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DEVELOPING AND IMPLEMENTATION OF A FATIGUE MONITORING SYSTEM FOR THE NEW EUROPEAN PRESSURIZED WATER REACTOR EPR

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1 A BRIEF HISTORY OF FAMOS

The FAMOS system was first thought of in the early 1980s. This was in Grafenrheinfeld/Germany, where the licensing authorities required the installation of a great deal of additional measuring equipment including long-term temperature measuring devices to find out more about the real component loadings effective during plant operation. As a result of these recorded thermal data it was discovered to everyone's surprise that the operating conditions of the plant differ from the assumptions and predictions. At this point it must be stressed that the operating conditions determined here are not worse but only different from the predicted ones. This did, however, provide the impetus for better monitoring of the operating conditions of the plant by additional structural temperature measurement to obtain as realistic as possible data on state and operating behavior of the plant. Moreover after years of monitoring a fatigue analysis based on realistic measured data can be performed, normally with lower fatigue damage factors than these included in the design report.

This realization brought FAMOS into being. From this time on, FAMOS has been implemented in every German nuclear power plant and in many plants abroad in the past few years, with this to include the new European Pressurized Water Reactor (EPR).

2 OBJECTIVES OF FAMOS

During long term operation of thermal power plants particular attention is given to the mechanism of material fatigue. Temperature changes associated with the operation of the plant cause structural loads, which have to be maintained within allowable limits to ensure the long term safety and availability of the plant.

During the design phase of the plant the mechanical behaviour of the components of the reactor coolant pressure boundary and of the interfacing systems is analyzed. To do that the relevant thermal loads expected during future operation are taken as a basis and their impact for the component is calculated. To be able to carry out such analyses load cases are defined for all systems and the expected frequencies of occurrence are specified for the service life of the plant. In addition, temperature and pressure fluctuations for every load case are defined.

On the basis of the many evaluations of real plant operations performed in the last decades it can be postulated that load effects during real operation may differ from the conditions assumed in the design phase. This makes it extremely worthwhile to use a system like FAMOS to collect real load data for a more realistic load database to obtain margins of fatigue damage.

To summarize, the objectives of FAMOS are

- determining the fatigue status of the most highly stressed components,
- identifying operating modes, which are unfavourable to fatigue,
- establishing a basis for fatigue analysis based on realistic operating loads and
- using the results for life-time management and life-time extension.

3 PHENOMENA CAUSING THERMAL FATIGUE

This section briefly describes some circumstances and phenomena, which cause cyclic loading and thus fatigue damage of the material during operation of the primary and secondary circuit.

Major loads acting on primary circuit components consist of thermal constraints, internal pressure and thermal transients. The loads vary during operation of the equipment, thus causing material fatigue. To determine the state of material fatigue is a very complex task. The reason lies in the uncertainties of boundary conditions, e.g. transient distribution of temperature and flow in the pressure-retaining components. Rather complex quasi-periodic, transient or fluctuating temperatures and flow rates were recorded with FAMOS measurement sections.

Long-term measurements performed in German NPPs during early eighties have shown that cyclic loading is much more important than was anticipated in design analysis. Several hundred thermocouples were installed on the components of the primary circuit. In the course of monitoring for a period of one year, many unexpected loadings were recorded:

- higher thermal gradients
- higher number of cycles
- load events not considered and analyzed in project design,
- malfunction of several components, for instance leakage of valves, which resulted in stratified flow.

At the same time it was shown that the amplitude and the number of cycles depend on the manner of operation, with significant differences documented between the control room operator shifts.

The next section describes some processes, which can cause cyclic loading for material during operation of the primary circuit.

3.1 Temperature Transients

Temperature transients in pressure vessels and piping systems are very often a result of sudden opening of a valve or starting of a pump. Cold water flows into a system, which was originally in a hot, steady state condition. The thermal field is axially symmetrical (see Figures 1 - 3).

