

# Qualification of Composite Liners and Pressure Tests at the Mock-up at Walldorf, Germany

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## ABSTRACT

Since the beginning of the French-German cooperation for the European Pressurized Water Reactor (EPR), investigations have been performed to study the feasibility of a composite liner (fiber reinforced resin) as an alternative to a conventional steel liner in combination with different types of concrete containment designs.

In this context a variety of qualification tests had been performed to demonstrate the suitability of composite materials for nuclear application, mainly their resistance under severe conditions like e.g. fire, radiation, chemical attack.

In addition a large mock-up has been erected by the civil construction company Hochtief at Walldorf in Germany to investigate together with Siemens in realistic scale application aspects and the behavior of composite liners on concrete in the case of multi-axial loading as well as of large concrete deformations associated with large crack widths.

During the mock-up tests which started in 1997 a variety of different liner systems had been implemented, tested and removed. The pressure tests had been successfully finalized in spring 2000 after having reached an ultimate absolute pressure of 1,7 MPa.

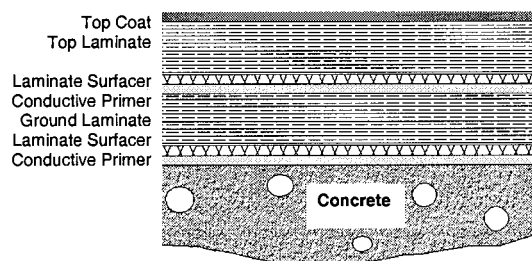
This paper presents a synthesis of the research activities.

## QUALIFICATION OF COMPOSITE LINER

### What is a Composite Liner?

In general composite liners are coatings that are applied on a substrate in order to ensure the leak tightness of a system, conventionally a tank, a basin or in this case a containment. Composite liners itself are constructions designed according to the specific design demands of their specific use. The liners are composed of selected non-metallic materials which are attached layer by layer to the substrate: steel, concrete or metallic components that are embedded in the concrete. In general a composite liner consists of a matrix, a resin for example like epoxy or vinyl ester, and layers of fibers for example from glass, carbon or aramid. Composite liners are already in common use for tanks and basins.

In context with the EPR project different composite liners were developed and tested with regard to the specific requirements as a leak tight barrier for a containment. Vinyl ester or epoxy resins combined with glass fibers have shown to be best suited for this purpose. The coating thickness ranges from approximately 3 to 8 mm depending on the liner design. A typical liner composition is presented below.



*Typical Liner Composition*

## HISTORY OF COMPOSITE LINER RESEARCH

### The EPR Project

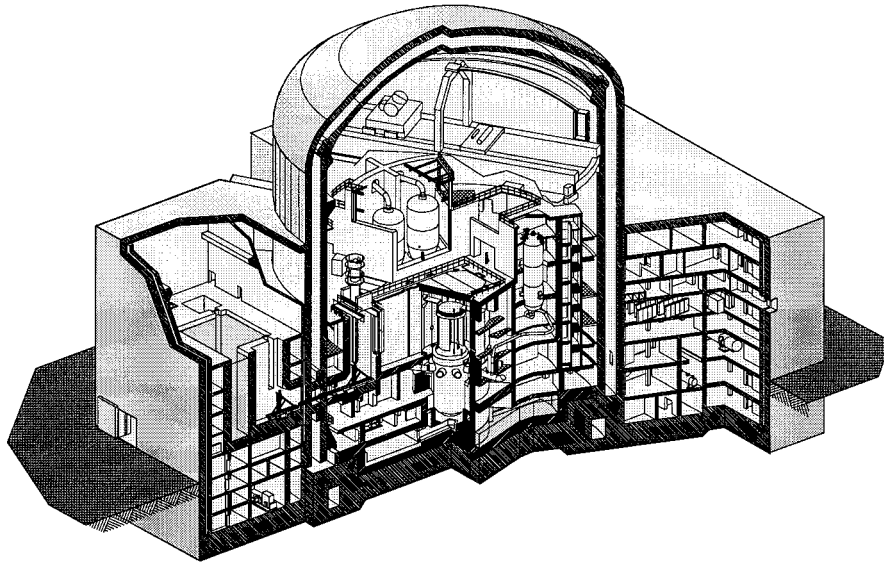
The composite liner development for the application at a containment is closely connected with the design of the European Pressurized Water Reactor (EPR). Framatome and Siemens started the development in 1989. Two years later, in 1991, Electricité de France (EDF) and nine leading German electric utilities came on board with the project.

