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THE STUDY OF THERMAL FATIGUE PROBLEM ON REACTOR RECIRCULATION PUMP OF BWR PLANT

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ABSTRACT

The experimental and analytical studies of the temperature fluctuation phenomena for both existing and improved type primary loop recirculation pump (PLR pump) for boiling water reactor (BWR) plant are described.Temperature fluctuation measurement tests were performed by mock up pump under high temperature and pressure typical of PLR pump operating conditions (278C, 72kg/cm^2) to confirm the quantitative effect of the temperature fluctuations for the thermal fatigue of the metal surface. The magnitude of the fluctuations measured were apparently affected by the amount of cold water injected into the hot region through the annulus. To improve the temperature fluctuation problem for the existing pump, the device called "seal purge heater" was developed and investigated by both flow visualization tests and temperature measurement mock up tests. Finally, the full scale pump test for improved pump was performed to confirm the validity of the mock up test results, and the reliability of the pump system for various operating condition specified for PLR pump.

INTRODUCTION

In modern boiling water reactor (BWR) power plant, two PLR pumps are generally employed to drive jet pumps equipped inside the reactor pressure vessel. Typical structure and design specification of existing PLR pump is shown in Figure 1.

As PLR pump is used to transport high temperature and pressure reactor water, two stage tandem type shaft mechanical seal is adopted for pump shaft sealing. To minimize the potential for seal failure due to crud contained in the reactor water and to avoid high radio active contamination, about 4 to 7 L/min clean and cold water is injected to the seal housing as "seal purge water". This seal purge water is divided into two part , ie., one is a flow through the two stage seal cavity as controlled bleed off flow (about 2.8L/min), and the other part is a flow into pump hot area through the shaft penetrating labyrinth annulus.The latter part of the cold water (net seal purge flow; Qp) mixes with hot reactor water at the hot side bottom end of the labyrinth area and cause temperature fluctuation (Figure 2).

In mid 1980's some shallow cracks were found on shaft labyrinth area of PLR pumps in Japan. As the cracks were found to be rather shallow and equally spaced circumferentially around the labyrinth area, it was concluded that the cause of the cracks would be attributable to the thermal stress fatigue due to the mixing of cold seal purge water with hot reactor water.

This research was performed to investigate the temperature fluctuation phenomena of the existing pump and to develop the improved pump against thermal stress fatigue for PLR pump by conducting very comprehensive experimental and analytical studies[(1)-(3)] under a Joint company research organization consisting of Japanese utility companies, plant manufacturers and pump manufacturer.

