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Experiments on Radiolysis Gas Detonation in BWR Exhaust Pipes and Mechanical Response to the Detonation Pressure Loads

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ABSTRACT

In the current work we consider a typical BWR exhaust pipe, which connects the high pressure steam piping with the ambient atmosphere, under the following ”worst case” scenario: (a) accumulation of radiolysis gas in an exhaust pipe, (b) fast valve opening to the high pressure system with steam at 70 bar, and (c) adiabatic pressurization of the radiolysis gas by the steam. Detonation experiments of radiolysis gas were performed in a real scale exhaust pipe of 12.25 m length made from stainless steel Nr. 1.4541. To reproduce the ”worst case” scenario for radiolysis gas after the steam pressurization we used a radiolysis gas mixture at 10 bar and 293 K which energetically (with respect to the pressure load) equals the pressurized BWR mixture at 20 bar and 602 K. The inert part of the tube was filled with nitrogen instead of steam to enable experiments at ambient temperature. The experiments showed that the maximum deformation occurred at the end of the radiolysis gas vessel. The maximum dynamic strain was measured to be 0.75% for the radiolysis gas detonations at 10 bar, with the maximum remaining deformation, using strain gauges and direct measurements, being about 0.15%. This means that the exhaust tube remains intact even under this worst case detonation scenario of the pressurized radiolysis gas mixture. To simulate detonation of the radiolysis gas mixture at 20 bar and 602 K with steam as an inert gas, the 3-dimensional CFD code DET3D [3] was used. Using a simplified 1D model for the mechanical response of a cylindrical pipe under an internal dynamic pressure load, the dynamic strain corresponding to these calculated pressure signals was determined. A comparison of these calculated strain values with the experimental signals showed a very good agreement.

1 INTRODUCTION

At full load, the steam in the primary circuit of a BWR of German design contains very low concentrations of hydrogen and oxygen originating from the radiolysis of water in the core (approx. 20 vol. ppm H_2, 10 vol. ppm O_2) [1]. In the event of a small steam leak at a safety and relief valve, radiolysis gas ($2H_2+O_2$) can accumulate in the vent pipe over a long period of time because the steam condenses and the radiolysis gases remain (Fig. 1). Flushing holes were therefore installed on the blow-off pipes of the Philippsburg nuclear power plant, which allow radiolysis gas to be reliably blown down by regularly spraying the condensation chamber. However, the Reaktor-Sicherheitskommission (RSK) recommendation "Basic requirements for measures to prevent inadmissible radiolysis gas reactions" [2] expects that the effects of an assumed maximum enrichment must be examined, regardless of the precautions already taken to prevent the accumulation of radiolysis gas. A system section completely filled with radiolysis gas and an effective ignition mechanism are to be assumed.

