Investigations of the Function of a Liner Leak Localisation and Venting System for High Temperature Reactors

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Abstract

The internal surfaces of prestressed concrete pressure vessels are fitted with a steel liner to preserve the gas tightness of the primary circuit. The occurrence of liner leaks is improbable, but, if a leak develops during reactor operation, it may be difficult to determine the position of the leak, because the liner area is very large. So the installation of a liner leak localisation system is being considered.

A promising system consists of vertical and horizontal channels installed in close proximity to the liner, surrounding it like a coordinate system. These channels represent a pressure sink for gas flowing behind the liner and it can be expected that the largest flow rates occur in channels lying nearest to the leak. The position of the leak is then determined by the coordinate of the vertical and horizontal channels with the highest gas flows.

To investigate the behaviour of such leak localisation systems a concrete wall (length 2.50 m; height 2.00 m; thickness 0.5 m) has been constructed, covered on one side with a liner, which is anchored with bolts in the concrete.
Behind the liner two channel systems have been installed, each consisting of vertical and horizontal channels.
The first system is immediately adjacent to the liner. The horizontal channels are perforated channels welded to the liner. The vertical channels were formed by putting rods into the concrete, touching the horizontal pipes. After the concrete had set, the rods were removed so that voids having the form of channels remained.
The second system consists of vertical and horizontal channels set into the concrete. These channels were formed by inserting rods which were removed after the concrete had hardened.

For the simulation of leaks, 30 holes of 3 mm diameter were drilled into the liner and pressurised helium was then injected.

In the original state before heating the flow rates of the single leaks were in the range 10^{-7} kg/h to 10^{-1} kg/h (He-pressure at the leak = 2 bar). After heating of the liner to 70° C the flow rates became larger, and the range was now between 8×10^{-4} kg/h and 1.5×10^{-1} kg/h.
Helium flowing behind the liner expands in the interface between liner and concrete and percolates into the concrete. The channels lying on the liner represent a better pressure sink than the other channels. To reach the channels some distance from the liner the gas must flow through the concrete pores, which represent a high flow resistance. The flow rates in these channels were found to be smaller.

The distribution of flow rates over the array of channels does not show such a distinct maximum as was found for the channels on the liner and after heating it was not always possible to localise the leak using these channels as a coordinate system.

The experiments have shown that the expansion of gas after liner leaks takes place in the interface between liner and concrete. If channels representing pressure sinks are installed on the liner, the localisation of the leak is always possible and a large expansion of the gas will not occur.
The localisation system therfore acts also as a venting system.

1. Introduction

The inner surfaces of prestressed-concrete vessels for high-temperature reactors are fitted with a liner consisting of steel sheet, which has to ensure the gas tightness of the primary circuit.
The occurrence of liner leaks is considered improbable. However, should there develop a leak during the reactor lifetime, repair measures may prove to be necessary, depending on the size of the leak.

In view of the size of the liner surface, a prerequisite for a meaningful repair strategy is a monitoring procedure enabling the localisation of a leak.
The most promising monitoring system under consideration consists of channels located in the concrete near the liner or installed directly on the liner, covering it like a grid of coordinates. The channels constitute a pressure sink for the gas flowing behind the liner. It is being expected that the highest gas rates will occur in those channels which are nearest to the leak, so that the location of a leak is marked by the intersecting point of the vertical and horizontal channels featuring the highest gas flows.

Channels close to the liner were originally introduced as venting systems for PCRV to prevent a pressure build-up between liner and concrete or in the concrete itself /1/.
In the following the propagation of the escaping gas is discussed. Then two channel systems, one immediately adjacent to the liner and the other set in the concrete, are described. Results of experiments performed for testing these channel systems are presented.

