ADVANCED PRESTRESSED CONCRETE PRESSURE VESSELS FOR GAS-COOLED FAST BREEDER REACTORS

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For application of PCPV’s for GCFR’s two types of structures were investigated: a multicavity pod-boiler version and a design with a central reactor vessel surrounded by satellite vessels for steam generators and auxiliary circulators, rigidly connected to the central vessel. Both types include an elastic hot liner and a temperature regulated vessel wall.

The first part of the paper describes a study carried out for the pod-boiler type. For the operating conditions

<table>
<thead>
<tr>
<th>Liner Temperature</th>
<th>Gas Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>steady state</td>
<td>245°C, 120 bar</td>
</tr>
<tr>
<td>emergency</td>
<td>275°C, 138 bar</td>
</tr>
</tbody>
</table>

a vessel was laid out with 30 m overall diameter and 27 m overall height including 10 pods in the vessel wall (3.50 m diameter) connected with the central vault (8.20 m diameter). The regulated concrete temperature is limited to 95°C and provides the elastic behaviour of the liner as well as the adaptability to different transient conditions during the lifetime of the plant. Assessment of the structure including prestressing, liner analysis and longterm behaviour of the vessel was carried out in accordance with accepted codes, especially with ACI/ASME Sect.III.

A large removable revolving concrete closure with a weight of about 3500 kN tightens the central cavity. The cover has a cold liner and transmits the inner pressure by hold down toggles to the vessel wall. The lateral pods have also concrete closures. Other singularities of the vessel e.g. the bottom of the cavities, the ducts between cavities and the perforations of the top closures are investigated with regard to their operational conditions.

The second part of the paper deals with an alternative vessel arrangement consisting of separate pods in a satellite-configuration. This design has to consider the special requirements of prestressing and a rigid connection of the satellites to the central vessel in the region of the gas ducts. Solutions for the critical areas are presented.

A critical comparison of the two concepts with regard to their technical and safety characteristics is given and discussed. A proposal for further development program for the PCPV with hot liner for a GCFR concludes the paper.
1. Introduction

The Austrian concept for a PCPV with elastic hot liner has been developed and tested for HTR-conditions for 10 years. Its adaptability to different working conditions was verified in designs for large-scale PWR and HTR-K (HTR with double-circuit) vessels /1, 2, 3/. The present paper discusses two alternative designs for a Gas Cooled Fast Breeder Reactor (GCFR). Besides a significant gain in operational safety this vessel type offers an inspectable and repairable liner and is floodable.

The specific GCFR requirements differ from previous designs, so that for a number of problems e.g.

- vessel geometry including intersections of the liner (hot gas ducts, closures, liner edge construction etc.)
- vessel assessment and adaptation for GCFR-normal operation and emergency conditions
- material behaviour in operational temperature range and stress state
- possible construction methods

special solutions were to be found.

Two types of structures

- a multicavity vessel
- a satellite version

influence both the primary coolant circuit design and the method and sequence of vessel construction.

2. The multicavity vessel

2.1 Basis of design

The central cavity for installation of the reactor core is surrounded by 6 steam generators and circulator vaults and 4 pods containing auxiliary core-cooling heat-exchangers (fig.1). The pods are connected to the core cavity by concentric gas ducts. The main data are:

- central vault - 8,20 m inner diameter
- steam generator pods - 3,50 m inner diameter
- revolving lid - 6,90 m diameter
- hot gas ducts - 1,50 m inner diameter

The cavities are sealed by concrete closures. The closure for the central reactor cavity has to be removable. During refuelling tightness has to be maintained and the closure has to revolve. The pod concrete closures are not to be opened periodically, nevertheless opening should be possible for steam-
generator removal and reinstallation. Due to their higher probability of failure and limited accessibility no compensators are used in this design.

