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TÜBİTAK

Aspects of Final Disposal of Radioactive Waste in Germany

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Abstract: Safe disposal of radioactive waste is required in all countries using nuclear power, radioactive materials in medicine and in industry or research. This contribution presents an overview of the strategy of final disposal of radioactive waste and summarizes the procedure and present status in Germany. It is concluded that the safe disposal of radioactive waste is feasible but that the public demand for safety has to be met by applying a stepwise, transparent, and traceable development procedure for a repository in a safety case to obtain regulatory and public approval.

Key Words: disposal, radioactive waste management, geochemistry, final repository, safety, long-term safety, safety case

Almanya'da Radyoaktif Atık Nihai Bertaraf Yönleri

Özet: Radyoaktif maddelerin ilaç sanayinde, endüstride ve araştırmada kullanıldığı veya nükleer santrallerin olduğu ülkelerde radyoaktif atıkların güvenli bertarafı bir zorunluluktur. Makale, radyoaktif atıkların nihai bertarafı stratejisine genel bir bakışı sunarken, Almanya'daki usul ve mevcut durumu da özetlemektedir. Sonuç olarak radyoaktif atıkların güvenli bertarafının mümkün olduğu ancak kamu güvenliği ve talebini karşılamak için düzenleyici ve kamunun onayının da olduğu güvenli depolanması için şeffaf ve izlenebilir bir geliştirme prosedürü uygulanması gereklidir.

Anahtar Sözcükler: atık, radyoaktif atık yönetimi, jeokimya, nihai depolama, güvenlik, uzun vadeli güvenlik, güvenlik durumu

Introduction

The safe disposal of radioactive waste is required for the protection of human health and the environment. In addition high-level-waste consisting of vitrified waste, structural parts of fuel elements and spent fuel elements contains radionuclides which have to be protected against possible use for terrorism or production and proliferation of weapons of mass destruction.

The radioactive waste is classified according to its origin and type. Different containers for radioactive waste and their intermediate storage are required. A strategy for disposal, selecting sites and possible host rocks has been developed. There are safety requirements for the operation and closure of a disposal site. The final closure of a disposal site requires a safety case for long-term safety with safety analyses and further arguments to demonstrate safety. The existing and planned repository sites in Germany are presented.

Classification of Radioactive Waste

The radioactive waste was classified initially as low, medium and highly radioactive as depicted in Figure 1. This classification became less important since the technical handling and storage of radioactive waste is mainly dominated by its heat generation due to the radioactive decay. Therefore, the current classification distinguishes between heat-generating radioactive waste and radioactive waste with neglible or no heat generation (Figure 1).

Heat generating radioactive waste has a radioactivity of approximately 10^{11} Bq/m^3 or more. The heat-generation will decline to a negligible level within several hundred years. The radioactivity will also decline but requires several hundred thousand years to reach a level comparable to the natural background of uranium deposits.

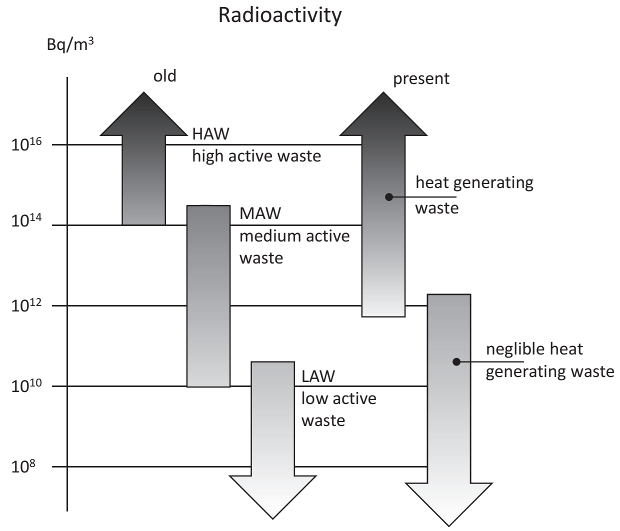

Figure 1. Classification of radioactive waste.

