Behaviour of a PCPV with Hot Liner

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Abstract

The main goal of a research and development program carried out by the Austrian industry and the Research Center Seibersdorf is the development of a Prestressed Concrete Pressure Vessel with Elastic Hot Liner.

For the verification of the new concept a prototype vessel has been erected which was laid out for conditions up to 1oo bar internal pressure and 3oo°C liner temperature. This vessel was submitted to an intensive test program with an accumulated operation time of 2 years with 1 year full load conditions. Some of the results will be presented.

1. Introduction

The main goal of a research and development program carried out by the Austrian industry and the Research Center Seibersdorf is the development of a Prestressed Concrete Pressure Vessel with Elastic Hot Liner.

This paper deals with the verification of this concept and the practical experience gained thereby. About the features of the concept has already been reported /¯1,2_7. Nevertheless the outlines of the concept shall be mentioned shortly (Fig. 1). Prestressed concrete reactor vessels for nuclear power plants built up to now are equipped with a cold liner. Liner and concrete wall are kept on a relatively low temperature. A thermal insulation covering the liner from the inside and penetrated by the reactor coolant, prevents the vessel wall from the internal high temperatures. A cooling system on the liner absorbs the heat transmitted through the insulation and has to guarantee the required low temperatures of liner and concrete. The concept of a PCPV with hot liner eliminates the inner insulation. The liner is now in direct contact with the primary coolant and accepts its temperature. The bare liner offers advantages for inspection and repair, there occur no problems with hot spots, and the design is insensitive to vibrations caused by circulators or an eddy flow. The temperature decrease now is placed in an insulating zone between liner and structural concrete. The main problem which is to be solved is the great difference in expansion of liner and concrete body due to the different temperatures. By the high coefficient of expansion of the liner material and by the high temperature difference between liner and concrete, restraints are created in the liner which may be far beyond the strength of the liner material.

It is one of the major design principles of the Austrian concept to keep the stresses of the liner under normal operating conditions in the range of elastic compression. This requirement can be met by two accomodations. Firstly, the concrete temperature is elevated up to a temperature of 12o°C - - 14o°C. By the use of a concrete with a high coefficient of thermal expansion and a steel quality with a low one, the difference of expansion can be reduced. As second accomodation a liner material is selected with a high yield strength, that is able to limit the still remaining restraints to the elastic range.

2. Prototype Vessel

According to the concept a prototype vessel has been erected which was laid out for steady state and transient operating conditions up to 1oo bar internal pressure, 3oo°C liner temperature and 12o°C temperature of the prestressed concrete (Fig. 2). The vessel dimensions are 1.5 m internal diameter, 3.6 m outer diameter and 12 m height. The dimensions are a compromise to be on the one hand large enough to represent a reactor vessel and on the other hand to enable the test rig to be handled in a practicable way.

The structure of the vessel wall, from inside to out, consists of: the hot liner, 5 mm thick, provided with anchor bolts as buckling prevention; in the following insulating concrete the temperature is reduced from 3oo°C to 12o°C; between insulating concrete and structural concrete the innermost cooling system is situated which absorbs the heat transmitted from inside. The tubes of this system are mounted on a steel jacket. This jacket improves the temperature distribution in this region, furthermore it serves as a concrete form during erection of the vessel and in case of an eventual leakage it limits the gas to the insulating concrete from where it can be evacuated under control. In the structural concrete further lines of heat exchanging tubes are provided. By this system the temperature distribution in the wall can be adjusted to the operating conditions. Heating up and cooling down can be carried out very rapidly. The vessel has a start up time to full load conditions of about 3 ÷ 6 days.

To apply the temperature to the liner a nitrogen circuit is installed with a blower, an electric heating system and a central gas duct. To investigate the behaviour of the several components the vessel is extensively instrumented with different types of gauges. For strain measurement in the concrete in regions up to 3oo°C, 3o Microdot strain gauges are installed. For regions up to 12o°C, 131 Telemac vibrating wire gauges are used. In addition 18 Glötzl gauges register directly concrete stresses. For temperature measurement 2oo thermocouples are installed. 95 strain gauges are flame-sprayed to the liner. Prestress load is measured by 12 load-cells. The moisture content is monitored by a neutron-probe inserted in holes through the concrete wall. On the outer surface the deformations are measured by dial gauges. In order to monitor the integrity of the vessel i.e. the counterplay of the different structural parts, radial bars made of invar lead to different depth of the concrete wall, measuring the radial displacement relative to the outer surface. The inner diameter of the vessel (1.5 m) is monitored during the temperature and pressure cycle by a distance measuring system containing a temperature compensated measuring bar and a differential transformer. A sophisticated method of data evaluation yields to an accuracy of some ± lo μm over the entire pressure and temperature range.

