SMiRT-12 / K. Kussmaul (Editor)



F10/4

# EXPERIMENTAL INVESTIGATION OF A FLAWED PIPE SYSTEM LOADED WITH TEMPERATURE STRATIFICATION AND PRESSURE

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## 1 INTRODUCTION

Pipings in nuclear power plants are loaded in different ways depending on the phases of operation. The mechanical and thermal loading (often originating from suppressed thermal extension) results in local stresses and strains. Unfavourable conditions as corrosive coolant chemistry together with a high number of load cycles may lead to crack formation and crack growth in piping made of ferritic steels. The experiments performed within test group E21 of Phase III of the HDR Safety Program /1/ (HDR = test facility based on the decomissioned Hot Steam Reactor near Karlstein/Bavaria) therefore have had the objective to simulate corrosion assisted crack growth under close-to-reality mechanical and thermal loading.

Especially test E21.2 was to investigate the effect of temperature stratification in a horizontal pipe on an already existing hoop crack grown during cyclic bending moments. Such cracks were in some cases discovered in horizontal feedwater lines where - despite of some thermal mixing and energy exchange - the cold feedwater may flow underneath the hot fluid because of the different densities. These flow conditions are characterized by extremely stable global stratification. Due to the larger expansion of the pipe material in the hot fluid region, axial and bending stresses as well as local deformations of the pipe cross-section occur.

The major objective of preceding stratification tests T33 of the HDR Project Phase II had been the measurement of instationary and steady state thermal stratification effects in a DN 400 pipe system under high pressure with different levels of the cold feedwater. The tests included also measurements of the position of the transition layer in which - under specific flow conditions - stable wave-like temperature fluctuations occur /2/. A multitude of thermo-couples and strain-gages showed the above mentioned effects including the initial thermal-shock produced by the running cold water front. The new test E21.2 covers crack growth and leak-before-break behavior of a 60° circumferential crack in a DN 425 ferritic pipe system under operating conditions (p = 10.8 MPa, T = 240°C) loaded with repeated temperature stratification in its horizontal part (simulation of a feedwater line as before). Emphasis is laid now upon the crack behavior under constant fluid boundary conditions (repeated stratification).

## 2 TEST SET-UP AND INSTRUMENTATION

The experimental pipe system connnected with the HDR reactor pressure vessel (RPV) was about 24 m long including four pipe bends (Fig. 1). The test section near the RPV nozzle (400 mm long, wall-thickness reduced to 16 mm) was made of the low alloy ferritic steel 20 MnMoNi 5 5 (similar to ASTM A508 (1)) and comprised a 60° long pre-fabricated crack with an initial depth of 30%. During the temperature induced loading phase the hydraulic cylinder producing bending moments before and there-after was fixed. Measuring comprised cylinder force and stroke, displacements of the piping, operating parameters as pressure and temperature of fluid and pipe, various strains (pipe outside and inside, around the crack position outside) and crack mouth opening displacement (CMOD, two positions inside), as well as acoustic emission signals in order to record the onset of cracking. The sum of all transducers amounted to 230; Fig. 2 shows a survey of the measuring instrumentation on the outside of the test section.

## 3 TEST RESULTS

The complete stratification induced stress in the wall of the horizontal pipe wall consists of several components: a) The initial running cold water front produces local thermal shocks. b) The steady state thermal stratification results in axial and circumferential stress distributions in the pipe wall. c) Under specific flow conditions in the pipe a stable wave-like structure of the transition layer occurs leading to temperature fluctuations acting on the inside pipe surface (this effect was investigated in /2/). As the highest bending stress is produced by low cold water levels /5/ a level of 12% was chosen (s. Fig. 3) that was independently used in a parallel test E23.2 which was dedicated to the nozzle/thermosleeve behavior /3/.

The pipe and the crack as well were loaded with 8+50 stratification processes of mostly half an hour duration; the second and third of them are presented here. Figs. 4 and 5 show the temperatures inside and outside the wall near the crack. The transition zone between hot and cold fluid is characterized by the known fluctuations, the fluid temperature at the bottom is less than the adjacent wall temperature. The temperature shock is decreasing with increasing distance from the cold water level. The behavior of the whole piping is characterized by the bending of the horizontal pipe due to the contraction of the pipes bottom (bimetal spring effect), see Fig. 6; the fixing of the piping by the cylinder causes force amplitudes up to 145 kN.

