Measuring dynamic displacement inside a reactor pressure vessel at 310°C and 110 bar

by Werner Zirnig and Klemens Meuer

In a research project sponsored by the West German Government, critical components of light-water nuclear reactors are being rigidly tested. One series of tests simulates a rupture in the primary-coolant circuit and measures the effect of resulting loads on the reactor pressure vessel and its internals. The displacement transducers used in the test are capable of very precise measurement despite extraordinarily high pressure and temperature conditions inside the pressure vessel.

The HDR Nuclear Testing Center located in Karlstein am Main, West Germany, enables testing on reactor systems and components at various scales up to full size for existing boiling-water (BWR) and pressurizedwater (PWR) reactors. The facility shown in **Fig. 1** was originally designed and built as a prototype superheated-steam reactor (or Heißdampfreaktor, from which comes the abbreviation HDR) intended to demonstrate the possibilities of producing superheated steam with a BWR by means of a reactor superheater. After 2000 hrs of operation, however, serious damage to the fuel elements forced operation to be discontinued.

From 1974-76 the plant was decommissioned, decontaminated, and converted into a reactor-safety testing site. Fuel elements and heat exchanger were replaced by a special test cycle which enables the pressure vessel to reach rated conditions of 310°C and 110 bar (590°F and 1595 psig). Now the boiler, circulation pumps, and control valves are all located outside containment. Electrical systems remaining inside containment, such as lighting, cranes, elevator, and valve actuators, are designed to withstand ambient conditions of about 160°C and 5 bar (320°F and 73 psig).

Fig. 2 shows a vertical cross section of the containment building which is a steel shell 60 m (200 ft) high and 20 m (65 ft) in diameter. The wall of the shell is 30 mm (1.2 in.) thick. Enclosing the steel shell is a 60-cm (2-ft)

Fig. 1: The HDR Test Facility in Karlstein am Main

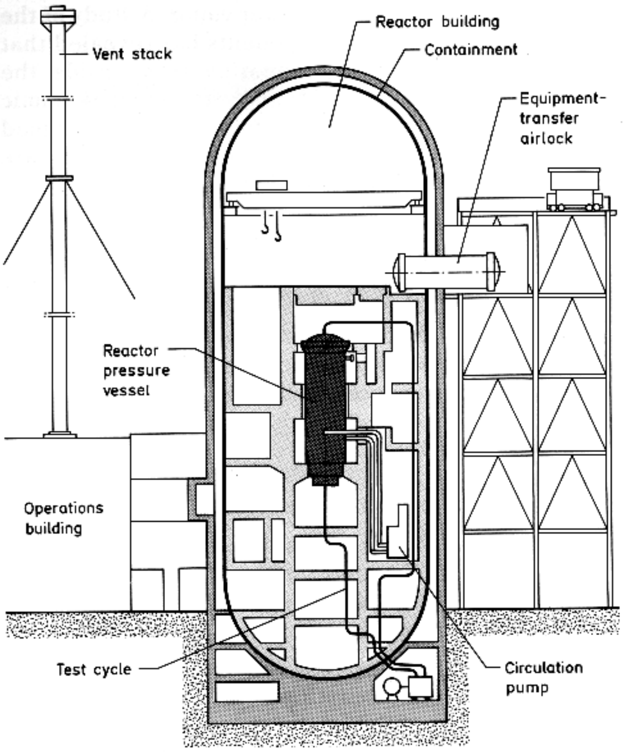

Fig. 2: Vertical cross section of containment building

thick concrete shell which is self supporting and leaves space 60 cm wide between it and the steel shell. The reactor pressure vessel in the center of the containment building has a wall thickness between 105 and 135 mm (4.1 and 5.3 in.) and a volume of approximately 75 m^3 (2650 ft^3).

The HDR reactor-safety program concerns itself primarily with full-scale testing of the principal components of light-water reactors such as safety valves, piping, pressure vessel, and containment. Its purpose is to learn more about the characteristics and behavior of these systems and components under normal and abnormal operating conditions, as well as to verify the dependability of existing design and testing procedures. Experimental data are used to check and improve computer models which describe phenomena occurring inside the reactor.

