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F10/3

STRESS CORROSION CRACKING IN HOTWATER AND FEEDWATER VESSELS - FINDINGS AND CONSEQUENCES FOR OPERATION AND DESIGN

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1. Summary

A number of cylindrical vessels for hot-water and steam supply were installed in one new erected steel work in 1968. Following a theoretical stress analysis on a total of five different types of vessels which have been subjected to a variety of operating parameters over a period of 25 years, recommendations were made with regard to in-service inspections of the analytically determined lower bound within the vessels. By means of non- destructive testing of the insides of the vessels (surface-crack detection by means of magnetic-particle examination as well as, to a limited extent, using US-testing), in addition to other flaws, cracks were also discovered parallel to circumferential weld seams (on the inside). A fracture-mechanical analysis of the findings provided indications of strain- induced corrosion. The frequency of the indications as well as their amplitudes suggested a water chemistry with a high oxygen content (> 200 ppb). This was also confirmed by subsequent measurements.

2. Introduction and Objective

In the course of the planning of in-service inspections on pressure vessels, a lower bound analysis was conducted in a steel work that was taken into service in 1968. The objective of the lower bound analysis was to decide on preferred locations for the in-service inspections to be performed.
The following were examined:

- vessels that had been subjected to cyclical internal-pressure stressing between p = 2.6 MPa and p = 1.2 MPa at T = 493 (medium: water/steam);
- vessels/tanks that had been subjected to predominantly constant internal pressure p = 0.6 MPa at T = 423 K (medium: water/steam);
- vessels that had been subjected to constant internal pressure p =1.1 MPa and T = 378 K (medium: water);
- vessels that had been subjected to constant internal pressure p = 0.2 MPa and T = 303 K (medium: water);
- vessels that had been subjected to an internal pressure p = 5.8 MPa and T = 573 K (medium: water/steam).

The above stressing had applied over a period of approximately 25 years with just approximately 25 brief interruptions (a few days around Christmas).

The dimensions and materials (ferritic) of the vessels that were examined within the steel works can be seen from Table 1.

Vessel	Operating temperature T K	Operating pressure p MPa	Materials	Outside diameter mm	Wall thickness mm
Steam accumulator	493	1,2-2,6	HSB 55 C	3200	29
Hot-water generator	423	0,6	H II	2200	13
Feedwater tank	378	1,1	St 37.2	3000	8
Return tank	303	0,2	H II	3200	11
Evaporation drum	573	5,8	17 Mn 4	1500	46

Table 1: Dimensions and Materials of Vessels Examined

There follows a brief description of the flaws that were discovered according to the lower bound analysis by means of surface-crack testing (inside and outside) as well as ultrasonic examinations. This report deals mainly with the documentation and analysis of the findings that were attributed to strain-induced corrosion and pitting.

3. Recording of Operating Data

Internal pressure, steam accumulator: The internal pressure was deduced from the documented operational measurements performed on 15.8.1989; see figure 1. The maximum and minimum values were recorded as approx. 2.8 MPa and approx. 1.2 MPa, respectively. According to the measured data, the operating-cycle duration is approx. 0.92 hours. The plant has been in operation for 25 years and has been operated for approx. 8.000 hours per year. Assuming approximately 200.000 operating hours, this corresponds to approx. 216.000 operating cycles.
Temperature curve, steam accumulator: The steam temperature was not recorded in operation. The temperature curve of the steam-accumulator wall (outside) was measured on all three vessels using applied thermocouples. The measured temperature curves were identical for all three accumulators. The temperatures run parallel to the internal-pressure fluctuations (saturation temperature) and have their maximum at T = 503 K and their minimum at T = 463 K. Temperature layering of approx. ΔT = 25 K across the cross section of the vessel also remains constant throughout the cycle; see figure 2.