The Basic Design of the EPR has now been completed, and the go-ahead for erection of the first plant in France is expected in around 2003, enabling actual construction work to start in 2006.

The EPR features a double (steel-reinforced concrete / pre-stressed concrete) containment design, with the inner containment coated additionally with the previously mentioned composite liner in certain areas. Under normal conditions the containment leak tightness is provided mainly by the pre-stressed concrete and the composite liner in the event of a postulated accident.

Extensive research has been carried out to verify this concept in both France and Germany. Containment mock-ups were erected at the Civaux nuclear power plant in France with the name MAEVA and at the Hochtief test facility at Walldorf (Germany) to enable testing of the leakage behavior of steel-reinforced concrete and investigation of the suitability of composite liners as a leak tight barrier. [1]

The following drawing gives an impression of the EPR – containment founded on a common raft with adjacent buildings of the nuclear island.



*EPR Double Containment*

The test and design pressure of the containment is 0,65 MPa, whereby the leak rate for a 24-hour period must be less than 1 percent by volume.

#### **Important Milestones of the Composite Liner Qualification**

In the early 1990s Siemens started to test composite liner materials. The important milestones of the liner development are summarized below:

1991	First ideas and tests at Siemens laboratory
1992	Tests with coated beam elements at Karlsruhe (Prof. Eibl)
1992	Start of cooperation with reputable resin manufactures
1994	EDF joins liner research
1995	Decision to test composite liners at MAEVA
since 1995	Qualification tests at Siemens, Hochtief and EDF laboratories for EPR
1997	First pressure tests at Walldorf (filling medium water, up to 1.1 MPa)
1998-2000	Three series of pressure tests at MAEVA (filling medium air, air-vapor phase, 0.65 MPa)
1999	Qualification of improved alkaline resistant liner systems
1999-2000	Third series of pressure tests at Walldorf (water, up to 1.7 MPa)

#### **Liner Qualification by Laboratory Tests**

The qualification of the selected composite liner materials had been jointly performed at the laboratories of EDF at Aix-en-Provence/France and at Siemens at Erlangen/Germany. The aim of the tests performed at Erlangen had been to back up the results of the EDF tests and to consider specific German requirements with respect to coating systems. In addition to the suitability of composite liners as a leak tight barrier for reinforced concrete containments with pre-stressing the suitability for containments without pre-stressing has been investigated.

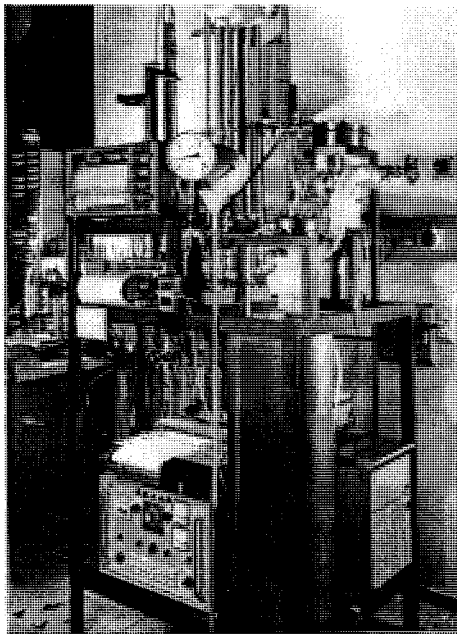
The following tests and studies were conducted to qualify selected composite liner systems:

- adhesion to concrete and steel substrate
- bridging behavior of cracks that arise in the concrete due to loading
- radiation resistance
- chemical resistance
- thermal resistance (aging)
- ease of repair
- LOCA resistance
- severe accident conditions

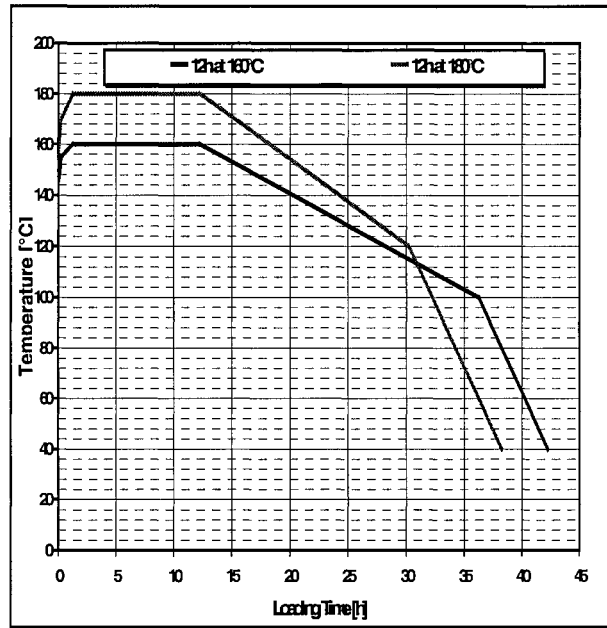
Several composite liner systems have been investigated during the progress of development but for the ease of presentation this chapter will concentrate on a selected epoxy liner. In the following some explanation of the test procedures and results will be presented.

### LOCA Resistance

LOCA resistance means the liner systems have to be resistant against the consequences of a specified loss of cooling accident (LOCA) in terms of elevated pressure and temperature loading. Non total loss of adhesion is required after loading of the liner system with LOCA conditions. The LOCA tests were performed at Erlangen with an arrangement and under the conditions shown in the following figures. At 200°C a blow down was performed and the liner systems were loaded in accordance with the temperature loading curves shown below. The liner systems were checked on visual detectable changes and with a pull-off test according DIN EN 24 624 after a controlled cooling down. The adhesion value and the break behavior were evaluated.



*LOCA Test Installation*



*Temperature Loading Curve*

No total loss of adhesion could be determined. The adhesion decreased for the epoxy liner system to a range of  $> 1$  MPa. Different loading times and/or loading temperatures did not significantly influence the adhesion. Only small cracks in the top coat layer could be detected after the loading. These cracks stop at the borderline between top laminate and top coat.

### Mechanical Behavior

The mechanical behavior was investigated by tensile strength test according EN ISO527-4. The test specimen were cut from a free film with dimensions in accordance with EN ISO 527-4 type 2 and then stored for 24h under standard operating environment DIN 50014-23/50-2.

The performance conditions are listed below:

Test specimen	6
Shape of test sample [mm]	250 x 25 x 5,1
Test velocity [mm/min]	2
Measuring length l0 [mm]	100

