressed gases

- High overpressure can result in the damage of waste packages and/or engineered barriers. Hence the presence of compressed gases in containers having a pressure exceeding 1.5 bar at 20 ºC in the waste are not allowed for storage and disposal.
- Additionally other non-compressed gas-containing items (isotope preparations) shall be limited, since the space filled by the gases would become a cavity (void) after gas escape. The void definition (for example 125 ml) may be used to limit the volume of isotope preparations filled with radioactive gas. Furthermore, it is advisable to limit the gas content to 1 vol%, similar to the restriction of free liquids.
- To mitigate against the gas-containing isotope preparations losing their sealing, the isotope preparations must be packed with an adsorbent capable of adsorbing at least twice the amount of gas, considering all possible directions of propagation. Additionally, a gas-tight packaging must be used.

Free liquids

- Free liquid in the disposal system may contribute to the corrosion of waste packages and the migration of radioactive isotopes, reducing the performance level of the safety functions. Liquids must be solidified, but the presence of free liquid cannot be completely ruled out.
- The origin of free liquid can be for example: (i) liquid-containing isotope preparations or small-scale equipment, whose dissolution or extraction and solidification of contents represents a

greater radiation protection risk than the limited quantity or expected effect on the container, (ii) condensation during solidification corresponding to the amount of liquid not absorbed in the solidifying material, such as the amount of water neither participating in the cement bond nor evaporating when making cement mortar.

- The amount of free liquid should be kept as low as possible. It is advisable to set the limit for free liquid content at 1 vol%. This is the threshold value above which free liquid can usually be detected and measured (e.g., in cemented waste can be detected using a non-destructive method).
- In the case of liquid, non-solidified isotope preparations, the amount must be limited not only in terms of volume fraction, but also relative to the absolute volume of any isotope preparation. It can be assumed that in the long term the packaging loses its tightness and free liquid content. In this case, a free space is created in place of the liquid, which, however, cannot be larger than the space defined for allowable void (for example 125 ml).
- Items containing limited volumes of liquid may be placed into the waste if there is an absorbent material present capable of absorbing twice the liquid volume in any possible direction of leakage.
- It is advisable to use combined packaging for non-chemically stabilized waste (e.g. organic solvents). The material and limited capacity of the inner packaging create an additional barrier to the release of radioactive material. The task of the outer packaging is to protect the inner packaging from physical influences and corrosion. Note: For the conditioning of waste containing tritium and radiocarbon - the guidelines of the IAEA document "TRS-421 Management of Waste Containing Tritium and Carbon-14" should be applied.

Reactants

- In the storage and disposal systems, corrosive substances such as acids, alkalis and salts accelerate the corrosion and degradation of waste packages and engineered barriers. Therefore, the amount of corrosive substances must be kept as low as possible (e.g. less than 1 m%)
- In the case of dilution of acids and alkalis, diluted volume limits can be matched with the limit for free liquid.
- Acids, alkalis and dissolved salts should be neutralized and stabilized. Exceptions could be open radiation sources placed in properly closed and sealed metal packaging similar to closed radiation sources.

Complexing reagents

During storage and disposal, complexing reagents may damage the material of the waste packages and engineered barriers through complex formation. Additionally, complexes do not readily bind to the components of the engineered and geological barriers, which is an unfavorable process if the complexes contain radioactive isotopes. It is advisable to set limits on the amounts of complexing reagents to make them as low as possible. The presupposed limit (for example 1% m%) should be conservatively valid in the safety analyses of the disposal system.

Complexing reagents can be liquids, hazardous substances and corrosive agents, therefore the limits for complexing reagents should be in accordance with other criteria.

7.2.6 Durability of waste form

The durability and performance level of the waste package depends both on the packaging and the waste form. The properties of the waste form shall be evaluated in a comprehensive way, taking into account all relevant parameters (partly detailed above) contributing to the durability of the waste package. This evaluation can be conducted mostly when site and design specific information are available, however the list of relevant properties can be determined in the development of the GWAC, to collect the information on the waste streams. The following aspects should be considered:

- Chemical parameters important for leaching under hydraulic or hydrothermal conditions (pH, Liquid-to-Solid Ratio, Redox Potential, Complexation, Desorption, Biological activity)
- Physical parameters important for leaching under hydraulic or hydrothermal conditions (Particle Size, Permeability, Porosity, Geometry)

- Waste form/container compatibility
- Radiation stability (radiation damage, hydrolysis, volume change, waste form change)

8 Formulation/Derivation of GWAC

The goal of this Chapter is to provide help in the process of GWAC derivation for the different categorized situations of waste management policy and systems. These situations are defined in Chapter 2.2 and they are listed here:

- No policy for waste management, no plans for waste management system
- There are policy and plans for waste management system, but there are no installations for waste processing
- There are waste processing capabilities but there is no storage option
- There are waste processing capabilities and storage options but there is no disposal option
- Existing management options in case of a new waste type.