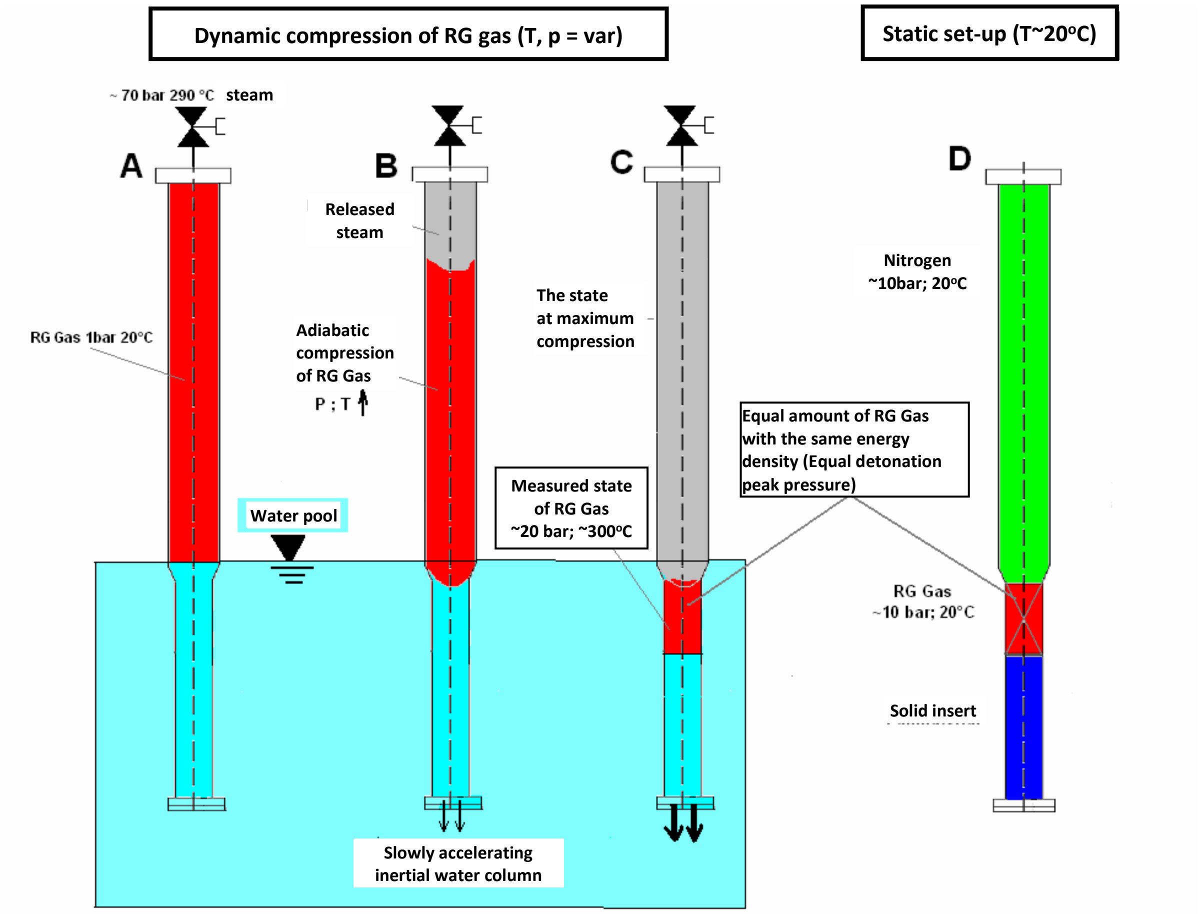

Figure 1: Schematic representation of the radiolysis gas compression during the venting process for three different points in time (A,B,C). The state of maximum radiolysis gas compression is simulated in a static equivalent test (D).

The aim of the experiments was the experimental simulation of this postulated situation and the investigation of the structural-mechanical stability of the vent tube in the case of radiolysis gas combustion. Fig. 1 shows three points in time for the scenario assumed here:

A) Condition in the vent pipe before opening of the S&E (safety and relief) valve; the blow-off tube is completely filled with radiolysis gas, po = 1bar, To = 20°C.

B) Condition in the blow-off pipe just after opening the S&E valve. If one conservatively assumes an ideal piston flow, an adiabatic compression of the radiolysis gas occurs, since the water column in the lower part of the tube moves more slowly relative to the steam due to inertia. During commissioning tests by Kernkraftwerk Philippsburg (KKP-1), maximum pressures of 20 bar were determined in the blow-off pipe.

C) State at maximum radiolysis gas compression. Between the inflowing steam and the outflowing water there is (conservatively) an adiabatically compressed radiolysis gas region of 20 bar and 602 K, which contains the entire amount of radiolysis gas originally present in the tube.

The dynamic state C is simulated by a static experiment with identical amount of radiolysis and energy density in the gas (D). According to the ideal gas law, this corresponds to a radiolysis gas condition of 10 bar and 300 K:

$$pV = nRT, \rho = n / V = p / RT \tag{1}$$

The vapor phase in stage C is replaced by nitrogen at 10 bar. In the experiment, the water surface moving downwards in reality is conservatively simulated by a fixed steel surface.

Combustion of radiolysis gas at a pressure of 10 bar leads to detonation after a flame passing 5-10 cm after a weak spark ignition. Due to this, the expected detonation pressures for the dynamic scenario C and the static test setup D were calculated before the tests. Table 1 shows that the detonation of radiolysis gas at 10 bar and 293 K should produce practically identical pressures as the dynamically compressed radiolysis gas at 20 bar and 602 K. The experiments are therefore equivalent in terms of energy release and pressure loading of the tube.

Table 1: Initial state of the radiolysis gas and calculated Chapman-Jouguet detonation pressure p_{CJ} at the maximum dynamic radiolysis gas compression (C) and at the static replacement experiment (D).

