ENGINEERING ANALYSES ON THE HIGH CYCLE THERMAL FATIGUE FATHER CASE

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ABSTRACT

Nuclear power plant piping may be submitted to time-history temperature fluctuations coupled with space fluctuations in mixing zones. Temperature fields resulting from this turbulent mixing lead to stresses that may cause fatigue damages. This High Cycle Thermal Fatigue (HCTF) phenomenon occurred on the Residual Heat Removal System (RHRS) of Civaux French Pressurized Water Reactor (PWR) in 1998 [1].

AREVA and EDF engineers have at their disposal a simplified approach for assessing the sensibility of the mixing zones with regard to HCTF [2]. It is based on a 1D thermo-mechanical calculation of temperature and stress in the pipe thickness and takes into account several conservatisms, particularly on the thermal-hydraulic loading and on the fatigue curves. The results are only qualitative and this method is only used to identify and to classify the mixing zones which could present a risk. This paper proposes to make a review of this engineering method on the particular case of the HCTF FATHER experiment [3]. The latter has been performed under a CEA/EDF/AREVA agreement. This mock-up is a representative mixing tee with a difference of temperatures between hot and cold legs of 160°C, with several surface finishes and welds.

In this paper, the use of the simplified approach on the Civaux RHRS case enables to highlight its conservatism. Then, it is proposed to apply the methodology on FATHER, first, using strictly the engineering method, this work leading to well identify FATHER as a mixing zone presenting a risk. Then, a second level of application takes into account the real temperatures measured on the mock-up. There, only the non-flushed welds present a risk in a specific azimuthal area, this conclusion being confirmed by the metallographic expertise.

Thanks to the confrontation of the results of this engineering approach with the damage assessment performed on the FATHER mock-up (location and depth of the HCTF cracks), the conservatisms of the approach may be finally discussed in terms of thermal-hydraulic input data, choice of the fatigue curve and definition of the fatigue damage.

INTRODUCTION

Piping systems of nuclear power plants include connections of branches conveying fluids at different temperatures. Thermo-hydraulic fluctuations arising from the turbulent mixing of the flows may affect the inner wall of the pipes and lead to fatigue damage. In May 1998, a leak ($30m^3/h$) occurred in the RHRS of the Civaux 1 French power plant (PWR type N4, 1400 MWe) which was then in a hot shutdown situation [1]. A 180 mm through-wall crack was found in a 304L austenitic stainless steel elbow in a mixing area of high and low temperature fluids.

After expertise, it was concluded that the main root cause of damage was HCTF due to temperature fluctuations of fluid in the mixing zones. Several studies have been conducted to better understand this problem and the FATHER experiment is included in this framework [2,3]. To reproduce the HCTF phenomenon, a representative endurance thermal fatigue test named "FATHER" was performed under a CEA/EDF/AREVA agreement [3]. The test lasted 300 hours. It was performed on a 304L stainless steel mixing zone of 7 mm thick and 6" diameter with a temperature difference ΔT of 160°C between cold and hot fluids. Different internal surface finishes were introduced in the test mock-up: coarse and finely ground, industrial polishing, as extruded surfaces and as welded or flushed joints. A lot of data of fluid and solid temperatures are available from this program and it is proposed here to use them in order to analyze this experiment with a simplified engineering method [2].

In this paper, the results of the simplified approach on the Civaux RHRS case will be first reported. Then, it is proposed to apply the methodology on FATHER. A first level of application is presented using strictly the engineering method. Then, a second level of application takes into account the real temperatures measured on the mock-up. The conservatisms of the approach may be finally discussed thanks to the confrontation of the results of this engineering approach with the damage assessment performed on the FATHER mock-up which has identified the location and the depth of the HCTF cracks.