2. Propagation of primary coolant gas after liner leaks

The primary coolant gas escaping from a liner leak will propagate in the liner-concrete interface, since there does not exist a perfect steel-concrete bond due to the roughness of the sheet metal and concrete surfaces.
Starting from the interface, the gas will penetrate into the concrete which contains a network of largely coherent micropores. The penetration rates may be intensified by cracks created in the concrete by shrinkage and mechanical and thermic loading.
The extent of escaping gas propagation in the interface depends very strongly on the gap width between liner and concrete in the vicinity of the leak.
In connection with a channel system embedded in the concrete, calculations relating to propagation were carried out under simplified conditions /2/.
Helium flows in a narrow gap of 50 µm gap width over a concrete surface near which channels are provided (see Fig. 1).
The channels are installed at a distance of 1 m from each other and at a depth of 0.3 m in the concrete. The permeability of the concrete is assumed to be $4 \cdot 10^{-16}$ m^2. Here cracks are not taken into consideration. As a result, about 60 % of the gas entering the gap at a pressure of 40 bars will distribute over the channels, while the remainder escapes at the end of the gap.
On the other hand, when assuming a gap width of 5 µm while retaining the same configuration, the gas volume entering the gap will be reduced more than a hundredfold. In this case, no large-area propagation of the gas takes place. Virtually all of the gas will be removed via the first two channels. This shows quite clearly, that the in reality undefined and inhomogeneous state of the liner-concrete interface exerts great influence on gas propagation and leakage rates.

3. Localisation and venting channel systems

3.1 Channel system on the liner

The principle of a channel system on the liner consists in offering pressure sinks to the gas propagating directly in the liner-concrete interface.
In connection with the cold liner concept, channels may be installed underneath the liner cooling tubes, such channels being open towards the interface by the provision of regularly arranged boreholes (see Fig. 3 /3/).
In vertical direction, channels are installed in contact with the cooling tubes, such channels consisting possibly of pipes with porous walls. There is also a possibility of providing bars or hoses, which are drawn after setting of the concrete.

3.2 Channel system in the concrete

The channel system in the concrete consists of two planes of parallel channels each. Channels in different planes are perpendicular to each other. The distance between channel systems and liner is in the range of 0.1 - 0.3 m (see Fig. 4). These channels are manufactured in the same way as the second part of the detection system which is located direct on the liner.

The channel system in the concrete was dealt with in section 2 under idealized conditions (gap of uniform width between liner and concrete, homogeneous concrete), where it was assessed that in the case of gap width in the range of 50 µm a large-area propagation of the gas in the interface is to be expected.
In a prestressed-concrete vessel, however, the state of the concrete near the liner cannot be regarded as homogeneous. On the one hand, there is a dense tie bolt grid extending right into the channel area and, on the other hand, the reinforcement system arranged on the liner provides for a distribution of cracks caused by thermally induced stresses and shrinkage. This will substantially increase the permeability in the concrete near the liner, counteracting a large-area gas propagation along the liner.

4. Experiment

4.1. Setup and implementation of experiments

Experiments were conducted in order to investigate the function of the channel systems described above.
A survey of the experimental setup is shown in Fig. 5. The object of experiments is a liner-concrete section with dimensions of 2.50 m x 2.00 m x 0.5 m /4/.
Inside the concrete wall covered by the liner, both a channel system on the liner and a channel system in the concrete are installed.
The channels arranged directly on the liner, which are open towards the liner-concrete interface due to the provision of boreholes, are placed horizontally at a distance of 0.1 m. The vertical channels complementing the system are located directly on the cooling tubes at a distance of 0.3 m from each other. They were provided by inserting bars, that were withdrawn after setting of the concrete.
The channel system in the concrete consists of vertical and horizontal channels arranged in two planes (at distances of 0.1 m and 0.3 m from the liner). The distance of the channels from each other are 0.5m.

They were likewise provided by inserted bars in the same way as the second part of the system on the liner.

Liner leaks are simulated by 3 mm boreholes fed with helium. When feeding helium into a selected leak, the other leaks remain hermetically sealed. A total of 30 points of leakage are distributed over the 5 m^2 liner. The feeding rates are measured via flowmeters.

The helium flowing to the back of the liner will distribute over the channels. The helium rates in the individual channels are determined as described in the following. Air is being sucked as carrier gas through the channel, whose gas rate is to be determined. This carrier gas mixes with the helium entering the channel. The concentration of helium in the carrier gas is ascertained via a mass spectrometer. The helium rate entering the channel may be determined via the carrier gas throughput and helium concentration.