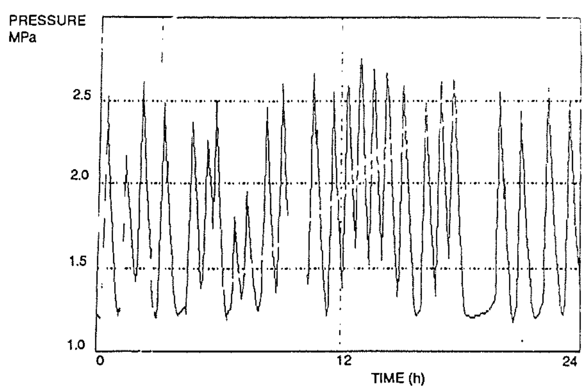

figure 1: Measured Internal-Pressure Fluctuation of Steam Accumulator on 15.8.1989

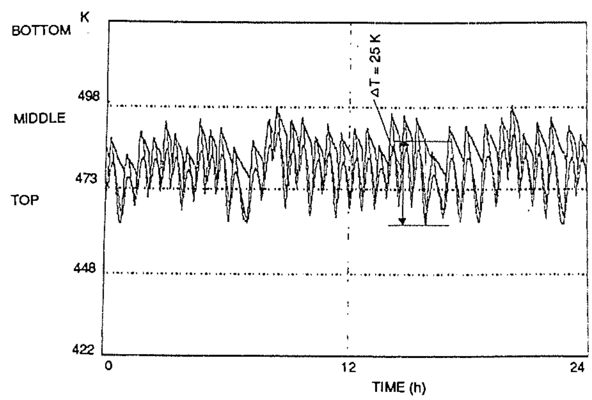

figure 2: Measured Temperature layering Fluctuation across the cross section of the vessels on 10.9.1989

Water chemistry, steam accumulator: An evaluation of the conductivity data between 01.01. and 13.04.1989 shows a maximum of approx. 120 µS/cm (see figure 3). The oxygen content was also measured intermittently. The measured data fluctuate between 50 and 2.500 ppb O_2, depending on the load cycle.

The hot-water accumulator is operated at constant pressure p = 0.6 MPa and T = 423 K. The heated water is drawn out of the horizontally installed hot-water accumulator in the region of the bottom cross-section crown. A temperature measurement at the outside wall of the vessel showed 383 K in the centre of the cross- section height and 368 K at the bottom crown (ΔT = 25 K). Once again, there are temperature layers within the cross sections of the vessel.

The feedwater tank as well as the return tank are operated at constant internal pressure.

The evaporation drums are operated at 5.8 MPa and T = 573 K. During a period of 24 hours, there are approx. 3 internal-pressure fluctuations per day per vessel, depending on the heats being produced.

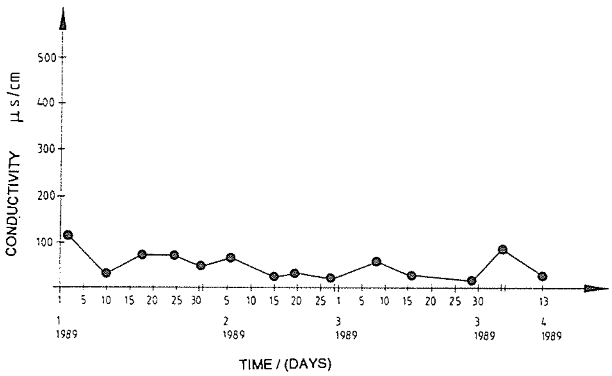

figure 3: Evaluation of Conductivity Values in Drum Region

4. Recommended In-Service Inspections

The drawing of a steam accumulator can be seen in figure 4. According to the design features and the non-ground circumferential and longitudinal weld seams of the individual shots as well as on the basis of the theoretical stress analysis, it was recommended that surface-crack testing should be performed at

- the supporting-plate weld-on points in the circumferential and longitudinal directions, from outside and
- circumferential and longitudinal weld seams of the shots, from inside.

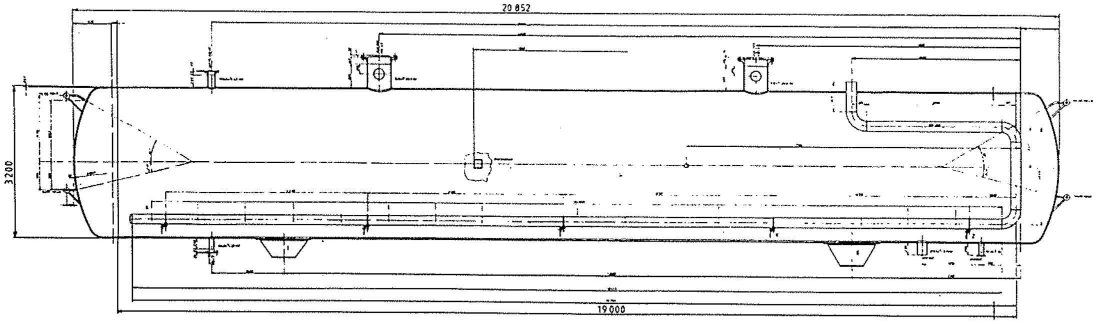

figure 4: Representation of Steam Accumulator 1 with Principal Dimensions

Identical areas for in-service inspections were recommended for the hot-water generator documented in figure 5.