These five situations are going to be examined from the GWAC derivation point of view. The subchapters are planned to describe the GWAC derivation process for each above listed situation. The approach is based on the previous considerations of this document. The steps of methodology to build up and derivate GWAC are as follows:

1) Collecting the baseline information and making decisions necessary for building up the GWAC (see Chapters 3.2 and 3.5)
    a. Identification of the status of radioactive waste management system, including identification of waste streams
    b. Decision on radioactive waste management policy
    c. Elaboration of radioactive waste management strategy or strategies
2) Defining the scope of GWAC and selection of the derivation methodologies.
    a. The waste management situation shall be categorized by waste classes to be managed via the waste management strategies, and capacity development demands of one or more waste management activity (see Chapters 3.3 and 3.5.)
    b. Waste types and associated waste processing methods (see Chapter 4.) shall be linked to potential storage and disposal solutions (see Chapter 5.)
3) The waste acceptance criteria shall be numbered/assessed for each of the waste management situations/categories (see Chapters 3.4 and 3.5)
    a. The safety related criteria such as radiation protection of workers, public and future generation, as well as the industrial safety aspects of workers and public shall be identified.
    b. The safety functions (such shielding, confinement, cooling, industrial safety aspects of technologies) related to the safety criteria shall be described.
    c. The acceptance criteria associated with the safety functions shall be accounted.
4) Derivation of radiological criteria shall be performed (see Chapter 6.)
5) Derivation of non-radiological criteria shall be performed (see Chapter 7.)

The most important thing is ensuring the safety of the public and the personnel who could be in contact with the radioactive waste. Whether there is an existing legal background or not, the appointed responsible organization has to ensure the safe keeping of the radioactive substances. In most cases administrative actions (closure of access to the site of the waste found, stored, etc.) can adequately limit the possibilities of being in contact with the hazardous material.

All actions can only be carried out by keeping the end-state (future storage and disposal of the waste) in mind. Only actions that can guarantee the stability of the waste form for a longer period and which can allow possible further processing are justified to make the waste suitable for further long-term storage or final disposal.

Table 5. Summarizing the goal of the waste management and the scope of the GWAC for different situations.

Options	Goal of the waste management	Safety concerns	Focus of GWAC
No policy/strategy No adequate facilities	Keeping the waste form safe until further processing is available	Radiation protection of the public	Criteria that will guarantee the safe keeping of the waste
Waste processing is available but there is no storage facility	Keeping the waste form until long term storage becomes available Processing of the waste does not have to jeopardize future long-term storage / final disposal	Radiation protection of the worker and the public Occupational health and safety criteria for protection of workers	Administrative actions, additional barriers, shielding, etc. to prolong the safe keeping of the radioactive waste
No disposal facility	Making the waste form suitable for the long-term storage Processing of the waste does not have to jeopardize future disposal	Radiation protection of the worker and the public Radiation protection of the future generation Occupational health and safety criteria for protection of workers Health and safety criteria for protection of workers and public	Criteria of the long-term storage but attention to needs of the future disposal
New waste form introduced into existing disposal system	The waste form has to be introduced into the existing waste disposal system	Radiation protection of the worker and the public Radiation protection of the future generation Occupational health and safety criteria for protection of workers Health and safety criteria for protection of workers and public	Criteria that takes into account the needs of processing and storage but is flexible enough to handle the future needs in preparation of the final disposal.

The role of the WAC is to identify safety concerns of the situation, provide criteria that ensures of the safe processing, storage and disposal of the radioactive waste. In cases there are limited resources available, it is important that no overambitious criteria shall be defined because they could not be fulfilled.

The typical GWAC parameters as minimal set of criteria what may be incorporated in GWAC are listed in Chapter 3.4. The formulation of GWAC (groups of criteria) based on IAEA Tecdoc 1515[8], referred in Chapter 3.3. complemented with the parameters listed Chapters 6 and 7.

The safety concerns and associated safety functions were identified in Chapter 3.4.

