The Inner Containment of an EPR™ Pressurized Water Reactor

Dirk Ostermann, Christian Krumb and Burkhard Wienand, Offenbach/Germany

1. Introduction

The EPR™ pressurized water reactor is a generation 3+ reactor. Currently, four EPR™ reactors are in the construction phase, one in Finland, one in France and two in China. The current paper gives an overview over the containment structure and the analytical, numerical and experimental validations that have been carried out.

2. Containment structure

The containment of the EPR™ reactor consists of an outer containment and an inner containment, see Figure 1. The outer containment shell is a reinforced concrete structure with high wall thickness and protects the inner containment from direct effects of external hazards, such as airplane crash and explosion waves.

The inner containment is a pre-stressed concrete structure, designed to bear loads from internal hazards, such as overpressure and high temperature resulting from a Loss of Coolant Accident (LOCA). The leak-tightness function is ensured by a steel liner on the inner surface of the containment that is anchored in the inner containment wall by L-profiles (so-called “continuous anchors”) and by headed studs. Further details on the containment of the EPR™ reactor are illustrated in [1].

2.1 Pre-stressed inner containment

The inner containment structure consists of the base slab, the cylindrical part and the dome part. The base slab is connected to the cylindrical part by the gusset area in which the wall thickness increases considerably. Cylindrical and dome part are joined by a ring beam. The function of the ring beam is to withstand the bracing forces caused by the dome and to enable the anchoring of the pre-stressing tendons. The cylindrical part with an inner diameter of 46.8 m has a wall thickness of 1.3 m. The wall thickness of the dome part is 1.0 m. At the cylindrical part three vertical pre-stressing ribs are arranged. The whole height from the base slab to the dome center is about 65 m. The concrete strength class is C60/75. The inner containment is equipped with a polar crane whose circumferential rail is supported by brackets anchored at the wall.

The cylindrical and the dome part of the containment are pre-stressed crosswise with 270 tendons, which are partitioned in 3 groups. Vertical and gamma tendons are anchored at the ring beam and in a pre-stressing gallery which is located below the base slab. Horizontal tendons are anchored at the pre-stressing ribs. Each tendon consists of 54 strands and has a...
pre-stressing steel area of 81 cm². One strand comprises 7 steel wires with diameter 1.5 mm. The maximum used steel stress is 1,488 MPa which corresponds to a tendon force of 12 MN. The tendon strands are threaded one by one in steel ducts. After tensioning the ducts are injected with grout, ensuring bond between strands and concrete structure. Furthermore, the used method pre-stressing with bond offers advantages relating to corrosion prevention and also in structural respect: a possible strand failure would remain a local event, because the force transfer to adjacent strands is ensured by the surrounding injection, see [3].

Due to the pre-stressing the concrete in almost each section remains under compression. This ensures the elastic behavior of the containment structure during the whole life time, see [2]. Losses of pre-stressing forces are caused by time dependent material effects as creep and shrinkage of the concrete and relaxation of the pre-stressing steel. The mean concrete compression therefore decreases from about 9 to 13 MPa (depending from direction) after construction to 4 to 9 MPa at the end of the lifetime under normal operating conditions. However, the compression buffer is sufficient even under LOCA conditions.

The time dependent material behavior is monitored by an In-service Inspection System [5] which comprises the measurement of concrete and liner strains, structure displacements, tendon forces, crack widths, concrete humidity and temperature.

### 2.2 Containment liner

The steel liner or so-called containment liner consists of a 6 mm thick steel shell that is anchored to the inner surface of the inner containment wall by headed studs (diameter: 8 mm) and L-anchors in different sizes. The steel liner is subdivided into liner fields of different sizes (max. field 1,830 mm x 766 mm). Figure 2 shows a steel liner assembly with L-profiles, headed studs and pipe penetration before installation.

The purpose of the steel liner is to provide leak tightness of the containment. The steel liner itself is not a structural member and needs not to contribute to the load bearing capacity of the containment. However, the steel liner has to follow the deformation of the pre-stressed containment. Furthermore, the steel liner is subjected to temperature loads in accident conditions. Both effects result in high compression forces in the steel liner.

### 2.3 Penetrations and installations

The containment has many openings, such as the personnel airlock, the emergency airlock, the equipment hatch, the fuel transfer tube, several pipe penetrations, heating, ventilation and air conditioning penetrations, and cable penetrations. All openings and seals are designed to withstand the design pressure at accident temperature and to remain leak tight.

The brackets of the polar crane are anchored at the inner containment. The support forces of the polar crane are transferred into the concrete structure.

In addition, numerous anchor plates are embedded into the inner containment wall to carry loads of steel platforms, pipe supports and cable trays.