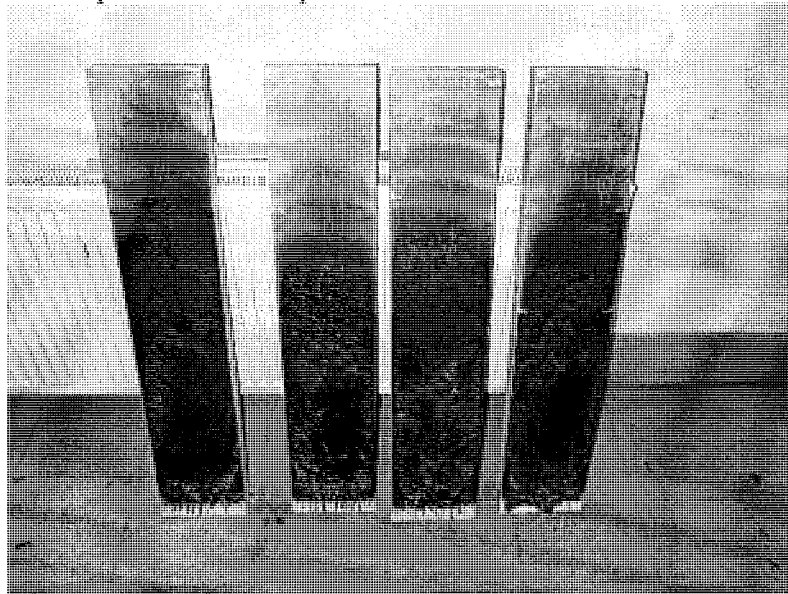
A tensile strength of 26,5 N/mm<sup>2</sup> (+/- 1,7) and a Young's modulus of 1795 N/mm<sup>2</sup> (+/- 145) were determined as average of six measurements. The elongation was 1,94% (+/- 0,27). Due to the elastic behavior of the epoxy liner system the values for the tensile strength and elastic modulus are relatively low. From the point of view of crack bridging and reaction in case of imposed deformations these properties are favorable.

### **Irradiation Resistance**

The epoxy liner system was tested up to 10 MGy  $\gamma$ -radiation exposure loading. No total loss of adhesion up to 5 MGy could be detected, only a brown discoloration of the surface and loss of gloss happened. A carbonization of the conductive layer with increasing  $\gamma$ -radiation loading could be determined which results into a decreasing of the adhesion.

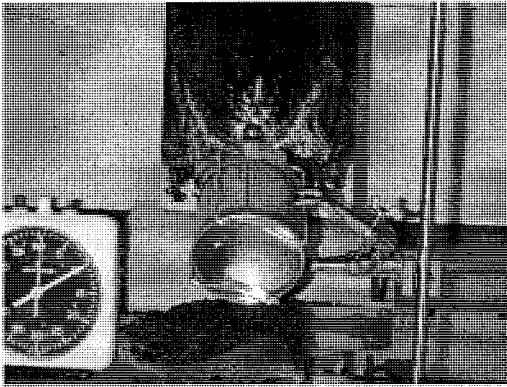
### **Fire Resistance**

The epoxy liner was tested with respect to its fire resistance in accordance with DIN 4102 Teil1. The test specimen were placed in an oven and then the flame device was started. The duration of the flame treatment was 10 min with a flame temperature of 500 to 600°C. The epoxy liner system fulfils the requirements for a class B1 classification. The requirements are given below together with a photo of four test specimen taken after the flame resistance test has been performed:

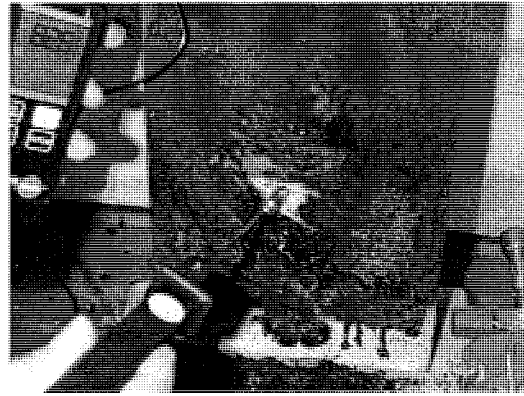


***Test Specimen after Fire Resistance Test***  
length of non affected surface > 15 cm  
max. flue-gas temperature < 200°C

In addition further flame resistance tests were performed. The areas loaded during the flame resistance tests were directly loaded with the flame of gas burner for again 10 min (flame temperature >800°C). No flame propagation on the top coat or other degradation effects could be observed.



