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The SWR 1000 (KERENA) Containment – Civil Design Aspects in View of High Robustness

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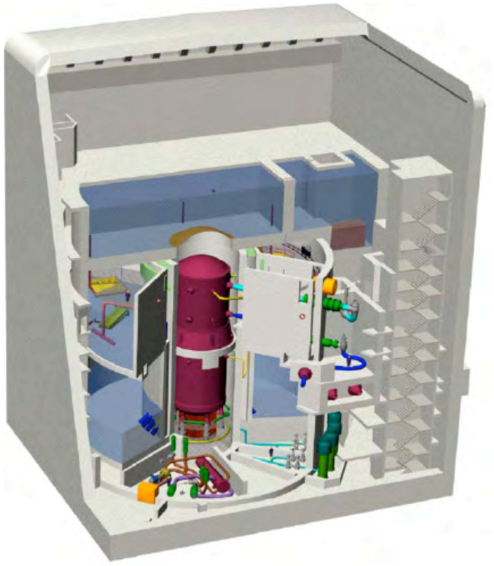
1 ABSTRACT

In 2008 AREVA and E.ON have formed a strategic partnership to perform the final basic design of the Boiling Water Reactor SWR 1000 now rebranded as KERENA. As for all reactor types of the New Generation Nuclear Power Plants KERENA (developed by AREVA) is designed for an operation period of about 60 years. Taking the construction and decommissioning time into consideration, the safe confinement of radioactive fission products must then be ensured for more than 80 years. The plant design of KERENA incorporates in addition to the active safety systems several passive safety features, to meet the requirements with regard to a non-aging and robust Boiling Water Reactor (BWR) design. This concept is also pursued in the structural design of KERENA.

Robustness, with regard to the structural design, is seen within this concept in a broad approach: not only is the selection of non-aging materials of importance, but also the use of "passive acting" structural members, which are examinable and reparable and additionally where areas with high load concentrations are avoided as far as possible. This task has also to be supported by modern safety concepts in the structural codes and standards.

2 INTRODUCTION

The Boiling Water Reactor SWR 1000, now rebranded as KERENA, is an evolutionary development by AREVA with a pronounced passive safety concept. Figure 1 gives an insight into the reactor building and the containment of the KERENA BWR with the key technical data.



Thermal output	3370	MW
Net electric output	~1250	MW
Plant design life	60	years
Reactor Building		
- length / width / height	57 / 51 / 65	m
- wall thickness	2.00	m
Containment		
- inside diameter	33.0	m
- inside height	34.7	m
- wall thickness	1.00 ÷ 1.20	m

Figure 1. Insight into the Reactor Building of the KERENA BWR with technical data [AREVA 2003]

As a nuclear power plant of the new generation KERENA BWR is designed for an operational lifetime of about 60 years. Taking into account a construction period of about 4 to 5 years and a decommissioning period of about 10 to 15 years, safety relevant requirements on the building structures have to be ensured for a time period of approximately 80 years. Thus, highly robust and durable structural members are required to avoid repairs and additional outages as far as possible.

The KERENA containment concept developed by AREVA provides several passive safety systems and has therefore a robust and well controllable behaviour. The structural engineering follows the same concept and provides structural members that meet the requirements on high robustness.

In the following sections, the current containment construction methods for Boiling Water Reactors and Pressurized Water Reactors (PWR) will be described. Based on this, some aspects which are addressed in order to achieve an as high as possible grade of robustness in the design of the KERENA containment will be shown.

3 CONTAINMENT CONCEPTS – AN OVERVIEW

With regard to safe confinement of fission products, two basic requirements have to be met by the structural engineering of the containment structure:

- Structural integrity
- Leaktightness

These requirements are met in different ways by the various types of containments, currently provided by the suppliers of BWR and PWR Nuclear Power Plants:

1. Prestressed containment without a liner or with a composite plastic liner.

   This concept fulfils both, the requirements on the structural integrity and the leaktightness through a high prestressing, which provides an overall compression in nearly all regular areas of the concrete structure. In non-regular local areas, where leaktightness might not be achieved, the composite plastic liner is laminated onto the inner concrete surface in order to achieve the required leaktightness rate.

2. Prestressed containment with a steel liner.

   Most regulatory authorities demand a steel liner to ensure the leaktightness whereby the prestressed concrete structure is used to provide the structural integrity. The liner, as a non load-bearing element, should be relatively thin in order to minimize interaction with the prestressing effects (wall paper concept).

