

THE KERENA™ STEEL LINER BASIC DESIGN

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ABSTRACT

As part of the final basic design for KERENA™ BWR containment vessel performed by HOCHTIEF, the containment steel liner was thoroughly analysed. New steel liner materials were investigated including stainless duplex steel and clad steel consisting of common pressure vessel steel with stainless austenitic steel cladding. The material properties and their effects on the steel liner structure, the anchoring elements as well as the concrete structure were analysed. Special construction features and an innovative steel liner erection concept with just a few large steel liner assembly parts were developed. Finally the containment steel liner and the anchorage were verified in a comprehensive analysis by means of a detailed local finite-element model.

INTRODUCTION

The KERENA™ (formerly SWR 1000) boiling water reactor (BWR) is an evolutionary development by AREVA. Based on the Construction Standard 72 from the German Nuclear Power Plant (NPP) Gundremmingen B and C, KERENA™ is an advanced development of the boiling water technology traditional in Germany. The generation III+ nuclear reactor is characterised by advanced operational safety features which result in greater overall plant security. The structural design fulfills the high international safety requirements thanks to the conceptual new design of the containment. In addition KERENA™ has a modern, highly robust and low-maintenance construction [1]. Figure 1 gives an insight into the reactor building with the containment of the KERENA™ BWR.

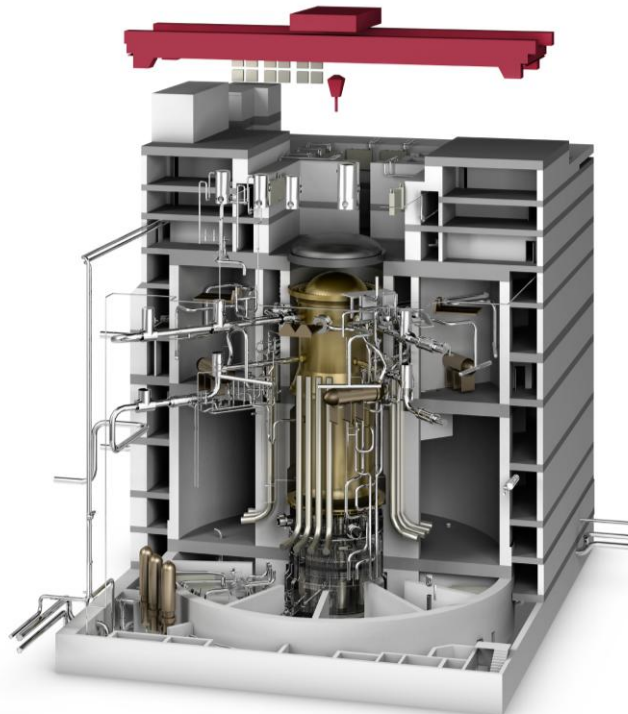


Fig. 1: Insight into the Reactor Building of the KERENA™ BWR [2]

Typical for BWRs, the containment vessel is cylindrical-shaped with a plane bottom and top plate. The containment vessel has an inner diameter of 33.0 m (1300 in) and an inner height of 34.70 m (1366 in). In contrast to its predecessor Gundremmingen BWR, the KERENATM containment vessel is a normal reinforced concrete structure without any prestressing. A steel liner is applied to the inner concrete surface. So the basic requirements for containment vessels were met by the reinforced concrete structure, thus providing structural integrity, while the steel liner ensures leaktightness.

In 2010 the basic design of the KERENATM containment vessel was finalised by the structural design department HOCHTIEF Consult IKS Energy. The BWR containment structure and the surrounding, monolithic connected annulus concrete structure were analysed and verified. Thereby particular attention was paid to the structural design of the containment steel liner.

In the following the most relevant structural design aspects for the containment steel liner are described. The characteristics of the steel liner structure and the developed erection concept will be explained. Further the selection of the steel liner material and the steel liner analysis and verification procedure are clarified.

CONTAINMENT STEEL LINER STRUCTURE

In contrast to pressurized water reactor (PWR) containment vessels, the BWR containment vessel is subdivided into different zones and chambers. The containment vessel includes the reactor pressure vessel with the control rod drive compartment beneath, surrounded by the pressure suppression chamber and the four core flooding pools placed above (see Fig. 1). The containment steel liner is applied to the inner concrete surface of the cylindrical-shaped reinforced concrete structure which contains the previously mentioned most important sections of the reactor building.

