# Safety Aspects in Radioactive Waste Management

***Peter W. Brennecke*[1]**

***Bezpečnostné aspekty manažmentu rádioaktívneho odpadu***

*In recent years, within the framework of national as well as international programmes, notable advances and considerable experience have been reached, particularly in minimising of the production of radioactive wastes, conditioning and disposal of short-lived, low and intermediate level waste, vitrification of fission product solutions on an industrial scale and engineered storage of long-lived high level wastes, i.e. vitrified waste and spent nuclear fuel. Based on such results, near-surface repositories have successfully been operated in many countries. In contrast to that, the disposal of high level radioactive waste is still a scientific and technical challenge in many countries using the nuclear power for the electricity generation. Siting, planning and construction of repositories for the high level wastes in geological formations are gradually advancing. The site selection, the evaluation of feasible sites as well as the development of safety cases and performance of site-specific safety assessments are essential in preparing the realization of such a repository. In addition to the scientific-technical areas, issues regarding economical, environmental, ethical and political aspects have been considered increasingly during the last years. Taking differences in the national approaches, practices and the constraints into account, it is to be recognised that future developments and decisions will have to be extended in order to include further important aspects and, finally, to enhance the acceptance and confidence in the safety-related planning work as well as in the proposed radioactive waste management and disposal solutions.*

***Key words****: Radioactive Waste Management, safety-related planning work*

## Introduction

During the operation of nuclear power plants, a radioactive waste and spent fuel assemblies are generated. The waste containing fission and activation products are also generated in the front and back end of the nuclear fuel cycle as well as from the decommissioning and dismantling of power reactors or nuclear facilities. In addition, the radioactive waste originates from nuclear research establishments as well as from an application of radioisotopes particularly in the industry and medicine.

The safe management of radioactive waste generated from the production of electricity using the nuclear energy has always been recognised as an issue of utmost importance for the protection of human health and the environment now and in future. In particular, an exchange of information and consensus on the safety of radioactive waste management are of benefit to all countries having either an advanced or limited experience in the nuclear field, in order to manage the radioactive waste properly, safely and without detrimental effects. Thus, having this in mind, main regulative issues, technology related aspects and experiences gathered so far regarding the management of all types of radioactive waste will be addressed and a respective survey given.

## Achievements made in the management of radioactive waste

In recent years, within the framework of national as well as international programmes, a number of different waste management and disposal strategies and concepts have been implemented or are being developed to deal with all types of radioactive waste originating in particular from the operation of nuclear power plants and back end nuclear fuel cycle facilities. The short-lived low and intermediate level waste, generated comparatively in large volumes, have successfully been managed world-wide.

This involves various steps such as the waste minimisation, segregation, collection, treatment, processing and packaging (conditioning), transportation, interim storage and the disposal. Adequate processes, technologies and equipments have been developed to maturity and used many years.

Compared to that, a progress in the management of the long-lived low and for intermediate level waste (i.e., alpha bearing waste) as well as the high level waste (i.e., vitrified fission product solution and spent nuclear fuel) is slow and different approaches have been followed. The management of these wastes comprises many different steps. A closed nuclear fuel cycle with reprocessing of spent nuclear fuel is a preferred route of the high level waste management for some countries, whereas others tend to the long-term engineered storage of spent nuclear fuel without reprocessing and to direct disposal or to keep open both options with respect to further developments and/or decisions to be taken in future. Up to now, there is no repository in operation for the high level radioactive waste worldwide.

[1] *Dr. Peter W. Brennecke*, Bundesamt für Strahlenschutz (BfS),Willy-Brandt-Straße 5, 38226 Salzgitter, Germany, PBrennecke@bfs.de
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Nevertheless, evaluating the management of all types of radioactive waste, notable advances and considerable experience have been reached in particular in the areas of:

- avoiding or minimising the production of radioactive waste at a source,
- conditioning (in particular the application of volume reducing techniques), handling, transportation and disposal of short-lived low and intermediate level waste (including the management of "legacy" waste, i.e. the waste generated some decades ago),
- vitrification of fission product solution on an industrial scale,
- engineered storage of long-lived high level waste, i.e. the vitrified waste and spent nuclear fuel.

Although national strategies differ, the approach and methodologies are often quite similar, thus creating a sound basis for an exchange of information and other co-operative activities.