The vessel assessment is based on the temperature and pressure conditions of the primary coolant in the core inlet range i.e. the service conditions of the liner. In tab.1 the main steady-state and transient conditions and their frequencies are specified. The design considered existing codes and regulations for PCPV's, e.g. ASME-Code, Sect. III, Div. 2.

2.2 Thermal assessment

For obtaining increased operational safety by reduced liner constraints the temperature loads are optimally distributed to the whole vessel wall, making use of the thermal behaviour of the materials. The design liner temperature of 275°C decreases within the thermal barrier to 95°C and this level is controlled by means of a simple temperature regulation system in the prestressed concrete. Thus, liner stresses are limited to the elastic range. During normal operation with 245°C liner temperature the liner stresses are restrained to 2/3 of the yield stress. The annual refuelling at 150°C cold gas temperature requires no or only insignificant cooling of the PCPV. An adaption of the vessel temperatures to changing service conditions and long-term stress redistribution is possible in a simple way with the temperature control system.

2.3 Design

Thermal and static analyses for the design load cases yielded the geometry of fig. 1. The vessel with 30 m outer diameter and 27 m overall height consists from the inside to the outside of:

- hot liner
- thermal barrier
- prestressed concrete with temperature regulation system

A leak-limiting barrier between thermal insulation and prestressed concrete allows for a leak-location and controlled leak-evacuation and, furthermore, prevents the possibility of pressurized cracks in the load carrying structure. Prestress is applied to the vessel by tendons as well as by wire-winding. Helical and dome prestressing improve, if used, the stress state and cause a better balancing of liner restraints.

A long-term analysis of local liner peak-stresses leads to sufficient safety factors against fracture based on experimental and theoretical low cycle fatigue-curves. Besides full load cycles due to start-up and shut-down, disturbances in normal operation and emergency loads were also considered. The long-term behaviour of the PCPV can be influenced and improved by a thermal stabilization before operation which means a heating of the vessel to the subsequent operation temperature.
2.4 Details of design

2.4.1 Revolving central cavity closure (fig. 2)

The large, removable revolving lid of the central reactor cavity with a weight of 3500 kN was designed with an inner insulation. This fact involves a more complicated inspection of the cover liner, but on the other hand the access to the closure liner is possible by removal of the closure.

The closure transmits its high loads resulting from internal pressure by hold-down toggles to the axial tendons of the vessel. The arrangement of a secondary back-up is basically possible, but because of the load transmission with compressed elements not necessarily required.

Both the main seals for service conditions and the inflatable rubber seals used during refuelling with the rotating cover, are fully exchangeable.

2.4.2 Closures of the pods

The closures for the boiler cavities are removable concrete plugs with hot or cold liner. Fig.3 shows a "hot" design, in which the liner is constrained by constructive means.

2.4.3 Hot gas ducts

For the connection of the cavities coaxial hot gas ducts are used. The intersections of the penetrations with the cavity liner are in accordance with the hot liner principles. They ensure a safe anchoring of penetration loads / 4 /

3. Different aspects of the satellite version

3.1 Vessel design

Arguments for the satellite configuration are the better whilst more uniform material exploitation (fig.4), lower tolerances and thus, allowability of higher system pressures as well as the qualification for natural circulation in the primary circuit.

Six satellites with 3,50 m inner diameter are rigidly connected to the central vessel with 8,20 m inner diameter (fig. 5, 6). The high position of the satellites containing the steam-generators and auxiliary systems allow for core-cooling by natural convection in the case of a circulator fall-out.

Some of the solutions, developed for the multicavity version, e.g. principal thermal and static assessment, constructive elements (closures, gas ducts etc) and material behaviour can be applied to this design. Different conditions exist for the rigid: connection of the satellites to the central vessel and the construction sequence of the vessel.
3.2 Site erection

Although most of the known prestressing methods can be applied to the satellite construction, inner-ring radial prestressing may offer significant advantages. Previous investigations indicate special solutions in the region of the vessel connections.