Gas condition	p_0 (bar)	T_0 (K)	p_{CJ} (bar)
C (Fig.1)	20	602	203
D (Fig.1)	10	293	208

2 EXPERIMENTAL DETAILS

2.1 Description of the Experimental Tube

The test tube used corresponds to the blow-off tubes installed in KKP-1. The drilling, which provides passive flushing of the pipe during operation, was omitted due to the conservative orientation of the planned experiments. Apart from a few minor exceptions, the test tube has the same dimensions. It is made of the same material (material no. 1.4541) and the welds are in the same positions. Tubing quality was checked according to standard requirements for nuclear components with X-ray fluoroscopy and with metallographic cross-sections of the welds. The tube essentially consists of two parts: a shorter, narrower part with greater wall thickness (length 4275 mm, outer diameter 419 mm, wall thickness 20 mm) and a longer, wider part with less wall thickness (7501, 510, or 15 mm). Both parts are connected via a 300 mm long conical spacer with a wall thickness of 20 mm (Fig. 2). The pipe is closed with flanges at both ends, which means that there are conservative boundary conditions for the pipe loading.

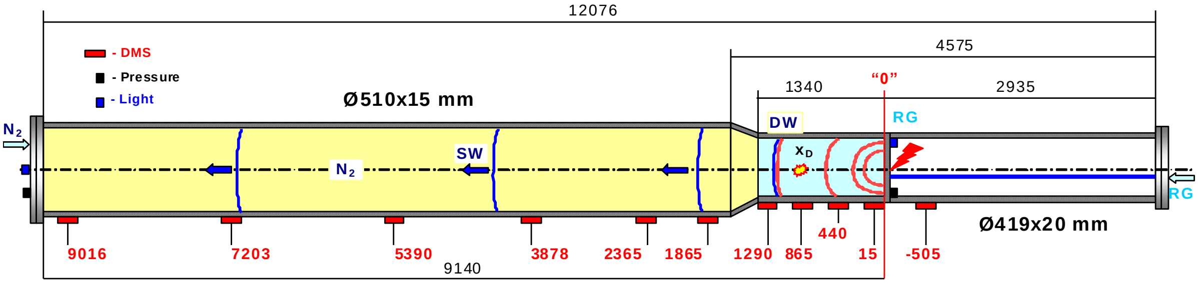

Figure 2: Dimension of the test tube and the radiolysis gas charge.

The cylindrical radiolysis gas charge installed in the tube has a length of 1340 mm and a volume of 135.7 l. At a pressure of 10 bar, the radiolysis gas tank contains 80 g of hydrogen. The cylindrical reservoir is constructed of thin-walled stainless steel (0.5mm) and a strong base plate that simulates the incompressible column of water at the bottom of the vent tube (Fig. 1C).

2.2 Description of the Measurement Setup

Filling the test facility. The simultaneous filling system was used for the radiolysis gas container (H2/O2 from the right) and for the test tube (N2 from the left). The tightness of the radiolysis gas container was ensured throughout the filling process by analyzing the pipe gas mixture (N2) for traces of H2. Before starting the filling procedure, the pipe, radiolysis gas tank and all filling lines were evacuated to a pressure of < 0.1 mbar.

Ignition of the radiolysis gas. A glow plug installed in the strong base plate of the radiolysis gas container served as the ignition source. The gas mixture is ignited remotely from a control room, which also houses a large part of the filling system. The chosen ignition location ensured complete combustion of the radiolysis gas and a conservative pressure load on the tube in the near field of the radiolysis gas charge, including the thin walled portion of the tube above the conical fitting. The expected combustion process is shown schematically in Fig. 2. After ignition, initially slow deflagration turns into a detonation wave DW after a certain distance x_D, which then passes through the remaining radiolysis gas. The detonation wave is extinguished in the nitrogen, so that only a shock wave SW runs to the end flange of the pipe.

Instrumentation and data acquisition. It was not possible to measure the pressure loads occurring during the radiolysis gas combustion with pressure transducers because this would require drilling in the pipe and would have affected the integrity of the pipe. For this reason, fast strain gauges (DMS) were attached in the longitudinal and circumferential directions along the pipe. The strain gages used are temperature-compensated for austenitic steels, which means that the measured values are not subject to interference from temperature changes in the pipe. According to the manufacturer, the DMS can record strains of up to 5%. In addition to material strains, the arrival times of the pressure wave at the various pipe positions can also be precisely determined from the DMS signals. Fig. 2 shows the longitudinal position of the strain gauges. For two cross-sections, four strain gages were installed in the circumferential direction. It was only possible to drill holes for pressure sensors, photodiodes, and supply lines for the ignition source and gas filling on the two end flanges.