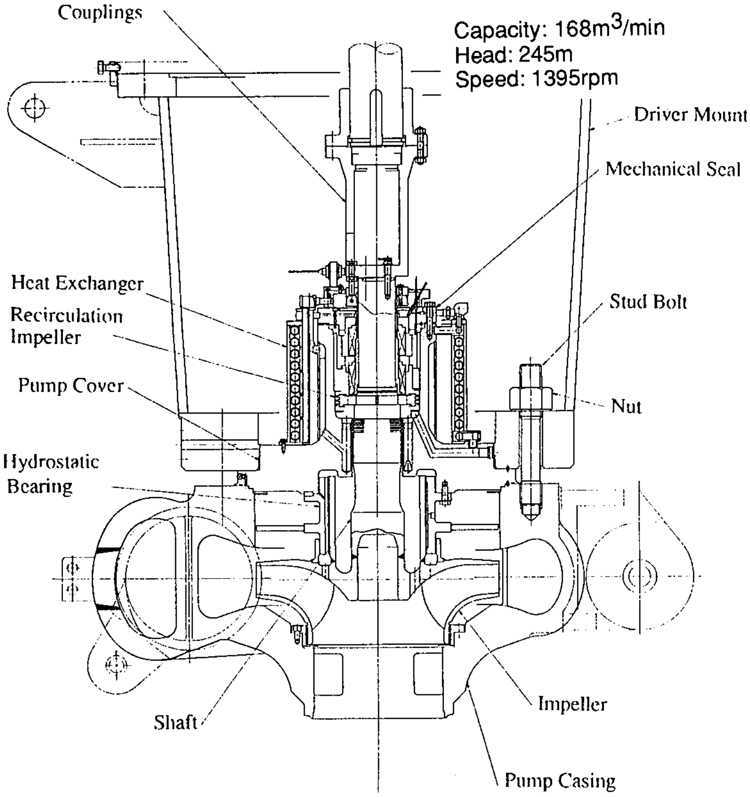

Figure 1 Typical PLR Pump Cross Sectional View

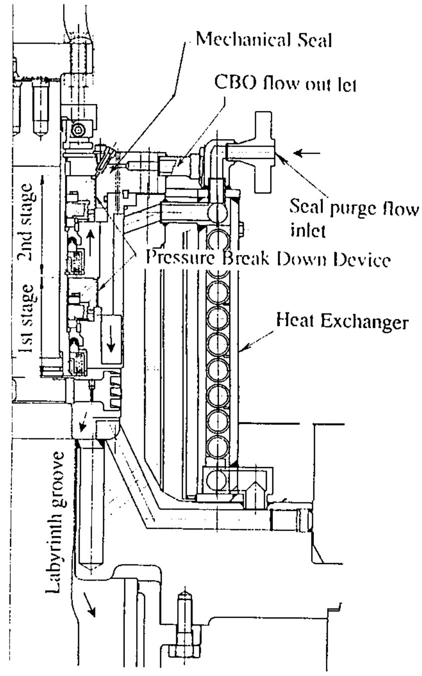

Figure 2 Schematic Seal Purge Flow

TEMPERATURE MEASUREMENT TEST FOR EXISTING PUMP BY MOCK UP TEST FACILITY

Figure 3 shows the mock up pump structure and Figure 4 shows the two different type of the tested models. Here, model 2A is an original design and has full length labyrinth, while the model 2B is a modification of type 2A and has relieved shaft. The relief on the shaft side of type 2B is to aim the mitigation of the temperature gradient and is realized by the machining work performed at site to remove cracks of type 2A shaft after few years of hot operation. The mock up pump was composed of pump cover, shaft, journal, hydrostatic bearing, mechanical shaft seal housing, and driven by 55kw variable speed electric motor. The clearance of the cover to the shaft was about 0.65 mm radially and screw type labyrinth grooves of the opposite spirals were machined both on the shaft and cover annulus. To measure the temperature fluctuation at the cover and shaft annulus, about 60 thermocouples of 0.5mm diameter (CA type) were embedded as shown on Figure 4 above. The thermocouples installed on the shaft side were connected to 16ch low noise slip ring mounted at the top of the shaft to take out the signals. About 120ch signals including 60 thermocouple signals were measured simultaneously for about 120sec by 200 Hz sampling rate on each test. The overall accuracy of the instrumentations was evaluated to be about $\pm$2.6 C for temperature measurement.

The testing parameters were, pump speed: N=280 to 1680rpm, net seal purge water flow: Qp= 0 to 15L/min, loop temperature: T_L=278C, seal purge temperature: Tp=15 to 35C, respectively.

Figure 5 shows the typical results of the temperature signals measured on the metal surface of the shaft at N=280rpm with Qp=4L/min seal purge flow case for type 2A and type 2B test models. As expected, a strong temperature fluctuations were observed near the exit of the labyrinth annulus due to the mixing of cold seal purge water with hot water. Although FFT analysis did not give meaningful frequency spectra because of the lack of clear periodicity, these fluctuation waves composed of N and N/2 (N: rotating speed) components as well as other miscellaneous small components. The general characteristics of the temperature fluctuation seemed to be similar for both type 2A and type 2B models, however, the fluctuation waves for type 2B were observed to be more unstable than for type 2A.

