1. Introduction

The coolant level in the reactor pressure vessel is a safety parameter of high relevance. In case of boiling water reactors the emergency core cooling injection systems are activated by level signals. Another important task of the level measurement is the prevention of the reactor overfeed. Standard level measuring systems in light water reactors base on the hydrostatic method. The level is deduced from the reading of a differential pressure transducer connected to the reactor pressure vessel by pulse tubes at two different elevations. These systems deliver the so-called collapsed level within the measuring range given by the locations of the lower and upper connections of the pulse pipes to the vessel. In case of two-phase mixture in the vessel the collapsed level is a virtual water level, which would establish in case of a perfect stratification of water and steam. Its calculation from the pressure difference requires a knowledge about the densities of both water and steam in the reactor, which are mostly calculated from pressure and temperature.

Since the differential pressure is measured against a reference water column standing in the plus-line of the differential pressure transducer (reference leg), the system is sensible to failures leading to density changes in the plus-line and/or to the depletion of it. This can happen, for example, as a consequence of evaporation of the water or a release if dissolved non-condensable gases (e.g. radiolysis gases) during a pressure decrease, or of a small leakage at the differential pressure transducer. Unfortunately, there are common-mode scenarios, where these effects can occur in redundant measuring points at the same time. This gave the reason for the German Reactor Safety Commission to issue a recommendation to develop diversified level measuring systems.

Diversified means that the working principle is based on a different physical effect. VGB Power Tech Service asked the Institute of Safety Research to develop a level indication device using an electrical conductivity signal. Laboratory samples of the device were built and tested at an experimental vessel in the Gundremmingen nuclear power station under conditions close to the working parameters at the reactor. The developed system has the potential to maintain function after pressure transients.

2. General requirements

The parts of the measuring sensor, which are in contact with the measuring medium have to withstand the nominal pressure and temperature of the reactor over a long period (typical parameters are 7 MPa, 286 °C). Degradation of the sensor materials must neither lead to a loss of the function nor to a coolant leakage. It was planned to achieve an operation duration of at least 5 years at nominal reactor parameters.

It was furthermore determined to design the level monitor in accordance to the requirements for reactor safety instrumentation. This includes that the device must maintain function during design

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base accidents. The conditions for a qualification as a reactor safety system are described in the KTA-rules 3505 in detail. In particular, the level monitor has to withstand

- an environment of the containment atmosphere during a loss-of-coolant accident (10 Bar, 180 °C, 95 % relative humidity),
- an integral radiation dose of $2 \times 10^5$ Gy,
- the mechanical vibration loads during earthquake and airplane crash.

This implied that electronic parts of the measuring transducer cannot be placed inside the containment respectively safety tank. As a consequence great cable lengths (~200 m) were required in order to place the measuring transducer outside the containment. For the sensor, which has to withstand the mentioned conditions, only radiation resistant materials could be used. A self-check procedure indicating the breakdown of the sensor caused either by loss of insulation properties or by signal line breakdown had to be implemented in the measuring transducer. By avoiding on-board processors for the data processing favourable conditions for a qualification according to the KTA rules were created, i.e. complicated qualification procedures for software components were not necessary.

3. Working principle of the diversified level monitor

The task was set to develop a local level monitor for the installation into a standpipe. In most of the boiling water reactors there are standpipes - vertical pipes of approximately 25 - 50 mm inner diameter - which are parallel connected to the reactor pressure vessel. In these standpipes a water level establishes which is characterising the coolant level in the reactor. In most of the cases, the hydrostatic level measuring systems are connected to these standpipes. The diversified level monitor has to deliver a binary information about the presence of water in the standpipe at the axial position of the sensor. If the level in the standpipe is above the sensor, the indicator has to generate a signal LEVEL HIGH, in the opposite case the signal LEVEL LOW has to appear.

The information about the presence of the liquid phase is deduced from an electrical current between two electrodes put into the measuring medium. The conductivity of the coolant is high enough for being detected. Even super-pure water at room temperature has at least a conductivity of about 0.045 µS/cm. Compared to this, the conductivity of steam can be neglected as long as the pressure is still distant from the critical point, which holds for the boiling water reactors in all operational and accidental regimes.