3. Reinforced concrete containment with a steel liner (as in the KERENA containment)

   In this concept, the requirements are separated in that the structural integrity is provided by the concrete structure and the leaktightness is provided by the liner. In comparison to a prestressed containment, the liner could be thicker and therefore can facilitate a high level of prefabrication. This is made possible due to the absence of the high compression forces in the liner, resulting from load redistribution from creep and shrinkage, as would be the case for a prestressed containment. Furthermore, due of its higher thickness, the liner could also serve as a load-bearing element.

The following Table 1 summarises the different conceptual containment designs. As described, the various containment concepts differ mainly with regard to prestressed or non-prestressed concrete structure combined with steel liner, composite plastic liner or even without liner. Due to the level of interaction between the concrete structure and the liner it is of upmost importance to discuss this in detail.

Table 1. Containment conceptual design in USA/Europe.

containment basic requirements			
concept no.		structural integrity	leaktightness
1	A	prestressed concrete	steel liner with headed studs anchorage
	B		steel liner with structural steel sections and plates for anchorage
	C		prestressed concrete with local composite plastic liner
2	A	reinforced concrete	steel liner with headed studs anchorage
	B		steel liner with structural steel sections and plates for anchorage

4 DISCUSSION ABOUT CONTAINMENT-CONCEPTS

4.1 Containment prestressing and liner concept

Prestressing of concrete structures is usually provided to meet the requirements of the Serviceability Limit States (SLS), hence to reduce deformations and crack widths to a defined value and to achieve a higher stiffness and leaktightness.

In the Ultimate Limit State (ULS) however, there are no differences between the load-bearing capacities of structures with prestressing or without prestressing. Comparing the prestressed reinforcement to an equivalent non-prestressed reinforcement the amount of normal steel reinforcement would be increased by a factor of the yield strength ratio.

Increased SLS-requirements have to be fulfilled for containment concepts where no full-surface liner is provided in order to satisfy the leaktightness conditions. Without a liner, the prestressing has to be designed to a value that a sealing compression zone remains in all cross sections. Usually, the prestressing is then provided to a ratio which will ensure a compression stress of about 1.0 MPa in the middle of the cross section in all regular areas. With a composite plastic liner, also used as local liner within local areas, where leaktightness could not be achieved, the prestressing ratio is chosen in such a manner to ensure a reduction in the crack widths to a value below the crack-bridging capacity of the reinforced plastic material (e.g. fiber reinforced plastic FRP).

The above mentioned requirements can be omitted in cases where a steel liner is used to ensure the leaktightness of the structure. The concrete structure has then only to provide the structural integrity. The provision of high prestressing forces over long time periods of 60 to 80 years are then no longer necessary. Thus, this opens up the possibilities to develop a robust “passive” containment concept without “active” applied prestressing forces. Such a “passive” concept was chosen within the development of the KERENA containment from AREVA.

4.2 KERENA reinforced concrete containment with steel liner

Containment erection in the past has shown that the liner is always on the critical path. This disadvantage can be avoided through the use of a higher ratio of prefabrication of the liner structure.

Large prefabricated liner elements necessitate inevitably a greater stiffness. In most cases, the construction stages and erection loading on the prefabricated liner governs the design of the liner, and therefore the liner thickness. In order to achieve a high degree of prefabrication combined with stability and a high resistance to deformation, the thickness of the KERENA liner is assumed to be 10 mm (0.39 in).

Prestressing combined with a liner thickness of 10 mm, or more, would lead to both a high redistribution of forces resulting from creep and shrinkage onto the liner and a loss of prestress forces within the concrete structure. Furthermore, various load cases which need to be considered in the design of the BWR containments are dynamic load cases, therefore with alternating signs, which results in the prestressing forces acting unfavourably additive with the external loads. For these reasons, the KERENA Containment is consequently developed with a steel liner, but without prestressing.

The increased thickness of the liner as a consequence of improving the erection conditions, combined with a full-surface anchoring with headed studs embedded within the structural concrete, consequentially lead to the idea, to take the structural load bearing capacity of the liner into account (as already mentioned above: in the past, the liner was only seen as being similar to a "wall paper"). Due to the relatively close spacing of the headed studs, the steel liner acts together with the concrete as a composite element, this means that the liner can be considered as a composite steel liner. This composite steel liner would considerably improve the load bearing behaviour of the containment as a whole, therefore reducing the required ratio of normal reinforcement.