THE FATHER EXPERIMENT AND THE METALLOGRAPHIC EXPERTISES

The FATHER program, initiated in 1999, is an experimental study on mock-ups representative of a mixing tee found in nuclear power plants (RHRS new configuration type) [3]. This experiment was carried out by CEA under a CEA/EDF/AREVA agreement. Two identical sections were manufactured by AREVA in AISI 304L austenitic stainless steel. The first one was equipped with specific sensors for the analytical thermo-hydraulic tests and the second one was used for an endurance test. The geometry of the mock-ups is intermediate between new N4 RHRS mixing tees of 4'' and 10'' diameters, that is to say an equal 6'' T-junction (Fig. 1): the thickness is about 7 mm in the branches and about 20 mm in the T-junction. The outlet branch is divided in three parts of 300 mm length welded together. The first two straight pipes are composed of 5 rings with different surface finishes. In order to easily locate them on a mock-up, the different rings are numbered from C11 to C15 and from C21 to C25 and the welds are identified by S1, S2 and S3. Rings C11, C14, C21 and C24 have a polished surface finish. Rings C13, C23 and C31 are as-machined. Rings C12 and C22 have a finely ground surface finish and rings C15 and C25 a roughly ground surface finish.

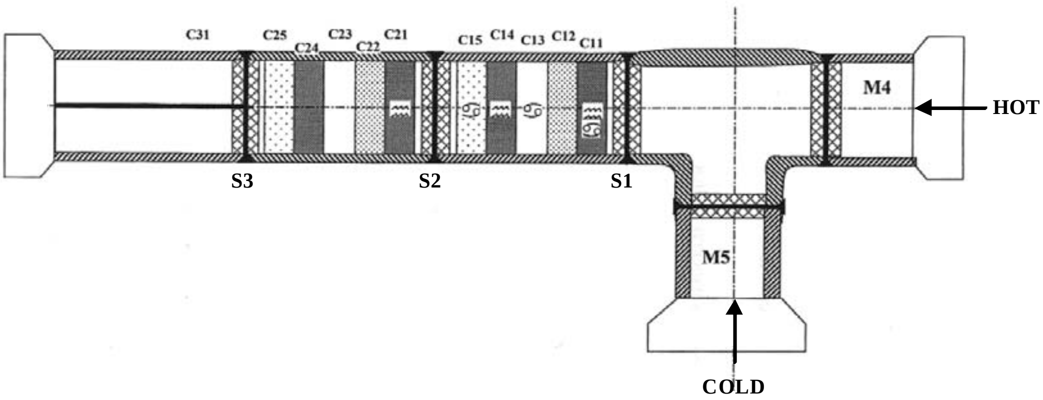

Fig. 1: FATHER mock-up

The high power (8 MW) of the facility allowed to drive trials with a difference of temperature of 160°C (difference between hot and cold branches) and a high flow rate ratio (20%) in particular for the endurance test of 300 h. A lot of data of the fluid and solid temperatures are also available from the analytical thermal-hydraulic tests.

Non Destructive Testing (NDT) and metallographic examinations highlight about 50 cracks in the FATHER mock-up, with depths varying from 100 to 1000 µm [4]. The plates cut from the mock-up and analyzed are located in an azimuthal zone around -40° and 40° where indications were found from several non destructive examinations. This study permitted to conclude that cracks initiate principally in non-flushed welds and in ground surface finish zones: cracks were located in welds S1 (non-flushed), S2 (non-flushed part) and S3 (non-flushed part) and in rings C12, C22, C15 and C25 (finely and roughly ground surface finishes). It is also important to notice that no crack has been found in the polished zones (even in the welds which were flushed and polished).

To sum up, FATHER expertises highlight that cracks preferentially initiate in geometrical discontinuities like weld toes or grinding striations. This illustrates the role of the surface state for crack initiation.

DESCRIPTION OF THE HCTF ENGINEERING METHOD AND APPLICATION TO CIVAUX

After the Civaux incident, it was necessary to build an industrial method with the purpose of selecting the piping systems sensitive to a possible mixing zone fatigue phenomenon. In order to identify and classify zones which could present a HCTF risk, a simplified method was developed for austenitic steels. This one dimension method (analysis by the thickness) has been described in [5] and the 1D assumption has been validated in [6]. The problem is modelled as an ideal linear physical system where the input is the fluid temperature loading and the output any thermal mechanical variable in the wall (temperature, strain, stress). This method is based on frequency response functions so that the input signal can be a random stationary signal. It was first used assuming that the input signal has a sinusoidal shape (from 1999 to 2003) and then conservative signals from mock-ups were used (since 2003) [2].