![Fig. 1: Conductivity of very pure water over temperature](image)

Comparing to this, the conductivity of steam can be neglected as long as the pressure is still distant from the critical point, which holds for the boiling water reactors in all operational and accidental regimes.
The main concern is a robust and reliable function of the level monitor with a minimum of false alarms. It was a challenge to find a method to derive the binary level information correctly without the need of an adaptive correction of a threshold over the entire expected range of the water conductivity (Fig. 1). The increase of temperature from room to reactor conditions alone leads to a growth of the conductivity to about 3.4 µS/cm at 180 °C. Additionally, dissolved ions, like corrosion products, may cause a further increase. It was assumed that the level indication has to operate up to a conductivity of 5 µS/cm at 25 °C, which corresponds to approximately 80 µS/cm at high temperature. It must be avoided that a false indication LEVEL HIGH appears, when the level is low in reality. This can happen if it is possible that liquid films (e.g. condensate films) form a connecting contact between the electrodes. In case of high water conductivity the current through thin water films can potentially be higher than the current through plain liquid with low water conductivity in case of high water level. This effect makes it impossible to use a fixed discrimination threshold to transform the analogue current signal into the desired binary output information, i.e. the discrimination level has to be adapted to the instantaneous conductivity of the liquid. The latter had to be avoided for reliability and qualification reasons.

The problem was solved by using a level sensor consisting of two probes mounted on the standpipe from opposing sides. Each probe consists of an electrode, which is insulated from ground and put into the standpipe through a sealed bushing. One of the probes is supplied with a small voltage (3 V). An electrical current appears at the second one, if the water level is above the sensor position. This current is transformed into the binary level signal. The signal LEVEL HIGH is generated if the probe current in this so-called foreign excitation mode exceeds a certain threshold.

If, on the contrary, the level is below the sensor, there is still the possibility of a liquid layer (e.g. condensate) being in contact with both electrodes in the same time. Nevertheless the current is then zero, since any imaginable liquid layer has a big contact area with the grounded surface of the standpipe and the current from the excited electrode cannot reach the opposite electrode. To avoid electrolysis effects, such as anodic corrosion or electrode polarization, an alternating voltage has to be applied. Usually, a sinusoidal voltage is used, which makes it difficult to suppress the influence of the high capacitance in cables of the high required lengths. For this reason, the excitation is carried out by a symmetrical, DC free rectangular voltage pulse. The capacitive loads of probes and cables cause a transient behaviour of the current signal. The current is sampled after this transient has settled (Fig. 2). In this way the sampled value reflects only the real part of the complex impedance of the sensor, i.e. the influence of the imaginary part, which contains the effect of capacitance loads, is eliminated.

Another important property of the measuring transducer is a low-impedance output of the driver cascades. So the excitation voltage is kept constant even if the
insulation of the probe deteriorates, provided that the output impedance is still significantly lower than the insulation resistance. A similar effect is achieved by low impedance inputs of the amplifiers used to detect the current at the receiving electrode, which is not excited. Due to the low impedance the potential of the receiving electrode cannot depart from ground potential. A deterioration of the insulation cannot cause a significant parasitic current towards ground, which would diminish the wanted signal. The low-impedance operation of the probes is therefore a powerful measure to maintain the function of the level sensor as long as possible, when the insulation of the probes is deteriorating. This helps to achieve a high lifetime.

Finally, the self-check is carried out by additionally measuring the current at the excited electrode, too. This operation mode is called self-excited operation [3]. If the obtained signal exceeds a given upper threshold, a binary failure indication is generated (LEVEL MONITOR DEFECT). For the purpose to check the integrity of the signal lines between probes and measuring transducer, the probes are equipped with shunts of about 50 kΩ creating a certain self-excited probe signal. If the line is interrupted, the current decreases and the break is checked by comparing the self-excited signal to a lower threshold.

4. Measuring sensor

The sealed bushing element of the electrode is shown in Fig. 3. The insulation is made of aluminium oxide (Al₂O₃) sintered ceramic. It has the shape of a cylindrical rod with a central orifice for the electrode. At one end of the rod an inner and an outer steel sleeve are soldered to the ceramic surface. These sleeves serve as connecting elements between the ceramic and the body of the probe respectively the electrode.

![Fig. 3: Sealed bushing made from aluminium oxide sintered ceramic](image)

Before soldering, the surface of the ceramic is plated with a metal layer. Both electrode and end-piece of the probe are laser-welded to the metallic sleeves. The end-piece is welded to the cylindrical body of the probe, both are made of stainless steel. A metal-clad cable is used to contact the electrode. The cable is welded into the back end of the end-piece. The metal-clad cable represents a second barrier against a leakage of the ceramic bushing. A view of the probe is shown in Fig. 4.

Two of the probes form the measuring sensor. They are mounted to the standpipe from opposing sides (Fig. 5). For the test of the level monitor, screwed fittings are used (Swage-Lock fittings). In order to keep the temperature low at the back side of the probe, a heat sink (see Fig. 5) is fixed to the outer surface. In this way, the corrosion attack of the measuring medium to the critical elements (metal-ceramic junctions) of the probes is minimized, since the hot medium can contact the ceramic insulation element only at the side of the mounting into the standpipe [4]. This strategy proved to be efficient to ensure a long lifetime of the measuring sensor.
The measuring sensor is equipped with two spring elements preventing the ceramic rod and the electrode from mechanical oscillations in case of vibration loads. This is a precaution against damages due to earthquake and airplane crash loads. Since all elements of the measuring sensor are made either of metallic materials or of aluminium oxide sintered ceramic, the required stability against ionising radiation is maintained.