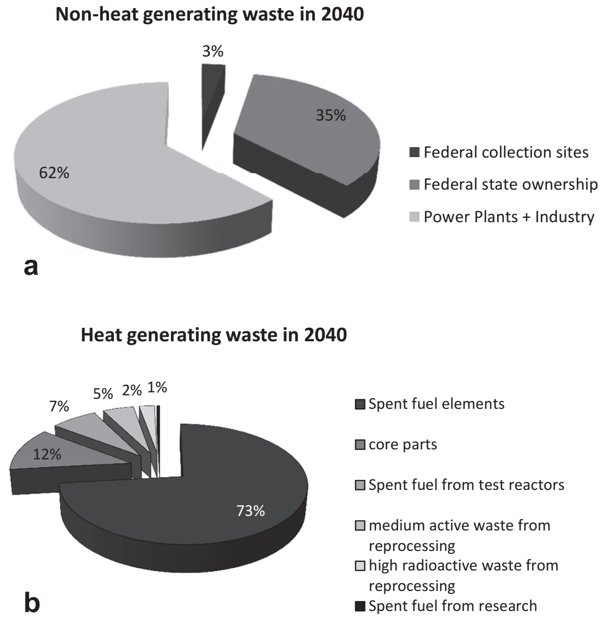

Figure 2. Radioactive waste in Germany in 2040 (BFS 2010).

Origin of Radioactive Waste

Radioactive waste from research and medical use has mostly a low radioactivity and has no or a low heat generating capacity. Nuclear power plants are the major sources for radioactive waste. They produce low, medium and highly radioactive heat-generating waste.

Non-heat-generating radioactive waste accounts for more than 90% of the waste by volume. This waste contains 1% of the total radioactivity.

Figure 2 depicts the origin of the different waste types and the estimated waste amounts for 2040, if the phase-out of nuclear power in Germany takes place. If the operating lifetime of the nuclear power plant in Germany is extended, the waste volume will increase. Radioactive waste from reprocessing originates from plants in England and France. Spent fuel elements from Germany were reprocessed under contract. These contracts have foreseen already a take-back obligation of the generated radioactive waste and its disposal in Germany.

Intermediate Storage of Radioactive Waste

Before final disposal, the radioactive waste is stored in containers in intermediate storage facilities. Different container types are used. The container 'Castor' is used to transport heat generating waste such as spent fuel elements (Figure 3a). The container 'Pollux' is designed for final disposal of spent fuel elements (Figure 3b). The 'cocilles' are for vitrified waste and residual components from reprocessing (Figure 4a, b). Simple steel containers or drums, with or without concrete shielding, are used for intermediate storage of non-heat-generating radioactive waste (Figure 5a, b).

The Current German Position on Selection of Disposal Concepts

Different strategies and procedures for disposal of radioactive waste have already been discussed and tested. Disposal in space, the oceans or a permanent control is very risky, internationally banned or impossible. Therefore it is agreed that disposal in deep geological formations is the preferred option for all types of radioactive waste in Germany. It allows a centralized disposal and provides isolation of the radioactive waste from the biosphere. The closed repository does not need maintenance and hampers any accidental penetration by human activity. A more detailed position on future human activities has been elaborated by the Working group on 'Scenario Development' (2008).