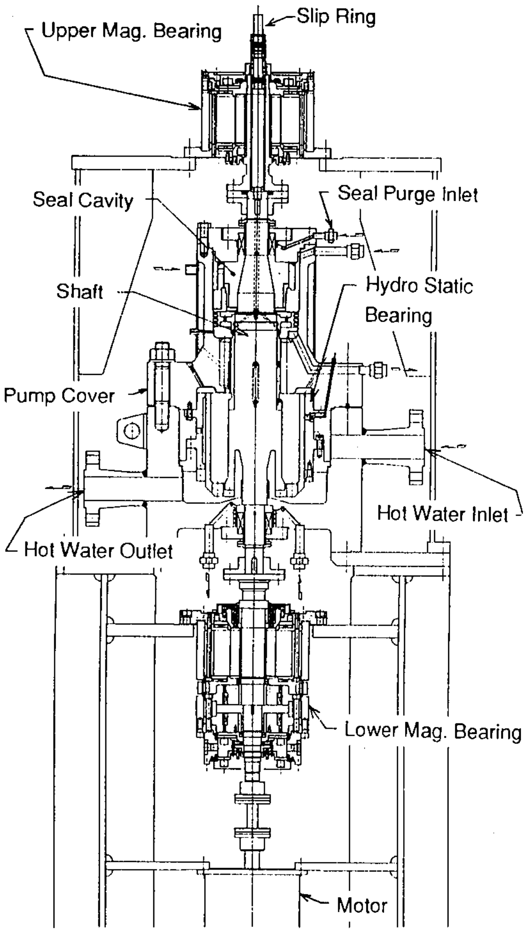

Figure 3 Mock up Pump Structure

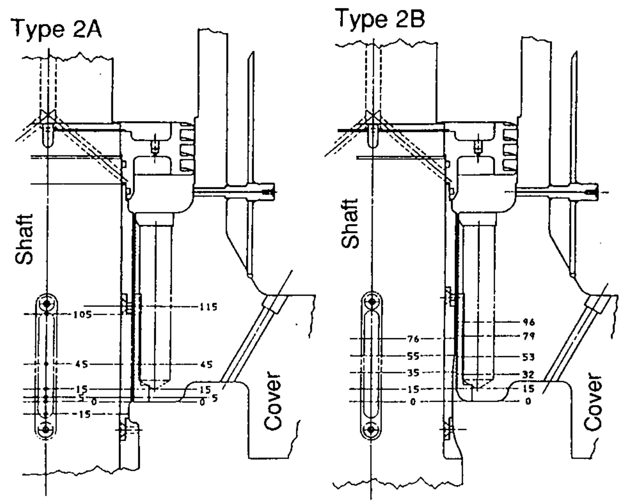

Figure 4 Thermocouple Layout of Tested Models

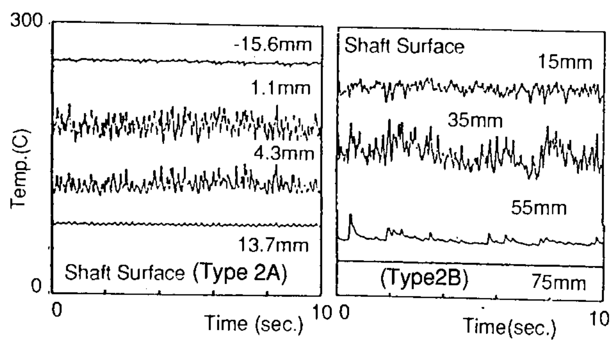

Figure 5 Measured Temperature Signals
(Type 2A, 2B; N=280rpm, Qp=4L/min.)

Figure 6 show the summary of the steady state temperature fluctuation measurement test . The temperature fluctuation magnitude were obtained from the $\Delta T(=T_{max}-T_{min})$ of 24,000 data sampled during 120 seconds at same location. As shown on the figures, the temperature fluctuation magnitudes become large by the increase of seal purge water flow rate for both shaft and cover. The hot water penetration depth into the labyrinth area was about 20mm for type 2A and about 60mm for type 2B respectively, and the locations where the maximum temperature fluctuations occured correspond to the area of steep temperature gardient.