Buttress prestressing offers the additional advantage of the possibility of tendon changing and its adaptation to the long-term behaviour of the vessels. Furthermore, it allows, like the radial prestressing concepts, a better control of liner stresses.

Both methods yield a favourable prestressing in the region of the gas ducts. The well-known wire-winding seems to be less qualified for the satellite configuration. Apart from the connection area which cannot be prestressed directly and the connection elements to be anchored separately, the single vessels have to be erected in a certain distance from each other for the passage of the wire-winding machine and then shifted into place. This leads to greater supporting structures and more extensive shifting of heavy loads. An application of the wire-winding in the regions all other but the vessel connection regions seems to be possible.

3.3 Vessel connection

A rigid vessel connection without any relative displacement is required. Vertical and horizontal loads are transmitted by a shear-resisting constructor and prestressing. The latter is most effective if it is provided in radial direction. A separable construction of the vessel connection is theoretically possible, but not necessary.

4. Conclusions and future work

In two feasibility studies the application of the Austrian concept of a PCPV with elastic hot liner for the specific conditions of a GCFR both for a multicavity version and a satellite-configuration was demonstrated. Clear and well proportioned design and a better and more uniform exploitation of materials for the satellite-version are to be compared with partially new or unproved construction and vessel connection methods. Besides the proof of feasibility of such a PCPV the studies offer sufficient solutions as a basis for a reference design. This future work should provide all investigations required for licencing, including an additional experimental program.
References


Tab. I: Main operating conditions of the PCPV for GCFR's

1. Normal operation

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady-state operation pressure</td>
<td>120 bar</td>
</tr>
<tr>
<td>Steady-state operation liner</td>
<td>245°C</td>
</tr>
<tr>
<td>Design load pressure</td>
<td>138 bar</td>
</tr>
<tr>
<td>Design load liner temperature</td>
<td>275°C</td>
</tr>
<tr>
<td>Start-up and shut-down pressure</td>
<td>Δp = ± 110 bar</td>
</tr>
<tr>
<td>Start-up and shut-down liner</td>
<td>ΔT = ± 145°C</td>
</tr>
<tr>
<td>Start-up and shut-down time</td>
<td>12 hours</td>
</tr>
<tr>
<td>Start-up and shut-down frequency</td>
<td>120</td>
</tr>
<tr>
<td>Scram</td>
<td>ΔT = + 30°C</td>
</tr>
<tr>
<td>Scram</td>
<td>10 sec.</td>
</tr>
<tr>
<td>Scram</td>
<td>400</td>
</tr>
</tbody>
</table>

2. Emergency loads

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary-circuit leak pressure</td>
<td>Δp = - 117 bar</td>
</tr>
<tr>
<td>Primary-circuit leak liner</td>
<td>ΔT = - 55°C</td>
</tr>
<tr>
<td>Primary-circuit leak time</td>
<td>400 sec.</td>
</tr>
<tr>
<td>Primary-circuit leak frequency</td>
<td>1</td>
</tr>
</tbody>
</table>
1 Hot Liner with Anchor Bolts
2 Insulating Concrete
3 Cooling Liner and Leak Limitation
4 Prestressed Concrete with Temperature Regulation System
5 Dismountable Outer Insulation
6 Hoop Wire Winding
7 Axial Tendons
8 Helical Tendons
9 Dome Tendons
10 Lid Insulation
11 Revolving Lid

PRESTRESSED CONCRETE VESSEL FOR GAS-COOLED FAST REACTOR
Multicavity Version

Fig. 1 PCPV with Elastic Hot Liner for GCFR
Multicavity - Version
Fig. 2 Revolving plug sealing and hold down

Fig. 3 Removable concrete closure with hot liner for steam generator cavities
Fig. 4  Exploitation of concrete in multicavity vessels

Fig. 6  PCPV with Elastic Hot Liner for GCFR-Satellite Version, Horizontal Section