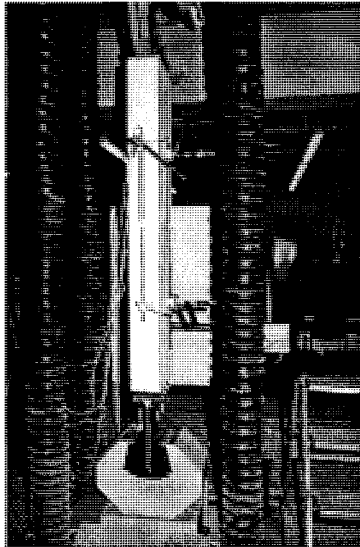
*Direct Flame for 10 min at 800 °C*



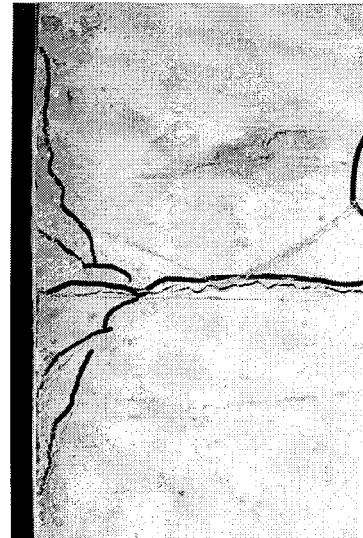
*Intact Resin under Carbonized Top Coat*

### **Additional Tests to Check the Crack Bridging Behavior**

A variety of different tests to check the crack bridging behavior had been performed at the universities of Karlsruhe and Kaiserslautern in Germany and at the Hochtief laboratories. An impression of the tests and the capability of the liner to branch large cracks (within the concrete) like a crack distributing reinforcement into several single cracks (at the surface) give the photos below:



*Testing of coated Beam Elements*



*Branching of a Crack by the Liner*

### **TESTS WITH COMPOSITE LINER SYSTEMS AT WALLDORF**

The project centered around pressure tests using a containment mock-up depicting the main features of a steel-reinforced concrete containment with a composite liner. Important issues that are of relevance for a real containment were examined:

#### design and construction:

- the arrangement of the reinforcement
- the design of openings (locks)

#### mechanical behavior under loading:

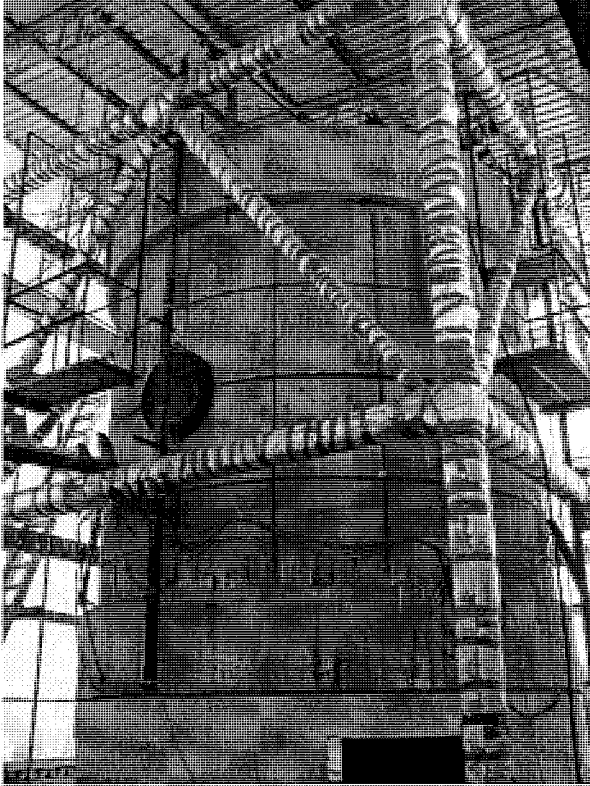
- global deformation behavior of the structure
- crack development in steel-reinforced concrete