As far as the disposal of short-lived radioactive waste is concerned, one of the achievements reached by these programmes is an establishment of a consensus between most of the experts in various countries in that repository sites can properly be identified and characterised, that repositories can be designed such that no short-term detriment to the human health and the environment will result from waste disposal, and that an acceptable level of safety is provided for times far into the future.

Internationally, the disposal of long-lived radioactive waste in geological formations is so far the most widely accepted approach to ensure a confidence about the long-term protection of the man and environment. This disposal concept relies on the capabilities of both engineered barriers and the geological setting to ensure that the vitrified waste and the spent nuclear fuel are isolated from the biosphere. Notable advances have been achieved in:

- the establishment of organisational structures and regulatory frameworks to govern the siting, construction and licensing of respective facilities,
- technologies for the site characterisation,
- conceptual repository design,
- the development and application of appropriate methods for the site-specific safety assessments.

There is interest, and resources are being spent, in a research on the partitioning and transmutation of long-lived radionuclides in order to reduce the amounts of long-lived radioactive waste. The overall balance of financial and practical aspects of this process is, however, still being debated. It is accepted, in particular, that the partitioning and transmutation would not remove the need to dispose of the long-lived waste permanently. Finally, some countries have a continuing interest in the possibility of regional or multinational repositories.

## Progress made in areas of special importance

In addition to the achievements given in Section 2, some of the major challenges currently faced by national and international programmes shall be discussed in more detail.

### Regulative issues and recommendations

Most programmes of international organisations encompass activities from which benefit countries regardless of their degree of sophistication in the use of nuclear energy. Consequently, with respect to the importance of safety in the radioactive waste management and disposal, there is a need for the awareness of international developments and the considerations of their implications at a national level.

In response to the safety-related requests for providing an assistance and fostering consensus on necessary steps, the International Atomic Energy Agency (IAEA) has been establishing standards for the safety of radioactive waste management, including the disposal through its Radioactive Waste Safety Standards (RADWASS) Programme. The RADWASS publications represent a comprehensive series of documents internationally agreed upon, to assist in the derivation of new, or to complement existing, national criteria, standards and practices. They are headed by the Safety Fundamentals document "The Principles of Radioactive Waste Management", published in 1995. It includes, in particular, the obligation to establish and maintain a legislative and regulatory framework to govern the safety of spent nuclear fuel and the radioactive waste management and the obligation to ensure that individuals, society and the environment are adequately protected against radiological and other hazards, inter alia, by appropriate siting, designing and constructing of facilities both during their operation and after their closure.

One of most important achievements in the international agreements and guidance is the establishment of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The Convention was opened for a signature in September 1997. Up to now, it was signed by 41 contracting parties. The Joint Convention applies to the spent nuclear fuel and the radioactive waste resulting from civilian nuclear reactors and applications and to the spent nuclear fuel and the radioactive waste from military or defense programmes if and when such materials are transferred permanently to and managed within exclusively civilian programmes, or when declared as a spent nuclear fuel or radioactive waste for the purpose of the Convention by the contracting party. The Convention also applies to planned and controlled releases into the environment of liquid or gaseous radioactive materials from regulated nuclear facilites.

The main objective of the Joint Convention is to achieve and maintain world-wide a high level of safety in the spent fuel and radioactive waste management, through the enhancement of national measures and international co-operation, including, where appropriate, a safety-related technical co-operation. Thus, the Joint Convention addresses the demonstration of appropriateness, adequacy and quality of respective national programmes. It considerably contributes to a higher degree of transparency in the national radioactive waste management and the disposal programmes not only for countries developing such a programme but also for countries having an established system.

Further safety-related activities are being pursued by the European Union (EU), the International Commission on Radiological Protection (ICRP) and the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA). Thus, additional guidance and recommendations are given that may have a direct impact on the national programmes. For example, the EU Council Directive 96/26/Euratom of May 1996 laid down basic safety standards for the protection of workers and the general public against the dangers arising from the ionising radiation or the ICRP radiological protection recommendations with respect to the disposal [1]. The OECD/NEA recently published an essential document dealing with the confidence in the long-term safety of deep geological disposal, and the ways in which this confidence can be obtained and communicated [2]. Furthermore, the OECD/NEA provides advisory and peer review services.

The most important international advisory standards are the recently published IAEA standard on the geological disposal [3] and – regarding the radiation protection issues – IRCP Publication 81 [1] as well as the report The Optimisation of Radiological Protection: Broadening the Process by the IRCP Committee 4 Task Group on Optimisation of Protection published in January 2006. Main safety-related issues being addressed in these documents comprise the stepwise approach in repository planning and development, the optimisation within given constraints as well as the requirements on a safety management system and the performance of a safety case.