Of principal interest in this article is a series of measurements taken inside the pressure vessel during a simulation of a loss-of-coolant accident. The purpose is to determine the loads placed on the pressure vessel and core barrel resulting from a break in the primary coolant circuit and compare actual data with those from computer models. In a nuclear powerplant, the primary circuit is made up of the reactor pressure vessel with fuel rods and control rods, recirculation system with pumps, and boiler through which demineralized water is circulated under high pressure and temperature to generate steam. Approximate steam conditions for a BWR: 70 bar, 285°C (1015 psig, 545°F); for a PWR: 160 bar, 300°C (2320 psig, 572°F).

One type of accident which the primary circuit and the surrounding containment must be designed to withstand is the rupture of the coolant pipe close to the inlet nozzle of the pressure vessel. Such an event causes the immediate and sudden release of pressure by the escape of steam and water vapor. A study of the pressure vessel and its components has revealed that depressurization waves emanating from inside the vessel after such ruptures lead to severe dynamic loads. The core barrel in real reactors must be designed so that neither it nor the fuel rods it contains are damaged by the shock waves from such an event.

The core barrel shown in **Fig. 3** is designed such that structural deflections are easily measurable. The fuel rods and controlrod guide tubes which would normally be in the core barrel are simulated by a mass ring of similar weight. The instrumentation lance in the center of the vessel is equipped with pressure and temperature sensors to measure conditions at the center of the vessel. In order to measure the forces involved, transducers for absolute pressure, differential pressure, temperature, expansion, displacement, and acceleration are mounted directly on the core barrel.

Test conditions closely simulate those found in a normal PWR: 110 bar and 308°C (1595 psig and 586°F). Temperature in the downcomer is kept at 40 K less than core-region conditions.

Rupture of the coolant pipe is simulated with a pneumatically controlled bursting device which opens the full cross section of the inlet nozzle of inside diameter 200 mm (7.9 in.) suddenly and completely in approximately 3 ms. Water inside the pressure vessel is expelled through the ruptured nozzle and expands down to saturation. The depressurization waves running through the pressure vessel cause the core barrel to deflect and vibrate. The relative movement between the core barrel and pressure vessel is measured with 25 displacement transducers distributed at various levels around the circumference of the core barrel.

Transducer evaluation procedure

Because the displacement transducers must operate under unusually harsh ambient conditions, the following special design requirements were necessary:

- Transducer and 15 m (50 ft) of cable had to be able to withstand an exceptionally corrosive mixture of steam and water at high temperatures (320°C, 608°F) and pressures (110 bar, 1595 psig). A cold pressure test as high as 140 bar (2030 psig) was also specified.
- The instrumentation system should not be influenced by fluctuations in temperature and pressure, or vibration. Transducers had to be able to withstand accelerations up to 1000 m/s^2 (3300 ft/s^2) without suffering damage.
- Since access to the transducers would be impossible during a series of tests, their measuring characteristics had to remain constant during the course of several separate tests.
- The measuring range for dynamic displacement within the first 200 ms of a depressurization test was specified at ± 5 mm (0.2 in.) on the basis of prior calculation. The measuring error, as far as it can be defined for the quasi-static transmission characteristics of the displacement transducer had to be less than ± 1 % of the range maximum.