- Radiation protection of the worker
  - Shielding
  - Containment of radionuclides by the waste form
  - Containment of radionuclides by packaging
- Radiation protection of the public
  - Shielding

- Containment of radionuclides by the waste form
- Containment of radionuclides by packaging
- Radiation protection of the future generation
  - Shielding
  - Long term containment of radionuclides by waste package
  - Long term containment of radionuclides by engineered barrier system
- Occupational health and safety criteria for protection of workers
  - Containment of hazardous material by the waste form
  - Containment of hazardous material by packaging
  - Design of technology
- Health and safety criteria for protection of workers and public
  - Inherent stability of waste form
  - Work safety functions of packaging
  - Design of technology

8.1 No policy or no plans for radioactive waste management.

Description of the situation:

Parts of Waste Management System	Availability
National policy for radioactive waste management	No
Strategy for radioactive waste management	No
Installations for waste processing	No
Temporary storage for radioactive waste	No
Storage facility	No
Disposal facility	No

8.1.1 Collecting the baseline information

This situation can occur when a country finds itself in the position of being responsible for unused and unwanted radioactive material (orphan source, contaminated soil, etc.).

The first step is to define the responsible organization. After definition of responsibilities, the most important step is to derive a basis of action from the existing regulations.

In case the regulatory background has limitations, international standards and recommendations on basic health and safety can provide a starting point. (i.e.: IAEA Basic Safety Standards) Potential cooperation with international organizations (i.e. IAEA) has to be taken into account.

To plan the strategy of the waste management the preliminary characterization of the radioactive waste is necessary.

Following properties of the waste have to be determined as a minimum set of information:

- Contact dose rate,
- Activity level, in case of DSRS categorization,
- Physio-chemical properties from Chapter 4.2.2.

Decisions regarding the waste management policies can be rather limited in the absence of the existing regulatory framework. The decisions are recommended to be based on the recommendations of the international organizations. Using their guidance can provide a way to elaborate the radioactive waste management programme.

8.1.2 Defining the scope of GWAC and selection of the derivation methodologies

Regardless of the waste types, the first steps of the definition of the GWAC are rather limited, only focusing on the limitation of the imminent danger caused by the presence of radioactive substances.

8.1.3 Derivation of GWAC

Goal of the waste management
In case of the absence of the waste management policy and strategy, where there is a situation when radioactive waste has to be dealt with, it's important to keep the waste in a safe place and safe form to prevent unnecessary dose to the public. When waste processing facilities are not available, the situation is the same from the GWAC derivation point of view. In this case of the derivation of GWAC the focus has to be on the safe waste keeping instead of the waste form or package itself.

Safety concerns
When there are no possibilities of waste processing and adequate storage, the criteria have to focus on the safety concerns of the radiation protection of the public and the associated safety functions.

Focus of GWAC
Limitations on dose rate, airborne and liquid release. Criteria can be formed that can guarantee the safe containment and isolation of the radioactive material, until further waste processing and waste storage options are available.

Scenarios to be taken into account

- Planned exposure in normal operation (safe keeping)
  - Shielding
  - Discharges during safe keeping
    - Gas release (including volatile nuclides)
    - Liquid release
- Emergency exposure situation (Anticipated accident scenarios)
  - Shielding failure
  - Discharges during safe keeping
    - Gas release (including volatile nuclides)
    - Liquid release

Potential parameters of the GWAC

- Ambient dose rate
- Gas release (including volatile nuclides)
- Resistance against environmental conditions (humidity, temperature, mechanical effects)

8.2 No adequate facilities for waste management

Description of the situation:

Parts of Waste Management System	Availability
National policy for radioactive waste management	Yes
Strategy for radioactive waste management	Yes
Installations for waste processing	No
Temporary storage for radioactive waste	No
Storage facility	No
Disposal facility	No

In this case, the legal background used to create the radioactive waste management system is given to an extent, but there are questions about the waste processing.

8.2.1 Collecting the baseline information

The first thing to make sure is whether the existing policy/strategy can give an adequate answer for the existing situation. If this is not the case, the redefinition of national policy/strategy is required. The system has to be developed to ensure the safe management of the waste. The structure of the policy and strategy has to be flexible, depending on the expectations derived from the planning of waste management. The planning of the strategy of the preliminary characterization of the waste is necessary. Following properties of the waste have to be determined:

- Contact dose rate,
- Activity level, in case of DSRS categorization,
- Physio-chemical properties from Chapter 4.2.2.

