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DEFECT ANALYSIS OF RECIRCULATION PUMP SHAFT CRACKING

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1. INTRODUCTION

BWR recirculation pumps have to be cooled in the bearing and in the sealing parts by injection water that is considerably cooler (typically 50°C) than the pumped water (typically 280°C). The flows of these two fluids have to join at some part of the pump. This region of the pump is especially prone to thermal fatigue by temperature fluctuations between the two extreme values mentioned. Therefore, in many designs, special precautions have been taken to mitigate the fatigue problem. Fig. 1 shows the design of such a pump. The critical area, where the injection water flows towards the hot water, has been protected by sacrificial material in design, i.e. by a thermal sleeve on the inside towards the shaft and a thermal bushing on the outside towards the casing.

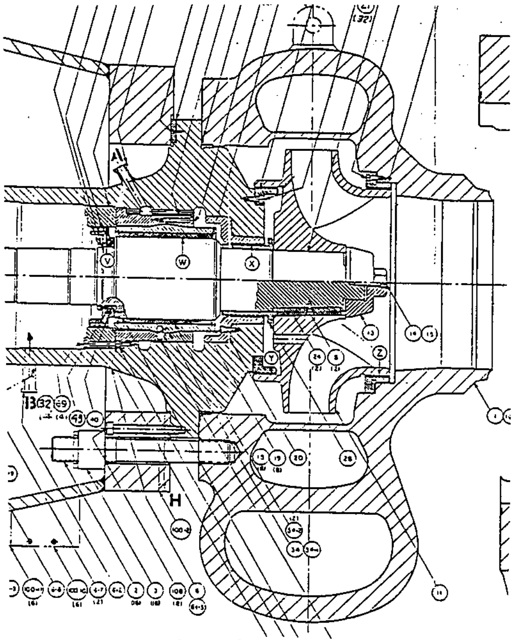

Fig. 1

Nevertheless, cracks have been found after some years of operation on the shaft, underneath the thermal sleeve. It became an open question why these cracks still would form under the protective sleeve. It was the intent of the analyses presented here to answer this question.

2. DESCRIPTION OF THE SHAFT CRACKING FOUND

On the occasion of planned pump overhauls, cracks were discovered in the pump shafts after 20'000 to 25'000 hours of operation. The cracks are located just above the upper end of the conical impeller fit, underneath the protection sleeve. The cracks are primarily longitudinal in orientation, see Fig. 2. About 75 cracks 12 to 20 mm long have formed all around the circumference. Maximum crack depth reported is about 3.5 mm.

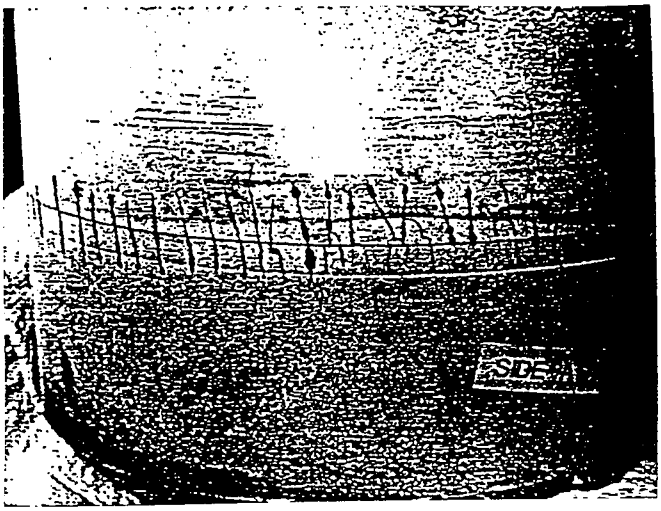

Fig. 2

3. HYPOTHESIS OF THE FAILURE MECHANISM

After some considerations, it soon became apparent, that the phenomenon could not be explained by a distant thermal action through the thermal sleeve. Nor could the mechanical loadings have caused the cracks. Therefore, water must have circulated between the sleeve and the shaft. The machining tolerances of both sleeve and shaft were such, that there was a small radial gap left at uniform temperature. This by itself would not yet explain the thermal fatigue, as constant flow would not lead to alternating temperatures and stresses.