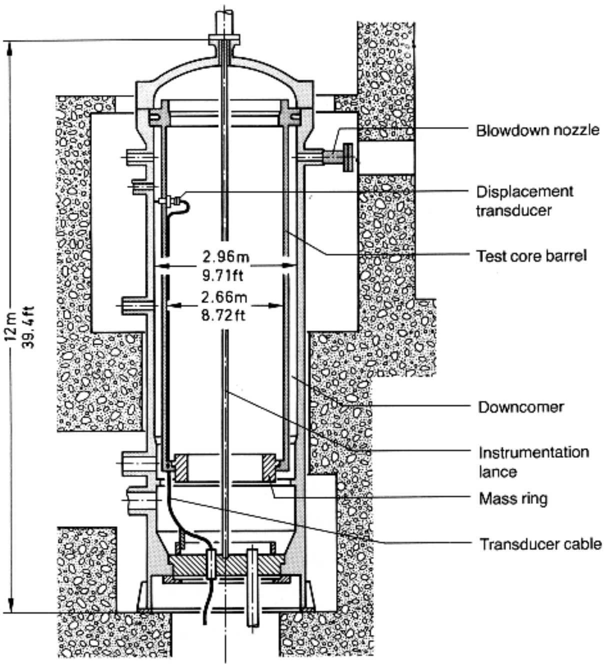

Fig. 3: Vertical section of reactor pressure vessel

In order to make certain that both the functional capability and measuring accuracy of the transducers would fulfill the stated requirements, a comprehensive evaluation program involving several different manufacturers was carried out.

The program consisted of several individual tests on prototype transducers designed to give an overall picture of their transmission characteristics and longterm stability. Their performance under actual conditions —including depressurization— was tested in a specially designed autoclave containing pressurized water. To make testing as realistic as possible, transducers underwent a total of 15 depressurizations.

The device finally chosen was a modified high-temperature inductive displacement transducer (HBM Type W 10 SST), exhibiting inherently high zero stability because of its symmetrical measuring arrangement. To prevent the infiltration of water or steam under high pressure, transducers have an integral steel-armored cable welded securely to the instrument housing.

Each transducer and its associated cabling is internally compensated for variation in sensitivity with temperature by installing a compensation circuit. Sensitivity is influenced by changes in the permeability of the nickel in the cable and copper in the windings with temperature. The transducer manufacturer guaranteed a variation in sensitivity no greater than 0.1 % per 10 K.

Preliminary tests showed that the length of steel-armored cable inside the pressure vessel had a significant effect on the sensitivity of the measuring circuit. This length therefore was included in the compensation. For example, 15 m (50 ft) of steel-armored cable heated to 300°C (572°F) would produce a sensitivity change in the measuring circuit of about 5 %. As shown in **Fig. 4**, calibration of the complete measuring circuit and built-in compensation enables sensitivity changes to be reduced within an acceptable tolerance band.

The actual variation in temperature sensitivity remaining after compensation was determined for each transducer during the final acceptance tests and then factored in as a numerical correction during final analyses. In addition to plotting correction calibration curves at normal ambient temperature, the transducer manufacturer also plotted curves at 100°C, 260°C, and 310°C (212°F, 500°F, and 590°F). Included in the calculation were actual measuring circuits and the 60 m (198 ft) bus cable.

Installing displacement transducers

It was anticipated that the depressurization tests would subject the transducers to very high accelerations, so a feature of particular importance in their design is as few movable parts as possible-including very short connection leads inside. The connections were packed in quartz sand in the cable socket of each transducer.

The cable used for the transducers has three nickel leads insulated with magnesium oxide and contained in a 3-mm-diameter (120-mil) stainless-steel sheath. Nickel was used as the conductor material because it does not suffer as much embrittlement as copper at high temperatures. After the cable leads are connected inside the transducer, the steel sheath of the cable is joined to the bods by a laser welding technique. In laser welding, energy is only fed to the weld intermittently, thus avoiding overheating and consequent embrittlement of the cable and transducer. Compared with electron-beam welding, it has the advantage of not requiring a vacuum; a normal inert-gas atmosphere is sufficient. This eliminates any problems in handling of the 20 m (66 ft) of cable attached to the transducer.