Selection of the temperature signal and calculation of a heat transfer coefficient

A first criterion establishes that a mixing zone may be concerned with HCTF if the difference of temperatures between the hot and cold branches is higher than a given ΔT level. A representative signal to the mixing zone is then taken from a data base (tests on mock-ups):

- For the auxiliary mixing zones, the temperature signal reference comes from measurements on an old RHRS configuration type mock-up. This signal is the most conservative with a flow rate ratio of 20% (called AC20C1F). The heat transfer coefficient is equal to twice the Colburn correlation (forced convection).
- For the primary mixing zones, for the main branch, the fluid temperature signal is extracted from the database of Chemical and Volume Control System (CVCS) nozzle corner tests. A conservative signal is taken according to the flow rate ratio. The heat transfer coefficient is equal to 1.5 times the Colburn correlation.

This signal is finally modified in amplitude and in time dilatation in order to have a conservative input for the simplified engineering method.

Calculation of the fatigue damage

The temperature and elastic strain fields are obtained via a 1D analytical approach and an extraction of elementary cycles is made with the Rainflow method [7]. Plasticity phenomena are taken into account through the K_ν plastic correction factor of the French RCC-MR methodology [8].

Stress cycles are then analyzed with a fatigue curve and the Miner linear cumulative rule to assess a time for crack initiation. The fatigue curves used come from the French RCC-M code [9] up to 10^6 cycles and are prolonged according to:

- Former ASME A curve [10] for the zones characterized by a good surface finish and weak mean stresses.
- Former ASME C curve [10] for the zones characterized by a poor surface finish and/or high mean stresses.

In case of non-flushed weld, a reduction factor of 1.5 is applied on the ASME C fatigue curve.

Application to Civaux

As an element of comparison for the following study, the case of Civaux 1 train A is analyzed here (two trains exist on the RHRS circuit for the redundancy of security systems). As described previously in this paper, the signal to be used with the engineering method, for this RHRS configuration, is the AC20C1F one (amplitude and time dilatation are adapted). The heat coefficient transfer calculated (equal to twice the correlation of Colburn) is 26000W/m²/°C and a difference of temperature ΔT of 135°C during 1500h (according to the operating history) is taken into account to perform the calculation. The through-wall crack was located in a weld, so the fatigue curve used here is the ASME C with the reduction factor of 1.5. The damage parameter calculated with the engineering method is equal to 14.

THE ENGINEERING METHOD APPLIED TO FATHER

First analysis level using strictly the engineering method

The FATHER experiment (representative of a new RHRS mixing tee) should be analyzed with the engineering method using the signal AC20C1F as input signal. The heat coefficient transfer is calculated by the Colburn's correlation (multiplied by 2) with the FATHER experimental data. The endurance test was done with a ΔT of 160°C, the signal is then adapted to this amplitude of temperature and a critical time dilatation is searched in order to minimize the initiation time calculated by the simplified method. The exercise is performed with the various fatigue curves at our disposal and the results in terms of damages, i.e. the ratio between the operating time (300h) and the initiation time predicted by the engineering method, are reported on Table 1.

	Initiation time	Damage
Polished and finely ground surfaces (ASME A curve)	209h	1.44
As-machined and roughly ground surfaces (ASME C curve)	169h	1.78
Non-flushed welds (ASME C curve + weld reduction factor)	18h	16.67

Table 1: Initiation times and damages predicted for FATHER with the engineering method

As a conclusion, FATHER is well identified by the engineering method as a zone presenting a HCTF risk and cracks are likely to preferentially initiate in welds. The method is quite conservative since the damage parameter calculated is close to the one calculated on the Civaux case but no leak have been observed on FATHER where thermal fatigue cracks have depths varying only from 100 to 1000 µm. Moreover, the zones in the straight pipe with various surface finishes seem to present a lower risk. All these results have been confirmed by the metallographic expertises and it can be concluded that a damage factor higher than 1 does not necessarily signify a proved risk.