The next step is to examine if there are adequate facilities available for waste processing. If there are no such facilities available, there are two possibilities: either looking for an international cooperation in order to have proper waste processing or the waste processing facilities have to be constructed in the country. This decision can be influenced by the amount of waste and the number of internationally available waste processing facilities.

Cooperation with international organizations can be envisaged to find proper counterpart for the waste processing and / or to design and commission radioactive waste management facilities.

8.2.2 Defining the scope of GWAC and selection of the derivation methodologies

In case there is an existing regulatory framework and it can be applied in the situation, the first important thing is still the safe keeping of the waste. One of the pillars of the criteria at this stage is that the waste needs (temporary) packaging, that is shielded to control contact dose rates and provides containment to prevent airborne or waterborne releases.

8.2.3 Derivation of GWAC

Goal of the waste management

In case of the absence of the waste management policy and strategy where there is a situation when radioactive waste has to be dealt with, it's important to keep the waste in a safe place and safe form to prevent unnecessary dose to the public. When waste processing facilities are not available, the situation is the same from the GWAC derivation point of view. In this case of the derivation of GWAC, the focus has to be on the safe waste keeping instead of the waste form or package itself.

Safety concerns

When there are no possibilities of waste processing and adequate storage, the criteria have to focus on the safety concerns of the radiation protection of the public and the associated safety functions.

Focus of GWAC

The derivation of the criteria has to focus on the limitations on dose rate, on the airborne and the liquid release. Criteria can be formed that can guarantee the safe containment and isolation of the radioactive material until further waste processing and waste storage options are available.

Scenarios to be taken into account

- Planned exposure in normal operation (safe keeping)
  - Shielding
  - Discharges during safe keeping
    - Gas release (including volatile nuclides)
    - Liquid release
- Emergency exposure situation (Anticipated accident scenarios)
  - Shielding failure
  - Discharges during safe keeping
    - Gas release (including volatile nuclides)
    - Liquid release

Potential parameters of the GWAC

- Ambient dose rate
- Gas release (including volatile nuclides)
- Resistance against environmental conditions (humidity, temperature, mechanical effects)

8.3 Waste processing is available but there is no storage option

Description of the situation:

Parts of Waste Management System	Availability
National policy for radioactive waste management	Yes
Strategy for radioactive waste management	Yes
Installations for waste processing	Yes
Temporary storage for radioactive waste	?
Storage facility	No
Disposal facility	No

If there is an existing waste processing facility in the country, its capabilities for all the waste types that are to be treated needs to be adequate.

8.3.1 Collecting the baseline information

The first important step is to dedicate a place where the waste is temporarily stored until later decisions are made. The waste has to be isolated and protected from environmental impact as much as possible. It is not justifiable to treat the waste without having an appropriate temporary storage place. It is also important to minimize the dose consequences of the waste processing and the risk of potential accidents or incidents. Waste processing is justifiable only if there is imminent risk of failure of the existing waste form, there is the danger of spreading or release of radioactive contamination.

Waste processing can only be started when there is temporary storage available for the product. The condition of the relevant waste processing is determined throughout by characterization of the waste. All possible radiological characteristics and physio-chemical properties have to be determined.

8.3.2 Defining the scope of GWAC and selection of the derivation methodologies

The scope of the GWAC focuses on the long-time preservation of the waste. It is important to avoid unjustified modifications to the waste, which can result in a much more difficult to handle situation in the future. Therefore, the focus of the GWAC must reflect the long-term needs which in this case are flexibility.

8.3.3 Derivation of GWAC

Goal of the waste management
Without storage options, waste processing is challenging, decisions have to be taken with the future state of the waste package in mind. Waste processing can be carried out if there is enough temporary storage place for the treated waste. It is not advised to carry out waste processing without having temporary storage. It is important that waste processing should be carried out without jeopardizing future waste management activities that can be performed on the waste package for the final disposal.

Safety concerns
Radiation protection of the personnel and the public during the operation of the waste management facility and the temporary storage is very important.

Focus of the GWAC

Criteria set by the GWAC has to focus on the safe preservation of the processed/non-processed waste. It needs to guarantee safe temporary storage until further waste processing options, storage capacity and/or disposal of the radioactive waste become available. Criteria set by GWAC in this case can be mostly fulfilled by using additional resources: administrative actions, additional barriers, shielding, etc. in order to prolong the safekeeping of the radioactive waste.

Potential parameters of the GWAC

Radiation related parameters:

- heat generation (only related to the temporary storage)
- contact dose rate and at a 1m distance;
- contamination;
- criticality, fissile content;
- isotope content (only related to the temporary storage).

