Fort St. Vrain PCRV Structural Response Monitoring and Verification

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ABSTRACT

The Prestressed Concrete Reactor Vessel (PCRV) is the structure that contains the reactor core and the entire primary coolant system including steam generators and helium circulators. It functions as the primary coolant pressure boundary and its design results in an exceedingly low probability of gross rupture or significant leakage throughout its design life. In addition it incorporates engineered safety features to backup the reactor coolant pressure boundary such as secondary closures in all penetrations and flow restriction devices in the penetrations that require them.

Instrumentation was incorporated in the FSV PCRV to obtain data for validating the design and construction and to monitor the structural response of the PCRV during its design life. The sensors include load cells on selected tendons, strain gauges embedded in the concrete, strain gauges on the steel liner, and thermocouples embedded in the PCRV. All sensors are monitored on a 600-channel digital data acquisition system (DAS). The DAS is capable of continually or intermittently monitoring the PCRV structural response. The output from the DAS appears on a digital voltmeter for local read-out, printer paper tape for record purpose, and punched paper tape for computer processing.

Due to the large mass of concrete contained in the PCRV, small shrinkage cracks occur near the outside concrete surface. These cracks are generally 0.015 inch or less in width and run for large distances along the surface of the PCRV. A periodic surveillance is performed on the PCRV surface cracks to measure their depth, length, width, and to monitor changes in these parameters. Each crack is given a unique number and is identified in table form with its corresponding data.

The long-term prestressing tendon loads have been conservatively estimated in the PCRV design and observed prestress losses are well within the design limits. In addition, a surveillance is performed on selected tendons to monitor their overall physical condition. The results of these surveillances under various internal vessel pressures have demonstrated that the PCRV is soundly constructed. It can be concluded that the surface cracks are of no structural concern and are largely due to normal shrinkage of the surface concrete.
1. INTRODUCTION

The only prestressed concrete reactor vessel (PCRV) in the USA to date was constructed to house a high temperature gas-cooled reactor (HTGR) for the Fort St. Vrain (FSV) 342 MW(e) nuclear generating station (Fig. 1). The surveillance program for the FSV PCRV is given in the Final Safety Analysis Report [1]. The monitoring and surveillance requirements of the FSV PCRV are consistent with those currently stipulated in the ASME Boiler and Pressure Vessel Code Section XI, Division 2. These requirements cover monitoring of prestressing tendons, corrosion surveillance and concrete surface examination. In addition to required monitoring of the reactor vessel as imposed by the U.S. Nuclear Regulatory Commission, prestressing tendon loads and concrete strains have been analyzed for the purpose of verifying the capability of structural analysis computer codes by comparison of the observed PCRV behavior with predicted structural response. Data from sensors installed in the PCRV have been collected since completion of PCRV construction.

In 1971, the structural response of the PCRV subjected to initial proof test pressure (IPTT) was evaluated utilizing the data provided by the installed sensors. The proof pressure test demonstrated that the PCRV was soundly constructed and that the overall structural response of the PCRV was essentially linear up to IPTT of 6.69 MPa (970 psi). The test results were in general agreement with those predicted by the elastic finite element analysis. The analytical results and test data obtained from the IPTT tests were used as the basis for verifying PCRV structural response in subsequent pressurizations during the reactor rise to 100% power. The results of the FSV PCRV structural response monitoring and verification are presented in this paper.

2. VESSEL SURVEILLANCE

At each surveillance, all visible surfaces around the perimeter of the PCRV are visually inspected. All cracks that are 0.30in (12 inches) or longer and that are at least 0.38mm (0.015 inches) in width are given a unique number. This number is stenciled in large letters on the surface of the concrete and the point at which the crack width and depth data is to be taken is also marked onto the surface of concrete. The width of the crack is determined by use of a steel wire feeler gauge, measured at the indicated point. The length of each crack is determined by marking the points at which the 0.38mm (0.015 inches) gauge wire first enters into the crack and the point when gently moving it along the crack the wire no longer moves freely. The horizontal distance between these points is measured and that distance is recorded.

