Concept of a Prestressed Cast Iron Pressure Vessel for a Modular High Temperature Reactor

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Abstract – High Temperature Reactors (HTR) are representing one of the most interesting solutions for the upcoming generation of nuclear technology, especially with view to their inherent safety characteristics. To complete the safety concept of such plants already in the first phase of the technical development, Prestressed Cast Iron Pressure Vessels (PCIV) instead of the established forged steel reactor pressure vessels have been considered under the aspect of safety against bursting. A long-term research and development work, mainly performed in Germany, showed the excellent features of this technical solution. Diverse prototypic vessels were tested and officially proven. Design studies confirmed the feasibility of such a vessel concept also for Light Water Reactor types, too. The main concept elements of such a burst-proof vessel are: Strength and tightness functions are structurally separated. The tensile forces are carried by the prestressing systems consisting of a large number of independent wires. Compressive forces are applied to the vessel walls and heads. These are segmented into blocks of ductile cast iron. All cast iron blocks are prestressed to high levels of compression. The sealing function is assigned to a steel liner fixed to the cast iron blocks. The prestressing system is designed for an ultimate pressure of 2.3 times the design pressure. The prestress of the lids is designed for gapping at a much smaller pressure. Therefore, a drop of pressure will always occur before loss of strength (“leakage before failure”). In addition to these safety features further technical as well as economic aspects generate favorable assessment criteria: high design flexibility, feasibility of large vessel diameters; advantageous conditions for transport, assembly and decommissioning due to the segmented construction; advantage of workshop manufacturing; high-level quality control of components. Nowadays, considering the globally newly standardized safety requirements, especially after the Fukushima accident, as well as the progress of the HTR-technology especially in China, the interest for the PCIV concept has been reactivated.

I. INTRODUCTION

Already 40 years ago the concept of a Prestressed Cast Iron Pressure Vessel (PCIV) for nuclear power plants was developed, primarily with respect to the High Temperature Reactor technology [1], [2], [3], [4], [5]. At that time goals like design flexibility, improved transport logistics and optimized safety characteristics were positioned in the center of the discussions between prospective manufacturers and users. However, after approx. 20 years of intensive and successful research work with some prototypical test vessels (Figs. 1 to 5), the final development steps were not initiated, influenced by the reduced global interest in pursuing the HTR concept as well as by the availability of established standardized forged steel pressure vessels.
The increased engagement for the so-called next generation reactor types, the successful development of Chinese HTR projects and the situation after the Fukushima accident leading to newly standardized safety requirements promoted the idea of a reactivation of the PCIV technique.

The following paper summarizes the basic design elements and major issues of the practical experience during the development phase.

II. OVERVIEW OF PCIV DEVELOPMENT

Research on the PCIV started in 1973. Following up on a feasibility study, a first prototype test vessel was built (Fig. 1, Table 1). At a scale 1:7.5 to the Reactor Pressure Vessel (RPV) of the Thorium High Temperature Reactor THTR-300 (that was in the design stage at that time) it already displayed all the main features of a PCIV.

The full-scale research on the PCIV-HTR started in 1975. Under the leadership of Siempelkamp there were diverse partners for reactor design and the development of major components like prestressing systems and steel liner. First work on a nuclear design code for the PCIV was done by independent experts [6].

To demonstrate the qualification of the PCIV concept, a helium storage vessel for the scram tank for the THTR-300 reactor was designed (Fig. 2, Table 1). The design was investigated by competent authorities who also required extensive material and component testing. The vessel received its nuclear license, was manufactured and went into operation in 1980 [7]. The test of the ultimate load behavior of the hoop prestressing tendon (that was part of the licensing requirements [20]) is described in section VI.1 of this paper.

The PCIV research project culminated in the design, manufacturing and extensive testing of the PCIV-HTR test vessel. At a reduced scale it featured the major design aspects of a full-size PCIV-HTR. (Figs. 3 to 5, Table 1) The design, manufacturing and assembly were supervised by competent authorities. The assembly and operation of this test vessel under a wide range of loading conditions successfully demonstrated the suitability of the PCIV as RPV for the HTR (selected results in section VI.3).
The feasibility of a PCIV-HTR was further studied in a follow-up investigation [8], [9], [10], [11], [12], [13], [24]. Its object was to further validate the technology, its safety features and its suitability, this time for a HTR module reactor. In this context Siempelkamp and multiple partners investigated the feasibility of passive decay heat removal for a PCIV-HTR. The primary cell wall was also designed using Ductile Cast Iron (DCI) blocks with integrated cooling elements instead of the standard design concrete wall (Figs. 6 and 7). These were components of an inactive and redundant cooling system using the principle of natural convection.