The circumferential strains are caused by ovalisation and widely influenced by the axial ones. At the deepest point the inner and outer strain gage in Fig. 7 clearly show two additional peaks in comparison to the adjacent ones (Fig. 8) indicating some thermal shock and a local bending; the thermal shock peak is growing with higher mass-flow of cold (here only 2600 kg/h) or warm water. The most important influence on crack growth is produced by the high axial strain peaks at the pipe's bottom up to 0.3%, see Figs. 9 and 10; strains outside the cooled zone reach only one third of that. Finally these local strains produce crack growth (or at least stimulate incipient cracking); so the two clip-gages (developped by MPA Stuttg.) show distinct crack growth according to the increasing CMOD level of 0.04 mm (Fig. 11). The whole 50 stratification cycles raised the CMOD level from about 0.45 to 0.58 mm (Fig. 12) /4/. After the final leak - reached only after 1000 corrosion-assisted bending cycles by a specific overloading - the fractographic examination of the crack showed average stratification induced crack growth rates from 8 to about 20 µm per cycle, comparable to or even higher than those due to corrosion assisted bending cycles with 8 ppm oxygen content in the water (4-8 µm/cycle).

## 4 SUMMARY

During an experiment examinating the crack growth in piping components at operating pressure and simulated operation induced bending moments a horizontal pipe simulating a feedwater line was loaded by 58 temperature stratification cycles. As already known from earlier tests the pipe shows severe axial strains up to 0.3% that can be influenced by the cold water mass-flow (thermal shock) and the position of the fixing points. CMOD measurement showed step by step crack growth, especially during the first cycles. Pipe failure did not occur in this phase; FEM calculations (not reported here) might be able to value the general importance of stratification loads compared with other loads.

## ACKNOWLEDGEMENT

The author appreciates the sponsoring of the HDR safety program by the German Federal Ministry of Research and Technology (BMFT).

## REFERENCES

/1/ Müller-Dietsche, W., Katzenmeier, G. October 1988. HDR Safety Program - Phase III, PHDR Work Report No. 05.44/88: Kernforschungszentrum Karlsruhe

/2/ Wolf, L., Häfner, W., Geiss, M., Hansjosten, E., Katzenmeier, G. 1992. Results of HDR experiments for pipe loads under thermally stratified flow conditions. Nucl. Eng. and Design 137: p. 387-404

/3/ Kußmaul, K., Mayinger, W., Diem, H., Katzenmeier, G. 1993. Behavior of a reactor pressure vessel nozzle with thermo-sleeve under thermal loading induced by stratified flow. Trans. SMiRT 12: Paper FG 13/4

/4/ Hunger, H. 1993. Quick Look Report-Test E21.2. PHDR-Technical Report No. 114-93: Kernforschungszentrum Karlsruhe (in German)

/5/ Talja, A., Hansjosten, E. 1988. Stresses in a horizontal pipe line due to thermal stratification - Evaluation Report test group T33. PHDR-Technical Report 81-88: Kernforschungszentrum Karlsruhe