#### in particular:

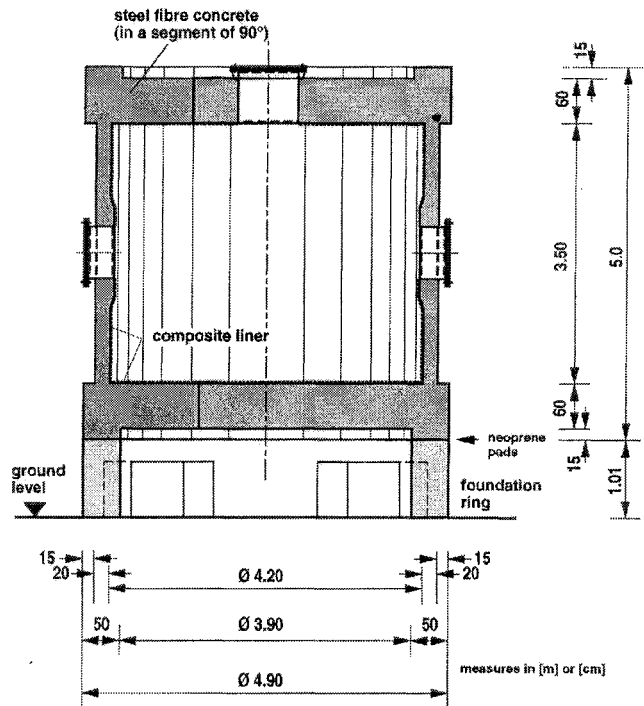
- application of composite liners
- the interaction of a system consisting of steel-reinforced concrete and a composite liner
- the leak tightness of a coated containment in the case of large concrete deformations.

The mock-up was designed in such a way that the radial and tangential expansions arising under pressure loading are similar to those that would occur at the planned EPR containment at the same load. One segment of the containment was poured with steel fiber concrete to check its improved performance due to a better crack distribution as compared to normal concrete and with respect to interaction with the composite liner. The reinforcement of the mock-up was selected in such a way that the occurrence of large crack widths in the concrete was pre-programmed. Furthermore special measures were taken locally to provoke cracking and concentrate deformations. This enabled testing of the liner systems under extreme conditions.

The photograph below gives an impression of the dimensions of the containment mock-up at Walldorf. It was taken on March 9, 2000, on reaching the planned limit pressure of 1,6 MPa. The internal pressure was applied by means of a water fill for safety reasons and ease of handling and leakage detection.



**Mock-up at 1.6 MPa without Leakage  
(2.7 times Design Pressure)**



**Cross Section of the Mock-up**

The first test programs were performed in summer 1997 with two different preliminary composite liners on vinyl ester base, with one series of tests at up to 0,65 MPa and two test series up to pressures of 1,1 MPa. This enabled confirmation of the fundamental feasibility of the composite liner as a leak tight barrier. However, local leaks occurred in all three test series as a result of isolated flaws, despite the fact that comprehensive quality testing was carried out in advance with the aid of the spark flashover technique using an electrical brush. As a result, improved liner systems were developed with a more complex structure incorporating two conductive layers to enable enhanced electrical quality testing.

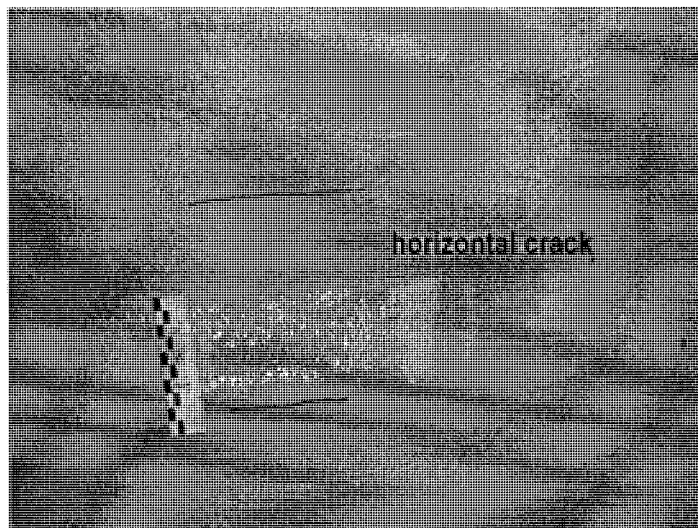
The tests were originally scheduled for completion in the fall of 1998. In the summer of that year, the preliminary liner was removed, and half of the containment mock-up re-coated with the improved liner system. Coating work on the second half had just begun when the vinyl ester liner at Civaux failed as a result of the alkali reaction described in [1]. As a result, it was decided to interrupt the Walldorf tests to enable the development of alkali-resistant systems. Two new optimized systems, one system on epoxy resin base and one system on base vinyl ester were applied to the remaining half of the mock-up. The arrangement of the liner systems in the containment floor/cylindrical section area is shown in below.