A special construction feature is required for the connection of the pressure suppression chamber ceiling to the containment vessel wall. Due to the fact that the containment steel liner cuts the two members exactly at their joint, a special steel liner construction is necessary for the transfer of internal forces. In Fig. 2 the newly developed steel liner construction, adapted for a rigid member connection is shown. The steel liner is penetrated by threaded rods with screwed standard couplers which allow a full strength joint to the reinforcing bars of the pressure suppression chamber ceiling and the containment vessel wall. The penetrating threaded rods are welded around on both sides to the steel liner so that leaktightness can be ensured. For the transfer of shear forces flat steels are welded onto the steel liner at the ceiling side, while aperture plates are used at the wall side.

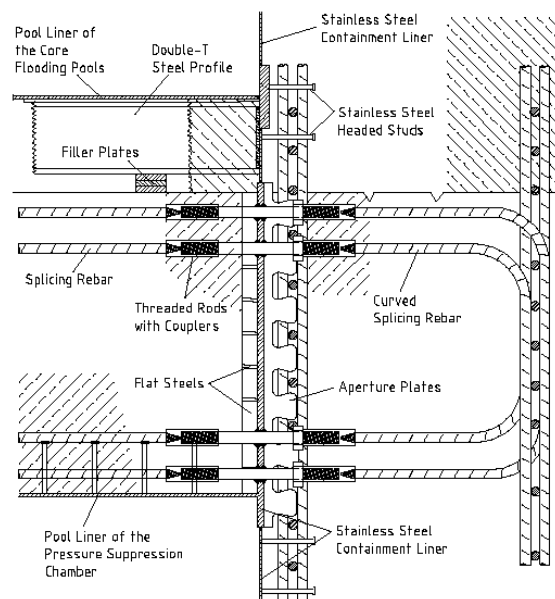


Fig. 2: Special containment steel liner construction as rigid member connection for e.g. the pressure suppression chamber ceiling and the containment vessel wall

The containment steel liner is anchored to the concrete structure exclusively by headed studs. The absence of steel plate stiffeners allows an arrangement of the reinforcement steel layers close to the steel liner (see Fig. 2). This, in turn, enables a small containment vessel wall and slab thickness of 1.0 to 1.20 m (39.37 to 47.24 in). For the liner calculations it was assumed that the headed studs with a diameter of 16 mm (0.63 in) are generally arranged in a rhombic pattern. In special areas, e.g. liner penetrations and openings, the number of headed studs can be doubled to a square spacing. Fig. 3 depicts the arrangement of the headed studs which matches the reinforcement grid with 150 mm (5.90 in) spacing.

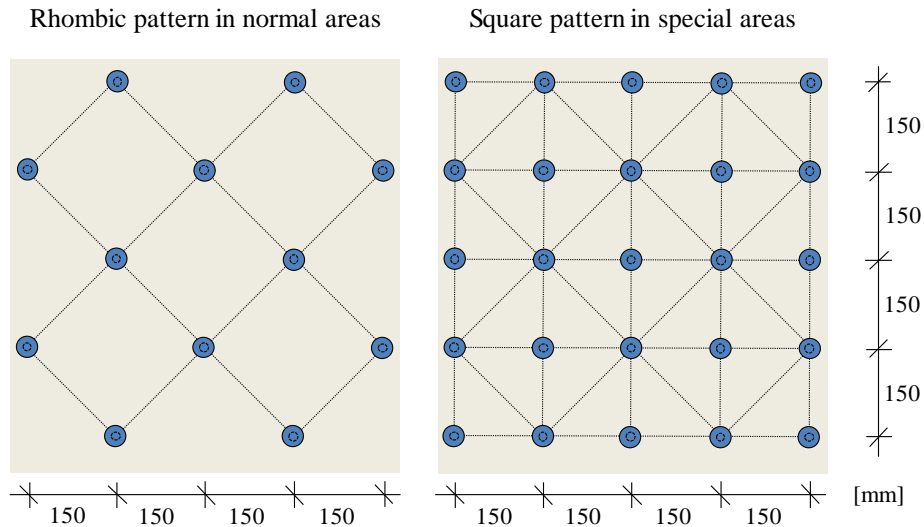


Fig. 3: Headed studs arrangement on the containment steel liner with a rhombic pattern in normal areas and square pattern in special areas

CONTAINMENT STEEL LINER ERECTION CONCEPT

In the past the construction of concrete containment vessels has shown that the steel liner erection is always on the critical path. This very time-consuming erection phase can be shortened by realization of a high prefabrication ratio for the containment steel liner structure. Large prefabricated steel liner segments inevitably necessitate a high inherent stiffness. In order to achieve a high degree of prefabrication combined with stability and high resistance to deformation, the thickness of the KERENA™ steel liner was chosen to be 10 mm (0.39 in) to 12 mm (0.47 in) in normal areas with an almost doubled thickness in special liner areas (see Fig. 2).