5. Measuring transducer

A simplified scheme of the measuring transducer is shown in Fig. 6, the most important signals in Fig. 7. Both probes of the measuring sensor are connected to pre-amplifier cascades of identical structure. The cascades consist of two operational amplifiers. The first is switched as an impedance transformer with a logarithmic characteristic. For the self-excited mode, the plus-input of this cascade is supplied with the rectangular pulse of the driving voltage, derived from the signal POS/NEG. Due to the feedback chain of the amplifier an identical pulse appears at the negative input pin and arrives at the electrode of the probe. The current flowing in self-excited mode brings the amplifier out of balance. After subtracting the driving voltage by the second amplifier, the output voltage is proportional to the logarithm of the instantaneous current of the excited probe. This signal is sampled by a sample&hold circuit (S/H) in the moment, when the transient has settled. This happens closely before the successive slope of the excitation voltage, controlled by the
signal S/H PULSES. In the result the signal for the self-check can be found at the output of the corresponding S/H circuit.

When the first probe is operated in self-excited mode, the second probe is working in foreign excitation mode. The plus-input of the first cascade of the pre-amplifier is grounded in this case. The voltage at the output of the second amplifier is proportional to the logarithm of the current flowing through the measuring medium. After sampling, this signal is carrying the level information. It is compared to a fixed threshold in the

**Fig. 6: Simplified scheme of the measuring transducer**

A - block scheme  
B - logarithmic pre-amplifiers

**Fig. 7: Pulse diagram of the measuring transducer control**
in the comparators COMP3 and COMP6. If the threshold is exceeded, the signal LEVEL HIGH is generated.

The operation mode of the two probes of the level sensor is periodically changed by the control signal SELF/FOREIGN. There are in total four S/H circuits, two for each probe. One for each probe is activated during the self excited operation period of the corresponding probe, the second is activated during the foreign excitation period. In this way, both probes undergo the self-check. The signal LEVEL MONITOR DEFECT is generated by comparing the self excited signal with an upper and a lower threshold. The comparators COMP1 and COMP4 are responsible for the insulation check. COMP2 and COMP5 are detecting the line break. The signal LEVEL MONITOR DEFECT is generated if at least one of the four self test checks fail.

6. Test facility in the Gundremmingen NPP

A facility for the test of different level measuring systems was built by Gundremmingen NPP (Fig. 8). A number of standpipes are connected to a pressure vessel (height 2.7 m, inner diameter 0.46 m, volume 0.45 m³), which is supplied with steam from the reactor of one of the Gundremmingen units (7 MPa, saturation). Due to condensation, the vessel is filling with water. At the standpipes, different versions of hydrostatic level measuring systems are tested. One standpipe was used for an endurance test of the described diversified level measuring system. Two level sensors (four probes) were mounted at two different axial positions, which have an axial distance of 0.2 m (Fig. 9). The binary outputs of the level monitors were used to control the condensate draining valve. When the upper level monitor delivered the signal LEVEL HIGH the valve was opened. Successively the level in the vessel dropped down. When the level falls below the lower measuring point, the valve is closed and the process repeats.

7. Test results

Fig. 10 shows characteristic time histories of the binary level signals, the reading of an analogue
hydrostatic level transducer and the position of the condensate draining valve. As visible, the control of the level in the pressure vessel by the level monitors was functioning. Since the accuracy of the binary level indication is given by the accuracy of the axial position of the measuring detectors, the turning points of the level can be used to assess the error of the hydrostatic method, which, in this case, delivered a negative systematic error of about 3-4 cm.

The test was continued over 4.5 years without the breakdown of a probe. After 10550 hours of operation the measuring sensors were taken out and examined visually. No evidence of corrosion was found neither on the metallic nor on the ceramic parts of the probes. The test is continued.

8. Summary

A diversified level measuring system was developed for boiling water reactors. The design was elaborated under consideration of the German requirements to reactor safety instrumentation (KTA 3505). An endurance test under conditions close to the application in the reactor has shown that the planned lifetime of 5 years can be achieved.

The qualification procedure for an application at the reactor is under way. The corresponding work is carried out by Framatome ANP. It comprises final design work, the development of a technology for series production, the preparation of the documentation for the qualification and practical examinations according to KTA rules.

References