4.2 Feeding rates of individual leaks

In the original condition prior to heating the liner, the feeding rates of individual leaks exhibited very large variations. In the case of a feeding gas pressure of 2 bars at the place of leakage, the rates were in the range of 10^{-7} kg/h to 10^{-1} kg/h of helium (see Fig. 6). These large differences in helium rates on a surface of only 5 m^2 show that the liner-concrete bond is locally very different. The gas flows virtually started at once and, in general, changed only insignificantly during the time of feeding ($\sim$ 5 min per leak). After temperature cycling, consisting in heating the liner to 70° C and cooling it to room temperature three times, the feeding rates were in the range of $8 \cdot 10^{-4}$ kg/h to $1{,}5 \cdot 10^{-1}$ kg/h at a pressure of 2 bars at the place of leakage. This process of repeated heating caused, on the one hand, a drainage of the concrete and concrete-liner interface; on the other hand, the liner-concrete bond was probably also influenced by thermally induced relative movements of the liner and concrete body. This led to an increase in feeding rates, comprising especially a shift of the lower limit (10^{-7} kg/h) by orders of magnitude.

Repeat measurements performed later revealed an increase in feeding rates by a factor of 2 for certain places of leakage.

4.3 Distribution of fed-in gas over the channels

Measurements on the distribution of fed-in gas over the channels were carried out for a multitude of leaks prior to and after temperature cycling (see Fig. 7). A localization of leaks was always possible for the system located direct on the liner. In all cases, both the horizontal and vertical channels located nearest to the leak exhibited the highest flow rates.

The distribution of flow rates over the channels also shows that channels located closer to a leak possibly take up less helium than more remote ones.

For this experiment, which was conducted after temperature cycling, the feeding rate of the leak borehole located in the central area amounted to approx. 9 Pam^3/sec. In the course of several hours, it rose monotonously to about 10 Pam^3/sec. The sum of flow rates measured in the channels amounted to approx. 14 Pam^3/sec. This sum is larger than the fed-in rate of the leak.

This paradoxical result may be explained quite simply, because the flow rates of the channels are determined one after another. When sucking air through a single channel a reorientation of the flow occurs above all in that area of liner-concrete interfaces were helium flows at low pressures. This is due to the fact that a slight underpressure is then produced in the channel, so that helium which otherwise would have taken a different course enters the corresponding channel as well.

However, the experiments show that most of the fed-in gas penetrates in the channels nearest the leak. So the channel system acts as a venting system preventing a large expansion of leaking gas along the liner-concrete interface.

Fig. 8 shows the distribution of gas rates for the channel system located in the concrete.

The horizontal channels located next to the liner clearly identify the place of leakage; in connection with the vertical channels located a little further inside the concrete it was found, that the flow rate in the outer channel was about equal to that of the channels next to the leak.

The fact, that the channel marked V 4 exhibited less gas than the channel V 5 proves that the permeability of the concrete near the liner is not homogeneous. Consequently, the flow into the concrete channel system is not only governed by irregularities of the liner-concrete interface, but also by the inhomogeneity of the concrete near the liner.

When interpreting these results, however, it should be noted, that the channel system on the liner influences the distribution of gas rates in the concrete channels by ensuring a good helium propagation on the liner.

5. Conclusion

The results of the performed experiments show, that channel systems are suitable for the localisation of liner leaks and for the venting of the leakage gas. However, it must be remarked, that the feeding at reactor-typical pressures was not possible in the tests, because the liner of the plane concrete wall would have loosened under such conditions.

Consequently, feeding pressures were confined to a few bars. In a reactor, the situation for the liner is different, since the coolant gas pressure presses the liner on to the concrete.

Thus, the conditions emerging for the liner-concrete interface are different as far as the influence produced by the leakage gas is concerned.

Moreover, the concrete near the liner in a reactor pressure vessel is considerably stressed mechanically due to prestressing and internal pressure.