3. Test Program

After the erection of the vessel the prestress load was applied. Then the vessel has been submitted to an intensive test program (Fig. 3). At first the thermal stabilization of the structural concrete has been performed. Thereby the prestressed concrete was heated up to 12o°C by means of the temperature control system, insulating concrete and liner were kept cold. Results of this period have already been reported /‾3,4_7. The prestress loss caused by creep and shrinkage of the concrete was compensated by retensioning. The pressure test was executed with 115 bar.

The next step was the drying and stabilizing of the insulating concrete at 14o°C. The first test cycle with 15o°C liner temperature and 8o°C concrete temperature and 5o bar internal pressure followed immediately. Two further 15o°C cycles were executed in which the principal behaviour of the vessel, the consequences of the stabilization and the reliability of the measuring systems were examined. After the satisfactory progress of the two cycles the liner temperature was increased up to 2oo°C in the 4th cycle. In the 5th cycle full load was applied with 3oo°C liner temperature, 12o°C concrete temperature and 95 bar internal pressure. During these five cycles with increasing load the principle behaviour of the vessel was investigated. In the following long term cycles, each of them lasted about 6 months, the stability of the vessel structure was examined. The accumulated operation time with full load conditions is nearly one year.

A special load program has been established for these test cycles. To investigate the reactions of the vessel on the different load levels, the load is applied step by step, separated in temperature and pressure. The load levels are kept constant for a time, from one day to a week, to achieve reliable measurements which can be referred to well defined load conditions. Furthermore eventual delayed transient effects can be detected. The shut down phase of the cycle has the same load levels as the start up phase. Thus changes in the vessel structure during the cycle can be detected. The same load levels are repeated in every cycle. By this way it is possible to detect changes in the vessel behaviour from cycle to cycle which may be caused by additional creep, shrinkage, or by a change of material properties, like Young's modulus or thermal expansion.

All these test cycles have the main purpose to investigate the operational behaviour rather then to perform overload or burst-tests.

4. Results

On the outer surface the axial deformations are measured by dial gauges. This deformations are mainly determined by the temperature expansion of the concrete. By subtracting the pure thermal expansion, the residual deformations caused by creep, shrinkage and pressure load can be obtained (Fig. 4). After 3 months thermal stabilization 6oo microstrains occured. After this period no significant further permanent deformation can be noticed on the outer surface of the vessel.

The prestress loss during the thermal stabilization was compensated by retensioning. The test period afterwards can be divided into two sections as far as the behaviour of the prestressing system is concerned (Fig. 5), characterized by the concrete temperature respectively the temperature of the tendons of 8o°C and 12o°C. Both periods show a similar progress. After an increase of loss at the beginning the tendons turn to a steady condition corresponding to the relaxation curves gained in previous tests with the prestressing steel.

In the structural concrete vibrating wire gauges are embedded. To detect long term drift and to compensate the thermal expansion so called "dummy gauges" are placed within the concrete. These gauges have the same temperature history but they are protected from mechanical load. By subtracting these "reference gauges" from the "working gauges" the strains caused by the mechanical load and creep effects can be separated (Fig. 6).

The different strain conditions corresponding to the different load levels of the cycles can be recognized evidently.

Similar load levels create similar strain conditions in every cycle. There is no significant change in the vessel behaviour. The permanent deformations are low after the first year of full load operation.

Similar results show the reading of the change of the internal diameter measuring system (Fig. 7). There is an identical behaviour in both cycles 6 and 7. A deformation Modul of the inner diameter of about 5,5 µm/m · bar leads to a Young's Modulus of the structural concrete of $3{,}7 \cdot 10^6$ N/cm^2. That is a bit smaller than expected from the laboratory tests. The Modul of thermal expansion of the inner diameter is lo,3 µm/m°C, that is in the range derived from the previous tests.