All these international activities successfully contribute to the fostering of exchange of information and the consensus on the safety of radioactive waste management in order to help countries in managing and disposing of radioactive waste safely.

**Radioactive waste conditioning**

For the conditioning of radioactive waste appropriate infrastructures for processing and packaging the short-lived or long-lived low, intermediate and high level wastes are available. Various treatments and conditioning techniques have been developed and successfully applied for many years. This comprises rather simple techniques as well as very advanced processes depending upon the respective national nuclear energy programme. A selection of the conditioning process depends on factors like the requirements of interim storage and disposal, acceptance of the process, and number/total volume of the resulting waste packages. This shall be discussed in some more detail focusing on the interaction between the conditioning and the disposal of low and intermediate level radioactive waste.

The waste acceptance requirements are relevant to the safety of a near-surface and/or geological repository in its operational and post-closure phase. In addition, both the guidance to the waste conditioning given by them and the costs for the disposal, e.g. per $m^3$ waste package volume, basically offer a sound basis to decide upon the waste conditioning concepts and the strategies taking in particular economical aspects into consideration. Technical and economical issues resulting from a repository help to increase the awareness of thoughtful practices in the proper selection of appropriate conditioning techniques and/or the adjustment of existing methods and procedures. The validity of waste acceptance requirements offering a security as well as fixed disposal costs are the most decisive prerequisites for decisions to be taken in the waste conditioning.

Thus, when a repository is available, it is to be anticipated that the most economical solution of waste treatment and conditioning will eventually be addressed and applied in practice. Having the existing waste conditioning techniques in mind, this may result in a decision that rather simple comparatively low-priced and well-proven conditioning techniques as the packaging of waste into drums, the decantation/dewatering or the immobilisation and grouting of waste may increasingly be applied, as compared to advanced conditioning techniques aiming at the volume reduction and the use of self-shielded packagings. Nevertheless, such developments depend on the respective waste acceptance requirements and require careful technical analyses and detailed economic considerations. The costs of particular waste conditioning techniques must be evaluated and compared with the respective number of waste packages produced as well as with the related shipment and disposal costs. Further aspects, in particular the radiation exposure, must additionally be taken into account. As a result, optimised procedures for the waste conditioning are to be expected whereby the required safety of a repository in its operational and post-closure phase will always be ensured.

## Interim storage facilities

Prior to the disposal spent nuclear fuel is stored, up to several decades in order to decay. For this purpose, storage pools within nuclear power plants or interim storage facilities are used, respectively.

Having in mind the September 11, 2001 terrorist attacks using large airplanes in the USA, it cannot be excluded that nuclear installations - including storage facilities - may become the target of such an attack. That is a reason why, for instance in Germany, it was decided to include an analysis of a terrorist attack with an airplane within the licensing procedures for interim storage facilities of the spent nuclear fuel. The legal basis for such an examination is given by the section 6 (2), no. 4 of the German Atomic Energy Act.

According to the German radioactive waste management concept, the spent nuclear fuel is packaged in thick-walled transportation and storage cashs (e. g., of the CASTOR type) and stored for a period of time of approx. 30 years (dry storage). For this purpose, two central and 12 decentralized (on-site) storage facilities are available.

Within the licensing procedures for the on-site storage of spent nuclear fuel successfully completed at the end of 2003, specific safety-related investigations taking terrorist attacks into consideration were performed. For the analyses of forced airplane crashes onto an interim storage facility, different sizes and types of modern airplanes have been considered, up to the Boeing 747-400 and the Airbus 340-600. The investigations include, among other things, maximum take-off weights as well as maximum fuel volumes. Thus, a wide range of possible mechanical and thermal impacts is covered.

For the different types of airplanes considered the time dependent mechanical impact to a heavily steel-reinforced concrete wall was calculated. The mechanical momentum of fuselage, wings and engines on a solid target was analyzed in order to determine whether an interim storage building can withstand direct airplane crashes. If not, the remaining momentum of penetrating airplane debris and the momentum of accelerated concrete wall and roof pieces were analyzed.