Therefore it is being planned to erect a prestressed-concrete test vessel for experiments under conditions similar to those prevailing in a reactor.

This vessel is to be used for systematic investigations relating to gas escape and propagation after liner leaks, to the suitability of channel systems for leak detection and leakage gas venting, and to the pressure build-up due to gas in the concrete.

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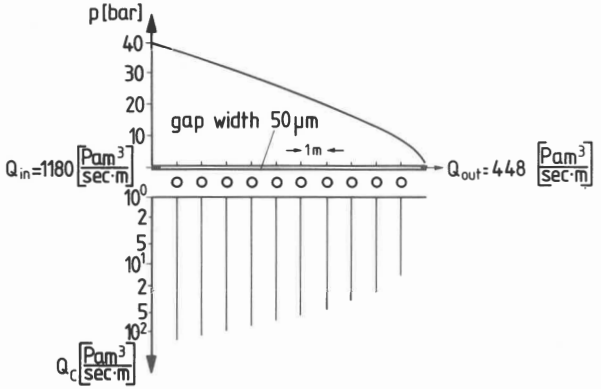

Fig. 1 Gas flow (Helium) along a 50 µm gap between liner and concrete. In the concrete channels are formed (distance from the concrete surface 0.3 m, channel diameter 30 mm, permeability of the concrete $4 \cdot 10^{-16}$ m^2). The pressure decrease along the gap and the flow rates into the channels are drawn ($P_{entrance}$ = 40 bar, T = 60° C).

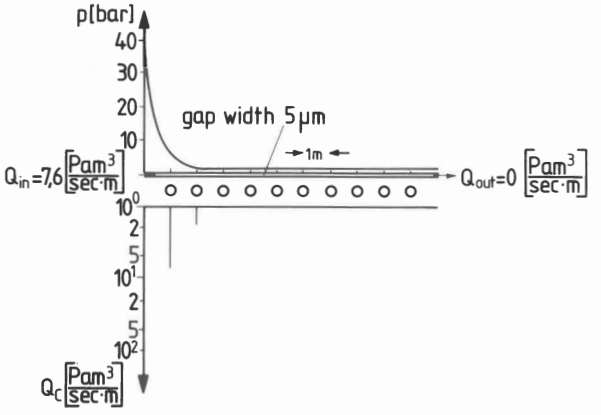

Fig. 2 Gas flow (Helium) along a 5 µm gap between liner and concrete (see Fig. 1).

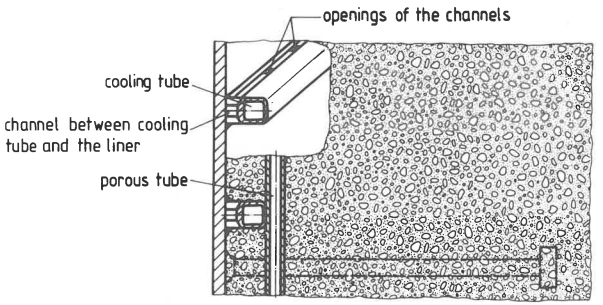

Fig. 3 Localisation and venting channel system immediately adjacent to the liner.

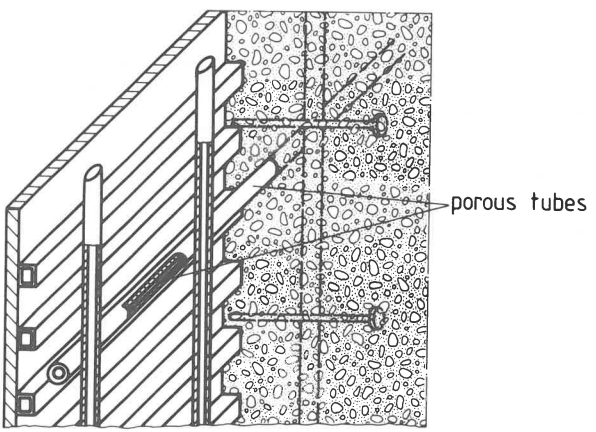

Fig. 4 Localisation and venting channel system lying near the liner in the concrete.