### 3. Design criteria

The decisive event for the global design of the inner containment and the steel liner is the LOCA. The correspondent loads are an inner pressure of 5.5 bar (abs) together with an inner air temperature of 170 °C. The pre-stressing system and the steel liner are designed to withstand this load scenario during the whole life time. The leak rate of the inner containment is limited to 0.3 vol.%/d.

### 4. Numerical and analytical calculations

Detail design calculations comprise a 3-dimensional Finite-Element-Model of the complete inner containment including the ring beam, the pre-stressing ribs, the gusset area and the big openings in the cylindrical part. The concrete wall has been modeled with volume elements for the concrete and shell elements for the liner. The pre-stressing forces have been applied to the structure according to their exact locations in the wall sections, considering friction losses as well as time dependent losses due to the material behavior.

Additional calculations have been performed to verify the steel liner strains, the displacements and forces of the steel liner anchors. These detailed calculations investigated mainly the steel liner buckling which can occur due to imposed compression strains. The calculation results have been supported by test results.

### 5. Experiments

During construction time a large test program concerning the material strength and the long-time behavior of the concrete and pre-stressing steel properties has been engaged, see [4].

#### 5.1 Tests on concrete

The tests on concrete specimens included the measurement of the concrete strength, the modulus of elasticity for fresh and hardened concrete and the creep and shrinkage.

#### 5.2 Tests on pre-stressing system

For the pre-stressing steel tests of the isothermal stress relaxation and deflected tensile tests have been performed. In addition, mock-up tests for the grout injection in deviated tendons have been carried out to avoid air bubbles in the tendon ducts, see Figure 3. With these tests the injection procedure, including grout mixture, injection pressure, injection velocity and air venting could be verified.

![Image](image1.png)  
**Fig. 2.** Steel liner assembly with L-profiles, headed studs and pipe penetration before installation.

![Image](image2.png)  
**Fig. 3.** Hardened grout in a tendon duct.

#### 5.3 Liner plates and welds

The steel of the containment liner has been tested in uniaxial and biaxial tension tests in order to obtain the stress strain...
diagrams up to fracture. These tests have been carried out on test specimens with weld and without weld. All test specimens were manufactured from original liner plates used for the construction site in Finland.

In addition, bending tests on welded test specimens have been carried out. These tests showed the high ductility of the material. A bending of almost 180° was possible without fracture of the test specimens, see Figure 4.

5.4 Continuous anchors

The liner is divided into liner fields L-profiles, which anchor the liner into the inner containment wall. These continuous anchors have been tested in order to find out the stiffness of these anchorages, the load bearing capacity, the ultimate displacement and the force-displacement diagrams. The tests have been carried out in pre-stressed concrete and in non-prestressed concrete (Figure 5).

5.5 Headed studs (tension, shear)

In addition to the continuous anchors the liner is also anchored to the inner containment wall by headed studs in a distance of 150 mm. For these headed studs an extensive test program has been performed in order to verify the interaction relation between tension and shear.

5.6 Liner mockup test

A specimen of the liner structure including a part of the concrete wall has been modeled and pre-stressed in order to examine the liner buckling behavior under LOCA conditions and concrete creep and shrinkage [6].

6. Containment tests

Before commissioning a pressure test of the inner containment has been performed proving the structural integrity. The test pressure was 1.1 x the design pressure at room temperature. The results of the In-service-Inspection System confirmed the elastical behavior of the pre-stressed concrete structure.

A subsequent performed leak tightness test (formerly integral leak rate test) is verifying that the leak rate does not exceed the limit.

During the pressure test existing concrete cracks on the outer surface have been monitored and could be identified as surface cracks. Crack propagation was excluded by evaluation of the crack width time development. Measured crack widths of new cracks remained below 0.1 mm.

The measured data during the pressure test and before, during the pre-stressing phases after construction, are a valuable basis for the assessment of future pressure tests and the ageing behavior of the containment structure life time.

The inner containment pressure test and the subsequent leak tightness test of the first EPR™ fulfilled the requirements with high margins compared to the allowable values.

7. Conclusion

The containment of the advanced EPR™ pressurized water reactor is developed on the basis of the French nuclear power plant operational experience and consists of

- The reinforced outer containment structure, designed to withstand external hazards (such as airplane crash),
- The pre-stressed inner containment structure, designed to bear the loads resulting from internal hazards (LOCA),
- The steel liner, designed to provide leak tightness resulting from internal hazards.

In addition to detailed calculations several test programs have been performed to verify and confirm the predicted behavior in normal operation and in accident condition. These extensive test programs exceeded the test programs that are commonly carried out for new-build projects and are unique for the construction of a nuclear power plant. It is the basis for the high safety standard of the EPR™ reactor.

8. References