*Arrangement of the Liners with Strengthened Chamfers*

The pressure tests had been resumed on a phased basis end of 1999:

- On 23<sup>rd</sup> November, 1999 the design pressure of 0.65 MPa was reached without any leakage.
- On 8<sup>th</sup> December, 1999 the beyond design pressure of 1.1 MPa was reached, again without any leakage. The inspection of the liner, both visually and by the electric brush procedure identified no degradation of the liner. Therefore, the next step up to ultimate conditions could be started.
- On 21<sup>st</sup> December, 1999 at a pressure of 1.4 MPa a leakage occurred. Wet spots and water from cracks at the junction between the bottom slab and the cylindrical wall around the total circumferencial area could be observed. The pressure dropped to 1.1 MPa after an hour and to nearly 0 the next day. The inspection of the liner gave the following observations. The liner showed no visual degradation. After a more thorough look at the liner a thin horizontal crack of around about 30 cm length was observed on the section of the optimized vinyl ester liner system at the chamfer connecting the bottom slab and the cylindrical wall (see picture hereafter).

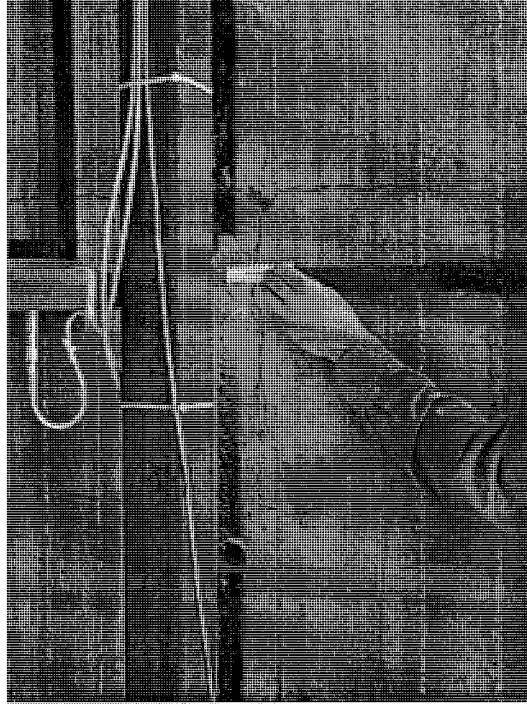


*Crack at the Optimized Vinyl Ester Liner after 1.4 MPa (2.4 times Design Pressure)*

After the first two tests (0.65 MPa and 1.1 MPa) this area had already been identified as a potential weak point where local detachment from the concrete surface was identified. This previous detachment was obviously the reason that the

leakage was distributed behind the chamfer and occurred simultaneously around the 360 ° of the mock-up. The vinyl ester resin is much stiffer than the epoxy resin and this explains that at the chamfers (which are areas of stress concentration) the risk of cracks at the vinyl ester liner is higher than at the epoxy liner.

It was decided to repair the crack and to improve all the chamfers at the bottom and top areas of the vinyl ester liners. The epoxy liner was not upgraded.



