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Design of spent nuclear fuel storage facilities for the load cases earthquake and aircraft impact - technical specifications, methods and examples for wet and dry storage

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1. Introduction

IAEA has published the fundamental safety principles [1], which establishes the fundamental safety objective to protect people and environment from harmful effects of ionizing radiation. This applies for all facilities and activities and for all stages over the lifetime of the facility. Based on this requirement 10 safety principles and concepts are specified. Principle 5 addresses the requirement to provide the highest level of safety that can reasonably be achieved throughout the lifetime of the relevant facility.

Within the collection of IAEA safety standards the Specific Safety Guide SSG-15 [2] provides guidance and recommendations on the design, safe operation and assessment of safety for the different types of spent nuclear fuel storage facility (wet and dry). Some of the important design requirements in section 6 are:

- Facilities should consist of preferably passive, inherently safe systems (§6.3) and the concept of defence in depth should be applied (§6.14)
- A multibarrier approach should be adopted (§6.4b)
- The facilities should maintain their structural integrity in all operational states and accident conditions (§6.15)
- Subcriticality, heat removal, containment of radioactive material, radiation protection and retrievability of the fuel should be fulfilled and structural and mechanical loads such as earthquakes are to consider properly (§6.25-§6.46)

The WENRA Report [3] has taken the above positions. Furthermore the external and internal events affecting the design are postulated. Earthquake as a natural phenomenon and aircraft crash (APC) as a human induced event are postulated in Appendix 1.

On national level the European countries have established their National Action Plan based on the above cited principles. As an example the German authorities set in force the guideline for dry storage facilities for spent fuel [4].

Technical guidance for the design are published for example in [5, 6] containing recommendations for the design basis earthquake (DBE). In [5] recommendations for civil engineering structures, earth structures, piping and equipment and for the selection of appropriate design standards are given. Furthermore section 5 gives recommendations to modelling techniques.

The load case design basis earthquake (DBE) has always been considered as mandatory load case for nuclear facilities and procedures have been prescribed by national regulations as for example in [7], [8], [9], [10].

Recommendations and requirements of applicable load functions for military aircraft and large passenger aircrafts are given for example in [11]. The discussion of fuel effects, applicable analytical approaches, design and qualification such as bending and shear effects, induced vibrations on structure and equipment, localized effects like penetration and fuel fires and explosions are also discussed.

National regulations have specified the conditions of verification, design and qualification for example in [12], [13], [14], [15].

However, uncertainties exist in several countries worldwide of how to specify and qualify spent fuel storage facilities. What is the most appropriate storage facility (wet or dry)? What is the expected service duration of the storage facility in front of the background, that final repository may not be operational soon?

2. Design procedures

3.1. Common Design Procedures for the Load Cases DBE and APC

The design of structures, systems and components (SSC) of nuclear facilities for the load cases DBE and APC is performed on the basis of design floor response spectra and acceleration or displacement time histories at the locations of the SSC, evaluated out of structural dynamic analyses [8], [9], [10]. The applied procedures are similar both for DBE and APC using the same mathematical apparatus, differing in the application of the excitation:

- Consideration of soil-structure-interaction (SSI) for soils which differ from rock conditions [8], [9], [10] with variation of site specific soil properties in order to take into account soil uncertainties [8] or using generic soil conditions, covering a wide range of different soils [8].
- Linear dynamic analyses using the modal superposition or direct integration time history method, considering impedance functions for incorporation of SSI or linear calculations in the frequency domain for evaluation of the dynamic response in terms of time histories at representative nodes of the structure [8], [9], [10].
- Evaluation of design floor response spectra out of the nodal response spectra by averaging, enveloping, broadening and smoothing [8] shown in Fig. 1.

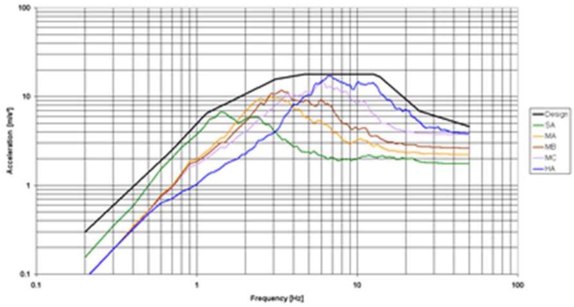

Fig. 1: Evaluation of Design Floor Response Spectra – Calculation Max Aicher Engineering GmbH

For both load cases APC and DBE, it has also to be verified that uplift criteria is satisfied [9], [10] in case of dynamic excitation.