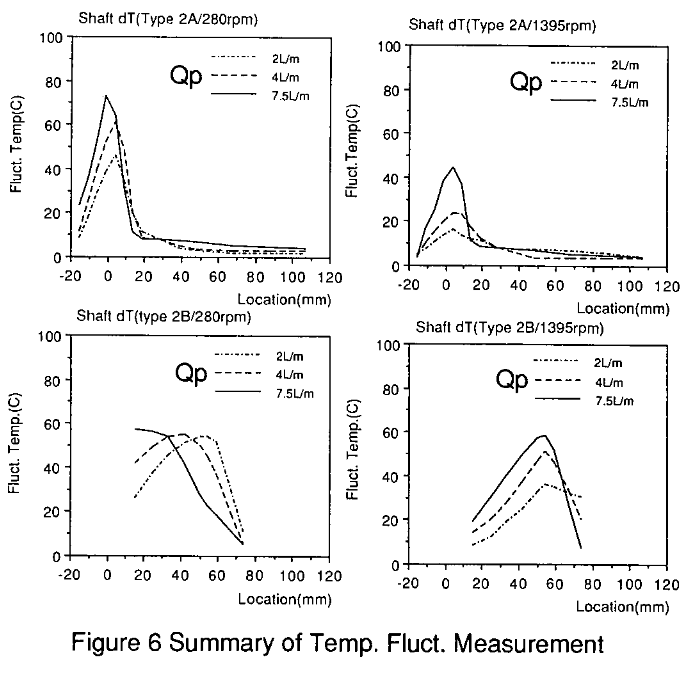

Figure 6 Summary of Temp. Fluct. Measurement

MEASUEMENT OF FILM COEFFICIENT FOR ROTATING ANNULUS

To evaluate the alternating stress due to the temperature fluctuation measured, it is necessary to know the heat transfer characteristics at the metal surface of the rotating annulus.

Figure 7 shows the experimental equipment for the measurement of film coefficient at the rotating annulus with and without labyrinth grooves. The film coefficients were measured both on the top and bottom of the labyrinth grooves by electroheating method, in which the thin foils of austenitic stainless steel were carefully attached to the metal surface and connected with DC power supply source to heat up bulk flow temperature by controlled constant heat flux.

Figure 8 shows the result of the measurement of film coefficient for various operating speed. From the figure, it is known that the film coefficient is alomost proportional to the shaft speed and the values of the labyrinth top are about 2.5 times higher than that for labyrinth bottom. The axial flow velocity (V_L) does not seem to affect the value of the film coefficient.

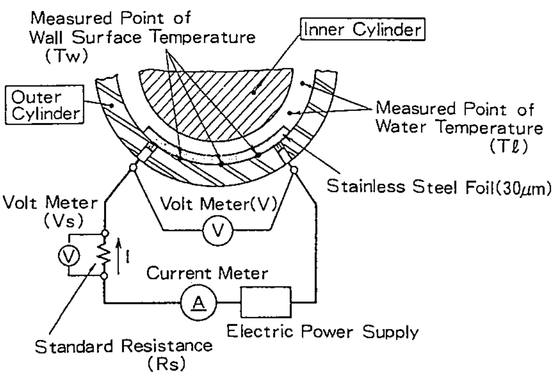

Figure 7 Experimental Apparatus for the Measurement of Film Co-eff.

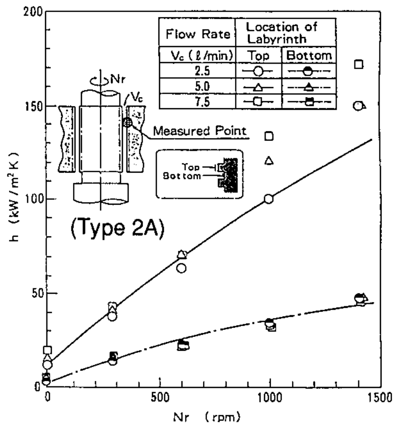

Figure 8 Measured Film Co-efficient of the Rotating Annulus with Labyrinth

EVALUATION OF MOCK UP TEST RESULTS FOR EXISTING PUMP

Figure 9 shows the fatigue stress evaluation results of the subject part for 4L/min seal purge flow case. The alternating stresses were derived from the measured max. ΔT multiplied by the stress factor $Y(=\alpha \times \beta)$ .Where, α is the stress conversion factor calculated from the finite element analyses for sine wave cyclic temperature thermal load and determined as 0.46 and 0.32 for flat and labyrinthed geometry respectively, while β is a thermocouples response factor calculated by finite element analysis using measured film coefficient . The crack initiation limit was derived from the best fitted curve of the material fatigue test considering the mean stress effect by modified Goodman's diagram. The alternating thermal stresses calculated from the experimental results show more than the limit for crack initiation at some locations, which has good correspondence to the cracked locations for actual pumps.