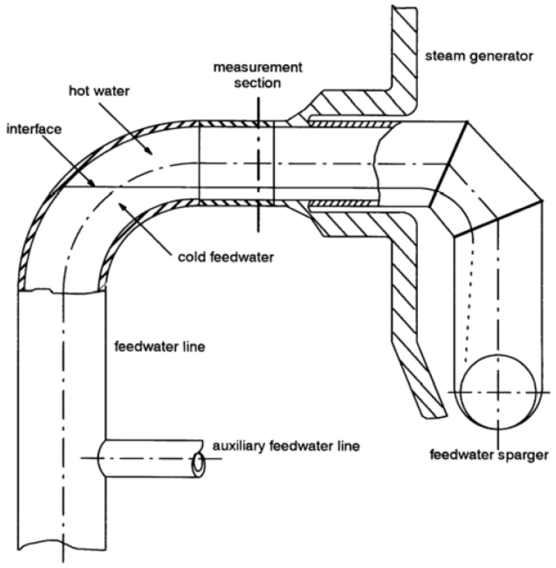

Figure 1: Old layout of feedwater inlet with stratification

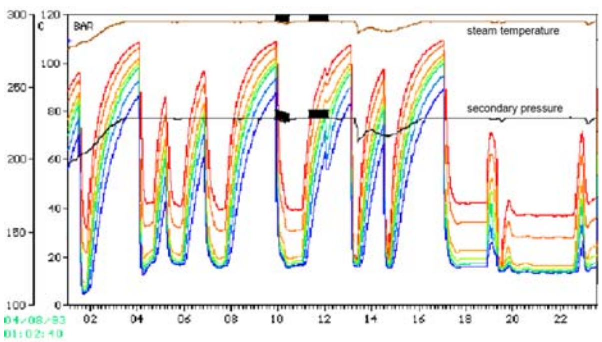

Figure 2: Intermittent feedwater injection induces thermal shock on structure; this condition is caused by a former PWR feedwater inlet design

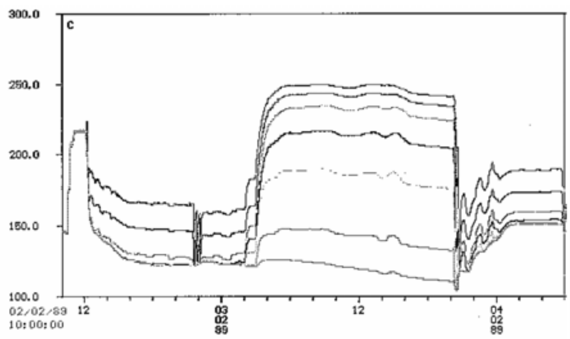

Figure 3: Leaking feedwater valve causes thermal stratification

Thermal stress is a result of thermal gradient in the wall. The amplitude of thermal gradient depends on the temperature difference and on the heat transfer through the wall. The stress in the wall is roughly proportional to the temperature difference between the inner and the outer surfaces.

The temperature on the outer surface can be measured directly by using a surface mounted thermocouple (see Figure 4).

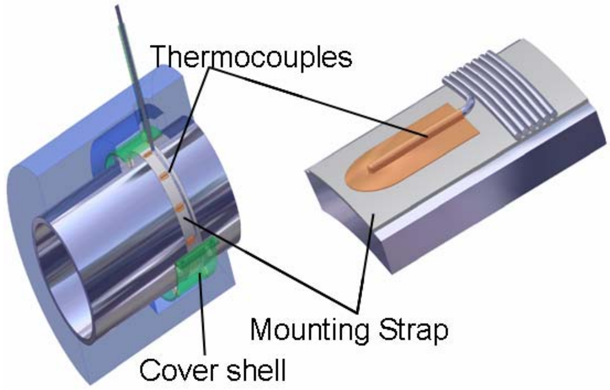

Figure 4: famos Measurement section

Determination of the temperature on the inner wall is much more complex and demands solving the parabolic heat conduction equation inversely.

From the fatigue load point of view the mentioned type of loading is dangerous in two cases. When operation with transient loads is relatively long term, the number of load cycles is high. This load phenomenon is pictured by Figure 1 for a former PWR feedwater inlet geometry [1].