The containment steel liner structure is subdivided into a few main assembly parts, each delivered and set in place as a whole: the control rod drive compartment, the pressure suppression chamber and the core flooding pools (four segments). Fig. 4 gives a containment vessel inside view with an extraction of the largest containment steel liner assembly parts. For erection of the containment vessel, the steel liner structure acts as formwork for pouring the concrete walls and ceilings. Due to this, as well as the transportation of the large assembly parts, temporary stiffener structures are installed inside the huge assembly parts (see Fig. 4). After in-situ concreting and curing, the temporary stiffeners can be removed.

The construction of the bottom steel liners in the control rod drive compartment, the pressure suppression chamber and the core flooding pools always follow the same principle. The huge steel liner assembly parts, shown in Fig. 4, have a wire wheel-shaped bottom framework steel structure. When the assembly part is set in place by a crane, the bottom framework will be fixed to the anchor plates which are embedded into the concrete floor below. Then secondary concrete is filled between the steel profiles up to the top of the bottom framework structure. Afterwards the bottom steel liner sheets can be placed on top of the secondary concrete and welded on the upper flanges of the bottom framework steel profiles. Finally all containment liner sheets will be welded together.

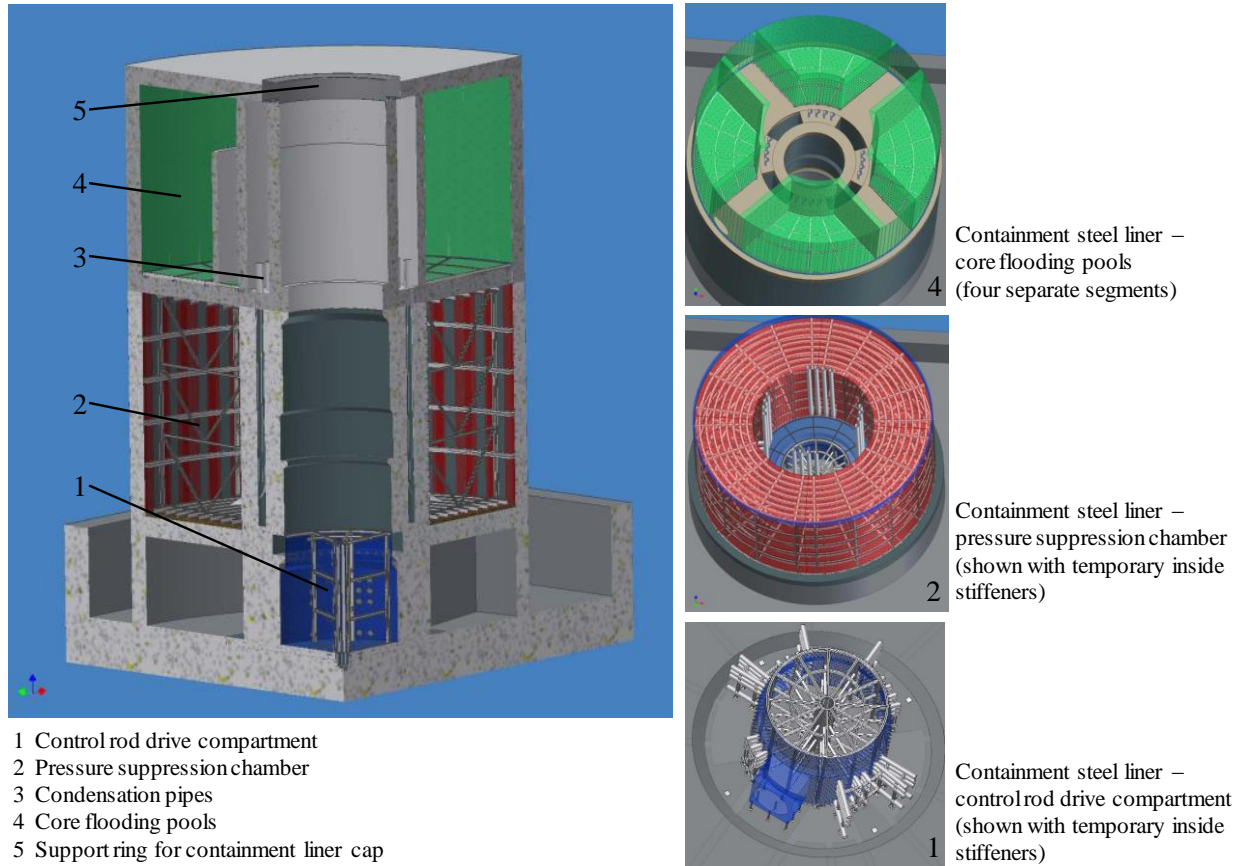


Fig. 4: Containment vessel inside view with the largest containment steel liner erection parts

CONTAINMENT STEEL LINER MATERIAL

BWR containment vessels typically contain large quantities of water. Within the KERENA™ containment vessel the pressure suppression chamber and the core flooding pools are usually filled with water. Therefore corrosion protection is necessary for the pool and containment steel liner sheets.

Existing BWR containment vessels (including Gundremmingen B and C) have a carbon steel liner with a special coating for corrosion protection, which requires intensive maintenance. 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. In addition the European community regulation on chemicals called REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) [3] lays down new rules for a safe use of chemicals. So far used coating systems were prohibited, leading to a process of rethinking the steel liner material properties.