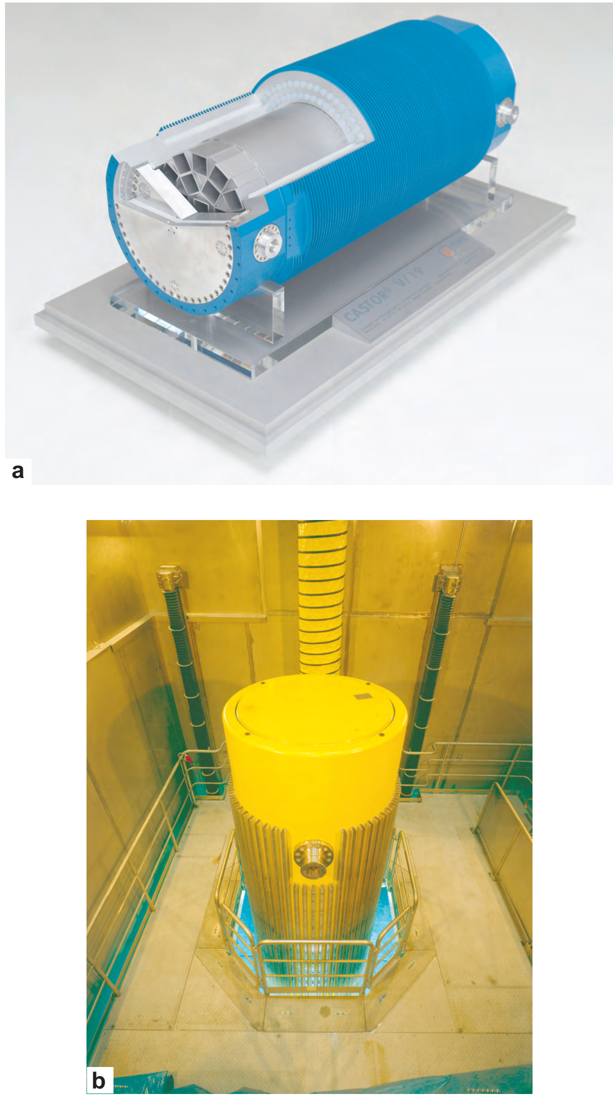

Figure 3. Containers 'Castor' **(a)** and 'Pollux' **(b)** for heat generating waste.

The German atomic energy act (Atomgesetz 2009) regulates that the federal state of Germany is responsible for the disposal of radioactive waste. The waste has to be disposed of in Germany. No radioactive waste must be accepted from other states. The disposal of heat generating waste and negligible heat generating waste is done separately. The costs of disposal have to be paid by the waste producers. Provisions must be made by commercial organisations.

The current discussion of site selection is considering two host rock formations in Germany: rock salt and clay stone:

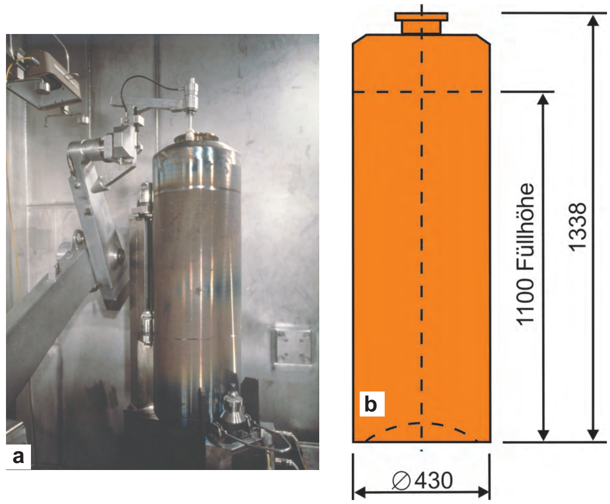

Figure 4. Cocilles for vitrified waste and structural parts.

- Rock salt provides the advantages of being impermeable for water, self healing processes for fractures and voids and being durable for high temperatures. The most important disadvantage is its solubility against low mineralized water.
- Clay stone has a very low permeability for water and may absorb released radionuclides very efficiently. Its disadvantage is a lower durability against high temperatures, thus requiring a larger rock volume for disposal.
- When constructing and operating a repository, the operational safety also has to be shown for hazardous incidents and beyond-design accidents.
- The closure of the repository has to comply with the Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste (BMU 2009). The requirements have the following objectives:
- to permanently protect man and the environment from ionizing radiation and other harmful effects of such waste
- to avoid unreasonable burdens and obligations for future generations

The safety requirements include safety principles and criteria. A step-by-step optimization has to be done. The extrapolated radiation exposure in the long-term phase is proposed as an indicator. Before any major decision concerning the site is made, a

Figure 5. **(a)** Containers for non-heat generating waste, **(b)** Shielded drums for non-heat generating waste.

comprehensive, site-specific safety analysis and safety assessment covering a period of one million years has to be carried out. Requirements applying to the long-term safety assessment are:

- Statement on the long-term integrity of the isolating rock zone
- Long-term radiological statement
- Proof of the robustness of the final repository system´s technical components
- Exclusion of criticality

That will be a safety case, which has been defined (e.g., by NAGRA 2002) as 'a set of arguments and analyses used to justify the conclusion that a specific repository system will be safe'. It includes, in particular, a presentation of evidence that all relevant regulatory safety criteria can be met. It also includes a series of documents that describe the system design and safety functions, illustrate the performance, present the evidence that supports the arguments and analyses, and that discuss the significance of any uncertainties or open questions in the context of decision-making for further repository development.

