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LINER LEAK SIMULATION TESTS ON PRESTRESSED CONCRETE REACTOR PRESSURE VESSELS

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SUMMARY

In the current prestressed concrete pressure vessels for gas cooled reactors, a mild steel liner is provided to keep the vessel gas tight. If, however, a small pinhole in a weld remained undetected during construction or if a leak developed during operation, coolant gas (CO_2) would be able to get behind the liner. In such a postulated event it is important to know if pressure could build up in voids behind the liner or in any cracks within the concrete.

The difficulties in building a model to demonstrate the effects of a leak are formidable so consideration was given to using actual vessels not yet commissioned. This paper reports on tests undertaken on two different vessels where gas was deliberately introduced between the liner and the concrete to simulate a liner leak. The subsequent rate of flow of the gas away from the leak point was determined, as were the positions on the outside of the vessel where the gas was venting.

The tests were undertaken on both an unprestressed and a stressed vessel prior to any heating of the vessels. The locations of the leaks were on a flat (floor slab) and a curved (boiler-pod wall) part of the liner. In both vessels there were prestressing ducts within the section of the slab or wall, a fact that contributes significantly to the likely leak path taken by the gas.

The results showed that with the vessel cold and unpressurised, the flow of gas from a small leak vented without pressure build up behind the liner. The gas flow was dependent upon the location of the leak and vessel configuration local to the position of the leak.

The most likely leak paths taken by the gas appeared to be along steel/concrete interfaces and within both horizontal and vertical prestressing ducts - the ducts in the vessels tested being of a spirally wound type.

By using portable gas monitoring equipment, the detection of leaks via the tendon ducts was possible. A leak which was equivalent to a rate approximately 7 Kg/day was easily detected venting from a number of anchorage points.

1. INTRODUCTION

The present generation of prestressed concrete pressure vessels for gas cooled reactors, are provided with a mild steel liner to act as a gas tight membrane to the carbon dioxide reactor coolant. Rigorous quality control and testing were maintained during construction but it can be postulated that a pinhole leak could remain undetected or develop during the life of the vessel. With such a possibility it is important to be able to assess its effect on the safety and serviceability of the vessel.

If reactor coolant gas penetrates behind the liner then it is possible that any cracks or steel/concrete interfaces would be pressurised. The pressurisation of the liner/concrete interface would result in a back pressure on the liner during a vessel depressurisation. The loadings would be dependent on the pressure gradient within the gas pocket or flow path. If the flow of gas were large enough, it may be further postulated that hot gas could find its way to the prestressing ducts with consequential damage to the stressing tendons.

A test programme was undertaken to assess these possibilities and their consequences. It was impractical to construct and test models or structural elements so it was decided to test full size vessels. Two geometrically dissimilar vessels were at a suitable stage of construction and the following test programme was undertaken.

2. TEST PROGRAMME

Three series of tests were made, simulating leaks from the inside of the vessels:

Series 1 These were on the liner of the bottom slab of a single cavity vessel (Vessel 1) which had vertical and hoop prestressing tendons within the vessel walls and slabs. The tendon ducts were ungrouted. The hoop tendons were laid out in groups of pairs, each pair subtending an angle of 180°. The anchorages of successive groups were displaced by 45° to obtain a reasonable uniform radial and circumferential prestressing force.

The liner of the vessel was constructed away from the reactor site and rolled into position above the bottom slab where it was grouted up. The construction of part of the liner to the base of the vessel is shown in Fig. 1.

Four "leak" points 6mm diameter, were drilled into the liner, three on a line between a pair of lugging flats at about 2 metres centres. The fourth point was at right angles to the first point, two lugging flats centres away.

The vessel was unprestressed and the applied leak pressure restricted to 1.7 bar. The pressurising gas was nitrous oxide (N_2O) which has similar flow properties to carbon dioxide (CO_2) used in operation, but without any chemical reaction with concrete.

The N_2O was applied at predetermined pressure and flow rates to each of the tapping points in turn and the pressure and flow at the other points measured.

With the N_2O applied to one of the tapping points, a search was made of the outer surface of the vessel using portable gas detecting equipment. The search concentrated around penetrations, stressing anchorages and concrete construction joints.