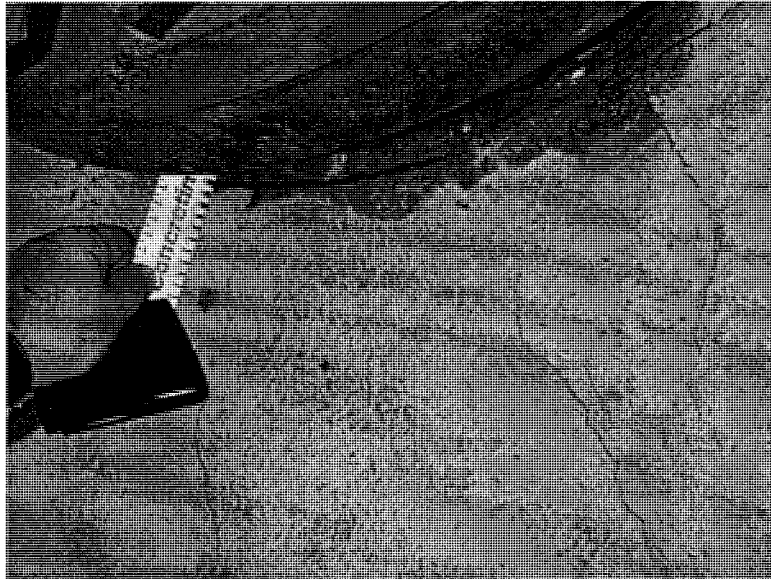
*Large Cracks at the Cylindrical Wall at 1.6 MPa*

As expected, at this level of pressure the reinforcement of the mock-up was already in the non-linear range with measured strains of up to 6.6 %.

As the mock-up was obviously able to carry this extreme loading it was decided to go further on with the pressurization. At a pressure of 1.7 MPa (corresponding to 2.9 times the design pressure) the first leaks started gradually at the connection between the cylindrical wall and the top slab and at the top penetration. An impression of the leaks and the large deformation of the reinforced concrete with cracks up to several millimeters wide are represented in the following photos, taken when the mock-up was fully pressurized .



*Slowly Starting Leakage at the Top of the Cylindrical Wall at 1.7 MPa*



*Large Cracks and Starting Leakage at the Penetration at the Top Slab*

Again, the inspection of the liner showed no visual degradation. The identification of the areas where the leakage occurred was only possible via the electric brush procedure. At the upper chamfer of the improved vinyl ester five small cracks were clearly identified as the reason for leakage.

## **CONCLUSIONS**

For several years EDF and Siemens have jointly investigated composite liner materials in order to evaluate their feasibility as a replacement for metallic liners and whether they can be added to unlined pre-stressed concrete walls in order to improve the leak tightness.

In this context a variety of qualification tests had been performed which demonstrated successfully the suitability of such materials for nuclear application, mainly their resistance under severe conditions like e.g. fire, radiation, chemical attack.

In addition a large mock-up has been erected by the civil construction company Hochtief at Walldorf in Germany to investigate together with Siemens application aspects and the behavior of composite liners on concrete in the case of multi-axial loading as well as large concrete deformations associated with large crack widths.

The conclusions of the mock-up tests at Walldorf can be summarized as follows:

- All optimized liner systems proved during the tests that they are able to safely provide the leak tight barrier at the EPR design pressure of 0.65 MPa.
- Leakages only occurred far beyond the design pressure and commenced slowly.
- Cracks in the containment wall of several millimeters were safely bridged by the liners without detachment from the concrete surface. The liners behaved like crack distributing reinforcement which branches large cracks into several single cracks.
- The mock-up tests at Walldorf have successfully demonstrated that appropriately designed composite liners are able to fulfil the requirements of a leak tight barrier for concrete containments.

## **Reference:**

[1] Danisch, R., Liersch, G. and Touret, J. P., "The EPR (European Pressurized Water Reactor) Containment – Concept, Testing of Leakage Behavior, FRP Liner", *VGB-PowerTech Volume 5/2001, International Journal for Electricity and Heat Generation*