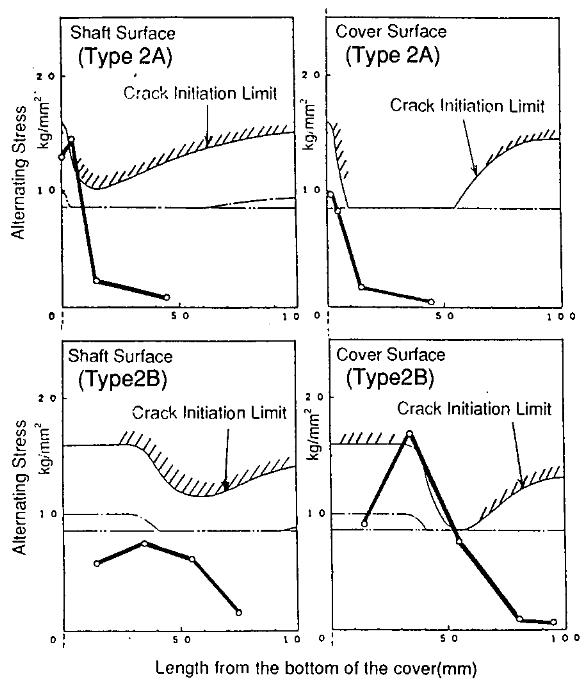

Figure 9 Evaluation Results for Existing Pump Models (N=280rpm, Qp=4L/min)

DESIGN OF IMPROVED PUMP ADOPTING SEAL PURGE HEATER

It is evident that some device which is able to heat up cold seal purge water before mixing with hot water would be effective to mitigate the temperature fluctuation phenomena. For this purpose, the built in self acting "seal purge heater" was developed as shown in Figure 10. When the cold seal purge water flows through the narrow annular clearance between the rotating shaft and heater, the hot water introduced to the multi passage drilled holes machined around the heater cylinder might heat up cold seal purge water before mixing with hot reactor water. The driving pressure of hot water is obtained by the centrifugal pressure gradient that exist in the annular area between the hydrostatic bearing journal and shaft. To minimize the flow resistance as well as to get high heat transfer performance and high mechanical strength, 60 drilled holes with 8mm diameter were selected as flow passage. The recirculation flow through these drilled holes was measured by mock up test rig and determined to be 800L/min at N=1395rpm which was quite satisfactory for the requirement of heater design.

TEMPERATURE MEASUREMENT TEST OF THE IMPROVED PUMP BY MOCK UP TEST FACILITY

To evaluate the effect of the seal purge heater, it was planned to measure the temperature fluctuation at the annulus between the shaft and heater by mock up arrangement similar to that described before.

Figure 11 show the typical results of temperature fluctuation signals measured on the metal surface of the shaft at 280 and 1395 rpm with 4L/min net seal purge flow case. As expected, the cold seal purge water at the inlet of the heater was gradually heated up by the drilled hole heater and flowed out to the pump hot area with small temperature difference. At low speed case (280rpm), some temperature fluctuation was observed at the shaft surface corresponding to the heater outlet area, however, at high speed case (1395rpm), temperature fluctuation was not observed at the same place. As the flow rate of hot water circulation through the heater was proportional to the pump speed, heater performance at low speed might be inferior than that of high speed case.