These advantages of a normal steel reinforced containment should also be considered with regard to the passive safety concept of the KERENA BWR. It is not very advantageous to provide high prestressing forces over very long time periods, which are designed for load cases, where the probability of occurrence is either extremely low (e.g. interior pressure during core melt accidents) or where the load occurrence frequencies are low (e.g. test pressure).

5 ROBUST CONSTRUCTION FEATURES WITH THE KERENA CONCEPT

5.1 General

The KERENA containment structure incorporates special construction features to achieve a high robustness. The following explanations will give an overview of these features.

5.2 Relief effects on sensitive structures

Specific areas of the KERENA containment structure are sensitive with regard to the structural design, for example areas of the containment which maybe extremely weakened by openings. Robust design for these areas is seen as a concept that enables the use of alternative load carrying paths and load redistribution. Such solutions are, as a rule, multiple statically indeterminate.

This concept becomes especially apparent in the area of cable penetrations and the air lock at the inner containment circular wall between the compartment rooms and the control rod drive compartment under the reactor pressure vessel (s. Figure 2). The radial walls in this compartment area are used to transfer the high earthquake base-shear. This earthquake base-shear is transmitted through the compartment walls, which act as shear-walls, directly into the foundation slab. The circular wall of the containment, which is weakened by the large opening and the penetrations, is unloaded as a consequence of this effect, reducing essentially the flexural loading of this wall area. This robust solution leads to additional safety margins for the KERENA containment with regard to the development for sites with higher earthquake loads.

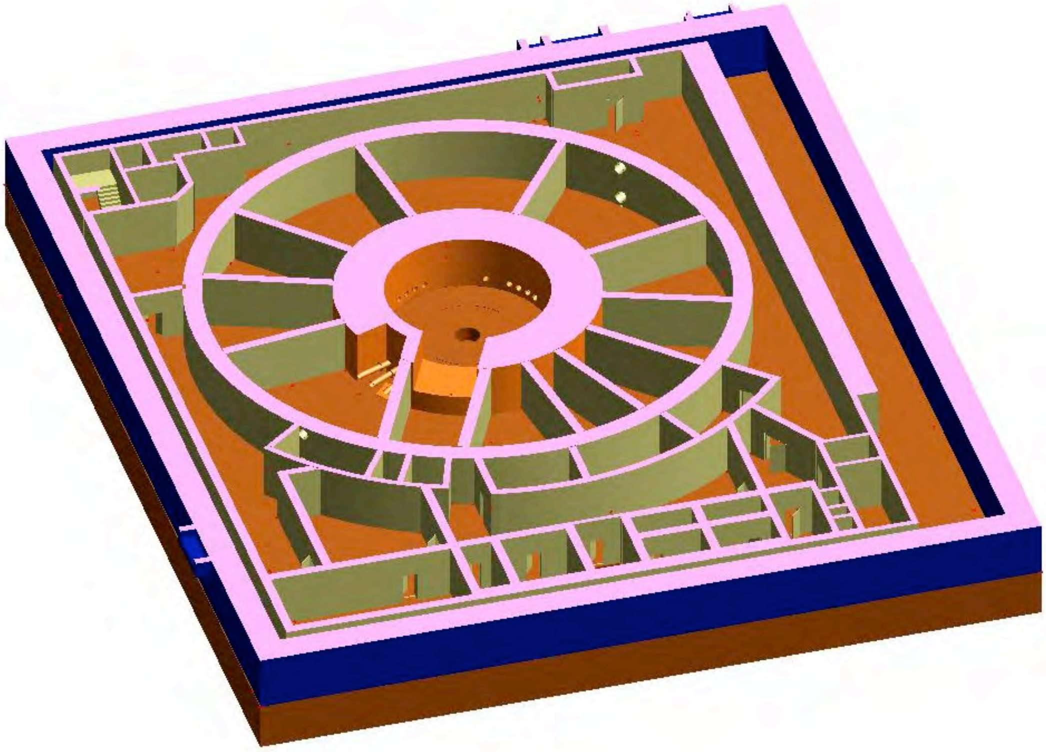


Figure 2. 3D-view on the compartment area underneath the pressure suppression chamber

Furthermore, this normal reinforced containment concept provides the possibility to have a monolithic connection of the inner containment with the neighbouring outer slabs and walls. By doing this, the surrounding concrete structures contribute essentially to the load transmission due to internal pressures and earthquake (s. Figure 3).