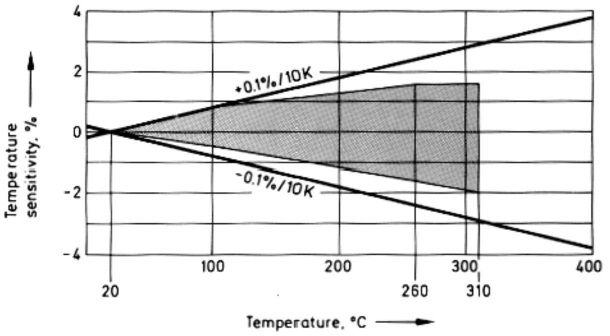

Fig. 4: Temperature sensitivity of displacement measuring system —including cable and built— in compensation-was kept within acceptable tolerance band (shaded area)

Transducers are mounted in the core barrel in special holders. **Fig. 5** shows a transducer installed in its holder along with necessary attachment and adjustment devices. **Fig. 6** illustrates how the transducer is inserted into its measuring position from the inside wall of the core barrel. The transducer and its holder can be removed for adjustment purposes and zero setting.

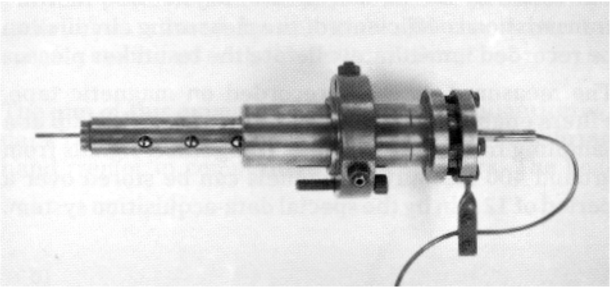

Fig. 5: Displacement transducer is shown in a special holder for insertion into the core barrel

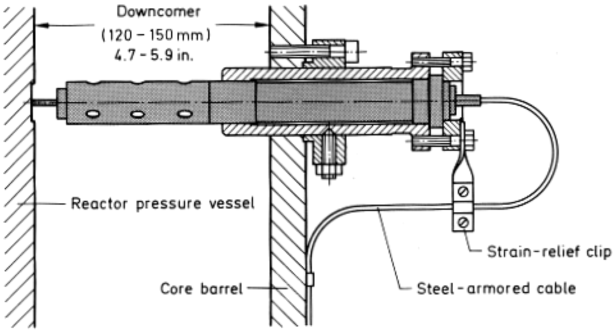

Fig. 6: Installed position of displacement transducer mounted from inside of core barrel

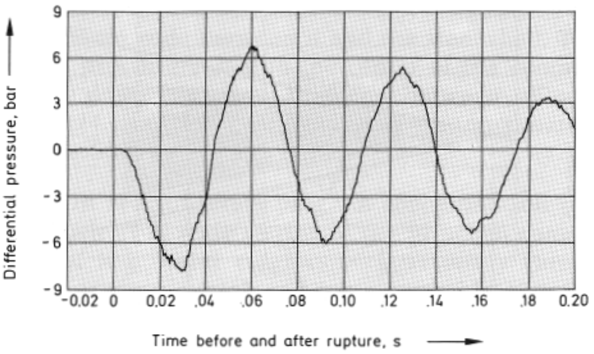

Fig. 7: Shock waves produced by depressurization cause a difference in pressure between downcomer and interior of the core barrel depicted in this trace

Cables are laid in channels to the bottom of the pressure vessel where there are cable glands to lead them out of the high-pressure zone. A relatively new type of screw gland was used which enables the thicker cable ends —where the steel-armored cable changes to flexible connecting wire— to be pulled through and then sealed to the thinner steel-armored cable. The actual seal is provided by graphite packing which is forced against the cable and gland by two pairs of split collars. Patent rights for the new gland belong to the Karlsruhe Nuclear Research Center.

Outside the pressure vessel, individual transducer cables are connected to a bus leading to signal-conditioning and data-acquisition equipment. Each of the 25 transducers is energized by a 5-kHz carrier-frequency measuring amplifier. Zero and calibration signals can be transmitted via a special switching unit controlled by the data-acquisition system, so that the transmission coefficients of the measuring circuits can be recorded immediately before the test takes place. The measured data are recorded on magnetic tape. Filters enable signals up to 1 kHz to be picked up at a sampling frequency of 5 kHz. Altogether, signals from around 400 measuring channels can be stored over a period of 12 min by the special data-acquisition system.