Analysis of the distribution of the FATHER loadings

83 signals from analytical thermo-hydraulic tests are used here. These signals correspond to a ΔT of 160°C and a flow rate ratio of 20% as in the endurance test. The measurements are recorded with a sampling frequency of 50Hz during 1 hour to reach good statistic parameters (the signal must be ergodic to be used with the engineering method). Fluid temperatures (56 signals) and solid temperatures in the wall (27 signals) are used. The fluid signals are filtered (low-pass filter) in order to take into account the time response of the sensor.

A first rough analysis of the mean temperatures and standard deviations of the 83 signals, the values being taken at the inner wall shows quite homogeneous results along the mock-up. In order to refine it, these variables are taken at determined azimuths for different rings. As a convention, the azimuth 0° is the bottom of the straight pipe. As it can be seen on Figures 2 and 3, the first analysis is confirmed since no significant evolution of the mean temperatures or standard deviations is highlighted along the length of the mock-up. On the other hand, the azimuth appears to be an interesting variable: Figures 2 and 3 shows that the levels of temperature and amplitude are not the same according to the azimuth.

Assuming that there is no impact of the longitudinal location, the 83 signals can be treated only by the azimuth (Fig. 4 and 5). It is clearly shown that the thermal fluctuation zone is located around -50° and 50°: the standard deviations are maximal at these azimuths.

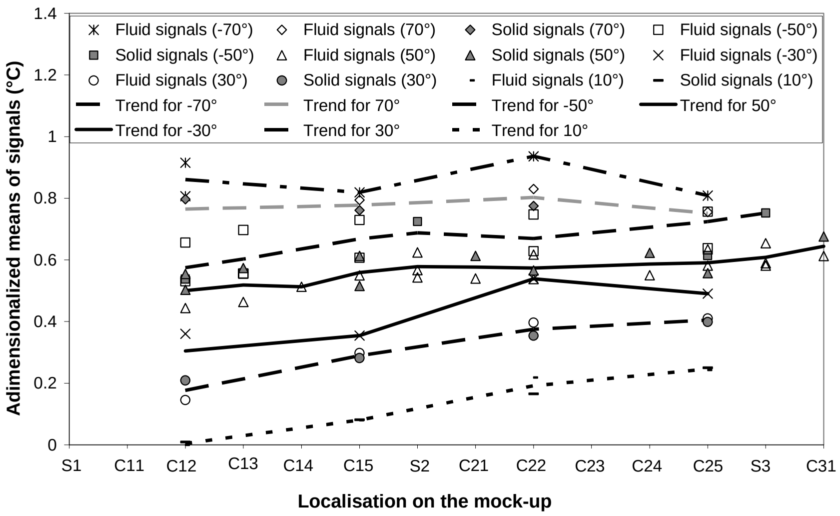

Fig. 2: Longitudinal distribution of the mean temperatures for several azimuths

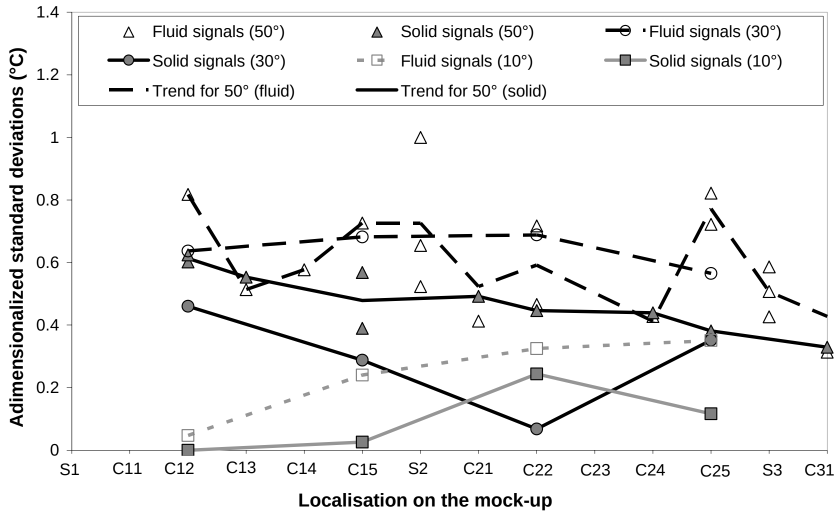

Fig. 3: Longitudinal distribution of the standard deviations for several azimuths