Section 2 This was a repeat of the series 1 tests on vessel but with the vessel prestressed. The pressurising gas was N_2O again but with a 5% addition of sulphur hexafluoride (SF_6) to assist in subsequent leak searches. The maximum gas pressure applied was 6.9 bar (c.f. operational pressure of 31 bar).

Series 3 These tests were on a multicavity vessel (Vessel 2) which had vertical prestressing tendons in ungrouted ducts and external wire winding. The test points were in the liner of one of the boiler cavities (Fig. 2). Four points were near the equator, the fifth just above the gas duct/boiler pod junction. The maximum pressure applied was 7.6 bar (c.f. operational pressure of 43 bar). N_2O with SF_6 as a tracer gas was again used for most of the tests but a final test and gas search was made using CO_2 to check its comparability with N_2O and the sensitivity of standard gas detecting equipment.

The following gas detecting equipment was used:

An Analytical Instruments Ltd. 'Leakseeker" which compares the thermal conductivity of a continuously taken gas sample to that of the ambient air. For N_2O the instrument has a detection limit of about 0.06% concentration, or 30 x 10^{-6} ml/s if a leak from a pinhole is probed. This instrument was used in the test series 1.

An Analytical Instruments Ltd. 'Leakmeter' was used in the Series 2 and 3 tests. This instrument uses a radioactive electron capture cell and has a detection limit of about 5 x 10^{-8}% concentration of SF_6. Using this instrument with the 5/95 gas mixture a detection limit of about 10 x 10^{-10} ml/s from a pinhole leak is possible.

The instruments for the CO_2 detection were a 'Drager' gas detector with a detection limit of about 0.02% and a 'Riken' gas indicator also with a detection limit of 0.02%.

3. TEST RESULTS

All the tests were conducted at ambient temperatures and unless otherwise stated, all the volumes quoted are referred to 20°C and 1 bar.

3.1 Flows and Pressure for Vessel 1

In the series 1 tests there was a flow of gas away from all the tapping points. The flow was proportional to the inlet pressure but varied for the different positions. The maximum flow reached 1.4 l/min. at an inlet pressure of 1.7 bar. Interconnected flow was only found between two tapping points.

In the series 2 tests (i.e. with the vessel prestressed) the flow characteristics changed to a non-linear relationship (Figs. 3-6). Interconnected flow between points along the same lugging bay was found but very little flow across the bays occurred. The maximum leak recorded was 10.5 l/min. at 6.9 bar.

3.2 Flows and Pressure for Vessel 2

There was considerable variation in the quantities of gas that were observed to flow away from the five tapping points. At the two equatorial points at or near a circumferential line relative to the centre of the vessel (Fig. 2 points G and H), the flow was less than 0.1 l/min. At the tapping points on a radial line from the vessel to the cavity (Fig. 2, F and I), the flow varied with pressure. Above 2 bar, this variation was linear and reached 1 l/min. at 6.4 bar. (Fig. 7). At tapping point E, adjacent to the lower gas duct, considerably greater flows were measured. Flows of 3.07 l/min. at only 1.37 bar were obtained.

For tapping points F, G, H and I, the volumes of pressurised gas behind the liner were so small that at any applied flow/pressure combination, the flow stabilised immediately. However, for tapping E, it took over an hour before stable flow/pressure conditions were reached, (Fig. 8). Clearly there was a large volume behind this position for gas to occupy. From Fig. 8, this volume was estimated to be 67 litres (assuming all the gas was at inlet pressure).

3.3 Detection of Venting Gases

During the first test on vessel 1, the venting gas could not be detected on the vessel's outer surface despite flows away from the tapping points. For the second test, the tracer gas was added to the N_2O and a more sensitive gas detector was used. A flow of 5 ℓ/min. was applied to one of the tapping points and venting gas was easily detected on the outside of the vessel. The main flows were detected at the vertical and horizontal stressing anchorages, the main concentration tending to be from those whose cable paths passed near the leak point. Leaking gas was also detected at the steel/concrete interface of the gas circulators and at a number of instrument penetrations.

The test continued for 26 hours, during which no decrease in the inlet flow rate was observed. The maximum continuous leak amounted to 5500 litres during the test period.