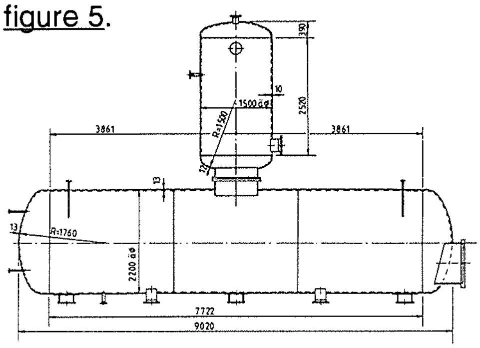

figure 5: Representation of Hot-Water Generator

Similar recommendations are made for the remaining vessels. With regard to the evaporation drum, the in-service inspection was extended to include the nozzle corners, inside.

5. Non-Destructive Testing

5.1 Surface-Crack Testing

Surface-crack testing on the cold vessel in accordance with DIN 54130 was conducted using a yoke magnet on all vessel weld seams which had been ground flat from the inside. The fillet welds of the supporting-plate weld-on points on steam and hot-water vessels were ground smooth.

5.2 Ultrasonic Examination

The ultrasonic examinations were performed on the insides of the vessels and were used likewise to determine the crack depths. A wall-thickness measurement on the steam accumulators revealed a wall thickness of between 27.5 and 30.5 mm in the cylindrical region.

6. Association of Findings

Flaws in the region of the weld seams were discovered on the following vessels; see Table 2.

Vessel*)	Steam accumulator			Hot-water generator
Year of test	1989	1989	1992	1990
Max. length of finding [mm]	1500	40	5	50
Max. depth of finding [mm]	27	1,5 - 2,5	0,2	1
Location of findings	Longitudinal and circumferential weld seams of supporting plates	Circumferential weld seams	Circumferential weld seams	Circumferential weld seams

*) Also pitting attack with a diameter of approx. 1 mm in the region of the circumferential weld seams ± 50 mm from the fusion line at the bottom crown of the vessel.

Table 2: Association of Findings

The longitudinal and circumferential indications between supporting plates and the vessel wall that have grown from the outside wall towards the inside wall can be ascribed to cyclical internal-pressure stressing. The flaws and extended pitting observed in the further course of the examination were found on the inside of the vessels parallel to circumferential weld seams.

6.1 Incipient Cracks Parallel to Circumferential Weld Seams (Inside)

Table 3 is a compilation of all the indications that were found parallel to circumferential weld seams as well as the theoretical considerations.

Vessel		Steam accumulator		Hot-water generator
Year of test		1989	1992	1990
Internal pressure	p [MPa]	2,6	2,6	0,6
Internal-pressure fluctuation	Δp [MPa]	1,4	1,4	-
Temperature layers	ΔT [K]	25	25	25
Crack depth	a [mm]	1,5 - 2,5	0,2	1
Change in circumferential stress	$\Delta\sigma_u = \frac{\Delta p \cdot D}{2 \cdot s}$ [N/mm²]	77,2	77,2	50,6
Change in longitudinal stress	$\Delta\sigma_L = \frac{\Delta\sigma_u}{2}$ [N/mm²]	38,6	38,6	25,3
$\Delta\sigma_{+h} = \alpha \cdot \Delta T \cdot E$; $\alpha = 10 \cdot 10^{-6} \frac{1}{K}$, E = 200 000 [N/mm²]		60	60	60
	$\Delta\sigma = \Delta\sigma_L + \Delta\sigma_{+h}$ [N/mm²]	98,6	98,6	85,3
Strain amplitude	$2 \cdot \Delta\varepsilon = 2 \cdot \frac{\Delta\sigma}{E}$ [%]	$9{,}86 \cdot 10^{-4}$	$9{,}86 \cdot 10^{-4}$	$8{,}5 \cdot 10^{-4}$
Stress-intensity factor	$\Delta K_I = \Phi \cdot \Delta\sigma \sqrt{\Pi \cdot a}$ [N/mm²]	8,9 where Φ = 1,14 /1/	2,75 where Φ = 1,113 /1/	5,42 where Φ = 1,134 /1/
Incubation time	Δt [s]	$6{,}048 \cdot 10^{8}$	$1{,}814 \cdot 10^{7}$	$7{,}2 \cdot 10^{8}$
Rate of crack growth	$\frac{da}{dt} \left[\frac{mm}{s}\right]$	$1{,}65 \cdot 10^{-9}$	$1{,}1 \cdot 10^{-8}$	$1{,}39 \cdot 10^{-9}$