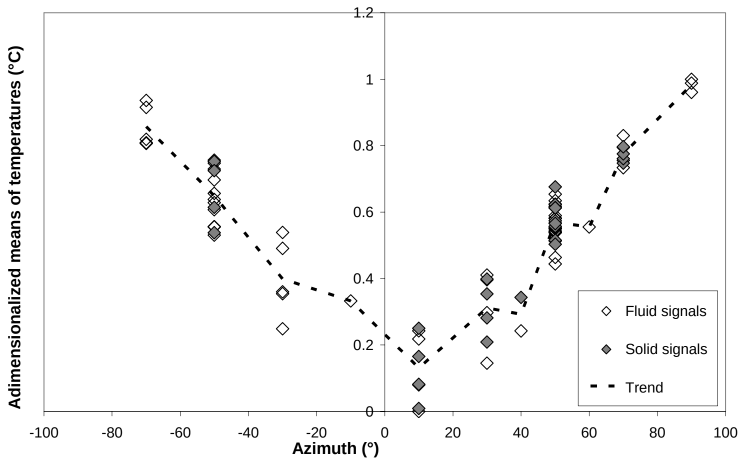

Fig. 4: Azimuthal distribution of the mean temperatures

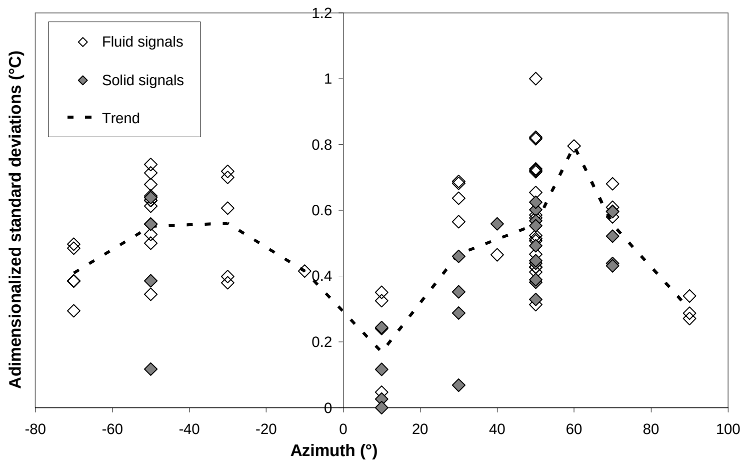

Fig. 5: Azimuthal distribution of the standard deviations

Second analysis level using the FATHER temperature signals

Crack initiation times are calculated with the engineering method using the signals described before. A first analysis is performed by ensuring the correspondence between the surface finishes of the various rings and the fatigue curves. More precisely, the rings C11, C12, C14, C21, C22 and C24 are analyzed with the ASME A curve; the rings C13 and C31 with the ASME C curve and the welds (S2 and S3, S1 not being treated) with the ASME C curve with a reduction coefficient of 1.5. The results are shown on Figure 8. The values higher than 1.10^6 hours, corresponding to no crack initiation prediction are not represented.

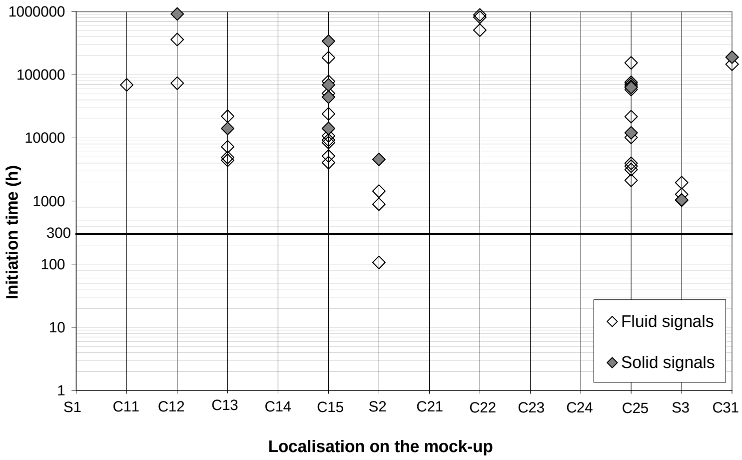

Fig. 8: Crack initiation times calculated with the engineering method and the FATHER temperature signals