Physical characteristics and configuration of the packages:

- Packaging properties
- Durability of container.

Mechanical stability of the waste form:

- compressive strength.

8.4 Storage available and no disposal option

Description of the situation:

Parts of Waste Management System	Availability
National policy for radioactive waste management	Yes
Strategy for radioactive waste management	Yes
Installations for waste processing	Yes
Temporary storage for radioactive waste	Yes
Storage facility	Yes
Disposal facility	No

8.4.1 Collecting the baseline information

It is important to guarantee the long-term stability of the waste package in order to prevent radioactive release to the environment. Therefore, it must be ensured that the existing storage conditions and the state of the waste package comply with the criteria for long term storage.

If there is an existing storage facility, then the conditions of the old waste packages should be checked to see if they can withstand the challenge of long term storage.

If there are old waste packages in the storage facility, their condition needs to be examined to check if they will be disposable in the future, or if there is a need for reprocessing. If there is a need for reprocessing the waste goes back to the state, where the decision was made, if there is an adequate waste processing facility available. In this case, the policy must include the relevant information for reprocessing the old waste.

8.4.2 Defining the scope of GWAC and selection of the derivation methodologies

The long-term storage has similarities with the final disposal but the retrievability and potential of modification of the waste is a given feature of the storage. The potential of the modification is given and may be used when the waste package is going to be prepared for final disposal, but it has to be taken into account with care. It is not advised to perform unjustified modifications on the waste forms/packages, because it can risk the performance of the waste package for the final disposal. Criteria therefore has to focus on the needs of the long-term storage, taking into account the safety of the waste processing, and the unclear future requirements of the final disposal.

8.4.3 Derivation of GWAC

Goal of the waste management
In this situation, both adequate waste processing and storage are available. When there is the possibility to safely store radioactive waste that has been processed, the requirements posed by the storage apply. The goal is to keep the waste as long as necessary, until the solution of the final disposal is ready for the programme. Attention must be paid to the type of waste packaging and waste processing used, to ensure there is no risk to the potential future waste management steps, that might be required for preparation for future disposal.

Safety concerns
Radiation protection of the personnel and the public during the operation of the waste management facility and the long-term storage. Definition of the waste package without compromising anticipated post-closure safety of the disposal site.

Focus on the GWAC
Derivation of the criteria has to focus on the following:

- safe processing of the radioactive waste,
- the needs of the long-term storage,
- the needs of the future disposal.

Scenarios to be taken into account
Scenarios to be taken into account to assess the radiation protection of the worker and the public during the operation of the waste management facility:

- Planned exposure situation (normal operation)
- Emergency exposure situation (Accident scenarios)
- Industrial incidents
  - fire
  - explosion
  - degradation of waste form characteristics
  - degradation of packaging characteristics.

Potential parameters of the GWAC
Radiation related parameters:

- heat generation (storage related)
- contact dose rate and at a 1m distance;
- contamination;
- criticality, fissile content;
- isotope content. (storage related).

Physical characteristics and configuration of the packages:

- Waste package shape and dimension
- Packaging properties
- Durability of container.

Mechanical stability of the waste form:

- compressive strength
- void space
- homogeneity

- content of fines
- content of sludges.

Mechanical stability of the waste package:

- freeze/thaw cycle effect
- withstanding higher temperature and pressure
- retention against load test
- retention against dropping and other mechanical test.

Fire and explosion hazard:

- content of combustible materials
- content of flammable liquids
- content of flammable solids
- content of self-reactive substances
- content of pyrophoric substances
- content of self-heating substances
- content of substances which, in contact with water, emit flammable gases (see also gas generation)
- content of solid desensitized explosives
- content of explosives.

Other dangerous characteristics:

- Oxidizing substances
- Organic peroxides
- Toxic substances
- Infectious substances
- Corrosive substances
- Miscellaneous dangerous substances and articles.

Other miscellaneous characteristics:

- Gas generation
- Items with compressed gases
- Free liquids
- Reactants
- Complexing reagents.

8.5 New waste type for existing disposal option

Description of the situation:

Parts of Waste Management System	Availability
National policy for radioactive waste management	Yes
Strategy for radioactive waste management	Yes
Installations for waste processing	Yes
Temporary storage for radioactive waste	Yes
Storage facility	Yes
Disposal facility	No

In this case everything is given for the full waste management cycle, but a new waste type poses a new challenge to be inserted into the system. It is important to create a waste form that is compatible with the disposal system, since it is anticipated that there were a lot of resources used to create the system.