For the new design of the KERENA™ containment vessel, stainless steel liner materials were investigated as an alternative to the carbon pressure vessel steel. Among them were a stainless duplex steel (X2CrNiMoN22-5-3, material no. 1.4462, S460) with a thickness of 10 mm (0.39 in), and 12 mm (0.47 in) thick clad steel consisting of 8 mm (0.31 in) pressure vessel steel (P275NL2, material no. 1.1104) with 4 mm (0.16 in) stainless austenitic steel cladding (X2CrNiMoN17-13-5, material no. 1.4439, S275). According to the national technical approval for stainless steels [4] issued by the DIBt (German Institute for Technical Approvals), the stainless austenitic steel belongs to corrosion resistance category III (medium) and the stainless duplex steel corresponds to category IV (high). Both stainless steels meet the material requirements regarding corrosion resistance, mechanical properties and steel processing.

The most relevant difference between these two steel options is given by the yield point. While the clad steel (pressure vessel steel and stainless austenitic steel) has a rather low yield point of about 275 N/mm², the stainless duplex steel has a much higher strength with a yield point of 460 N/mm². On the one hand a high steel strength facilitates the containment steel liner erection; but on the other hand steel liner heating due to accidental conditions would also lead to high steel liner forces. Further the problems of dissimilar (black-white) connections were taken into account. The application of the stainless duplex steel liner requires the use of headed studs made of stainless steel too. In this case the stainless steel standard material (X5CrNi18-10, material no. 1.4301, S235) was chosen for the headed studs.

CONTAINMENT STEEL LINER ANALYSIS

For the structural design of the KERENA™ BWR containment vessel, a separate analysis of the concrete and the steel liner structure was conducted as usual. First the reinforced concrete structure, which has to provide structural integrity of the containment vessel, was designed to withstand all normal and abnormal operation situations as well as accidental situations. Despite the fact, that the steel liner is fully bolted to the concrete structure, the steel liner is not considered as a load bearing element. However the unfavourable behaviour of the steel liner, e.g. thrust effects due to suddenly arising temperature loads or resistance to concrete creep and shrinkage deformations, was taken into account.

In a second step the containment steel liner and the anchoring elements were designed to ensure leaktightness by the analysis of a detailed local finite-element model with appropriate joint properties of the steel and concrete elements. The already calculated concrete strains due to concrete creep, shrinkage and dissipating hydration heat were simulated. In addition forces and temperature loads acting directly on the steel liner are applied. In the case of KERENA™ the governing design stresses for the steel liner are caused by an abnormal operation situation, namely the failure of the ventilation system combined with a blow down event.