The results of the verification program up to now demonstrate that it is possible to design, construct and operate a PCPV at higher temperatures if the specific properties of the materials are taken into consideration.

5. References

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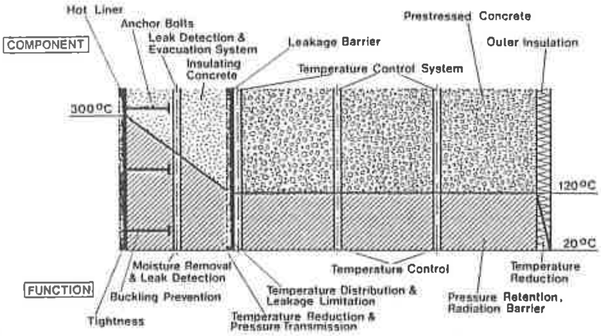

Fig. 1: PCPV with elastic hot liner

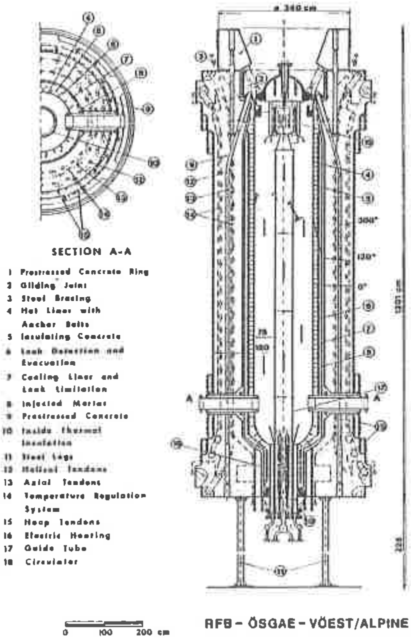