The (NEA 2008) defined a safety case for the post-closure phase of a geological repository as a synthesis of evidence, analyses and arguments to quantify and substantiate that a repository will be safe after closure and beyond the time when active control of the facility can be relied upon.

Long-Term Safety Analysis

The long-term safety analysis is a part of the safety case and is based on a set of scenarios. In the German safety requirements these scenarios have to be classified with regard to their probabilities. Some scenarios are likely; others are less likely. Both have to be analyzed in the safety case. Other scenarios are very unlikely and may be considered in the long-term safety analysis as what-if cases. Based on the current state of research and technology the compliance with regulatory objectives has to be shown by numerical modeling and analyzing the likely and less likely scenarios.

Figure 6 depicts a what-if scenario of repository in rock salt which can be used to demonstrate robustness for unlikely scenarios. There may be an event generating a water path connecting the groundwater flow to the repository. The intrusion of water / brine will enhance the corrosion of the containers and dissolve radionuclides, which may then be released to groundwater and migrate to the biosphere.

The long-term safety analysis will analyze the consequences of a scenario in terms of radiation exposure to man. This numerical modelling requires site-specific information and data as well as continuing research in order to understand the relevant processes (e.g., sorption and solubility of radionuclides, transport phenomena, etc). This will generate models for computation and simulation of

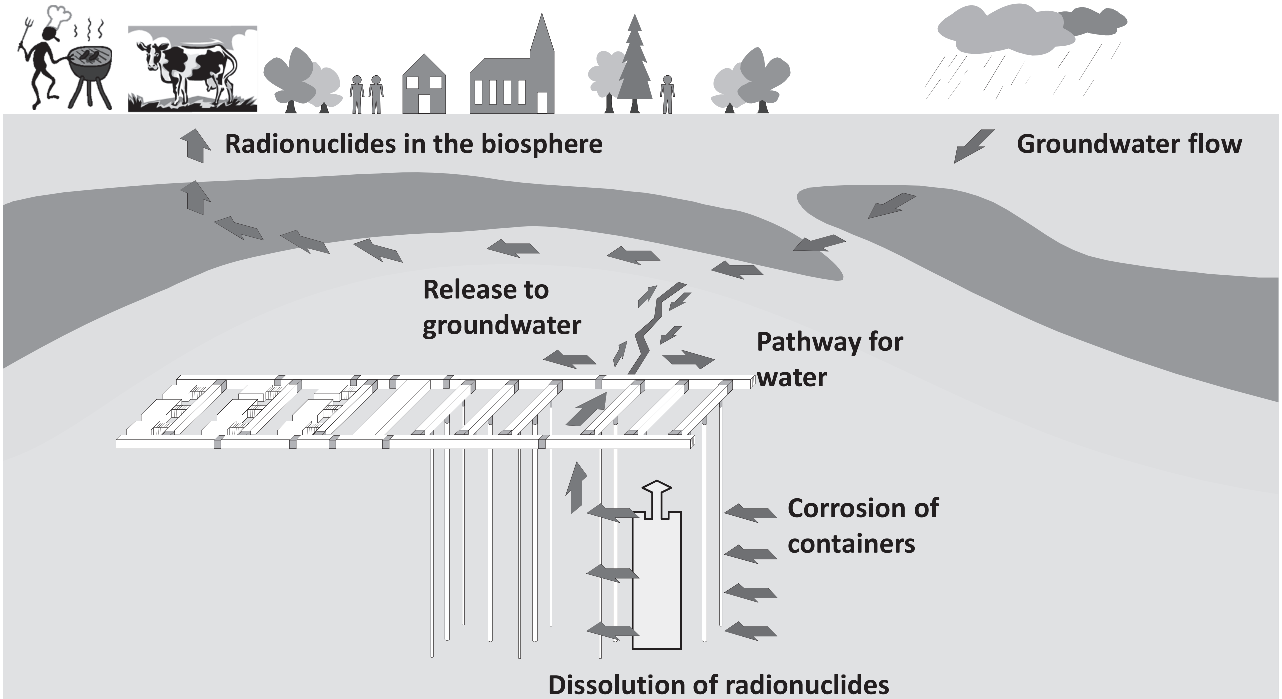

Figure 6. What-if scenario for release of radionuclides from a repository.

radionuclide retention, release and transport and allow the assessment of potential radiation exposure.