Figure 2 shows the corresponding measured temperatures for the feedwater nozzle as shown in Figure 1. The plant condition is zero power output, so-called hot standby. In the course of time, feedwater temperature becomes much lower than the temperature of the steam generator. The water level in the steam generator, however, has to be maintained either by feeding continuously at very low flow rates thereby inducing thermal stratification (see Figure 3) or by feeding intermittently at nominal flow rate (see Figure 2) thus accepting occurrence of thermal shock.

Another process of high accumulation of fatigue load can be important in cases where the geometry of the nozzle is complex. When a thin-walled part is connected to a massive one then the latter does not allow the deformation of the thinner part, thus inducing constraint stresses.

3.2 Thermal Stratification [2]

Thermal stratification can be characterized by a thermal field, which is symmetric to the vertical axis of a cross-section of a pipe positioned horizontally. Stratified flow occurs when a low flow rate creates two layers. The warmer fluid will stay in the upper part of the pipe above the heavier (colder) fluid without any appreciable mixing of the two. When the temperature varies in the vertical direction the pipe tends to bow. The stresses induced in the material decrease with flexibility of the piping system supports.

When the temperature interface is sharp, the temperature gradients in the metal are high. The stress is highest in cases when the interface between cold and hot fluid is in the middle of the pipe. When the sharp line between cold and warm fluid moves vertically, the local temperature gradients (and therefore local stresses) change too. In such a situation cyclic load occurs, despite the fact that the temperatures of cold and hot layer of fluid are both constant. Therefore it is important to measure not only the temperatures on the top and bottom of the pipe, but also the temperatures at several points around the circumference of the pipe. The use of two thermocouples only may result in underestimation of both amplitude and number of load cycles.

Thermal stratification is created in various ways and the temperature field in the fluid and in the metal differs in accordance with the processes creating the stratification.

In cases of stratified flow with low flow rate the boundary between cold and hot fluids is sharp and stable. Very often this is the case for valve leakages with low pressure drop (see Figure 3).

3.3 Turbulence Penetration [3]

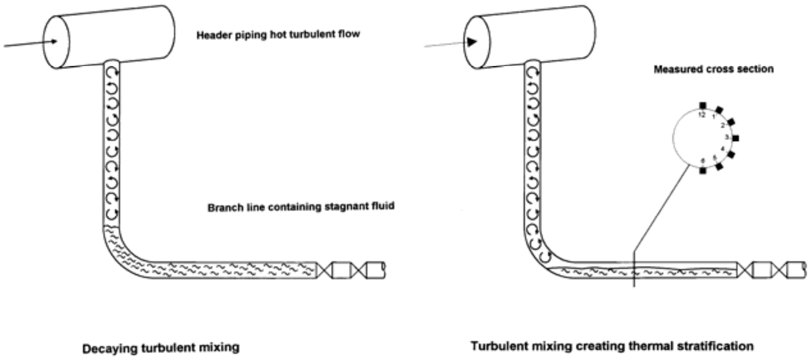

Figure 5: Turbulent mixing in a branch line containing stagnant fluid

This phenomenon exists in a piping system with a hot turbulent flow that penetrates into a branch line that contains a stagnant cold fluid. The intensity of the turbulence decays exponentially from the header pipe into the branch, but the temperature remains fairly constant with main flow temperature over a length of several diameters (see Figure 5).

If the turbulence penetration depth extends just into a horizontal line thermal stratification can occur within that line. Because of turbulence the interface is not stable. This results in fluctuating interfaces and additional fatigue load.

This phenomenon exists in every pipe routing pictured above. The FAMOS way to find locations like that is to look for the typical configuration, pipe routing with a closed vertically bent down branch followed by a horizontal line. A precise prediction of the penetration depth using FAMOS is not possible. However, an empirical exponential equation exists,, which is able to calculate the penetrating depths as a function of the mass flow, the diameter of the branch and the viscosity of the fluid.