A wall and primary cell segment was built. This full scale mock-up included all components of a 20°C sector. The extensive tests showed that this design can safely handle a loss of coolant accident (selected results in Section VI.4).
With the research program on the HTR module reactor and the mock-up for testing decay heat removal the large publicly supported research programs came to an end. In a much smaller follow-up program the design of a PCIV for a Boiling Water Reactor (BWR) was investigated. The design requirements of a diameter of 6.9 m and a pressure of 8.8 MPa were the largest ever for PCIVs.

Up to the HTR module reactor the design had always called for double-walled DCI blocks connected by ribs. The axial tendon was placed in the wall center (Figs. 3, 6, 7, 14). With the challenge of the BWR a slimmed-down single wall design was developed. In addition, the separate DCI anchor blocks for the liner were also eliminated. The liner bolts were anchored directly to the single cast iron wall blocks. The axial tendons were placed outside (Fig. 8). Temperature gradients in the cast iron now were much smaller than before, reducing the associated stresses.

A major question was the stress concentration in the wall caused by the holes for the liner anchors. Extensive stress analysis for stationary and transient conditions followed [23]. It was found that the stress concentrations can be kept on an acceptable level.

The last investigation up to date was the design work for a PCIV-HTR 600 module reactor. This was done by Siempelkamp as a sub-contractor in the EU supported international project RAPHAEL. The design was executed for inside dimensions of 7.3 m in diameter by 21.7 m in height and a pressure of 6.5 MPa. The total weight of DCI blocks, prestressing systems and liner added up to just over 4,000 tons. A major element of the design work was an in-situ cooling and decay heat removal system in the cast iron wall. This is in extension of the concept of passive heat removal in the primary cell that was designed and tested in the preceding project (Section VI.4). With the help of the in-situ wall cooling, the design temperature of the wall could be reduced to 270°C.

Table 1: Overview PCIV design and testing.

<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Inside diameter</th>
<th>Temperature and medium</th>
<th>Design pressure MPa</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Prototype test vessel</td>
<td>2 m</td>
<td>40°C, water</td>
<td>3.9</td>
<td>Shows feasibility of PCIV concept before start of extensive research program</td>
</tr>
<tr>
<td>1981</td>
<td>Scram tank</td>
<td>2 m</td>
<td>30°C, helium</td>
<td>22.6</td>
<td>Nuclear license and service in THTR-300</td>
</tr>
<tr>
<td>1986</td>
<td>PCIV-HTR test vessel</td>
<td>4 m</td>
<td>130°C, water</td>
<td>5.3</td>
<td>Production and assembly experience. Wide range of tests of a PCIV</td>
</tr>
<tr>
<td>1987</td>
<td>Design of PCIV for HTR Module</td>
<td>5.9 m</td>
<td>300°C, helium</td>
<td>7.0</td>
<td>Design extended to a passive heat removal system in the primary cell</td>
</tr>
<tr>
<td>1989</td>
<td>Test facility for passive heat removal</td>
<td>20° sector</td>
<td>max temp. at heater 610°C</td>
<td>-</td>
<td>Wide range of tests of passive decay heat removal of PCIV-HTR and primary cell</td>
</tr>
<tr>
<td>1994</td>
<td>Design of PCIV for BWR-1000</td>
<td>6.9 m</td>
<td>300°C, water</td>
<td>8.8</td>
<td>PCIV design for boiling water reactors. Liner anchors directly in the DCI wall</td>
</tr>
<tr>
<td>2006</td>
<td>Design work on PCIV for HTR-600</td>
<td>7.3 m</td>
<td>300°C, helium</td>
<td>6.5</td>
<td>PCIV design for HTR-600, in-situ cooling system integrated into DCI wall</td>
</tr>
</tbody>
</table>

III. PCIV DESIGN ELELMENTS

The most important design principles of the PCIV are the separation of the load carrying structure of wall and heads from the prestressing system and the separation of strength and tightness functions. The load carrying structure of the cylinder is a solid wall (at the outset the design had called for double-wall blocks). The top and bottom heads are structures with solid faces connected by ribs. Cylinder and heads are segmented into blocks. These blocks are made from DCI material. The wall and heads are prestressed by straight axial and wire-wound hoop tendons. A liner is anchored to the castings by bolts (Fig. 8).