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Fig. 2: Prototype PCPV

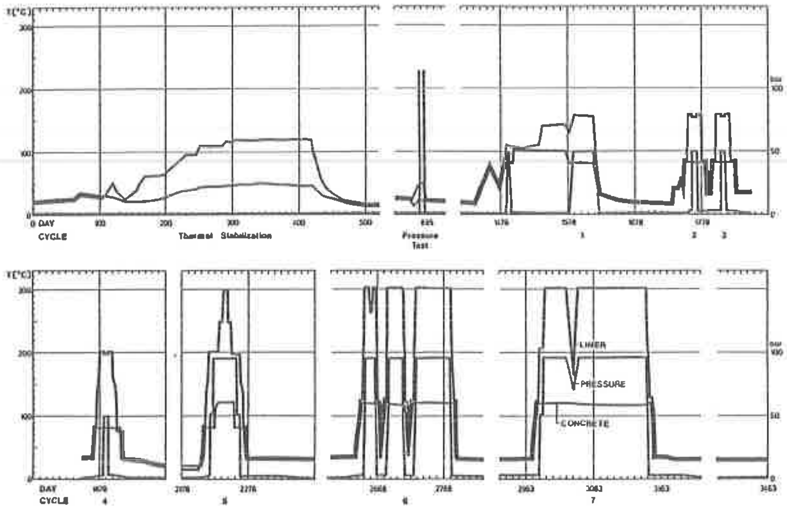


Fig. 3: Load history

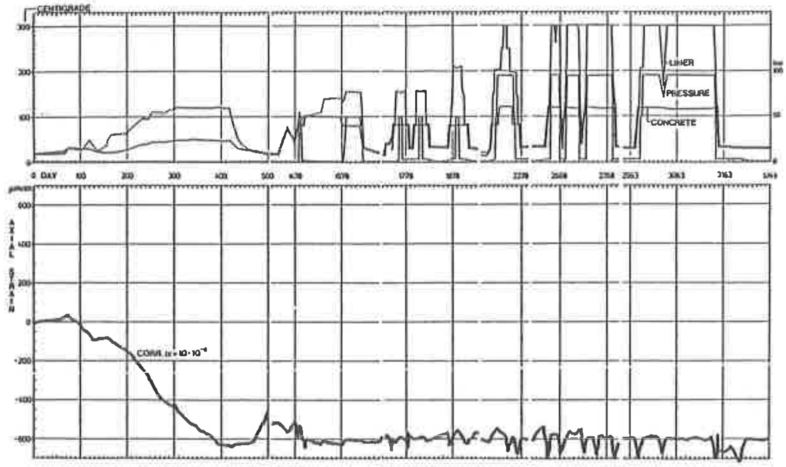


Fig. 4: Dial gauge measurement on outer surface

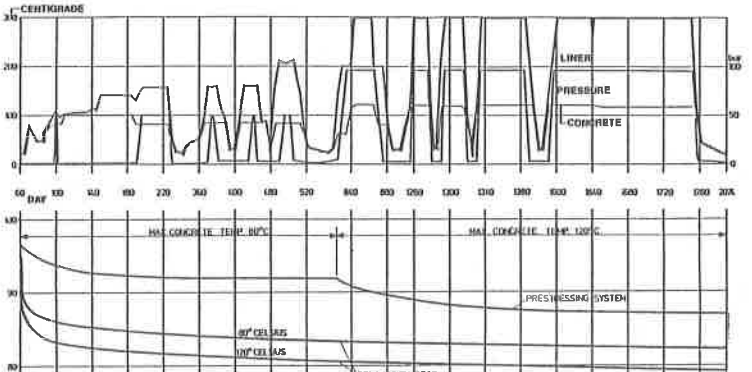


Fig. 5: Prestressing system

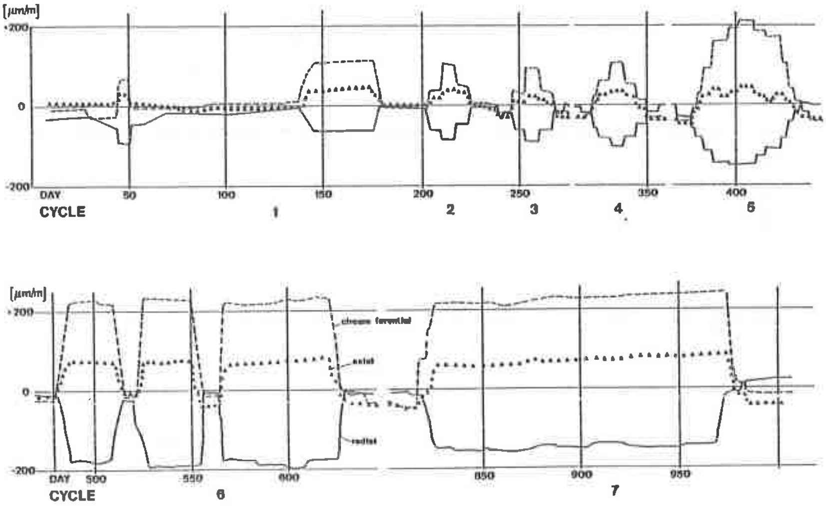
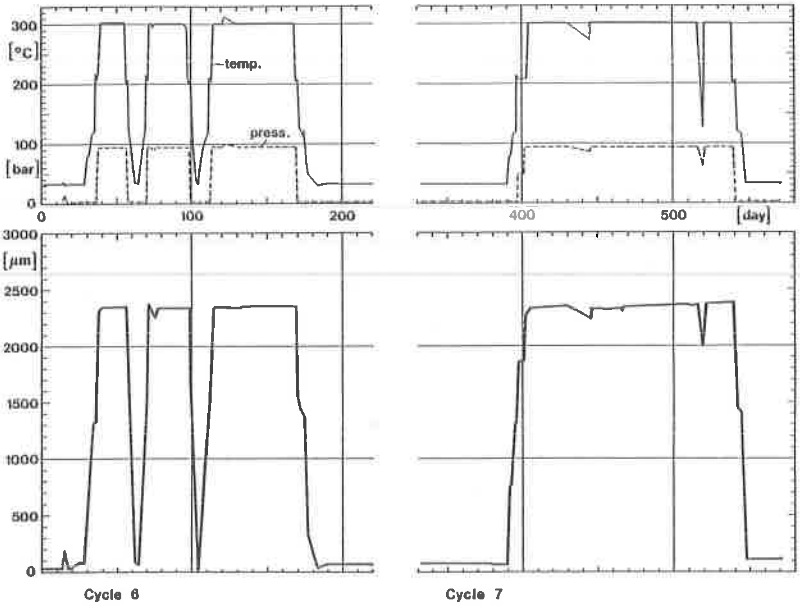


Fig. 6: Structural concrete deformations



Cycle 6

Cycle 7

Fig. 7: Change of inner diameter