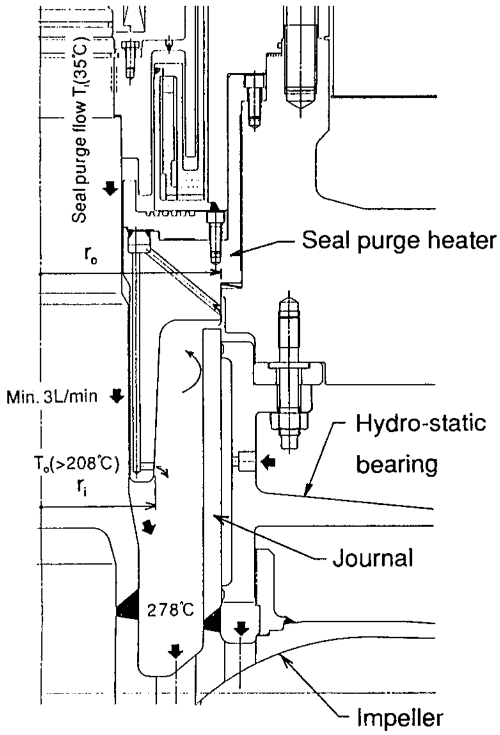

Figure 10 Structure of Seal Purge Heater for Improved Pump

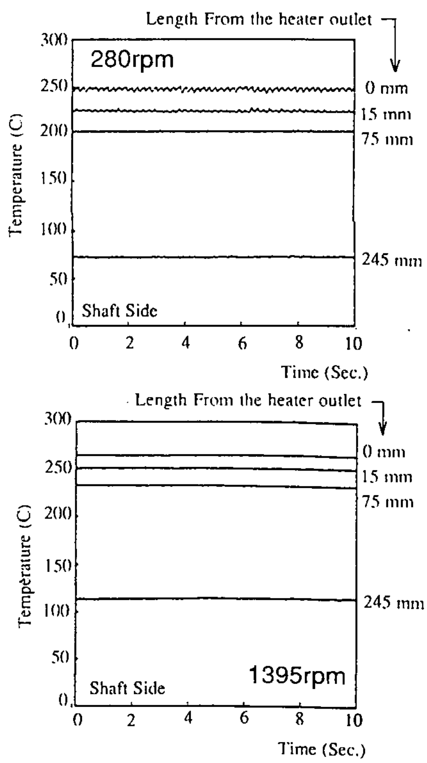

Figure 11 Measured Temperature Signals (Improved Pump Model, Qp=4L/min.)

EVALUATION OF MOCK UP TEST RESULTS FOR IMPROVED PUMP

Figure 12 shows fatigue stress evaluation results of the improved pump mock up test. The alternating stresses were derived by the same manner as explained before for existing model, while the allowable alternating stress(dashed line) was derived from the design fatigue curve "C" for austenitic stainless steel specified in ASME Nuclear Pressure Vessel design code Sec.III. The alternating thermal stresses calculated from the experimental results were very small against design criteria. In this research, the applicable operating range for the developed seal purge heater without thermal crack was estimated conservatively as follows.

Pump speed : N=280 to1680 rpm
Net seal purge flow: Qp≤7.5L/min

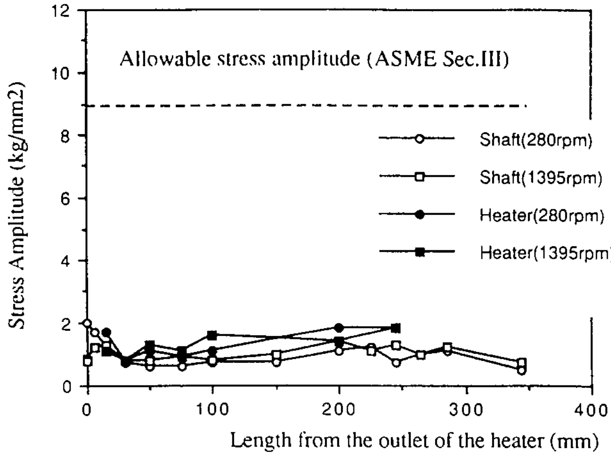

Figure 12 Evaluation Results for Improved Pump Model (Qp=4L/min)

FULL SCALE PUMP TEST

As the performance of the seal purge heater to prevent thermal crack had been excellent, the full scale pump test to confirm the applicability and reliability to actual pump was finally performed at high temperature and high pressure condition by factory test facility. The full scale pump was operated for about 500 hours under various operating conditions and the measured temperature fluctuations during the tests showed good correspondence with the results of the mock up test, and the general pump performance was very satisfactory. After completion of the test, both heater and shaft parts were dye checked and no thermal crack was observed.

SUMMARY AND CONCLUSION

The temperature fluctuation measurement test and stress evaluation for both existing and improved pump structure have been conducted. The test results of the existing pump show the magnitude of the temperature fluctuations become large by the increase of the seal purge flow rate.The performance of the improved pump was confirmed to be excellent both by mock up test and full scale test under various operating conditions and evaluated to be applicable to the operating range from 280 to 1680rpm pump speed at less than 7.5L/min seal purge flow rate.

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