In addition to the loads and thermal effects, steel liner imperfections were considered. Tolerances due to steel liner manufacturing as well as the erection process (inter alia concrete pouring against the steel liner acting as formwork) can cause imperfections. Because of the steel liner thickness of more than 10 mm (0.39 in) and provided that the containment steel liner is stiffened appropriately during erection, imperfections due to the erection process can be neglected. So steel liner manufacturing tolerances remain which could be considered according to the European standard EN 1993-1-6 [5]. As shown in Fig. 5 different kinds of imperfections were investigated as a singular and a longitudinal buckle, as well as an eccentricity and a kink at the welding zone.

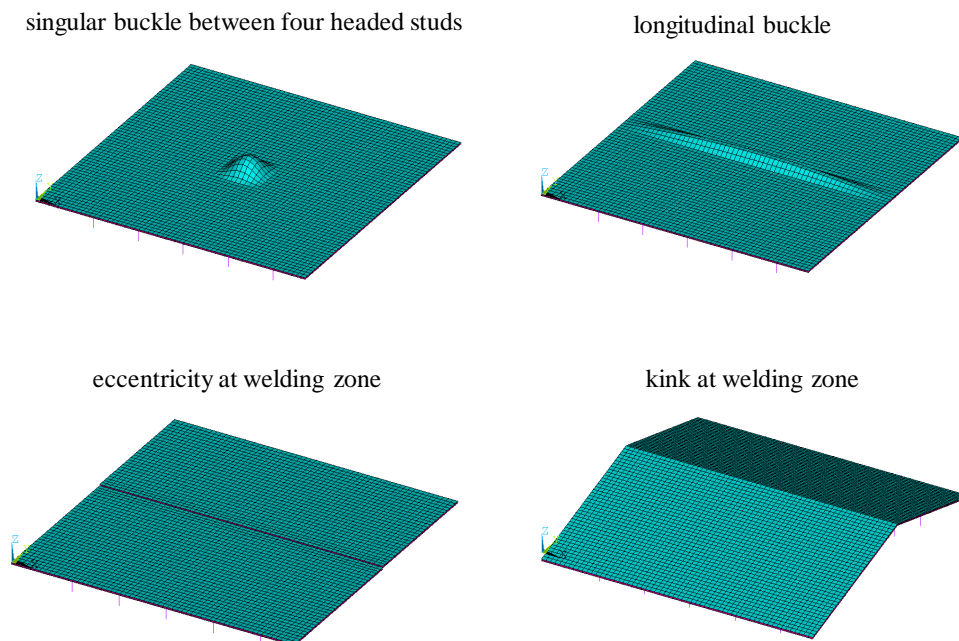


Fig. 5: Steel liner imperfections due to manufacturing tolerances according to EN 1993-1-6 [5]

Fig. 6 gives an impression of the steel liner analysis with the local finite-element model using stainless duplex steel. Due to the applied steel liner actions, several buckles arise between the headed studs. Maximum steel liner strains and anchoring forces arise at the predefined imperfection, which is e.g. a singular buckle in the middle of the finite-element model as shown in Fig. 6.