The result of such an analysis is given as a theoretical radiation exposure (dose) which can be attributed to the release of radionuclides from the repository. These model results inherently suffer from data uncertainties and model assumptions. A safety margin to the regulatory guideline should sufficiently cover these uncertainties to be robust. Figure 7 depicts the results from the Swiss safety case for a repository in Opalinus clay (NAGRA 2002). The calculated dose is some orders of magnitude below the regulatory guideline.

Isolating Rock Zone

The German safety requirements foresee the safe enclosure of the radioactive waste within the repository for at least one million years. The prediction of the future evolution of disposal compartments repository, geology, hydrogeology, biosphere is becoming increasingly uncertain with time. The evolution of human societies may be predicted for some decades, whereas the evolution of the biosphere may only be predicted for a few hundred years and the evolution of the hydrological systems for several hundred years. It is impossible to predict their evolution of these systems for up to one million years. Geological evolution may be predicted up to a million years based on the data available from the history and its size (Figure 8).

Therefore the German safety requirements foresee the safe enclosure of the radioactive waste within an isolating rock zone surrounding the repository (Figure 9).

The isolating rock zone shall release no or only an insignificant amount of radionuclides. The insignificant amount of radionuclides is deduced from the radiation exposure of man, which is currently permissible, and serves as an indicator. If it can be shown that there is no exposure or a negligible exposure by released radionuclides from the isolating rock zone, then the compliance with the regulatory requirements can be agreed. Any additional decrease of the exposure by hydrology is not considered.

Clearly, the size and the characteristics of the isolating rock zone are parameters which can be

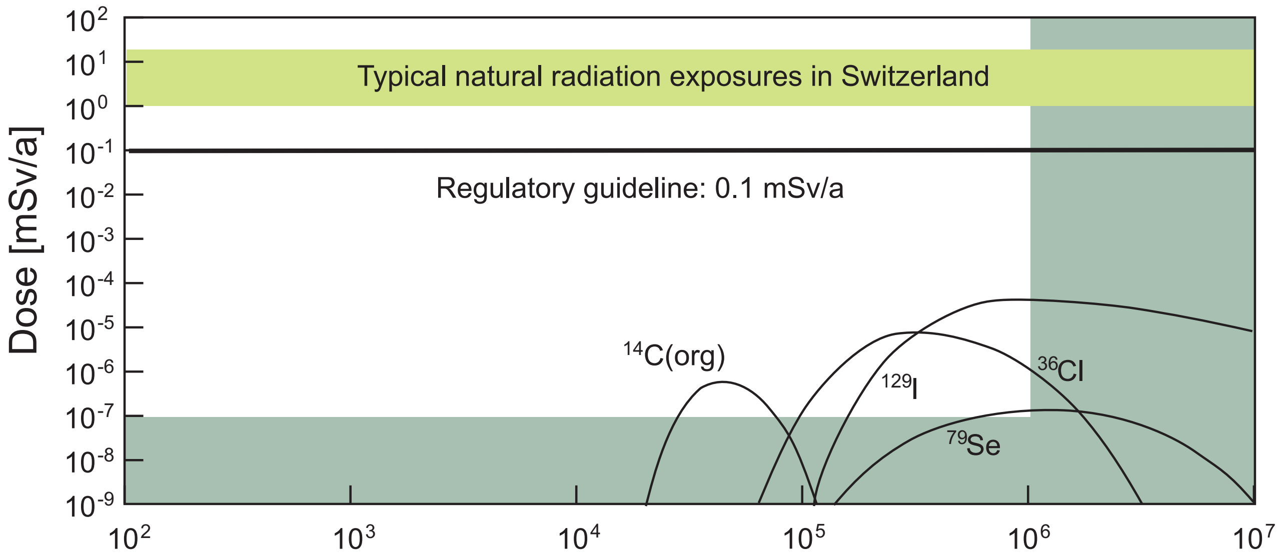

Figure 7. Radiation exposure depending on time for a Swiss safety case (Nagra 2002).