Results of reactor-displacement testing

The test shows a clear picture of the events which could follow an actual primary-inlet-pipe burst. The shock waves produced by depressurization cause a difference in pressure between the downcomer and interior of the core barrel which is plotted in **Fig. 7**. The results of the measurements are shown for the time frame -0.02s to +0.2s. The reference point t = 0 is the instant of opening of the rupture disc, or in actuality the commencement of blowdown. In Fig. 7, negative amplitudes of differential pressure indicate a lower pressure in the downcomer than in the vessel interior.

The displacement of the core barrel with respect to the outer wall of the pressure vessel is shown in **Fig. 8** for two transducers placed at 180 degrees to each other. Positive displacement amplitude indicates a reduction in the size of the downcomer.

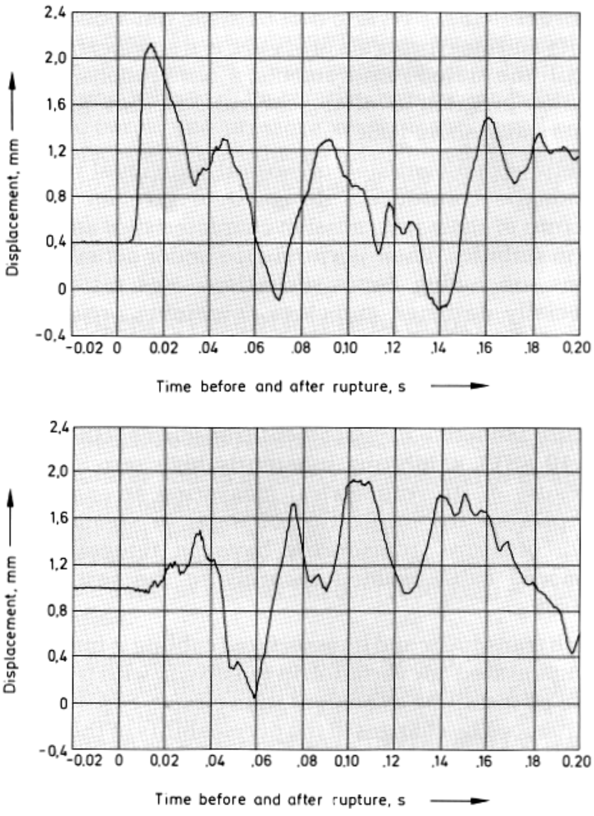

Fig. 8: Trace of pressure-vessel-wall displacement using two transducers at 180 deg to each other

A study of the trace of variables immediately after blowdown shows a clear connection between differential pressure and displacement. At first there is a negative pressure in the downcomer and its width narrows accordingly. After the first oscillation the core barrel undergoes a complex motion because it is not rigid. The differential pressure in the downcomer oscillates in a uniformly decreasing manner with a frequency of approximately 15 Hz.

The possible uncertainty of the displacement-measurement method described has been examined by comprehensive error analysis in which the magnitude and effect of all possible individual errors on the measuring circuit have been taken into account. Factors considered were uncertainty of calibration, temperature effect on transducers and measuring circuit, linearity and hysteresis of transducer and amplifier, deviations in gain, digitizing errors in data recording, and conversion errors in measured data display. Measuring uncertainty for the nominal displacement of 5 mm (200 mil) is ± 82 µm (3.2 mil), and ± 72 µm (2.8 mil) when the measured displacement is 1 mm (40 mil).

Werner Zirnig and **Klemens Meuer** wrote this article while the Karlsruhe Nuclear Research Center performed reactor testing under contract with the Battelle Institute, Frankfurt am Main. Werner Zirnig is now with Ruhrgas AG, Essen, and is engaged in volumetric-flow measuring systems for gases.