The very probable hypothesis for the phenomenon was therefore found in the following way: There is a constant pressure head created by the small radial pump at the hot end of the sleeve, leading to a forced circulation of water between shaft and sleeve. The choking of the flow in the annular gap however has an instationary nature: While injection water flows, the sleeve is cooled at a faster rate than the thick shaft and therefore the gap is getting closed. This leads to stopping of the flow, which again leads to heating of the sleeve and enlarging of the gap. This instationary process may explain the occurence of the cracks.

It was decided, that firstly stationary analyses, and secondly instationary analyses, should be performed in order to assess the phenomenon more quantitatively. The next two chapters present these analyses and their results.

4. STATIONARY THERMAL FINITE ELEMENT ANALYSES

The suspected phenomenon described above can be bounded by consideration of two extreme cases as follows: The case where injection water can flow between shaft and sleeve, and the case, where this flow is stopped completely.

Therefore, two bounding analyses were performed in order to obtain the temperature distributions for the two cases. The finite element program ANSYS was chosen, which allows the implementation of fluid flow elements into the thermal solid model. The heat transport by mass flow can thereby be modelled.

The finite element mesh is shown in fig. 3. It shows the shaft, the sleeve, and parts of the impeller and the casing in an axisymmetric model. Along the inside and outside of the sleeve, fluid elements have been placed.

Figure 4 shows the temperature contour plot of the case with no water flow between shaft and sleeve.

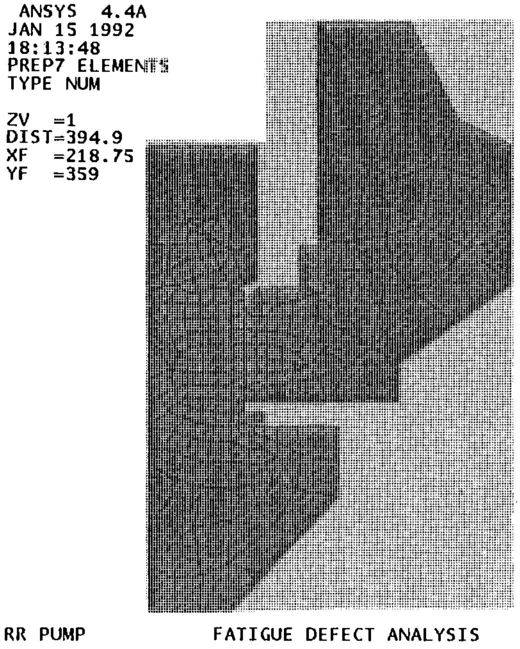

Fig. 3

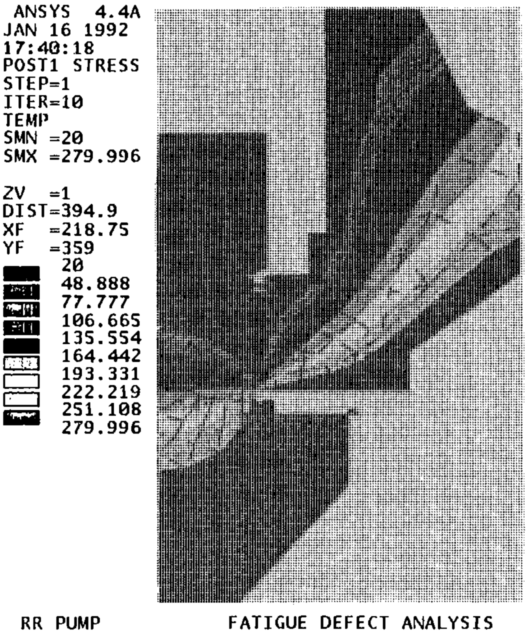

Fig. 4

Figure 5 shows the temperature contour plot of the case with an upper bound water flow between shaft and sleeve.

In order to know the areas which are most sensitive to the flow, a temperature difference field was formed between the two bounding cases.

Figure 6 shows the contour plot of the difference field. It is very interesting to see, that the maximum differences are located exactly at the position where the cracks have been found. This is a strong indication that the phenomenon is actually caused by a fluctuating mass flow between shaft and sleeve due to the instable thermal "breathing" of the sleeve as described above.

