Protective structures for mid- and long-term dry intermediate storage of spent fuel assemblies in casks - state of the art and recent trends

Dipl.-Ing. Martin SALLMANN, Dr.-Ing. Joerg MOERSCH, Dipl.-Ing. Anna GALLINAT
Max Aicher Engineering GmbH, Teisenbergstraße 7; 83395 Freilassing, Germany
m.sallmann@max-aicher.de, j.moersch@max-aicher.de, a.gallinat@max-aicher.de

1. Introduction

In response to the nuclear accident in Fukushima, the German cabinet decided in 2011 that nuclear energy technology would no longer be used for the generation of electric energy after the year 2022 [1]. At this time there is no final repository for mid- and high-level rad waste in Germany.

In 2013, a law was passed for the purpose of finding an official site for a nuclear repository in the territory of the Federal Republic of Germany, starting an open-result solution finding process. By 2023, several potential sites are to be investigated; by 2031 a final storage site should be determined; by 2050 the final repository shall be operational [2]. This long timeline underscores the importance of interim storage facilities for the interim period. Even after the final repository becomes operational, it will most likely take several decades to fill the storage facility with rad waste.

All interim storage facilities in Germany are designed as dry storage facilities, in which transport and storage casks loaded with spent fuel assemblies or vitrified high-level radioactive waste are stored. Various versions of the interim storage facilities are approved (STEAG-, WTI- and tunnel-type). They differ mainly in the arrangement of the storage areas and in the building wall thickness.

The permissions for German interim storage facilities are valid for 40 years. After 2039 the last German interim storage facility for high- and mid-level rad waste will no longer have an operating license [3]. Even if the operating permits were to be extended at all, this would only be possible on the basis of updated licensing requirements. This means the original load-case scenarios have to be supplemented by today’s hazards resulting from climate change and man-made threats such as aircraft-impact and terrorist threats like armor-piercing weapons.

This paper describes the requirements to be reasonably considered for safe interim storage and presents novel solutions.

2. Protection objectives for intermediate storage facilities to be considered by design

The radiological protection objectives which have to be met by the protective structure, as well as by the technical design and operation of the interim storage, are as follows:

- avoid any unnecessary radiation exposure or contamination of humans and the environment,
- keep any radiation exposure or contamination of humans and the environment as low as possible, taking into account the state of science and technology, and taking into account all circumstances of the individual case below the set limit values.

The planning of constructional or other technical protective measures against design-determining malfunctions has to fulfill the requirements of Sections 49 and 50 and Section 117 (16) of the StrlSchV [4], as well as the following basic objectives:

- safe containment of radioactive substances,
- reliable removal of the decay heat,
- maintaining sub-criticality and
- avoid unnecessary radiation exposure, limit and control the radiation exposure of the operating personnel and the population.
- shielding of ionizing radiation,
- simple operation and maintenance by optimized design,
- safety-oriented organization and operation,
- safe handling and safe transport of radioactive substances,
- design against incidents and failures
- measures to reduce the damaging effects of beyond-design-basis events.

3. Safety requirements

3.1 Principle

The safety requirements for nuclear power plants in the revised version of 30.03.2015, [5], also defines the technical safety concept for the storage of spent fuel assemblies according to §6 AtG (atomic energy act).

The basic principle is:

> "In order to meet the radiological safety objectives, the radioactive substances in the nuclear power plant have to be contained several times by technical barriers or restraint functions and their radiation has to be shielded sufficiently. (...)
> A defense-in-depth concept is to be implemented which ensures the fulfillment of the protection objectives and the maintenance of the barriers and restraint functions on several staggered security levels as well as internal and external impacts. "

The safety concept is consistently applied to the safety requirements and the resulting structural requirements for the protective structure of an interim storage facility.

3.2 Safe containment of radioactive substances

The safe containment of radioactive substances has to be done by a system of technical barriers and restraint functions. There are several options. The safe containment in total can be achieved technically, depending on the individual option, by a combination of several barriers and restraint functions.

According to [5] the following barriers and restraint functions have to contribute:

• On security levels 1 (normal operation) to 4a (very rare events), inventories and safety casks (requirements see [5]) are considered to be barriers and have to act together; if spent fuel assemblies are handled or stored outside the containment, or if the cask is opened in a planned manner, the absence of this barrier is compensated by the hot cell as a restraining device. This guarantees safe, controlled containment of the radioactive substances in all operating phases.