Similar detections were made from vessel 2. A leak of N_2O/SF_6 mixture of 1.65 ℓ/min. at 1.37 bar was introduced to tapping point E. Gas was detected at the upper tendon anchorages of the boiler closure ring and to a lesser extent at a number of lower anchorages. (There was a considerable atmospheric pressure gradient between the underside of the vessel and the top slab, causing a constant draught up the cable ducts.)

To check the possibility of gas venting along concrete constructions joints, SF_6 was introduced into tapping point F. This position was deliberately chosen to coincide with a construction joint. No clear proof of leaking gas was obtained, although gas was detected at a nearby thermocouple penetration/concrete interface.

Finally CO_2 was introduced at tapping point E at 3.07 ℓ/min. and 1.37 bar. Two different gas detecting instruments were used at the vessel surface. CO_2 concentrations between 0.02 and 0.2% were detected at a number of the upper stressing anchorages.

4. DISCUSSION

From the tests, it is evident that should reactor coolant gas penetrate the liner then it will find its way along the numerous steel/concrete interfaces. The most favoured path appears to be towards and then along the prestressing ducts. In the case of the two vessels tested, these ducts are made from spirally wound, unwelded steel tube and provided no barrier to the gas. Ingress of gas into ducts of different construction such as solid drawn tube, must be considered less likely although the passage of gas up their outside interfaces would still be possible.

Significant flows of gas were obtained and values of 11 litres/min. for an applied pressure of 6.9 bar were measured on vessel 1. The flow characteristics were not linear at the higher pressures which suggests that the liner bowed slightly with the applied back pressure to increase the flow area. Simple calculations on a transverse section of a lugging bay, show a central deflection of 0.2mm is possible for a pressure of 6.9 bar. However, under normal operation, the liner will be subject to the reactor gas pressure so flow paths would be dependent on a pressure differential across the liner.

The flow/pressure characteristics for vessel 2 were linear suggesting the boiler liner was not deflecting. This was not unexpected because of the inherent stiffness of a curved liner.

The only tapping point with any significant volume behind it was point E. This was adjacent to the intersection of the boiler liner and the lower gas duct where there was a polystyrene insert. This insert was estimated to occupy a volume of about 20 litres. The simplistic tests at tapping E indicated a pressurised volume of 67 litres. This would result in a back pressure on the liner during a hypothetical maximum depressurisation of the vessel (assuming no gas vented back via the leak). At normal blow down rates, no such back pressure would develop (Fig. 9).

The volume of gas behind points F, G, H, and I was negligible. Consequently there would be no danger of pockets of pressurised gas behind the liner in the event of an emergency reactor blowdown. The rate of pressure change for point F is shown in Fig. 9.

The fact that leaking gas found its way to the prestressing ducts has given an opportunity to develop a system for regular monitoring surveys to detect an early occurrence of a liner leak.

5. CONCLUSIONS

For the test conditions reported it has been shown that gas will flow away from a liner leak and seek a path to the vessel surface. Thus pressurisation of the liner/concrete interface at normal reactor shutdown will not occur.

Marked differences in gas flows were recorded between the different regions of the vessels but it was possible to identify the main exit routes when a strong leak was established, e.g. the prestressing ducts.

Using standard portable CO_2 gas detectors, it was demonstrated that small leaks could be detected. The leak at tapping point E was equivalent to a rate of about 7 kg/day and this was detected venting via a number of anchorage positions.

6. ACKNOWLEDGEMENTS

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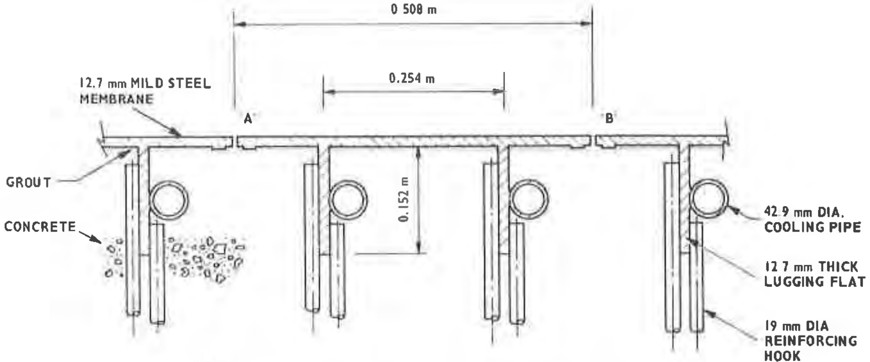