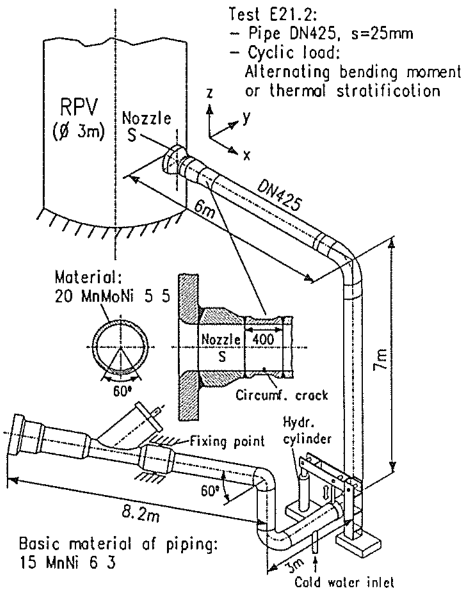


Fig. 1 Experimental arrangement for pipe failure test E21.2

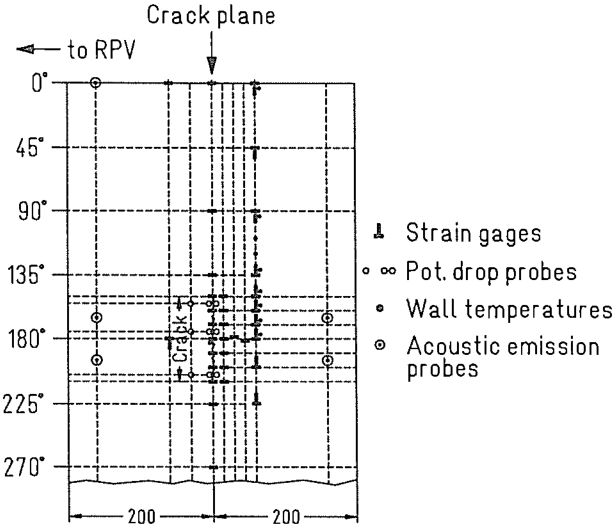


Fig. 2 Outer surface of test section with instrumentation

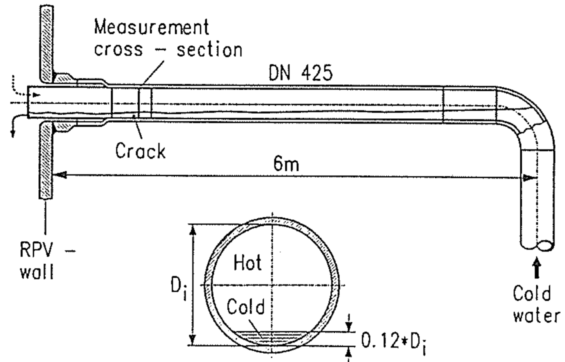


Fig. 3 Schematic view of the thermal stratification in the E21.2 test pipe

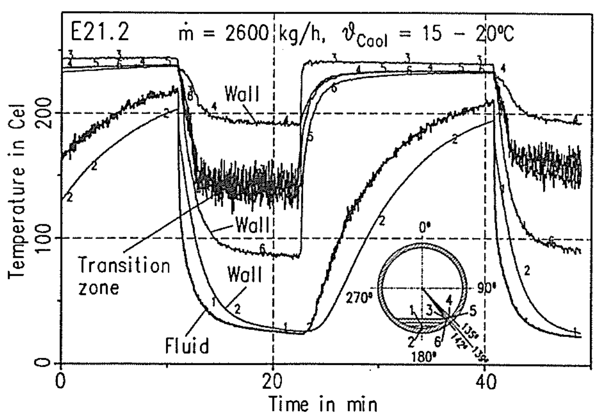


Fig. 4 Thermal load: Fluid temperatures and stratification level

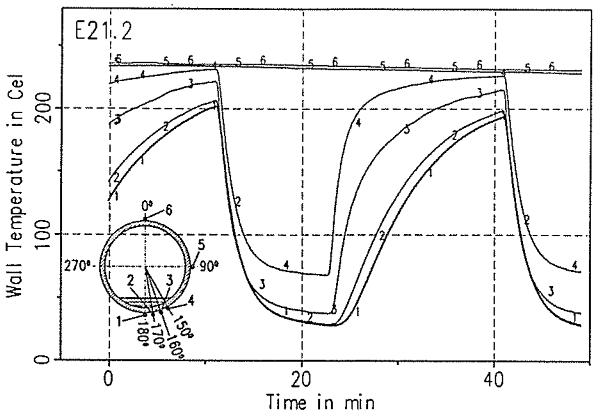


Fig. 5 Thermal load: Outside wall temperatures

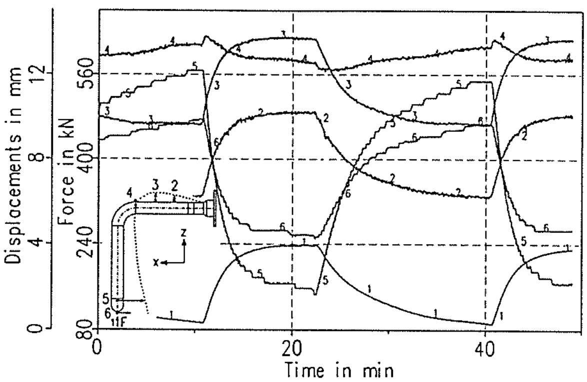


Fig. 6 Displacements of the piping and cylinder force due to stratification