At each surveillance all initial survey cracks are reinspected to record their new length, width and depth. Any new cracks that are found, are evaluated for their significance considering length, width, and depth.
The results of the surveillance performed in March 1979 with the PCRV at atmospheric pressure recorded 101 surface cracks varying in width from 0.38mm (0.015 inches) to 1.02mm (0.040 inches). The surveillance performed in February 1981 recorded 8 cracks not recorded in the 1979 survey that varied in width from 0.39mm (0.015 inches) to 0.76mm (0.030 inches). The PCRV pressure was 4.59 MPa (665 psia). The results of the reinspection of the 1979 survey cracks showed essentially no change in the widths or depths of the cracks and only minor changes in the lengths of the cracks. The locations in which some of the cracks exceeded 0.38mm (0.015 inches) in width were in localized areas, possibly due to thermal cycling effects of the PCRV and not structurally significant. The 8 new cracks recorded in the 1981 survey were due to the PCRV being pressurized at the time of the survey. It is felt that the cracks on the surface of the PCRV are superficial in nature and are due to thermal effects and shrinkage of the PCRV surface concrete.

In addition to the PCRV crack map surveillance, surveillances are performed to evaluate tendon corrosion and tendon load cell calibration. Corrosion-protected wire samples of sufficient length are inserted with selected tendons (those tendons with load cells). Upon removal of the tendon cover, an inspection is made of the tendon cover interior, the stressing washer, the shims, and button head for evidence of rust or condensed water vapor. It is also verified that the corrosion inhibiting compound, an amber transparent greaselike material, is normal and has not been degraded. If the sample wire exhibits general rusting, a tensile test is performed. The results of the tendon surveillance performed in 1979 showed no rust or corrosion on the tendons. The corrosion protection provided for the PCRV prestressing components is considered to be fully adequate to assure that the required prestressing forces are sustained throughout the operational life of the plant.

A surveillance is performed on the tendon load cell to check for possible shift in the load cell. Monitoring of the tendon loads assures that deterioration of structural components including progressive tendon corrosion, concrete strength reduction, excessive steel relaxation, etc., cannot occur undetected to a degree that would jeopardize the safety of the vessel. The results of the surveillances show close agreement, within tolerance, between the load cell reading and the actual tendon load.

3. SHORT-TERM PCRV RESPONSE

The behavior of the Fort St. Vrain PCRV has been monitored since completion of construction. The short-term PCRV response to reactor rise to 100% power level was evaluated from measurements of tendon loads, concrete strains and temperatures. The maximum internal vessel pressure reached was 4.85 MPa (703 psia), corresponding to the normal working pressure. The structural response of the PCRV to pressurization was verified by comparing the tendon load changes and concrete strains with anticipated values which were established based on the analysis of the initial proof pressure test results. The maximum tendon load changes as recorded by the load cells installed on
representative tendons were within the established limit of 0.13 MN (30 kips), approximately 2.0% of the initial tendon load over the effective prestress of an unpressurized vessel. The development of concrete strain with internal pressure generated by strain gauges at control locations of the PCRV is presented in Figures 2 through 4. The recorded strains were in general agreement with predicted values obtained from the three-dimensional elastic finite element stress analysis of the PCRV under pressurization. Measured strains recorded in the initial proof pressure tests are included in the figures for comparison. Consistent overall responses exhibited in both initial pressure and subsequent reactor rise-to-power tests not only verify the essentially elastic PCRV responses to short-term pressure changes but also establish the reliability of embedded strain gauges in the concrete. The deviations of measured data from the analytically predicted values are within the limits established in the initial proof pressure test. No creep effects were considered in the finite element elastic stress analysis used for predicting the short-term PCRV response to pressure changes.