• At the security level 4b (events with multiple failures of security devices), the integrity of at least one barrier have to be ensured. If spent fuel assemblies are handled or stored outside the cask, the absence of this barrier is compensated by the hot cell as a restraining function.

• For the general maintenance of the level of redundancy, the hot cell has to be arranged within the protective structure.

• The protective structure contributes to the shielding of ionizing radiation and is considered to be a device with restraining function.

3.3 Criticality safety

When nuclear fuel is temporarily stored, it has to be ensured that the spent fuel and its assemblies remain subcritical during storage, cask handling and all incidental accidents, as well as during aircraft crash, armor-piercing weapons and external blasts. The requirements according to DIN 25403, Part 1, have to be observed, in particular the technical safety measures mentioned therein, as well as the safety principles, which relates to the protection against interfering events and the demonstration of the criticality safety [6].

The proof of the criticality safety during the storage of nuclear fuel has to be carried out for the most unfavorable conditions to be expected under [7].

3.4 Heat removal

Removal of the decay heat has to be ensured in such a way that temperatures on the casks and inventories as well as for the interim storage building will remain below admissible limits at which compliance with the protection goals is reliably ensured for the entire duration of storage. It is absolutely necessary to dissipate heat to the environment passively by natural convection.

The protective structure has to provide adequate exhaust air openings to dissipate the decay heat of the stored spent fuel assemblies and of the heat-generating radioactive waste. The air-flow-related design has to be carried out in such a way that the air heated up by the casks is released to the environment and an adequate volume of fresh air is supplied to the casks. It is necessary that the maximum design temperatures of the building structure are strictly observed.

3.5 Shielding of ionizing radiation

In the interim storage of spent fuel assemblies and heat developing radioactive waste, a sufficient shielding of the ionizing radiation is necessary for the protection of the population and of the operating personnel by the design of the casks and the hot cell as well as by the appropriate constructional design of the protective structure. The limit values to be observed are specified in the StrlSchV [8].

Due to the requirements of the transportability of the casks as well as by the limitation of the radiation exposure of the population and of the operating personnel, dose rate targets for gamma and neutron radiation at the cask surface have to be guaranteed by the cask design, depending on the shielding effect of the protective structures and the sealing concept. In case of a high shielding effect of the protective structure, the dose rate at the cask surface is limited either by the requirement of transportability or by reasons of operational radiation protection (avoidance of restricted area conditions inside the storage area).

For the approval of the necessary shielding by calculation of the radiation exposure in the environment and the operating environment, the gamma and neutron radiation including the scattered radiation and secondary radiation have to be considered. For the calculation, the highest possible gamma and neutron source intensity in the casks as well as the entire protective structure and the worst possible spatial distribution of the radiation sources, including transport and handling procedures have to be assumed. Any other radioactive substances which may occur (e.g. radioactive waste, contaminated or activated empty casks) have to be taken into account when recording radiation sources.

For the design of the protective structure, in particular for the design of air supply and exhaust openings, gates as well as expansion joints, the aspect of shielding has be taken into account.

3.6 Radiation protection

According to § 6 of the radiation protection ordinance (StrlSchV) [4], any unnecessary radiation exposure or contamination of humans and the environment shall be avoided. The protective structure shall be divided into radiation protection areas according to the radiation protection conditions. Monitored-, controlled- and restricted areas have to be designed according to § 36 StrlSchV [8]. Areas with localized dose rates, which would require the establishment of a restricted area, should be avoided.

The radiation monitoring in the protective structure of the interim storage facility as well as in the surrounding area is also regulated in [5, 9], the release of radiation and the release of substances accordingly.

4. Constructional requirements for new protective structures to be erected

In Germany, the construction works shall be done according to the states' building regulations of the German federal states and according to the generally accepted rules of technology (state of the art). In addition, further design requirements arise from the safety engineering investigations on the intended operation of the interim storage facility as well as for incidents.

• When designing the protective structure, the intended use has to be taken into consideration with regard to the suitability and durability of the building materials and components (life time aspect).

• Supply and exhaust air openings of the protective structure have to be arranged and dimensioned in such a way as to ensure reliable removal of the decay heat from the inventory.

• The temperature stress and aging resistance of the building structures as a result of the heat released by the casks have to be taken into account when designing the structure.