3.2. Design Procedures for the Load Case DBE

The design of the building structure is performed on the basis of response spectrum method calculations for consideration of the DBE, taking into account SSI, and load case combinations with forces due to permanent and variable static loads [8], [9], [10].

3.3. Design Procedures for the Load Case APC

More and more regulatory commissions require a verification that the nuclear facilities, designed on the basis of DBE, are capable to resists aircraft impact. Although the load function for a military aircraft is standardized and public available [12], until today there is no standardized load function for impact of large commercial aircrafts. The definition of this load function is defined by close cooperation of the operator with the regulatory commission. Therefore, for different nuclear facilities huge differences of the prescribed APC load functions are present, depending on the selected aircraft parameters and primary on the adopted impact velocity, as shown exemplary in Fig. 2.

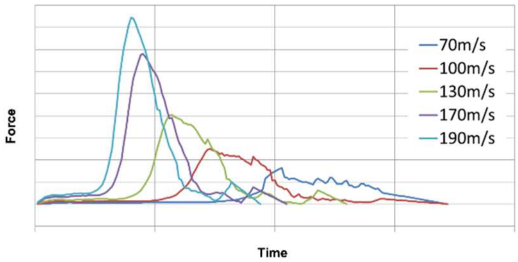

Fig. 2: Influence of APC Impact Velocity on Induced Force – Calculation Max Aicher Engineering GmbH for A380

The verification of APC resistance consists of following steps [13], [14], [9]:

- Nonlinear calculations for design check of bending capacity at most unfavorable impact locations
- Design check of shear resistance
- Design check of resistance against penetration, scabbing and perforation

The above described methods were applied successfully in several cases and have led to save storage facilities even in severe load cases. Examples for this are given in the following section.

3. Examples for high end long-term storage facilities

Dry storage facilities are widely in operation using casks like CASTOR® to fulfill the protection objectives even in the human induced hazard case of an aircraft crash. The casks remain tight – this has been proven since decades. The storage building itself does not need to withstand an aircraft impact. The aircraft fuel needs to be drained to avoid heating of the casks.

Advantages of dry storage facilities are for example the lower initial investments, mobility of the spent nuclear fuel, easy passive cooling system and easy to repair.

In the case that a final repository is not available, intermediate storage of spent fuel over a duration of more than 100 years is an option for a long-term and safe storage. In this case it might be an option to open the cask to manipulate the spent fuel assemblies and radiation protection needs to be covered by the building itself. In Germany the first dry storage facility, which is able to withstand DBE and aircraft impact of a large commercial aircraft A380 is under development. A first layout concept with wall thickness of 1,5 m to 1,8 m is presented in Figure 3.

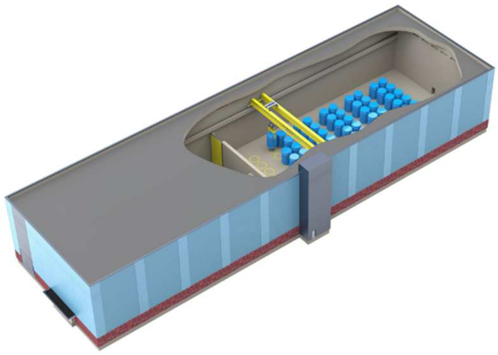

Fig. 3: Layout 100 year intermediate dry storage facility – source WTI/GNS

One wet storage facility as a stand alone building successful in operation for more than 10 years was erected in Switzerland – Gösgen site (see figure 4). It was designed to withstand DBE and APC.

Fig. 4: Kernkraftwerk Gösgen-Däniken AG © –Fuel pool

Advantages of wet storage facilities are lower variable cost at marginally higher initial investment for an aircraft crash resistant building, flexible storage of different fuel types (MOX, high enrichment), small space required and the spent fuel is accessible and retrievable.

Both storage types can achieve easily a lifetime of 100 years.

4. Conclusions

The design of spent fuel storage facilities is well established, the application of modern calculation methods delivers earthquake - and aircraft impact resistance. However, the trend to long-term intermediate storage of spent fuel of about 100 years needs a new concept of building technology. To meet the safety principles over a lifespan of 100 years the building itself has to act as a durable full barrier.

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