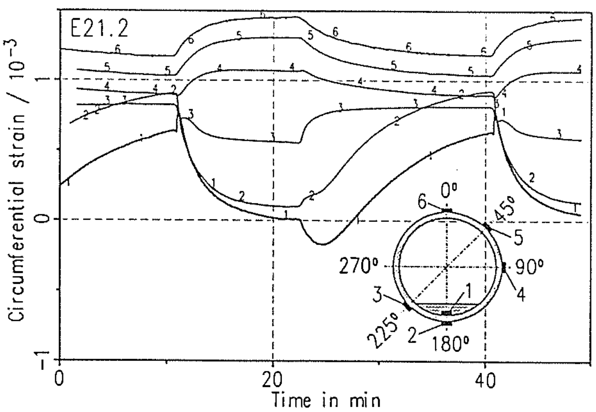


Fig. 7 Circumferential strains inside and outside of cross-section Q09

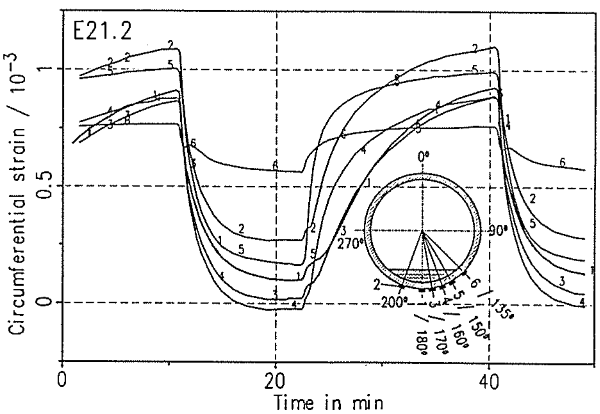


Fig. 8 Circumferential strains outside in the cooled zone

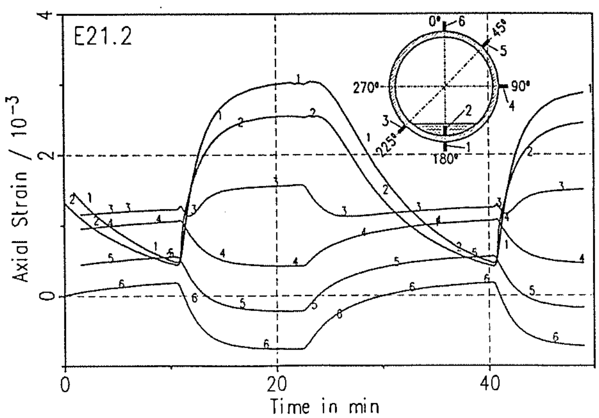


Fig. 9 Axial strains inside and outside of cross-section Q09

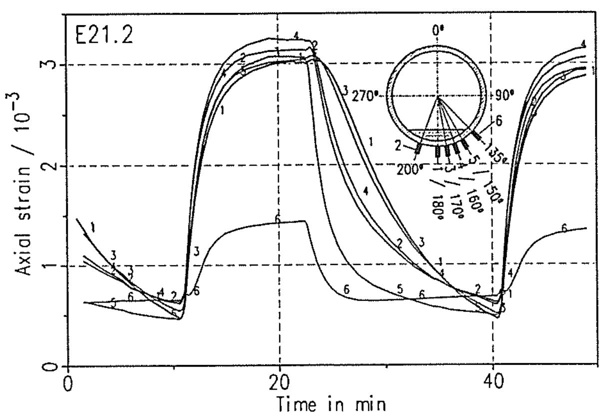


Fig. 10 Axial strains outside in/near the cooled zone

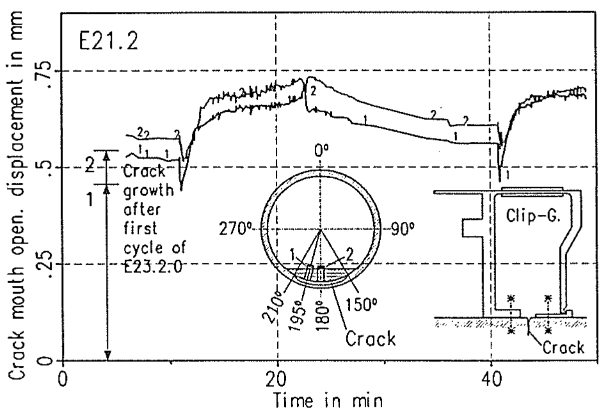


Fig. 11 Crack mouth opening displacement measured by two clip-gages

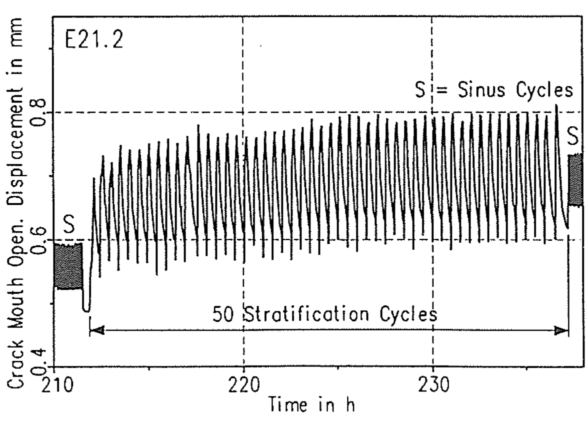


Fig. 12 CMOD measurement during the whole of the 50 stratification cycles of E21.2