• Loading areas and cask maintenance stations (also known as reception areas and maintenance areas) have to be designed with surface coatings that allow easy decontamination.

• The components of the protective structure have to have sufficient temperature-, pressure- as well as wear- and tear-resistance. The floor in the storage area has to be provided with a compacted, smooth-drawn outer layer.

• The bottom plate of the protective structure has to be designed for traveling with transport vehicles and for the cask loads according to the intended occupancy. Partial conditions have also to be considered.

• In the case of construction, the impact of loads during transport operations has also to be applied, provided that this is not excluded by measures. Likewise, the crane loads and loads of other heavy plant parts, e.g. shielding scoops, as well as special loads from the effects of inside and outside have to be taken into account.

• In the event of a load crash, the building structures in the storage and loading area have to be designed in a way that the damage remains limited that the safety functions of the protective structure (stability, shielding and heat removal) are maintained and the possibility to repair the damages has to be given. To limit the stress on casks and building structures, special measures, such as the use of shock-absorbing structures in the possible crash area, might be necessary.

• Storage and loading area form separate fire sub-sections, as long as no significant fire loads are stored in the loading area. Adjacent buildings, such as office and social areas, laboratories, workshops, have to be built as separate fire sections.

5. New concepts for intermediate storage facilities

As licensing authorities in Germany tend more and more to a position that "safe containment of radioactive substances", as required by the "ordinance on protection against damage caused by ionizing radiation" [4], means a demand for a multi-barrier-concept, Max Aicher Engineering (MAEG) has developed a conceptual design for an intermediate storage building for high-level rad waste with outer dimensions as follows: length: 80 m, width: 27 m, height: 18 m

Several numerical simulations were made for an aircraft impact scenario, based on the following requirements:

- Impact of a twin engine fighter jet with a mass of 20 Mg (Phantom F4)
- Impact speed – 215 m/s
- Circular impact area - 7 sqm

The angle of impact was square, both for the simulation of the impact on the roof and for the impact on the wall. The load-time-function was chosen in accordance to [10]:

time (ms)	load (MN)
0	0
10	55
30	55
40	110
50	110
70	0

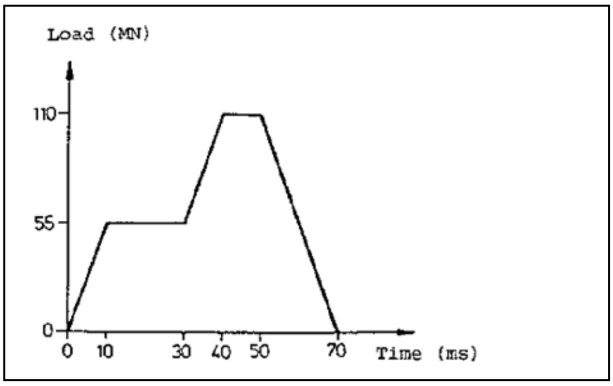

Figure 1: load-time-function according to DIN 25449: 2008-02 "Buildings made of reinforced concrete and prestressed concrete in nuclear installations - Safety concept, effects, design and construction"

Furthermore, the dynamic simulation was carried out under the following assumptions:

- High strength steel: SAS 670/800 [11]
- Wall thickness: 1.6 m
- Concrete: C50/60

6. Results

It could be found that a wall thickness of 1.6 m, using a combination of high-strength steel SAH670/800 and high performance concrete offers a reasonable level of protection for the structure of the building to withstand an aircraft impact even under extreme conditions (square impact).

- Max. elongation of concrete, $\boldsymbol{\varepsilon}_C$: 0.3 %
- Max. elongation of steel, $\boldsymbol{\varepsilon}_S$: 1.2 %

Additional risks for the structure might arise from fuel combustion and should be dealt with accordingly.

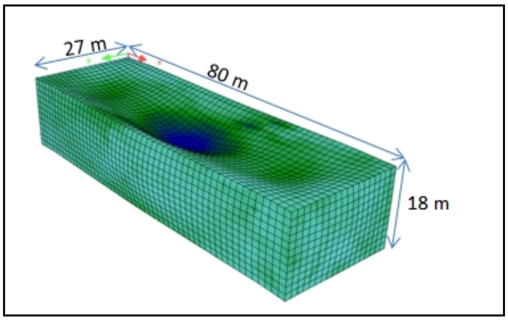

Figure 2: dynamic simulation of an aircraft impact of a twin engine fighter jet on the roof of an intermediate storage facility with a wall thickness of 1.6m using high-strength steel [11] and high performance concrete.