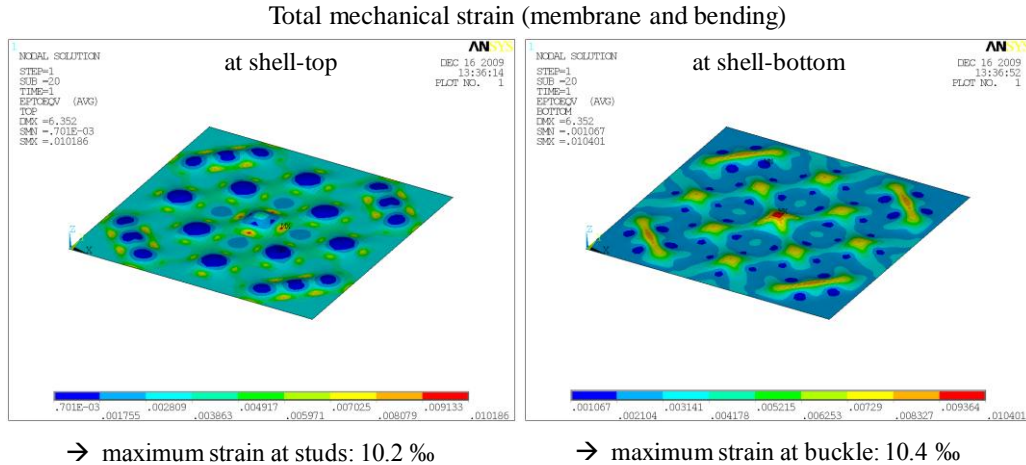


Fig. 6: Calculation of steel liner strains with the local finite-element model

In a first step the effects of the different imperfections on the steel liner strains and anchoring forces were investigated. Therefore the stainless duplex steel with headed studs arranged in a rhombic pattern (see Fig. 3) was chosen. The sizes of the imperfections were determined in accordance with EN 1993-1-6 [5] which defines the three fabrication tolerance quality classes A (excellent), B (high) and C (normal). A high fabrication quality (class B) was assumed. The analysis results shown in Table 1 clarify that maximum steel liner strains and anchoring forces arise by assuming a longitudinal buckle imperfection. Stresses due to an eccentricity or a kink at the welding zone are rather low.

Table 1: Different types of steel liner imperfections with corresponding effects on steel liner strains and headed studs forces

Steel liner material		stainless duplex steel S460 (material no. 1.4462)			
Anchor arrangement		rhombic pattern (a = 212 mm)			
Imperfection class B		buckle 3.39 mm	buckle 2.40 mm	eccentr. 2.0 mm	kink 3.0 mm
Description of imperfection		singular buckle between four anchors	longitudinal buckle	eccentricity between the anchors	kink between the anchors
max u_z	[mm]	6.3	5.1	3.2	3.7
max σ_{M+B}	[N/mm ²]	334	353	333	336
max ϵ_M	[‰]	7.6	11.4	4.0	5.3
max $\epsilon_{M+B,top}$	[‰]	10.4	15.1	6.6	9.4
max $\epsilon_{M+B,bottom}$	[‰]	10.2	18.0	7.1	7.8
max V_{sd}	[kN]	36.2	47.9	11.0	20.3
max N_{sd}	[kN]	27.6	49.3	15.7	24.0

In a second step the effects of the different steel liner materials (stainless duplex steel and clad steel) on the steel liner strains and anchoring forces were investigated. Again a rhombic pattern (see Fig. 3) of headed studs and the fabrication tolerance quality class B was chosen. The analysis results given in Table 2 show that the steel liner strains are almost identical for both the stainless duplex steel and the clad steel. However the anchoring forces and,

therefore also, the effects on the concrete structure differ. As a consequence of the very different material strengths, the stainless duplex steel causes considerably higher anchor forces than the clad steel.

Table 2: Comparison of the two steel liner materials - stainless duplex steel and clad steel - regarding their effects on steel liner strains and headed studs forces

Steel liner material		stainless duplex steel S460 (material no. 1.4462)	clad steel S275 (mat. no. 1.1104 + 1.4439)
Steel liner thickness		10 mm	8 mm + 4 mm
Anchor arrangement		rhombic pattern (a = 212 mm)	
Imperfection class B		single buckle 3.39 mm	
max u_z	[mm]	6.3	5.5
max σ_{M+B}	[N/mm ²]	334	213
max ε_M	[%]	7.6	7.1
max $\varepsilon_{M+B,oben}$	[%]	10.4	11.4
max $\varepsilon_{M+B,unten}$	[%]	10.2	10.0
max V_{sd}	[kN]	36.2	29.8
max N_{sd}	[kN]	27.6	24.7

CONCLUSION

The design of a BWR containment steel liner is a challenging task for the structural engineers. Due to the subdivision of BWR containment vessels in several separate chambers and pools, special construction features and a sophisticated steel liner erection concept are required for realizing a short construction time. Further the steel liner material should be chosen carefully as the pressure suppression chamber and the core flooding pools are usually filled with water. Stainless steel or a stainless steel cladding could be good alternatives to the common pressure vessel steel which requires inevitably a special coating for corrosion protection. For the verification of the steel liner leaktightness, the steel liner strains and the anchoring forces should be calculated by the use of a local finite-element model. Beside the actions arising during operation and accidental situations, steel liner imperfections have to be considered. The assessment of fabrication tolerances is of great importance for the analysis results.

In the case of KERENA™, the final basic design of the BWR containment vessel including the containment steel liner was conducted successfully by the structural design department HOCHTIEF Consult IKS Energy.

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