The observed increase in bulk concrete temperature as indicated by embedded thermocouples during the reactor rise to 100% power level was as expected. In general, the concrete temperature was well within the design limit of 54°C (130°F). Several exceptions to the expected concrete temperature level were found in small local areas at discontinuities or internal attachments to the cavity liner. Additional design assessment involving detailed thermal and structural analyses performed for each hot spot area to demonstrate its acceptability by ASME code design criteria is outside the scope of this paper. Generally, local hot spots have been shown to have insignificant influence on the overall PCRV structural response.

4. TIME-DEPENDENT PCRV RESPONSE

Records of tendon load cells and concrete strain data collected since PCRV construction have been reviewed and presented on a log-time scale so that the overall trends of time-dependent responses of the PCRV can be compared with design limits and analytical predictions. Figures 5 and 6 show the time-dependent responses of a typical vertical tendon and a circumferential tendon at PCRV mid-height as predicted for PCRV design with their corresponding load cell data. As can be seen, the actual prestress losses are well within the design limits. Similar comparisons of predicted and measured circumferential and vertical concrete strains are presented in Figures 7 and 8. The analytical results were obtained from creep analyses using an axisymmetric finite element model similar to that reported in the FSV Final Safety Analysis Report [1]. In the analysis, the PCRV time-load history from initial prestressing to startup and reactor rise-to-power tests including major events leading to 100% power level was represented in 63 time steps. Temperature input was based on representative concrete temperatures as indicated by the embedded thermocouples in the PCRV. The initial prestressing loads were taken from anchor loads recorded by the tendon load cells. The prestress tendon steel relaxation was taken into account by incorporating a series of relaxation factors in terms of initial prestress corresponding to the time steps under consideration.
The assessment of time-dependent tendon load and concrete strain responses indicates that the creep analysis overestimated creep recovery resulting from vessel pressurizations. Despite the overestimate of creep recovery, the time-dependent PCRV response as predicted by an axisymmetric creep analysis agrees reasonably well with the measured data. Since the PCRV is assumed axisymmetric in the analysis, better correlation of analytical results is expected in regions where axisymmetric response is anticipated. The many cycles of pressurizations and temperature fluctuations experienced by the vessel during the startup and reactor rise-to-power tests were not fully accounted for by the time-load history used in the analysis and by the material parameters necessary to define the concrete constitutive model. With these limitations in mind, the measured data are considered adequately verified by the analytical results.

5. CONCLUSIONS

Based on analyses of the PCRV sensor data obtained during the reactor rise-to-power tests, the PCRV generally responded as anticipated in design. The overall PCRV structural response to pressure changes was essentially linear, and the test results were in general agreement with that predicted by the elastic finite element analysis. The consistency exhibited in the concrete strains obtained from the initial proof pressure test and subsequent tests during the reactor rise-to-power indicates no significant change in the PCRV structural stiffness. The long-term tendon loads have been conservatively estimated in the FSV design and the observed prestress losses are well within the design limits. Good correlations between analytical results and measured sensor data verify the adequacy of the axisymmetric creep analysis code used to predict the time-dependent structural response of the FSV PCRV.

Concrete surface examinations have shown that surface cracking on the FSV PCRV was confined to normal drying shrinkage and thermal strain effects and no structurally significant cracking has been observed.

Experience with the FSV PCRV monitoring has shown that local hot spots are to be expected, particularly around penetrations and at attachments to the liner. Monitoring of these regions should be maintained and supported by analytical assessments to establish their structural acceptability at the expected and measured temperature levels.

References
Figure 5 - Typical Vertical Tendon Force Versus Time

Figure 6 - Typical Circumferential Tendon Force at PCRV Midheight Versus Time

Figure 7 - Concrete Strain Versus Time for a Circumferential Gauge at PCRV Inner Midplane

Figure 8 - Concrete Strain Versus Time for a Vertical Gauge at PCRV Outer Midplane