With respect to thermal impacts, it was considered which amount of aviation fuel would enter the interim storage building and contribute to a thermal impact onto a spent fuel cask. Besides the aviation fuel, combustible parts of an airplane were taken into account. Thus, an aviation fuel fire of about 15 min with temperatures of maximum of up to 1,100 °C was determined. For other combustible materials the temperature of about 700 °C and a fire duration of about 25 min was calculated. The most important result of the analyses is that the thermal impact onto spent fuel casks does not cause any severe decrease of the leak tightness (from ≤ 10 (exp-8) Pa·m$^3$/s to 10 (exp-4) Pa m$^3$/s at maximum).

Using the detailed information on the consequences of mechanical and thermal impacts possible releases of radioactivity and subsequent radiological consequences were calculated. The results clearly demonstrate that a forced airplane crash onto an interim storage facility does not lead to any risk of health or life due to the radioactivity releases. The respective dose limits are not exceeded; on the contrary, the radiological effects remain far below the protection goal of 100 mSv per person.

## Near-surface and geological repositories

The disposal of short-lived level waste has already been practised and long-lived waste disposal projects have been launched. In order to outline the current status, a couple of typical examples is referred to.

### *Realisation of disposal programmes*

In June 2006, the Belgian Government decided that the short-lived low and intermediate level waste will be disposed of in a near-surface repository within the borders of the municipality of Dessel. This decision will make it possible to develop the next phase of the work programme in order to realize this repository. The design phase, during which all necessary detailed studies will be carried out, should lead to a binding agreement laying down the rights and obligations of the various parties involved, and to finally obtaining the construction and operating licenses.

In various countries, near-surface repositories of different design have been operated. For instance, in France, the Centre de l´Aube disposal facility started operation in January 1992. Its capacity amounts to 1,000,000 m$^3$ of short-lived low-level and intermediate-level radioactive waste. Subsequent to the conditioning on-site, waste packages are stacked in engineered concrete boxes 25 m long and 8 m high. On average, about six concrete boxes are annually filled with a waste package volume of about 15,000 m$^3$ in total. As the Centre de l´ Aube is designed to accept an annual waste package volume of about 35,000 m$^3$, the operational lifetime of this facility is estimated to last more than 50 years.

As to the geological disposal of radioactive waste in the United States of America, the Waste Isolation Pilot Plant (WIPP) near Carlsbad/New Mexico started operation in March 1999. This facility is the world´s first approved geological repository specifically designed for the disposal of long-lived low and intermediate level radioactive waste. Its capacity amounts to about 175,000m$^3$ of alpha bearing waste including hazardous chemicals generated during the production of nuclear weapons (so-called mixed waste). The waste packages are stacked in disposal rooms at the emplacement level at a depth of approximately 655 m in the massive Permian rock salt. Up to now, more than 5,000 waste shipments were received by WIPP. Three underground panels accomodate more than 85,000 containers holding approx. 45,000 m$^3$ contact-handled transuranic (TRU) defense waste resulting from the removal of all TRU waste from 10 generator sites. The operational lifetime of this facility is expected to be about 35 years; the total activity to be emplaced amounts up to the order of magnitude of $10^{17}$ Bq.

With respect to the long-lived high level radioactive waste, the feasibility of its safe disposal was confirmed in Switzerland. The priority has been given to Opalinus clay, a formation located under Zürcher Weinland close to the German border. In June 2006, the Swiss Federal Council announced its approval of the Entsorgungsnachweis project (demonstration of feasibility of disposal). The decision of the Federal Council represents an important milestone on the Swiss radioactive waste management programme. Once the Federal Council has specified the procedures and criteria for the site selection in the sectoral plan (Sachplan) for repositories in geological formations, the next step will be to initiate the selection procedure for concrete sites for future repositories. NAGRA, being the responsible agency for the radioactive waste disposal in Switzerland, is presently preparing the technical basis for this procedure.

In the United States of America, a site at Yucca Mountain/Nevada has been studied over the past 20 years to determine whether it is suited to host a disposal facility for spent nuclear fuel and high level radioactive waste. It is still not quite clear when this site may open and start its operation. Furthermore, Finland choosed the Olkiluoto site for the high level radioactive waste in 2000, and Sweden is currently carrying out an additional research to reach a decision between the Östhammar and Oskarshamm sites.

***Re-examination of disposal programmes***

Despite of the fact that the confidence of most experts in the safety of a repository during its operational and post-closure phase has been confirmed, this is not necessarily matched by an equally favourable attitude of politicians, regulators, critical experts or non-expert groups. Thus, several repository-development programmes are undergoing an increased scrutiny and are expected to be adjusted according to political decisions, new findings or specific evaluations. In the Federal Republic of Germany, Canada and in the United Kingdom, the hitherto radioactive waste management and disposal programmes are presently being re-examined and revised programmes are to be developed seeking a national consensus in both countries, respectively.