8.5.1 Collecting the baseline information

A new waste type may have a lot of unknown properties which could affect the suitability of the disposal system. Waste characterization have to be carried out throughout as well as the assessment of the capabilities of the waste processing system, to determine if it can handle the new waste form or if some improvement is needed.

8.5.2 Defining the scope of GWAC and selection of the derivation methodologies

The goal of the GWAC is to define criteria for the waste to be treated in a form that is going to be acceptable in the disposal facility and also provide a safe enough containment that can protect the workers of the waste processing facility. Compliance with the criteria of GWAC in this case must ensure the safe processing, and storage until the circumstances of the disposal of the particular waste form become clear.

8.5.3 Derivation of GWAC

Goal of the waste management
Since there is an existing solution for the final disposal of radioactive waste, it is likely that new waste types will be disposed of in the existing system in an adequate form. The criteria is to define the state in which the waste form can be preserved in, until a capable waste processing technology is developed, to comply with the WAC of the disposal system.

Focus of GWAC
The focus in this case is to define criteria for the waste to be treated into a form that is going to be acceptable in the disposal facility but provide safe enough containment that can protect the workers of the waste processing facility.

Scenarios to be taken into account
Scenarios to be taken into account to assess the radiation protection of the worker and the public during the operation of the waste management facility:

- Planned exposure situation (normal operation)
- Emergency exposure situation (Accident scenarios)
- Industrial incidents
    - fire
    - explosion
    - degradation of waste form characteristics
    - degradation of packaging characteristics.

Scenarios to assess radiation protection of the future generation for the post-closure period:

- Normal evolution scenario
- Alternative evolution scenario.

Potential parameters of the GWAC
Radiation related parameters:

- heat generation;
- contact dose rate and at a 1m distance;
- contamination;
- criticality, fissile content;
- isotope content.

Physical characteristics and configuration of the packages:

- Waste package shape and dimension
- Packaging properties
- Durability of container.

Mechanical stability of the waste form:

- compressive strength
- void space
- homogeneity
- content of fines
- content of sludges.

Mechanical stability of the waste package:

- freeze/thaw cycle effect
- withstanding higher temperature and pressure
- retention against load test
- retention against dropping and other mechanical test.

Fire and explosion hazard:

- content of combustible materials
- content of flammable liquids
- content of flammable solids
- content of self-reactive substances
- content of pyrophoric substances
- content of self-heating substances
- content of substances which, in contact with water, emit flammable gases (see also gas generation)
- content of solid desensitized explosives
- content of explosives.

Other dangerous characteristics:

- Oxidizing substances
- Organic peroxides
- Toxic substances
- Infectious substances
- Corrosive substances
- Miscellaneous dangerous substances and articles.

Other miscellaneous characteristics:

- Gas generation
- Items with compressed gases
- Free liquids
- Reactants
- Complexing reagents.

Durability of the waste form:

- Chemical parameters important for leaching under hydraulic or hydrothermal conditions (pH, Liquid-to-Solid Ratio, Redox Potential, Complexation, Desorption, Biological activity)
- Physical parameters important for leaching under hydraulic or hydrothermal conditions (Particle Size, Permeability, Porosity, Geometry)
- Waste form/container compatibility
- Radiation stability (radiation damage, hydrolysis, volume change, waste form change).

Others:

- Migration and sorption of the chemical form of released radionuclides
- Reactivity with the environment.

9 Upgrade of GWAC to WAC

9.1 Description of the conditions when it is required to turn GWAC into WAC

GWAC are formulated for situations where insufficient information about a waste management facility, its anticipated technologies, and its host geological formation do not allow for formulating the fully valid waste acceptance criteria.

Typically, GWAC are defined for a disposal process (requirements on a product of waste conditioning for disposal), but they can be selected also for all predisposal stages, e.g., for waste treatment if a conditioning process has not been installed, or for waste processing without appropriate storage solution. A big advantage of predisposal GWAC is that they can be determined with respect to international experience and, thus, they are in most cases identical with the final WAC: the exemptions are usually linked to limits of specific activity of radionuclides significant for the long-term safety of waste management facilities. Nevertheless, when transforming disposal GWAC into WAC, the effectiveness of such an approach may not be guaranteed, given that the long-term safety of each disposal system relies on specific characteristics of the engineered barrier and the natural structure of the host.

As explained in previous paragraphs, the turning point for the decision for updating GWAC to WAC is the selection of a technology and a site for the missing waste management facility, such as a solidification process, a type of a storage, and/or a disposal facility.