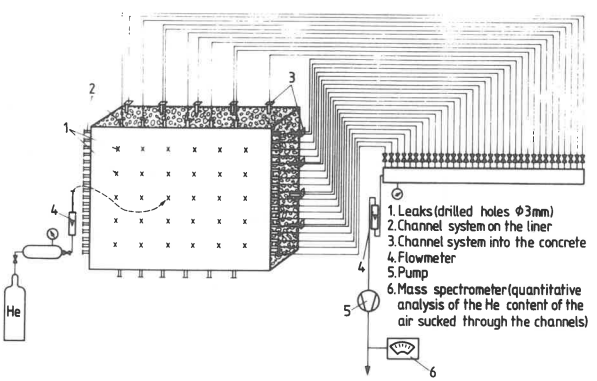

Fig. 5 Experimental arrangement for testing the function of the channel systems.

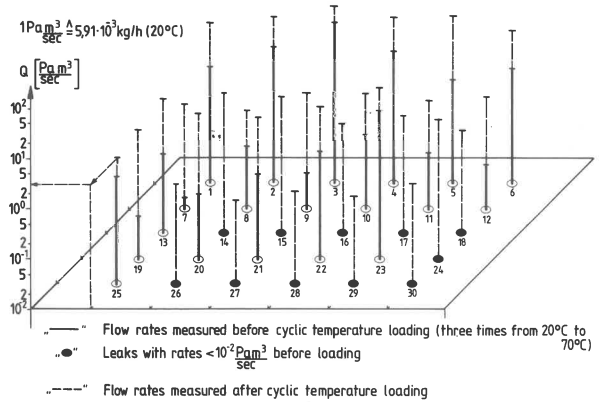

Fig. 6 Helium flow rates of the single leaks before and after cyclic temperature loading (fed-in pressure 2 bar_{abs}).

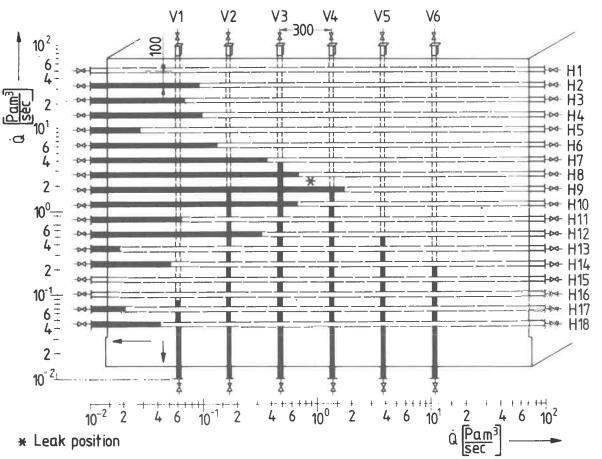

Fig. 7 Distribution of Helium flow rates over the array of the channels immediately adjacent to the liner (fed-in pressure 2 bar_{abs}).

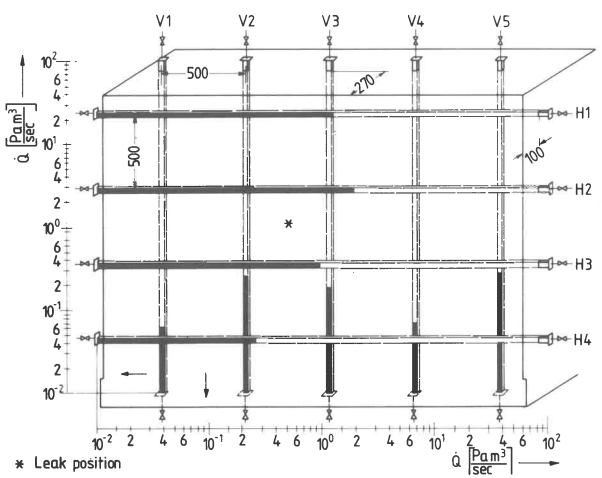

Fig. 8 Distribution of Helium flow rates over the array of the channels into the concrete (fed-in pressure 2 bar_{abs}).