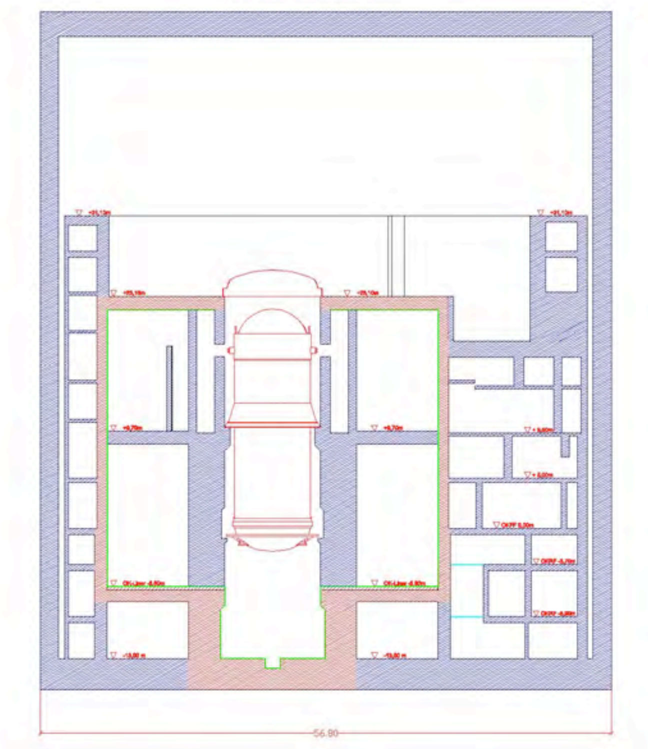


Figure 3. Section through the reactor building

5.3 Use of low-maintenance requiring materials

Robust structures should be designed in such a manner that they require only low or even no maintenance during the operation period. In case of damages, they should be easy to repair or specific structural elements should be replaceable. This concept should also be kept in mind with regard to the selection of the materials. One good example is the selection of the liner material. Existing steel liners are normally made of ferritic steel, which needs a new coating approximately every eight years. This coating is not only time consuming and therefore expensive with regard to the outage of the plant, but also very unfavourable in relation to the health hazards for the work team applying the coating. Structures with low-maintenance requirements should minimise those works. It is therefore under discussion to use a stainless duplex steel liner for the KERENA liner, which causes approximately 4 to 5 times higher capital costs than a ferritic steel liner, but will result in lower life cycle costs considered over the operational lifetime of the plant. Table 2 gives a list of advantages and disadvantages of using a stainless duplex steel liner.

Table 2. Advantages and disadvantages of using stainless duplex steel liners

Advantages	Disadvantages
corrosion resistance, no more coatings necessary	high material costs
no risk for lamellar tearing	dissimilar metal connections
minor thermal conductivity	major welding distortions
minor elastic modulus	more welding effort (cleanness, aftercare)

5.4 Liner and penetration liner as composite steel structure

Previous codes and standards, such as ASME (2007), DIN V 25459 (1990) or the design specifications for the BWR Gundremmingen/Germany, the predecessor of Kerena BWR, have considered the liner only as “wall paper”, which means not as a load bearing element. The unfavourable behaviour of the liner however e.g. from the thrust due to temperature or redistribution due to creep and shrinkage had to be taken into account. As these liner effects turned to be very unfavourable, it was already agreed with the regulatory authorities for the BWR Gundremmingen that the liner could be considered as a load bearing composite steel element in such load cases, where the liner thrust loads are acting.

As already mentioned above the possibility of load bearing composite steel liner is considered. Under ambient temperatures, a steel liner with a yield strength of about 460 MPa could result in a significant increase in the load bearing capacity of the containment and could therefore be taken into consideration for various load cases, e.g. for earthquake loads. The combination of the different materials which form the composite structure requires calculations and verifications in accordance to the standards and regulations for composite structures, also taking into account the non-linear load-deformation behaviour of anchoring elements (e.g. headed studs). So far, especially if in combination with high prestressing, the liner was always assumed to be in a compression-yield state. The headed studs were then designed to resist the forces resulting from liner imperfections and local liner buckling. In load cases, where the liner was imposed to tension loading (e.g. high internal accident pressures), the load bearing capacity of the liner was neglected.