A AND B - 6 mm TAPPING POINTS AT LOCATIONS PREVIOUSLY USED AS PRIMARY GROUTING CONNECTIONS

FIG. 1 SECTIONAL VIEW OF GAS FLOW TEST POINTS, VESSEL 1

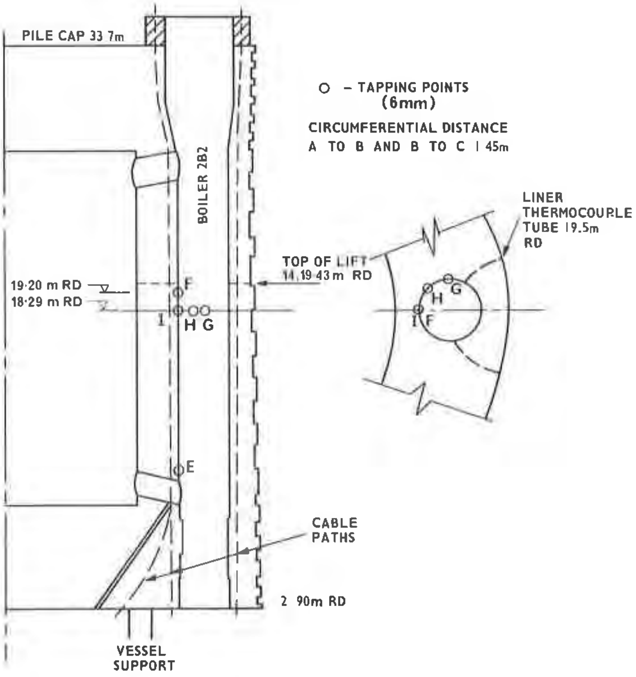


FIG. 2 POSITIONS OF TAPPING POINTS, VESSEL 2

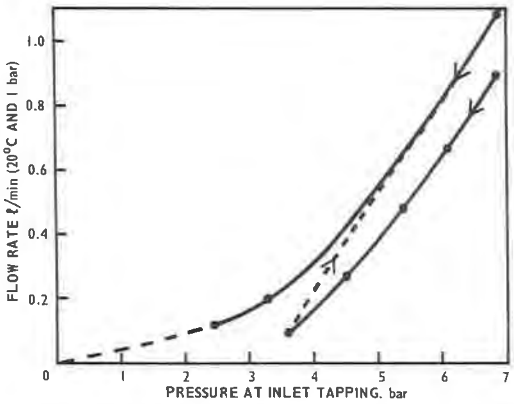
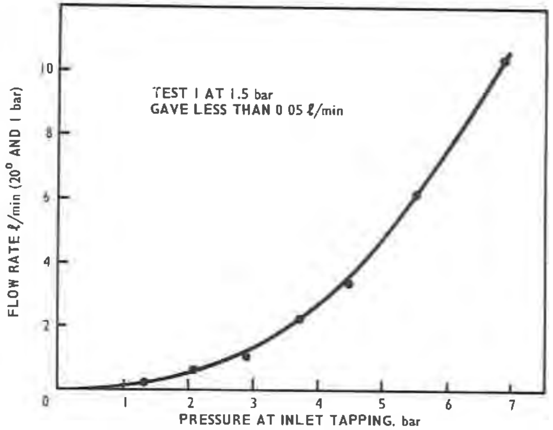