The sensor signals were recorded during an experiment with two fast data acquisition systems (5 µs sampling rate). The signal from the pressure sensor, which was positioned close to the point of ignition in the base plate of the radiolysis gas container, served as the trigger.

3 RESULTS AND DISCUSSION

3.1 Test Matrix

A total of four tests were carried out using the test arrangement described. The first two tests with 1.6 and 5.0 bar filling pressure served mainly to test the test technology and the pipe instrumentation. The actual main test with an initial pressure of 10 bar was repeated in order to check the reproducibility of the measured pipe expansions.

Table 2: Experimental parameters.

Test	Volume fraction RG(%)	Filling pressure (bar)	Initial temperature (°C)
Phil01	100	1.6	6
Phil02	100	5.0	7
Phil03	100	10.0	7
Phil04	100	10.2	10

3.2 Transition to Detonation

The ignition of the radiolysis gas leads to flame acceleration and a detonation transition. Interestingly, the run-up distance to detonation was determined from the deformation of the radiolysis gas containers (Fig. 3). Up to the transition point, the casks showed their original cylindrical shape, but were then expanded to the inner diameter of the pipe and partially deformed in a wavy manner. The run-up distance was 1.14 m in the test with an outlet pressure of 1.6 bar, 0.88 m at an outlet pressure of 5.0 bar and 0.075 m at an outlet pressure of 10 bar. The last value resulted from DMS signals.

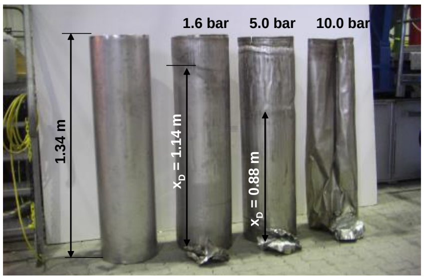

Figure 3: Radiolysis gas containers before (left) and after the experiment (right). At an initial pressure of 1.6 and 5.0 bar, the run-up distance to detonation (x_D) could be determined from the deformation of the cylindrical container wall.

3.3 Maximum Dynamic Pipe Expansion

In the test with an outlet pressure of 1.6 bar, the measured maximum dynamic pipe expansions were in the elastic range (< 0.1%). At an initial pressure of 5.0 bar, the maximum elongation was in the beginning of the plastic range (<0.5%) and at a filling pressure of 10 bar, elongation of up to 0.75% was achieved.

Fig. 4 shows the axial distribution of the measured maximum dynamic pipe expansions for the 10 bar case. In all tests, the highest pipe elongation occurred at the end of the radiolysis gas zone. The expansions decrease sharply in the N2-filled, thin-walled pipe section because of the end of the radiolysis gas reaction and because of the enlarged pipe cross-section. This tendency exists in both hoop and longitudinal strains.

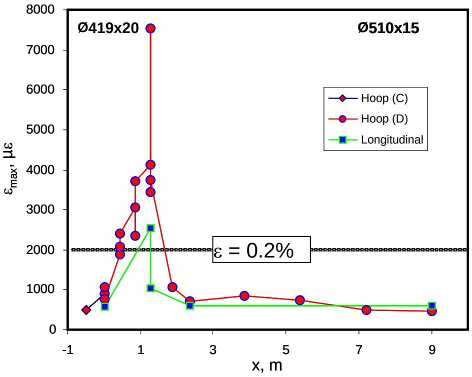

Figure 4: Measured maximum dynamic pipe expansion in the test with 10 bar filling pressure.

3.4 Residual Plastic Pipe Strains

After all pressure waves had died down, the temperature-compensated strain gauges showed a signal that was constant over time, which can be traced back to a remaining plastic strain after the test. Fig. 5 shows this plastic strain component for the tests with 1.6, 5.0 and 10.0 bar initial pressure. The plastic strains increase continuously with the initial pressure and reach their local maximum values at the end of the radiolysis gas zone. This pipe area experiences the highest pressures and the longest loading times.

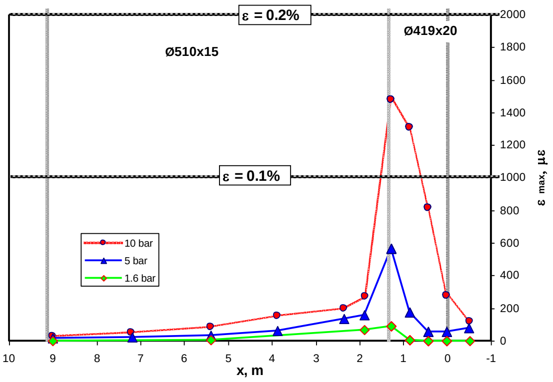

Figure 5: Plastic pipe strain determined from DMS signals after tests with 1.6, 5.0 and 10 bar radiolysis gas pressure.