After a decision is made on the construction of a new facility, two potential scenarios shall be considered:

a) GWAC, particularly formal and technical ones (unique identification, waste package, container, their weight/size/dimensions, handling equipment, etc.), could be used as inputs/requirements to be respected in the design and construction of a new facility, or
b) The facility is designed and constructed according to newly formulated requirements, which may result in the request for retrieval and repacking/reprocessing of already generated waste forms.

It is evident that the former approach allows for the smooth conversion of GWAC to WAC, while the latter may require the need to implement technically complicated and expensive measures. Thus, whenever possible, the first approach is should be preferred.

International experience advises that the key set of criteria affecting optimal decision should be linked to radiation characteristics of the waste forms to be disposed of. In any case, the decision on how to turn GWAC to WAC should be based on an analysis assessing new requirements, addressing safety (both operational and long term), technical conditions, and economical aspects of considered actions. It is noted that at most operational disposal facilities, the limits set in the WAC are not reached, which creates a certain safety reserve for their management.

What is the necessary information to carry out the change?
For the decision about whether and how to transfer GWAC to WAC, two groups of inputs shall be collected, namely (i) total characteristics of waste to be disposed of, incl. their form, and (ii) detailed description of the new waste management facility. The assessment of the performance and long-term function of a disposal system requires detailed information about its particular components, including engineered and natural barriers and the surrounding environment. Radiochemical composition and physical characteristics of waste forms to be disposed of is the other set of inputs needed for the evaluation of waste acceptance system. This also includes proof of the long-term performance of considered waste forms by the set of tests, known as waste form qualification process. All this allows for the qualified decision to be made, whether the GWAC ensures the required level of safety of the new waste management facility, or whether they need to be revised and adopted so that potential impact on the environment is within legal limits and requirements.

Is it always necessary? How to determine whether it is necessary.

The revision of the suitability of GWAC for the new RWM facility must be done in any case. The stimulus for this activity is the collection of sufficient information for the thorough assessment of safety of this facility. In optimal case, GWAC will be identical with WAC defined for the new facility, however, determination of specific activity limits in a package and total activity limits for critical radioisotopes can be anticipated in most cases.

9.2 Steps for turning GWAC to WAC

The procedure for transferring GWAC to WAC can be described by the following steps:

1) Collect information about generated waste (volume, mass, activity of safety sensitive radioisotopes, radiochemical analytical data, physical properties, used packages, etc.), and about anticipated waste streams and waste forms to be accepted in the new RWM facility.
2) Collect data needed for performing safety assessment of the new facility.
3) Perform safety studies to determine limits and conditions for the operation of the new facility as well as for ensuring the required level of long-term safety of the old facility.
4) Assess whether the GWAC ensures that the set limits and conditions of the operating facility are met.
5) If needed, update GWAC or develop new acceptance criteria to comply with requirements for the safe operation of the new facility.
6) Decide on retrieval/reprocessing of waste which does not comply with WAC defined for the new facility.

References

[1] L. Harvey, C. De Bock, C. Bucur: Milestone 88: Current use of Waste Acceptance Criteria (WAC) in European Union Member-States and some Associated Countries, European Commission EURAD ROUTES (WP9) Milestone MS88, November 2020.

[2] J. Feinhals, J. Miksova, A. Savidou, S. Coninx, M.C. Bornhöft, H. Vojtechova, E. Langegger, R. Beyerknecht, G. Bracke, L. Cizelj, M. Tomić, J. Wolf, I. Paiva, G. Zakrzewska-Kołtuniewicz, I. Kaissas, A. Baptista: Collection and Analysis of Actual Existing Knowledge about Disposal Options for SIMS, Final Version as of 17/05/23 of Deliverable D9.10 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593

[3] L. Nachmilner, L. Karásková-Nenadálová: International approaches to establishing a waste acceptance system, PREDIS Deliverable 2.4, August 2021.