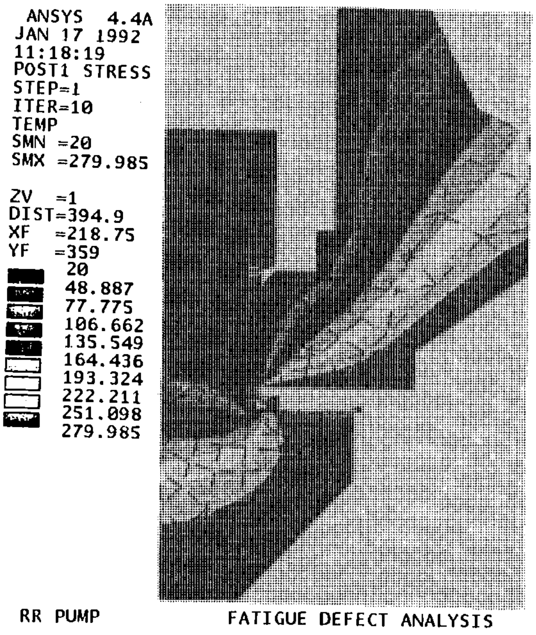

Fig. 5

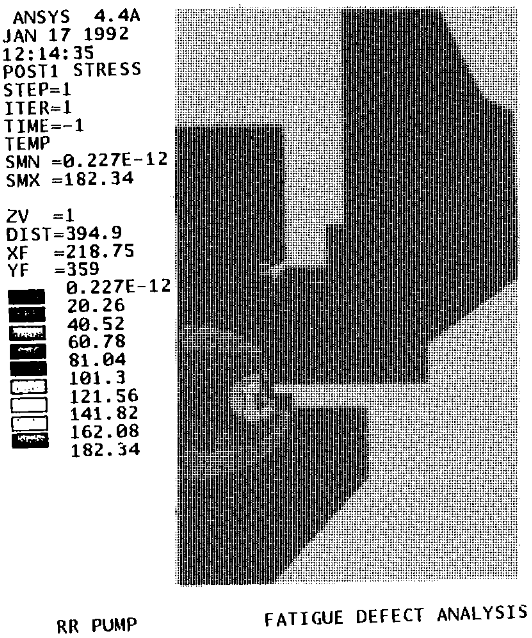

Fig. 6

5. INSTATIONARY THERMAL FINITE ELEMENT ANALYSES

In a second part of the analyses, it was attempted to get a more quantitative assessment of the actual phenomenon frequencies and temperature differences in the shaft surface. This can be accomplished by an instationary transient thermal analysis. However, there is a complication by the thermo-mechanical coupling, because the radial displacement of the sleeve governs the mass flow of water in the inner gap.

This difficulty was overcome by a special trick in the thermal analysis: The temperature of a critical node of the sleeve is chosen as the control value for switching on and off arrays of control elements. Since this temperature can be interpreted as a measure for the radial sleeve displacement at its critical location, it is used for opening control elements, one at a time for a certain value of the temperature. The flow between two nodes of the gap is controlled with an array of 10 parallel pairs of fluid elements, each pair being used in series with a mass flow control element. These fluid all have different gap sizes and corresponding real constant values.

Since the 20 fluid elements mentioned are also transporting convection heat to and from the walls (shaft and sleeve), also the heat flow must be controlled by arrays of heat flow control elements. Since each fluid pipe has two nodes for heat conduction, thare are 40 heat control elements necessary to control the corresponding heat flow.

Fig. 7 shows some results of the analyses performed: The curves show the behaviour of some node temperatures in the critical region. It can easily be seen that the process is really unstable and that a frequency of about 0.03 sec^{-1}. Fig. 8 shows the graph of the flow rate between shaft and sleeve and which also fluctuates between a maximum value and almost zero.

This frequency of thermal fatigue would lead to high cycle type of failure. The temperature fluctuation range obtained was somewhat too low to explain the formation of cracks. However, the analysis was found sensitive to several poorly known parameters like exact gap width, exact injection water temperatures etc., so that it cannot be excluded that other assumptions would lead to larger temperature ranges.