Due to high levels of prestress the wall structure operates in compression under all loading conditions. Faces between the segments are areas of zero tensile stress. Shear forces are held to minimum by orientation of segment faces normal to major compressive stress. Remaining shear forces are transmitted by shear keys. Just as for conventional prestressed concrete structures, the cross sections of
the DCI blocks are much larger than the cross sections of the prestressing tendons. The loads under all operating conditions therefore are primarily carried by the cast iron: its level of prestress is reduced.

DCI is a material with very good strength and high ductility. There is very much experience in high quality manufacturing. It has a fine grained and ferritic microstructure. The pearlite content is small. The graphite nodule count is high (Fig. 9). These properties result in very good fracture toughness. DCI is not sensitive to cracks. There were extensive material investigations [14], [15]. Noticeable improvements of its properties also resulted from the development of DCI casks for storage and transport of radioactive material (e.g. CASTOR®).

There is a wide range of applications that includes highly stressed and heavy walled components as for large press frames and wind power, among others. DCI can be manufactured with large wall thicknesses. It is suited to operate at elevated temperatures. In the PCIV the segments operate under compressive mean stresses and thus in its range of maximum fatigue strength.

All standard inspection procedures can be applied. Siempelkamp is equipped and licensed for these tests. DCI is a material well suited for ultrasonic inspection for internal flaws. When required the inspection can encompass 100% of the volume. Inspection for surface flaws is standard, either as dye penetrant or magnetic particle test.

System tightness for operation conditions of the PCIV is assigned to a steel liner anchored to the DCI blocks [19]. The liner is prestressed together with the DCI blocks. The bolts are designed to keep the liner from buckling. The bolts are designed to transfer shear and are closely spaced. They are not subject to tension.

Heads of PCIVs can be designed as removable lids. The axial prestress of removable heads is designed such that they can be removed while axial prestress of the remaining vessel is upkept. Hoop prestress is not affected.

The concept of the PCIV shows high flexibility of design. If required, wall thicknesses of the DCI blocks can be produced with high material quality up to 400 mm. Heights and widths of the segments can be adapted to any particular design and assembly requirements. There is no practical limit on vessel height. Axial tendons of any length can be manufactured and assembled. Vessel diameters can be very large. For all practical reasons there is no
limit on the amount of hoop prestress. With appropriate structural design of the vessel heads, the diameters of a PCIV can exceed that of welded steel vessels. The challenges of manufacturing, machining, transport and assembly do not increase with vessel size. Flexible block shapes, dimensions and weights are further important advantages for handling and transport. The logistics of component production are relatively simple. The same holds for transport, assembly and disassembly. These aspects have been proven by the two test vessels as well as by the PCIV for the THTR-300 scram tank described in Section II. All three vessels were dismantled after use respectively after decommissioning.

The DCI material required for the vessel is a standard product and readily available. All demanding production and inspection steps are done in the shop and not during on-site assembly.

After licensing and completion of all design and first-of-its-kind work, a PCIV-HTR would require on the order of two years for completion. That would include casting and machining of the segments, transports, assembly of liner and DCI segments and finally axial prestress and wire-winding.

Despite the segmentation of the vessel wall into DCI blocks, the PCIV structure can be efficiently pre-computed by finite element analysis. The machining tolerances of the blocks are very small. The assembled structure responds to prestress like an unsegmented solid structure. This was extensively monitored during the prestressing sequence of the PCIV-HTR test vessel. Prestress levels measured by strain and forge gages and displacements of the vessel due to prestress were in good agreement with pre-computed values. There was no shear movement between blocks. This good agreement between pre-computed and measured stresses and displacements also held true under internal pressure and temperature loading. The joints between the blocks did not gap under design loads.

Experience was gained with the manufacturing of conventional segmented wire-wound DCI structures like the press frame shown in Fig. 10.

IV. SAFETY FEATURES

The concept for RPVs requires the exclusion of large fractures. By definition a large fracture will lead to loss of coolant. A fracture is also defined as to develop quickly (< 1 s). This may cause an explosion of the vessel which in turn yields to wide distribution of large amounts of radioactive material. The kind of radioactive isotopes developing in an accident also depend on the rapidity of vessel fracture and explosion.