4 FAMOS MANUAL (JUSTIFICATION OF THE MEASUREMENT SECTIONS)

The preparatory phase, known as Stage 0 consists of drawing up the "FAMOS Manual" for the power plant in question. The FAMOS Manual identifies those components, which on the basis of the design calculations but also in the light of the local loadings known from operating experience, are expected to undergo fatigue more quickly than other components. The fatigue-enhancing transients (shock transients, stratification transients) are identified separately for each component and the parameters to be examined for fatigue monitoring are defined. These include parameters that are used to analyze the plant status. The instrumentation already in place for monitoring operation of the plant is used as far as possible. But in order to gain a realistic picture of local loads, additional thermocouples have to be installed. The final step in the preparatory phase is the compilation of an instrumentation map. Thus, the FAMOS Manual gives information on the ‘where’, ‘why’ (a detailed justification) and ‘how’ of the local FAMOS instrumentation. (The next phase of FAMOS consists of manufacturing/implementation of the FAMOS system.)

In the following, more details how the typical structure of the main chapter about selected locations and their justification looks like are presented.

The first step is to set-up a table of the systems that will be considered for fatigue monitoring including general system information. These systems are usually separated into 3 groups:

- primary circuit
- safety systems – primary circuit
- secondary circuit systems

The second step comprises performing the evaluation and selection process for the locations prone to fatigue, including the justification of each selected location. This step is based on the following:

- evaluating stress and fatigue analyses by the responsible system specialists by using all the, necessary parameters for this task for each component as follows
    - o ΔT between the different flows, mass flow rates,
    - o Dimensions, orientations and slopes of pipes
- evaluating system data
- evaluating system layout
- taking advantage of the experience gained by mechanical and system specialists from AREVA NP
- taking advantage of operating experience for similar systems/plants

A component will be regarded as a leading component for fatigue when it is expected that the measured load history may lead to significant changes in stresses and therefore that this component will be exposed to higher fatigue rates than its neighbouring components. Conversely, components, which are known to be loaded less or without a degrading effect, will not be suggested for fatigue monitoring. The results for the selected systems and fatigue monitoring locations are presented in subchapters like the following:

- System involved
- Brief description of designation and operation of the system
- Interfacing systems relevant to fatigue
- Expected phenomena relevant to fatigue and other reasons substantiating measurement at this location
- Number and type of measurement sections
- Measurement section location
- Isometric and flow drawings with their FAMOS measuring locations drawn in
- to define the location in graphic form to simplify understanding and provide greater detail
- Other necessary operational signals

In addition, to give an overview of all necessary information concerning location, clear text names, etc. for the measurement sections, a table with all fatigue relevant measurement sections is provided. For example, this shows the number of thermocouples in each MS (measurement section), the KKS (plant station code) identifier of the pipe on which the corresponding MS is placed as well as the measurement section KKS. Moreover, information is given about the priority of each MS - each MS is classified in the priority groups ’absolutely necessary’, ’high‘, ’medium‘ or ’low‘. This ranking allows the number of MS to be reduced easily if necessary.

5 EVALUATION AND POSSIBLE FOLLOW-UP STEPS

Data Evaluation, Fatigue Analysis

Since the visual analysis of measured data profiles – together with the operational measurements the data measured by FAMOS thermocouples are directly passed to the plant computer - is relatively time-consuming, a tool is provided to permit quick simultaneous off-line evaluation of the fatigue-related parameters in the period of observation for all components. The temperature and pressure profiles associated with the components are examined for fluctuations by means of a rainflow algorithm [4], [5].

The result of the quick evaluation consists essentially of a list that identifies for each component the number of cycles for different levels of thermal and pressure amplitudes. The counts from sub-periods are accumulated. Such lists very quickly reveal periods in which individual components have experienced no or only moderate fatigue-related loads compared with the thermal loadings assumed during the design phase of the plant. These analyses provide a qualitative view on the fatigue behaviour, compared with the design analyses of other operating periods. But it could also lead to the final phase of FAMOS, where a new fatigue analysis is needed to quantify the current and future factors of fatigue damage.

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