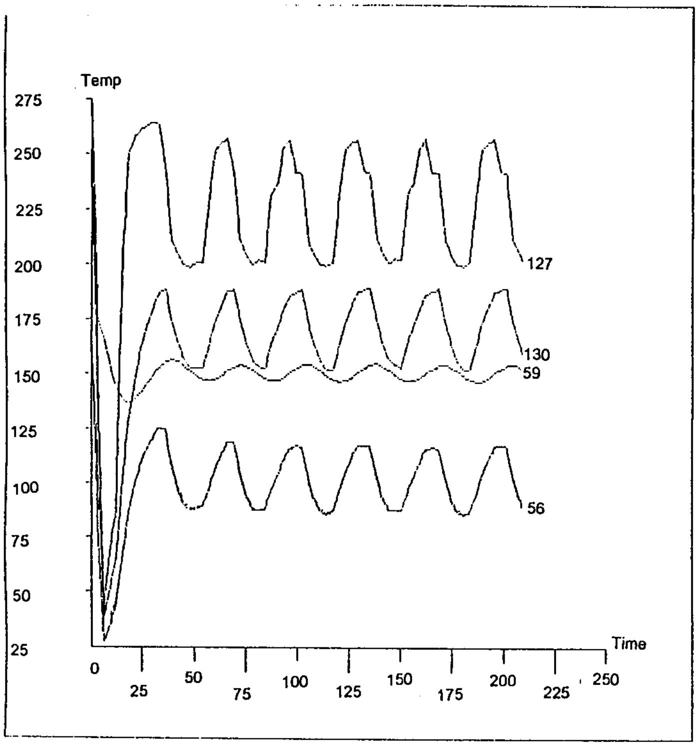

Fig. 7

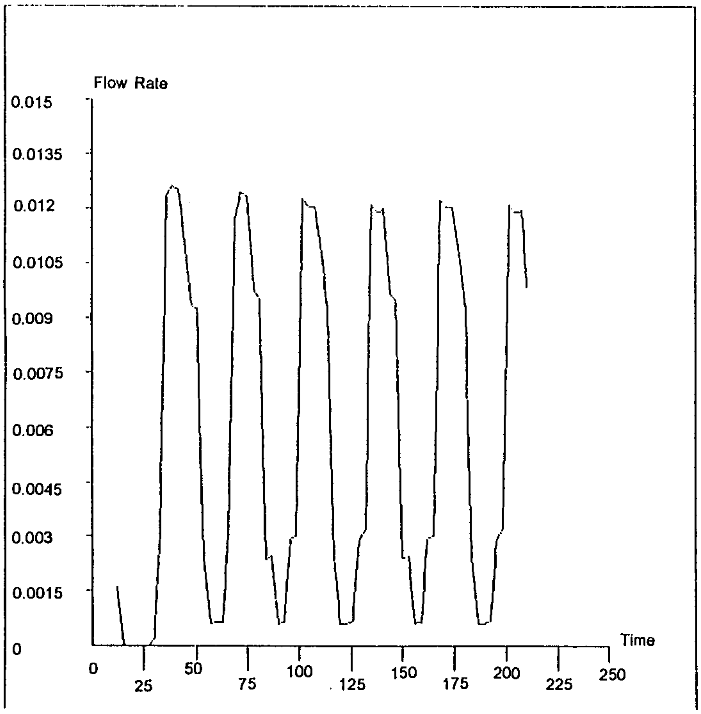

Fig. 8

6. CONCLUSIONS AND DESIGN REMEDY

The results of this detailed transient analysis show that the process in fact can be instable. The frequency of such a behaviour would be governed mainly by the behaviour of the sleeve, which opens and closes the gap betwween shaft and sleeve alternatingly.

Because several parameters and assumptions cannot be assessed very well, it was felt that further analysis would not lead to better quantitative understanding of the phenomenon.

Nevertheless, the location of the cracks could be identified as the location in the shaft that reacts most sensitively to changes in the assumptions on injection water flow between shaft and sleeve. This fact could be verified by both the stationary and instationary analyses.

The design cure for the problem would be:

- The water has to be prevented from flowing between shaft and sleeve by appropriate machining tolerances and/or welding
- The small radial ring which acts as a pump should be eliminated

7. ABSTRACT

Cracks have been encountered in the shaft of a BWR recirculation pump. It was the purpose of a special analysis effort to explain the cause of the cracks and to suggest improvements. The thermal finite element analyses presented in the paper were able to show that an alternating injection water flow between shaft and sleeve is the cause for the cracks. Desing remedies are indicated.