By this analysis, the FATHER mock-up should present cracks only in the S2 weld (on the non-flushed part): there is only one initiation time (106h) lower than the operating time of the FATHER endurance test (300h). It can also be concluded that for polished zones or ground surface finishes, there is no HCTF risk predicted with the simplified method. As previously noted, no significant impact of the longitudinal location can be assumed and all the signals can be so considered as representative to the loadings close to the welds. This allows presenting an azimuthal distribution of the crack initiation times in the welds (Fig. 9).

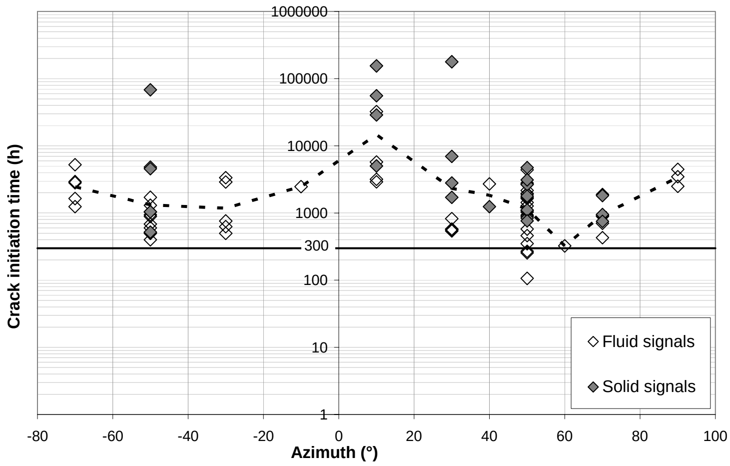

Fig. 9: Crack initiation times calculated in the welds according to the azimuth with the engineering method and the FATHER temperature signals

Taking into account more temperature signals for the welds, it is shown that non-flushed welds present a HCTF risk on the FATHER mock-up. Nevertheless several calculated crack initiation times are close to 300h. It can also be noted that the most damaged azimuthal zones are close to -50° and 50°, that corresponding to the highest standard deviations.

DISCUSSION

FATHER metallographic expertises highlighted cracks in non-flushed welds and in ground surface finish zones. The engineering method is not an expertise one but its use with real loadings gives quite good results. No crack initiation is predicted in the polished straight pipes and the S2 non-flushed weld is well identified as a zone where cracks appear in 300h (crack initiation time of 106h). A large part of the conservatism of the engineering method, which strictly predicts crack initiations in polished zones in 209h and in non-flushed welds in only 18h, is so included in the thermal-hydraulic input data.

However, it must be also noticed that the S3 non-flushed weld and the ground surface finish zones are not identified with this method. So these applications raise some questions which may be in connection with the discussion on fatigue design curves mainly initiated by [11] which proposes a new curve more conservative than the former ASME C one. To go further, an exercise has been done taking into account this new fatigue curve. No more difference of surface finishes is then made. It is proposed to analyze the FATHER mock-up with the new curve for all the rings and taking into account the reduction factor of 1.5 for non-flushed welds.

Results are presented for non-flushed welds (Fig. 10) and for the other locations (Fig. 11). The benefit of taking into account real signals is here counterbalance by the conservatism of the fatigue curve since one obtains:
- Time initiations lower than 20h for non-flushed weld locations,
- Time initiations close to 100h for the straight pipes, these results being not in agreement with the expertises.