[4] Andra et al. (2018), Waste Acceptance Criteria and requirements in terms of characterisation, European Commission THERAMIN Deliverable D4.1

[5] L. Harvey, D. Galson, S. Catherin, M.-A. Romero, M. Fournier, A. Fuller, S. Wickham (2020), Development of Generic Criteria for Evaluating the Disposability of Thermally Treated Wastes, IOP Conf. Ser.: Mater. Sci. Eng. 818 012013

[6] ERDO (2022), Minimum set of WACs for near-surface disposal of VLLW-LLW, ERDO Technical Note ERDO-WG – LWC project – Task 2

[7] Radioactive Waste Management Ltd (2016), Geological Disposal: Generic Disposal System Specification Part B: Technical Specification, NDA Report no. DSSC/402/01, December 2016

[8] International Atomic Energy Agency: Development of Specifications for Radioactive Waste Packages, IAEA-TECDOC-1515, Vienna, 2006

[9] C. De Bock, L. Harvey, T. Harrison (2023). Suggestions for the management of challenging wastes while maintaining compatibility with options for disposal: ROUTES Task 4 Final Report, Final version as of 15/12/2023 of deliverable D9.9 of the HORIZON 2020 project EURAD. EC Grant agreement no: 847593.

[10] International Atomic Energy Agency: Characteristics of Radioactive Waste Forms Conditioned for Storage and Disposal: Guidance for the Development of Waste Acceptance Criteria, IAEA TECDOC 285, Vienna, 1983

[11] International Atomic Energy Agency: Characteristics of radioactive waste forms conditioned for storage and disposal: Guidance for the Development of Waste Acceptance Criteria, TECDOC-285, Vienna, 1987

[12] International Atomic Energy Agency: Policies and Strategies for Radioactive Waste Management, IAEA Nuclear Energy Series No. NW-G-1.1, Vienna, 2009

[13] International Atomic Energy Agency: Classification of Radioactive Waste, General Safety Guide No. GSG-1, VIENNA, 2009

[14] International Atomic Energy Agency: IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2018 Edition

[15] International Atomic Energy Agency: IAEA Safety Standards Regulations for Safe Transport of Radioactive Material, Specific Safety Requirements SSR-6 (Rev. 1), Vienna, 2018

[16] International Atomic Energy Agency: Strategy and Methodology for Radioactive Waste Characterization; IAEA, TECDOC 1537, Vienna, 2007

[17] International Atomic Energy Agency: Handling and Processing of Radioactive Waste from Nuclear Applications, Technical Report Series No. 402., Vienna, 2001

[18] International Atomic Energy Agency: Storage of Radioactive Waste, IAEA WS-G-6.1 , Vienna, 2006

[19] Organization for Economic Co-Operation and Development, Nuclear Energy Agency, Storage of Radioactive Waste and Spent Fuel, Radioactive Waste Management and Decommissioning, NEA No. 7406, 2020

[20] International Atomic Energy Agency: Interim Storage of Radioactive Waste Packages, Technical Report Series No. 390, Vienna, 1998.

[21] International Atomic Energy Agency: Containers for Packaging of Solid Low and Intermediate Level Radioactive Wastes, Technical Report Series No. 355, Vienna, 1993.

[22] F. Hila, Ronald Piquero, J. Jecong The Philippine journal of Science, Engineering, Environmental Science, Physics Dose Rate Analysis of Upgraded Storage Drums for Disused Sealed Radioactive Sources by a Multivariate Interpolation Program Developed Using MCNP5 11 September 2019

[23] International Atomic Energy Agency: IAEA Safety Standards for protecting people and the environment, Disposal of Radioactive Waste, Specific Safety Requirements No. SSR-5, IAEA, Vienna, 2011

[24] International perspective on repositories for low level waste, Ulla Bergström, Karin Pers, Ylva Almén, ISSN 1402-3091, R-11-16, SKB International AB, Stockholm, December 2011

[25] International Atomic Energy Agency: Disposal Aspects of Low and Intermediate Level Decommissioning Waste: Results of a coordinated research project 2002-2006, IAEA-TECDOC-1572, Vienna, December 2007

[26] Initial state report for the safety assessment SR-PSU, Technical Report TR-14-02, Svensk Kärnbränslehantering AB, November 2014

[27] Aspects on the acceptance of waste for disposal in SFR, Börje Torstenfelt, LILW, Operations department, Swedish Nuclear Fuel and Waste Management Co, Stockholm

[28] Acceptanskriterier för avfall i SFR1, Moa Lihnell, Karoline Södergren, 1336074 3.0, SKB, April 2018, Stockholm

[29] Waste Acceptance Criteria and requirements in terms of characterisation, THERAMIN deliverable report D4.1, May 2018

[30] International Atomic Energy Agency: Derivation of activity limits for the disposal of radioactive waste in near surface disposal facilities, TECDOC 1308, Vienna, 2003.

[31] European Agreement concerning the International Carriage of Dangerous Goods by Road Class 7 Radioactive material