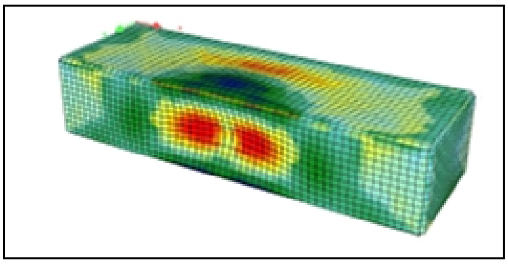

Figure 3: dynamic simulation of an aircraft impact of a twin engine fighter jet on the wall **of an intermediate storage facility with a wall thickness of 1.6m** using **high-strength steel [11] and high performance concrete.**

Furthermore the use of precast concrete elements instead of cast-in-situ can offer a tremendous reduction of time for construction as shown below for the construction of an emergency diesel building (ZX):

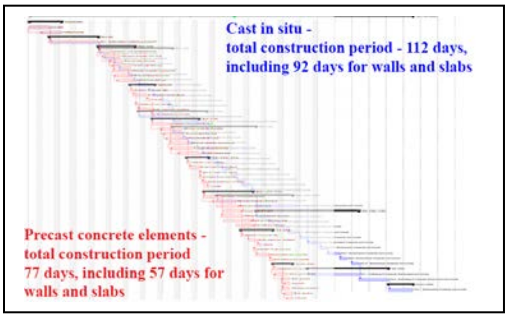

Figure 4: project timeline for the construction of an emergency diesel building (ZX), 38% savings in construction time by using precast concrete elements (red timeline) with special eccentric coupler system

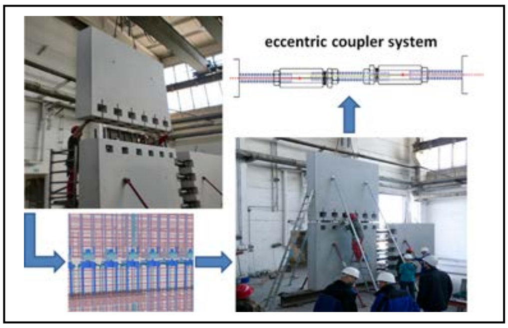

Figure 5: state of the art wall construction with precast concrete elements and use of eccentric coupler system [11] for the connection of elements

REFERENCES

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[3] German federal office for radiation protection, Bundesamt für Strahlenschutz, RS-Handbuch, A.17, Facilities for nuclear supply and waste management in Germany, version 12/15, p.5, Zwischenlager Nord (ZLN)

[4] German radiation protection ordinance – Strahlenschutzverordnung, Section 6 (1), (2), (49), (50), (117), No. 1 StrlSchV, 20.07.2001(German federal law gazette, BGBl. I S. 1714)

[5] German federal ministry for environment, protection of nature, construction and nuclear safety, “Safety requirements for nuclear power plants in the new version of 30.03.2015” (Bundesanzeiger, BAnz AT 30.03.2015, B2)

[6] DIN 25403: Criticality safety in the processing and handling of nuclear fuels, Part 1, Principles. Edition: 06/2007

[7] KTA 2206: Design of nuclear power plants against lightning effects, version 2009 – 11

[8] StrlSchV; Ordinance on protection against damage caused by ionizing radiation (radiation protection ordinance - StrSchV) of 20 July 2001, Federal Law Gazette I No. 38 of 26 July 2001, p.1714 ff., last amended by Article 5 (7) of the Reorganization Act Circulation and Waste Management from 24.02.2012, BGBl. I No. 10 from 29.02.2012, p. 212

[9] Announcement - guidelines of the German federal nuclear waste management commission for the dry interim storage of spent fuel assemblies and heat developing radioactive waste in casks and guidelines of the German nuclear waste disposal commission for the interim storage of radioactive waste with negligible heat generation; From: 22.11.2013; German federal ministry for the environment, protection of nature and nuclear safety; BAnz AT 22.01.2014 B3

[10] DIN 25449: 2008-02 "Buildings made of reinforced concrete and pre-stressed concrete in nuclear installations - Safety concept, effects, design and construction"

[11] Steel SAH 670/800 thread bar system by Stahlwerk Annahuette, Germany, www.annahuette.com, Ø 18 - 75 mm