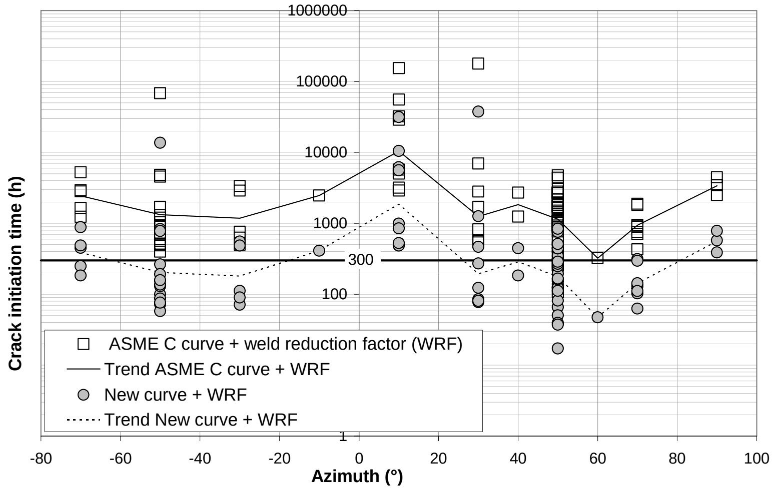

Fig. 10: Comparison of results with ASME C curve and new one for non-flushed welds

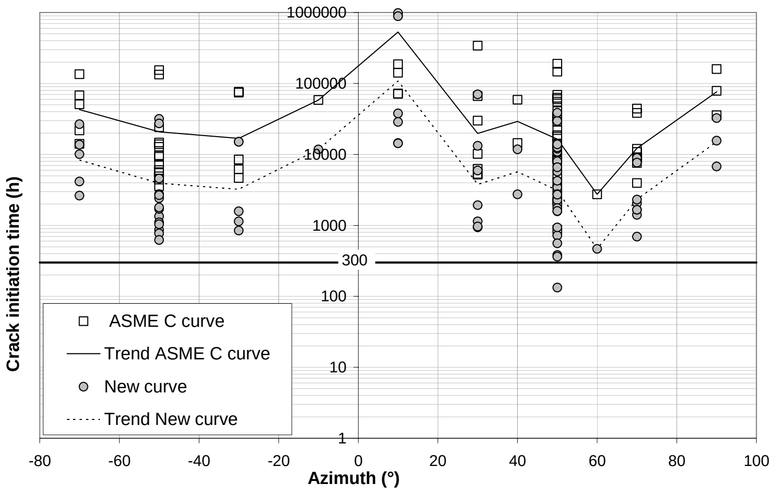

Fig. 11: Comparison of results with ASME C curve and new one for straight pipes

Except the conservatisms on the thermal-hydraulic data, considerations about the fatigue curves seem to be a priority to master the approach. Using fatigue design curves is the most suited to treat industrial cases. Transferability factors are taken into account to link laboratory specimen results with industrial component configurations and so cover mainly result scatter, scale, environmental and surface finish effects. However, the methodology developed to generate these fatigue design curves may be sometimes too conservative by assuming a multiplication of the aggravating effects.

A second element to think about is the definition of the crack initiation. In the FATHER experiment, only 1 mm depth crack has been observed but this kind of damage may be noticeably weaker than the fatigue damage level usually corresponding to the number of cycles to rupture in uniaxial fatigue tests (approximately 2 or 3 mm length crack). So a good consistency is needed between the damage level that one wants to predict and the tools and particularly the fatigue curves that one uses in the analysis.

CONCLUSIONS

An engineering method to analyze HCTF phenomena in mixing zones has been reminded in this paper. Applying strictly this approach permits to clearly identify the FATHER mock-up as a zone presenting a risk, which is the major objective of the methodology. Nevertheless, according to a second level of analysis, with real signals measured on the mock-up, only the non-flushed welds present a risk in a specific azimuthal area, this conclusion being confirmed by the metallographic expertises.

Thus, the conservatisms of the current approach in terms of thermal-hydraulic data have been clearly highlighted and its relevance has been proved if one is able to reduce this point. Another element of the method which is discussed in this paper is the use of appropriate fatigue design curves. In particular, the treatment of the aggravating effects and the definition of the crack initiation are the main points on which it would be useful to think.

ACKNOWLEDGMENTS

The authors are grateful to O. Braillard (CEA) who was responsible for the tests on the FATHER mock-up. They also express their thanks to all the contributors of AREVA, CEA and EDF who carried out the metallographic expertises.

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