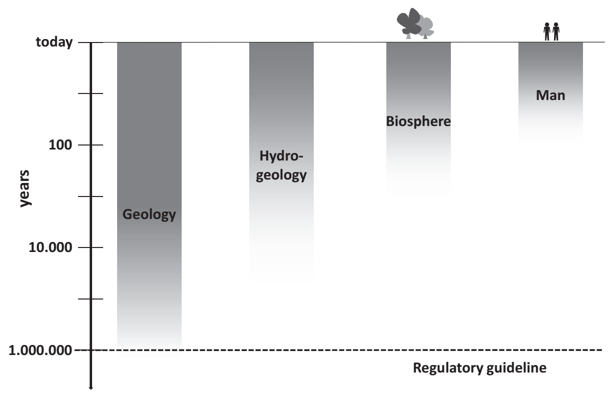

Figure 8. Predictability of compartments.

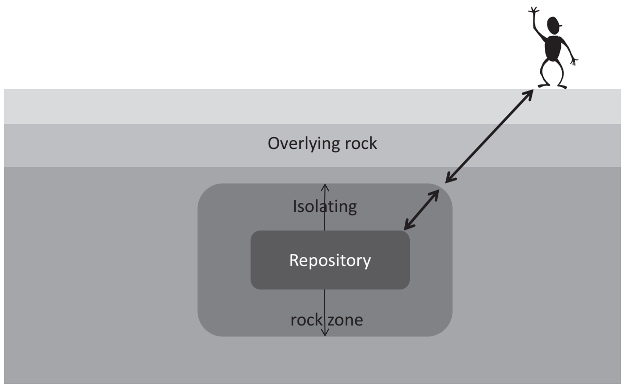

Figure 9. Concept of isolating rock zone.

varied within a certain range. The advantage of this approach is that the proof of compliance is restricted physically to the repository system. In total, this concept imposes higher safety requirements for final disposal of radioactive waste, but is be more feasible in technical aspects for numerical modelling. The safety assessment becomes more comprehensible and gains credibility.

Current Status in Germany

Germany has four sites which have been used or are discussed for the disposal for radioactive waste. These sites are called Gorleben, Morsleben, Konrad and Asse.

1. The Gorleben site is a salt dome which was investigated to determine its suitability for the final disposal of heat-generating radioactive waste. This investigation was stopped in 2000 for 10 years due to a political agreement. The investigation and the elaboration of a preliminary safety case were restarted in October. Currently it is not planned to compare different sites for final disposal of heat-generating radioactive waste, in contrast to the proposed procedure from the AK End (2002) and the ongoing stepwise site selection process in Switzerland (BFE 2008).
2. The Morsleben site is a repository for low- and intermediate level waste located in a salt

Figure 10. Location of repositories for radioactive waste in Germany.

formation. The repository was established in the former German Democratic Republic and was continuously used for some years after reunification. The disposal was stopped in 1998. Since then the closure has been reconsidered and the licensing procedure was started. All documents were handed in for a public review. It is estimated that this process will take 20 years until final closure of the repository.

3. The Konrad site has been licensed for final disposal of negligible heat generating radioactive waste since 2007. The erection of the facilities is under way and disposal of radioactive waste is scheduled to start in 2014.

4. The Asse site is a former salt mine located in a salt dome. Radioactive waste was disposed of from 1967 to 1978 as a trial. Brine has flowed into the mine since 1988, presently at 12 cbm per day. Since 2009 the responsibility for operation and closure of the repository lies with the Federal Office of Radiation Protection. The new operator decided to investigate the retrieval of the radioactive waste despite the unresolved technical challenges, since there is a risk of unintentional flooding of the mine.

Summary and Conclusion

The long-term safety of radioactive waste disposal shall be provided by geological disposal in Germany. The current concept for the safety assessment considers an isolating rock zone which is supported by its surrounding host rock.

The predicted radiation exposure in different scenarios, obtained by numerical calculations in the long-term safety analysis, serves as an indicator for the isolation of radionuclides. It does represent a theoretical radiation exposure which is supposed to have a robust safety margin to the regulatory guideline.

The final assessment of all data and information has to be presented within a safety case to obtain a license for operation and closure of a repository for radioactive waste.

Overall, the safe and final disposal of radioactive waste, which means protection of man and the environment for the next million years, is supposed to be feasible. Since the public demand for demonstration of safe disposal is increasing, the demonstration of its safety has to be updated in a step-wise approach to comprehensively and credibly meet this demand.

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