The composite steel liner is imposed to tension loading and thus also the headed studs have to transmit high forces, resulting from the moment gradients into non-regular areas of the structure. This load bearing effect, even though it was always existent, was not considered in the codes and standards, so that adjustments and modifications might be necessary.

Verifications for the composite steel liner structure and its anchoring elements, considering the non-linear elastic bond behaviour, would allow realistic verifications in the compression and tension state of the liner, and therefore also a realistic statement to the robust and ductile overall structural behaviour.

5.5 Standard construction products with reliable long-term behaviour

The predecessor of the KERENA BWR, the prestressed containment of Gundremmingen, required a lot of special technical solutions. Nowadays, many standardized and effective construction products are available on the construction market. For these construction products, such as reinforcement couplers, stud shear reinforcement, new composite elements and many more, the general European Technical Approval documents are normally already available, so that no further approvals for special use are necessary.

In special areas of the KERENA containment, where high connection forces from the reinforced concrete structure have to be transmitted perpendicular through the liner, standardised structural elements are used. These construction products have already been on the market for a considerable period of time, and therefore sufficient existing practical experiences justify their application.

The main advantage of these products, with regard to robust design, is the fact that the use of those products allows high-quality workshop solutions, therefore avoiding expensive and time-consuming field welding on large special structural steel elements.

6 ROBUST STRUCTURES VERSUS MONITORING

New monitoring methods are by now able to measure and document nearly all changes in materials over long time periods. Although it is very useful to check materials with regard to long term deteriorations, one should be aware of the fact that monitoring only makes sense if repair is feasible or if the development of the deterioration can be slowed down. Robustness should also be seen from this point of view, as given in the following examples:

- Accessible Omega-sealing strips should be used instead of sealings embedded in the concrete
- Waterproof concrete basin instead of bituminous waterproofing
- Monolithic structures instead of joint structures
- Use of prestress tendons only in combination with monitoring

7 STATE OF CONTAINMENT STANDARDS IN GERMANY

Structural design with regard to high robustness must also been supported by the appropriate codes and standards. Based on a coherent and consistent safety concept, design procedures for robust structural members should be made available. These design methods should cover the overall integrity of the containment together with consideration for the liner, penetrations and hatches.

Parallel to the development of the KERENA BWR, the new German codes DIN 1045 (2008) for “Reinforced and prestressed structural members” (which directly corresponds to EN 1992, Part 1-1 (2005)) and DIN 25449 (2008) for “Reinforced and prestressed structural members in nuclear power plants” have been issued. A Committee for Standardisation was established in 2008 in order to revise DIN V 25459 (1990) “Reinforced and prestressed concrete containments”, with the objective to harmonise and adjust this code to the new safety concept of DIN 1045 (2008) and DIN 25449 (2008). These three codes, all based on a common safety concept, offer for the first time in Europe a contained set of codes for the design of concrete containments for nuclear power plants.

8 CONCLUSION

The described high robustness concepts of structural elements comply consequentially with the well balanced combination of active and passive safety systems of the KERENA BWR plant design.

With regard to structural elements, the term “robustness” should be seen in a broader view, in order to avoid deterioration of materials, allow repair or replacing methods, offer redistribution of loads to other structural elements and install design procedures to verify ductile behaviour of the structure.

Doing this, a robust plant design is not only an important task for the plant engineers but also for the structural engineer.

REFERENCES

AREVA (2003): SWR 1000 – An advanced Boiling Water Reactor with Passive Safety Features: General Description SWR 1000, Information brochure, March 2003.

ASME (2007): ASME Boiler & Pressure Vessel Code – Section III: Rules for Construction of Nuclear Facility Components. New York: The American Society of Mechanical Engineers, 2007.

DIN 1045 (2008): Concrete, reinforced and prestressed concrete structures. Berlin: German Institute for Standardisation, 2008.

DIN 25449 (2008): Reinforced and prestressed concrete components in nuclear facilities – Safety concept, actions, design and construction. Berlin: German Institute for Standardisation, 2008.

DIN V 25459 (1990): Reinforced and prestressed concrete containment for nuclear power plants. Berlin: German Institute for Standardisation, 1990.

EN 1992-1-1 (2005): Design of Concrete Structures – General rules and rules for buildings. European Committee for Standardisation, 2005.