The separation of load carrying functions into castings and tendons and the sealing function of the liner allows for optimizing each component. The prestressing tendons of a PCIV are designed to withstand an ultimate pressure of 2.3 times the design pressure. Under overload pressure (at a level to be determined by the designer) the joints between the DCI segments will lose their prestress. All further load increase will then be carried by the prestressing system alone. This design feature ensures that there is always gapping and reduction of pressure before failure by bursting. This important property was successfully demonstrated in the PCIV-HTR test vessel (Section VI.3).

The prestressing system is of redundant design. Tendons carry loads independently of each other. Failure of individual wire cross sections cannot and do not propagate to other sections. Both prestressing systems are designed for carrying ultimate loads. Under ultimate load the prestressing systems display yielding and no sudden failure. This was clearly shown in full scale tests for both hoop and axial tendons (Sections VI.1 and VI.2).

In-service instrumentation can be installed for permanent surveillance. Cable forces and therefore also the level of vessel prestress can be monitored by redundant force gages, for axial cables as well as hoop tendons. This concept was used and executed in the PCIVs described in Section II. The tendons are accessible for in-service inspection.

DCI provides good shielding. The level of neutron radiation on the prestressing system is much reduced. This reduces the potential for embrittlement of the wires.
V. MANUFACTURING AND ASSEMBLY

DCI blocks for PCIVs are produced in the same way as castings for a wide range of other applications. Blocks with weights far exceeding 100 tons are standard in every-day production. Siempelkamp is the leading manufacturer of heavy sectioned DCI castings. The castings are made with sand molds. The number of castings required for a PCIV could be performed by Siempelkamp by itself within a very reasonable time frame.

Machining of the blocks can be performed by Siempelkamp itself and by a host of external shops. For a short production schedule of a PCIV there would be several shops involved. Machining to very small tolerances is routine. Fitting the blocks together poses no problem. Machining of the blocks for the PCIV-HTR test vessel was done by three different shops. In pre-assembly and during wire-winding the segments displayed a perfect fit.

The axial tendons for the PCIV follow the established design of Bureau BBR. This is a design with widespread application in civil engineering. There is a parallel arrangement of round wires that are anchored with button heads (Fig. 11). For the PCIV the tendon forces must be very high. This requires a much bigger number of wires per tendon. Therefore the sizes of the anchor heads must also be much larger. As part of the PCIV-HTR development such anchors and tendons were built and tested by SUSPA and HRB (see Section IX.2). The axial tendons are manufactured completely in the shop and then transported to the construction site.

On-site construction of the PCIV begins with the assembly of the blocks of the bottom head. The bottom head is partially prestressed with a few wire layers in a raised position and lowered onto the vessel supports. The shop-machined liner panels for the bottom head and the transition to the cylinder are put in place in raised positions so as to permit welding and inspection from both sides of the welds. After lowering the liner bottom into its final position, work continues with welding together of the full-height panels of the cylinder liner. This includes all forgings for the penetrations. The liner bolts are welded and inspected starting with the bottom head and continuing with the blocks of the cylinder that are placed ring by ring and also partially prestressed with a few wire layers. Bolts with welding defects can be removed and new bolts placed. A perfect fit and plane surface, for example for the seals of the lids, is achieved by local on-site machining of the liner forgings. Both of these procedures were successfully tested in full-scale mock-up tests and in the PCIV-HTR test vessel. Finally the axial prestressing tendons are put in place. Axial prestress is done in sequence with winding more circumferential wire layers.

VI. MAJOR RESULTS OF LARGE-SCALE TEST SETUPS

VI.1 Ultimate load behavior of a hoop tendon

The circumferential wire winding was a first-of-its-kind design. The competent authorities in the nuclear licensing of the PCIV scram tank required a full-scale mock-up test of such a hoop tendon up to failure [20], [21]. For the test, the wires were applied indirectly onto a large number of stressing shoes spaced uniformly over the circumference of the wall section (Fig. 12). The stressing shoes were lifted radially by high pressure tension-bars (simulating internal pressure). The complex hoop tendon behaved similar to a standard tensile specimen. A linear phase was followed by a non-linear phase with tension-bar forces and radial displacements still increasing. This was followed by a yielding phase. One by one individual wires in the lowest two layers (subject to the highest increase in stress) ruptured. However, this did not result in a reduction of overall tendon force, since neighboring wires took up the difference. Testing continued until several dozen wires had failed. The average stress in the total wire package at that point had reached 97% of the nominal tensile strength of an individual wire.