The measured maximum plastic strain was 0.15%, which does not represent any risk for this highly ductile steel. The DMS results for residual plastic strain were also confirmed by measuring the pipe diameter before and after each test. These manual measurements also resulted in a maximum of 0.15 (± 0.03)% plastic strain after the 10-bar test.

4 NUMERICAL SIMULATION OF THE RADIOLYSIS GAS DETONATION

4.1 Numerical Simulation of Dynamic Pressure Load

The radiolysis gas detonation was numerically simulated with the program DET3D [3]. DET3D solves the three-dimensional Euler equations (without viscosity term) for a chemically reacting multi-component gas (H2, O2, N2, H2O). The numerical cell size was 15 mm, a total of 160,000 cells were used. The calculation started at the experimentally determined DDT time and considered the shock (M=1.6) preceding the accelerating flame. In front of the shock wave, the unburned gas is in its initial state of 10.0 bar.

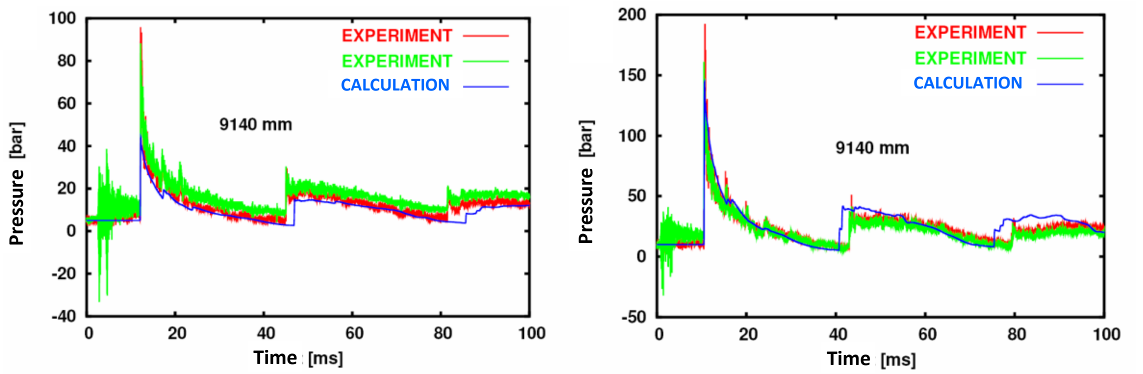

Figure 6: Comparison of calculated and measured pressure curves at the inert pipe end for an initial pressure of 5.0 bar (left), and 10.0 bar (right).

Fig. 6 compares the pressure curves measured at the reflecting pipe end with the numerical results. One or two pressure sensors were installed in the end flange, their distance from the ignition point was 9140 mm. There is a very good agreement for all experiments. In the analyzed problem, within the time of 100 ms, the shock wave from the radiolysis gas detonation arrives at the end flange first (1st peak), and then two more reflections of the primary shock wave appear, with shock waves traveling back and forth through the burnt gas (H2O) and nitrogen.

4.2 Numerical Simulation of Dynamic Tube Deformation

The verified DET3D calculation also provides pressure-time curves for every location in the test tube. These results were used as input for an elastic structural dynamics model that solves the equation of motion for an annular element of the pipe wall (breathing mode).

Fig. 7 shows a comparison of the measured and calculated maximum dynamic strains along the pipe for the tests from 1.6 to 10 bar of initial pressure. In the first case, where plastic behavior plays a minor role, the experimental values agree surprisingly well with the results of the simple point model. In the 10 bar test, there are differences especially at the reflective end of the pipe because the structural dynamic model does not take into account the clamping forces of the flange (multidimensional case).