FIG. 3 INLET TAPPING POINT A, VARIATION OF GAS FLOW RATE WITH APPLIED PRESSURE



TEST 1 AT 1.5 bar
GAVE LESS THAN 0 05 ℓ/min

FIG. 4 INLET TAPPING POINT C, VARIATION OF GAS FLOW RATE WITH APPLIED PRESSURE

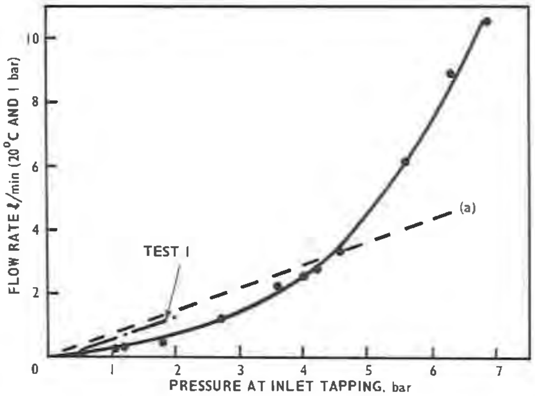


FIG. 5 INLET TAPPING POINT B, VARIATION OF GAS FLOW RATE WITH APPLIED PRESSURE

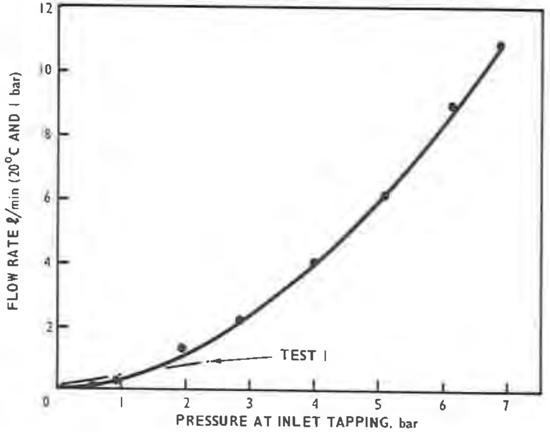


FIG. 6 INLET TAPPING POINT D, VARIATION OF GAS FLOW RATE WITH APPLIED PRESSURE

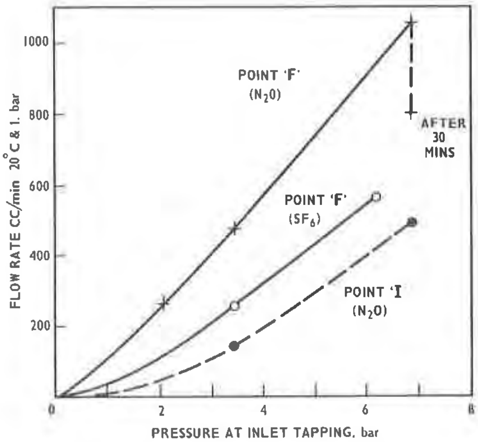


FIG. 7 INLET TAPPING POINTS 'F' AND 'I'. VARIATION OF GAS FLOW RATE WITH APPLIED PRESSURE

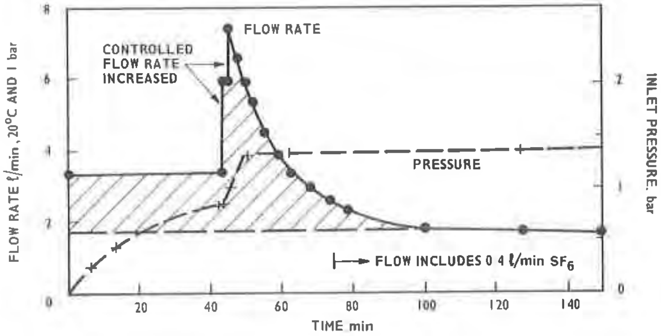


FIG. 8 PRESSURE AND FLOW RATE AT TAPPING 'E' WITH NITROUS OXIDE

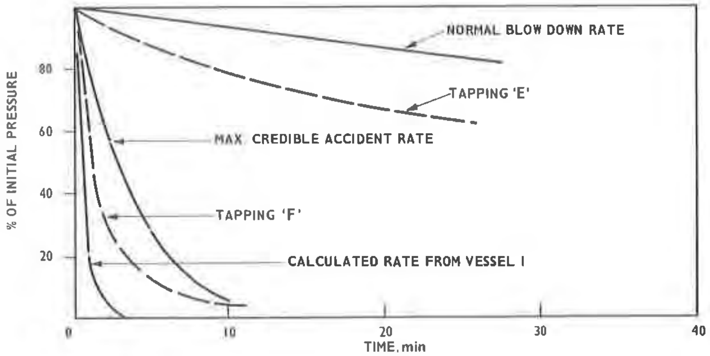


FIG. 9 DEPRESSURISATION RATES