VI.2 Ultimate Load Behavior of an axial tendon

The axial tendons used in all of PVIC-HTR research were designed by Bureau BBR of Switzerland. The design for the RPV at the time of this test called for axial tendons made up of 324 round 7 mm wires. Such a tendon was tested under stepwise load increase up to ultimate loading. The test was terminated under marked yielding and after several wires had ruptured. These ruptures did not
lead to a drop of total tendon force. The maximum force corresponded to 104% of the nominal tensile strength of the 324 wires. The anchor remained intact. It could be concluded from the performance of the anchor head that heads with up to 400 wires are feasible [22].

VI.3 PCIV-HTR Test Vessel

The test vessel featured the major design aspects of a full-sized PCIV-HTR. The number of DCI blocks was very large in order to study the performance of a segmented wall in assembly (machining tolerances, liner, prestress) and under loads. The internal pressure was equal to that of the reference HTR at that time (5.3 MPa). Prestress was designed for an ultimate load of $2.3 \times 5.3 = 12.2$ MPa. In order to limit costs, water and not helium was used as pressure medium. For the same reason of costs the temperature was limited to 130°C, allowing water to be used as pressure medium. Otherwise the external peripheral components of the heating and pressurizing circuit would have been demanding and too cost intensive.

Segmentation of the bottom head into 13 blocks represented the top head segmentation of the reference PCIV-HTR. A very large opening in the top slab received a removable lid. It was placed eccentrically in order to cause non-symmetric deformations for the surfaces at the ring seal under loads. The machining of the DCI blocks was done by several subcontractors. There was no problem with the dimensional tolerances during assembly.

The test vessel was fully instrumented. Besides strain and temperature gages, force gages were measuring the forces in the axial and hoop tendons. Surface displacements were measured against an outside frame. Displacement gages also monitored block joints. Agreement between measured and computed results was good. This shows that the finite element pre-computations can simulate PCIV behavior despite its complex structure.

The block joints did not gap under design pressure. Gapping at the lid was specified to occur at an overload pressure of $1.3 \times 5.3 = 7$ MPa. In order to measure a helium leak rate, the seal was located in between two concentric ring areas. The inner ring area was under helium pressure (equal to water pressure). In the outer ring the helium leak rate was measured. Up to a pressure of >6.5 MPa the leak rate was minute. Leakage occurred under the specified pressure of 7 MPa. At that point the compression of the seal had been reduced by 0.4 mm. Leak-before failure was demonstrated.

For the ultimate loading test the axial prestress of the lid against the top head had to be increased in order to avoid gapping at the lid. The PCIV mastered the pressure of 12.2 MPa. There were marked gaps at a number of joints.

VI.4 Test of passive decay heat removal system for a PCIV-HTR Module Reactor

A full-scale mock-up of the RPV wall and primary cell were built as a 20° sector of about 2 m in height with original geometry (Fig. 7) and materials. To simulate the symmetry conditions in the cylinder wall (no heat flow circumferentially and vertically) there was massive insulation on the respective faces (Fig. 13). One of the test goals was to measure the details of the heat flow from the electric heater through the complex structure to the cooling pipes and the primary cell outside surface to improve future pre-computation.

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The maximum heat flow in a HTR cooling accident of 5 kW/m² could be safely handled by the passive cooling system, despite a near doubling of the temperatures in the structure. The feasibility of a PVIC for a HTR module reactor with passive decay heat removal was confirmed.

VII. CONCLUSIONS

The design of the prestressed cast iron vessel was investigated deeply since the mid 1970’s. Many companies and research institutes renowned in the field of nuclear engineering took part. Material research took place on components like cast iron, prestressing steels and liner. Most of the design features were thoroughly analyzed and extensively tested in large scale realistic tests and full-scale mock-ups. As a rule this also covered behavior under ultimate loads. Much of the work was accompanied by seasoned experts. In one case a nuclear licensing procedure was run through for a PCIV that went into service in a nuclear power plant. For political reasons the research slowed down after the Chernobyl accident and came to a halt in Germany about twenty years ago. No further work is planned at this stage. The PCIV is a promising concept for a reactor pressure vessel, especially with view to today’s enhanced safety requirements. The level of design validation is high. Nevertheless, significant work would remain for advancing from the concept stage to nuclear licensing.

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