Table 3: Compilation of Evaluated Crack Indications

The flaw discovered in the hot-water generator is shown in figure 6.
All the values of the calculated strain amplitudes are within the range of the fatigue strength, as is shown by the ASME Design Curve, figure 7, with the strain amplitudes determined in Table 3. This result yields into conclusion that other crack initiation mechanism as cyclic loading was responsible for creation of incipient cracks. The form of the findings (short cracks starting in pits on the inside surface connected to a long crack) revals the assumption that the cracks grown under constant load in a strain induced corrosion mode. Therefore the findings were compared with ASME-section XI values.

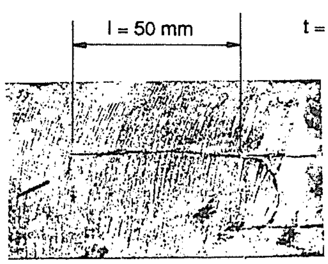

figure 6: Indication in Hot-Water Generator

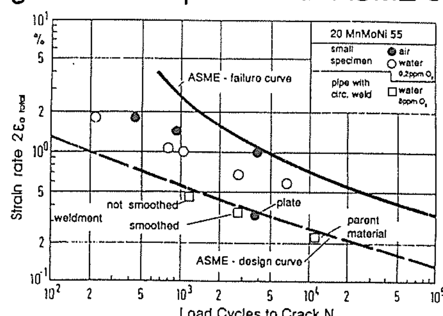

figure 7: ASME Design Fatigue Curve

According to figure 8, ASME Section XI Curve /2/ and BTB-Jansky reference curve /3/, the values calculated in the steam accumulator in 1989 and in the hot-water generator in 1990 are below the reference curve according to ASME. An evaluation of the indications in the steam accumulator from 1992 revealed that this value is above the ASME Section XI Curve. The described flaws may be therefore attributed exclusively to strain-induced corrosion.

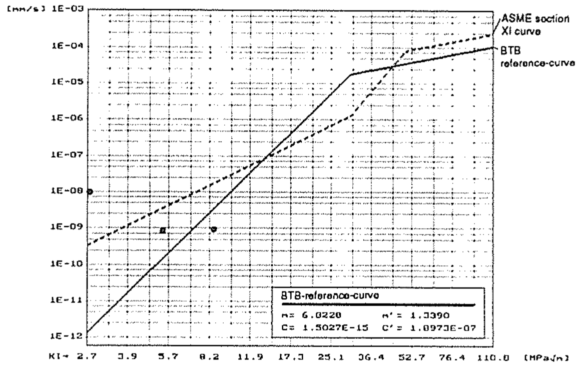

figure 8: Crack-Growth Curves: BTB-Jansky Reference Curve and ASME Section XI Curve (New)

7. Conclusions

The fracture-mechanical analysis of the findings pointed to strain-induced corrosion of the vessels examined. The measured rates of crack propagation da/dt are well described by the ASME curve for ferritic materials. The frequency of the indications as well as numerous pitting attacks parallel to circumferential weld seams and also their amplitudes allow the conclusion that high an oxygen content (> 200 ppb) of the medium is the cause of the strain-induced corrosion.

8. References

/1/ Bruchmechanik metallischer Werkstoffe (Fracture Mechanics of Metallic Materials), 1980 edition, K. H. Schwalbe

/2/ Publication at NRC Aging Research Information Conference, March 24-27 1992, Rockville, MD: "Environmentally Assisted Cracking and Fatigue of Reactor Structural Materials in LWR Environments"; authors: T. F. Kassner, W. F. Ruther, J. Y. Park

/3/ Publication at PRESSURE VESSELS AND PIPING CONFERENCE; San Diego, June 23-27, 1991,Page 25-35, J. Jansky, C. Scherer, Th. Andrä, "New method for ensuring safety and aivailability of pressure retaining components"

9. Figures