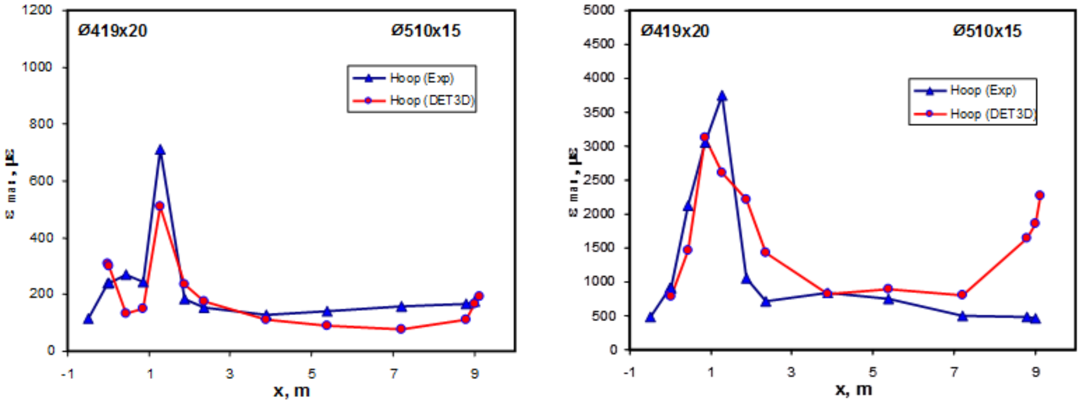

Figure 7: Comparison between measured and calculated maximum dynamic pipe expansions for the tests with a) 1.6 bar, b) 10 bar of radiolysis gas pressure.

4.3 Comparative Calculations for Pressure Loads From Real Cases and Experiments

Fig. 1 shows that a static substitute experiment (D) is assigned for dynamic real case (state C). With the verified DET3D program it is subsequently possible to check the justification of this assumption. For this purpose, a comparative calculation for the two cases was carried out: a) radiolysis gas at 20 bar and 602 K, water vapor at 20 bar and 419 K in the other part of the pipe; b) radiolysis gas at 10 bar and 280 K, nitrogen at 10 bar and 280 K. The location for the deflagration-detonation transition corresponded to the measured run-up distance (7.5 cm).

Fig. 8 shows a comparison of the calculated pressure curves for the highly loaded pipe section shortly before the end of the radiolysis gas area, 1290 mm from the ignition point. In both cases, the peak pressures are close to 300 bar, whereby the experimentally investigated case (10 bar, N2) is slightly conservative. The drop in pressure over time is practically identical in both cases. The oscillations superimposed on the general drop in pressure can be traced back to transverse waves in the pipe, which are caused by the widening of the cross-section at the transition from the narrower to the wider pipe section. At other pipe positions, there is similarly good agreement between the pressure load in the "real case" and in the equivalent experiment.

These three-dimensional comparative calculations confirm that the static 10-bar experiment comes very close to the postulated dynamic scenario with ignition at the time of maximum radiolysis gas compression.

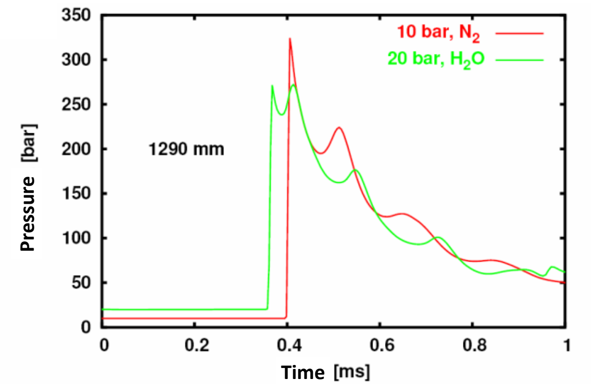

Figure 8: Comparison of calculated pressure loads shortly before the end of the radiolysis gas zone in the postulated dynamic ignition scenario and in the static substitute experiment.

5 SUMMARY

The following radiolysis gas scenario was investigated in the experiments: - the blow-off pipe is completely filled with radiolysis gas, - after opening the S&E (safety and relief) valve, the radiolysis gas is adiabatically compressed by the inflowing steam without mixing, - at the time of the highest pressure (20 bar) the radiolysis gas is ignited.

This dynamic scenario was examined in statistical replacement tests with a test pipe that corresponded to the blow-off pipes installed at KKP-1. The equivalence of the 10-bar test with the dynamic "real case" in relation to the local pipe loads was verified with three-dimensional detonation calculations.

In the tests, the maximum dynamic strains and the remaining plastic deformations of the test tube were measured as a result of detonation pressure load. The initial pressure of the radiolysis gas charge was 1.6, 5.0 and 10.0 bar. The greatest tube deformations always occurred at the end of the radiolysis gas zone, at the transition from the narrower to the wider tube section. The maximum dynamic strain measured was 0.75% and the maximum remaining plastic strain reached 0.15% (both in the test with 10 bar initial pressure). Apart from these minor plastic strains, the pipe was not subjected to any further deformations.

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