In the United Kingdom and Canada, the initial investigation work to find a suitable site was carried out mostly on the basis of scientific criteria, but did not prove successful. Authorities in both countries have decided to re-initiate the process from scratch by implementing a dialogue and a consultation at the national level with a view to selecting long-term management options and the appropriate structure for the process itself. In Canada, the process has resulted in the recent proposal to implement a geological repository for spent nuclear fuel.

## Areas for a further development

### Groundwater-related safety aspects

According to the existing legal regulations to water in some countries, in radioactive waste disposal an attention must be paid not only to the radiological impacts but also to the chemical impacts of certain waste constituents. For instance, in order to demonstrate the safety of a geological repository particularly in its post-closure phase, possible releases of organic and inorganic contaminants via the water path, resulting in a pollution of near-surface groundwater, are to be investigated. Thus, in addition to the assessment of radiation exposure and radiological impacts during the operational and post-closure phase of such a facility, it has to be clarified whether non-radioactive toxic substances in the waste packages present an additional long-term hazard to future generations. In this context, it must be recognised that radionuclides are the minor mass fraction in the waste to be disposed of. The major mass fraction is made up of non-radioactive organic and inorganic material including chemotoxic substances. A complete site-specific safety assessment must therefore cover hazards and impacts associated with both, radioactive and non-radioactive constituents of the waste to be disposed of. The procedure and assessment of non-radiological groundwater-related impacts in the radioactive waste disposal were successfully demonstrated, for the first time, within the licensing procedure for the German Konrad repository project [4].

**Retrievability**

The defining characteristic of the post-closure status is that no further engineering measures are expected to be necessary in order to ensure a proper future performance of the disposal facility. In a geological repository, for example, the post-closure phase pertains to the period of time following a final shaft sealing and surface facility decommissioning. Nevertheless, a geological repository may provide the possibility of retrievability in early periods of time. Thus, on a national level, it should be helpful to examine how far the present concept of radioactive waste disposal in deep geological formations would need to be modified to ensure the retrievability at several time scales. This also introduces the issue how to determine the timing closure based on environmental and ethical concerns.

## Status of integrated, optimised and cost effective radioactive waste management systems

In addition to the scientific-technical areas, the consideration of issues regarding economical, environmental, ethical and political aspects has been increased during the last years. Hence, there is a need for the examination of such issues in more detail and, if appropriate, for introducing respective results in a further radioactive waste management and disposal options and/or planning work. For example, the elaboration of criteria for choosing a candidate repository site from a number of potentially suited sites should be faced or the human intrusion into and the retrievability of waste packages from geological repositories (cf. Section 4.2) be re-assessed and transferred to broadly accepted solutions. As far as economical aspects are concerned, respective considerations, to some extent, still seem to be rather in their initial phase and need a better understanding. If, for example, a potential site has carefully been investigated, this investigation finally results in its suitability to host a repository, then possibly required investigations of further sites in different host rocks must be evaluated considering in particular economical aspects, too. Thus, specific features of a nationally implemented waste management system may be favoured (or not) and, consequently, adjusted in an appropriate way.

## Conclusions

Reviewing the current status of and examining the perspectives for the technological infrastructure needed for a safe, environmentally sound and effective management of radioactive waste originating in particular from the operation of nuclear power plants, back end nuclear fuel cycle facilities and nuclear research establishments including decommissioning and dismantling, respectively, it can be concluded that:

- the technology is available to manage, in a safe and cost effective manner, the waste originating from the operation and decommissioning of nuclear facilities,
- feasible methods have been developed and mature solutions found to deal with waste issues,
- a schemes have been developed and adopted to ensure that the resources needed to implement waste management programmes are available.

Nevertheless, the disposal of high level radioactive waste originating from the reprocessing and spent nuclear fuel is still a scientific and technical challenge in many countries using the nuclear power for the electricity generation.

Taking differences in national approaches, practices and constraints into account, it is to be recognised that future developments and decisions will have to be extended in order to include further important aspects and, finally, to enhance an acceptance and confidence in the safety-related planning work as well as the proposed radioactive waste management and disposal solutions. In particular, an international consensus on the safety of radioactive waste management and disposal, including the respective procedures and steps to achieve this, will be one of the essential key elements with respect to the protection of human health and the environment.

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