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Reactor Water Level Measurement: A Report by the Working Party on Boiling Water Reactors

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The mission of the NEA is:

– to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally sound and economical use of nuclear energy for peaceful purposes;

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The Committee on Nuclear Regulatory Activities (CNRA) addresses NEA programmes and activities concerning the regulation, licensing and inspection of nuclear installations with regard to both technical and human aspects of nuclear safety. The Committee constitutes a forum for the effective exchange of safety-relevant information and experience among regulatory organisations. To the extent appropriate, the Committee reviews developments which could affect regulatory requirements with the objective of providing members with an understanding of the motivation for new regulatory requirements under consideration and an opportunity to offer suggestions that might improve them and assist in the development of a common understanding among member countries. In particular it reviews regulatory aspects of current safety management strategies and safety management practices and operating experiences at nuclear facilities including, as appropriate, consideration of the interface between safety and security with a view to disseminating lessons learnt. In accordance with *The Strategic Plan of the Nuclear Energy Agency: 2017-2022*, the committee promotes co-operation among member countries to use the feedback from experience to develop measures to ensure high standards of safety, to further enhance efficiency and effectiveness in the regulatory process and to maintain adequate infrastructure and competence in the nuclear safety field.

The committee promotes transparency of nuclear safety work and open public communication. In accordance with the NEA Strategic Plan, the committee oversees work to promote the development of effective and efficient regulation.

The committee focuses on safety issues and corresponding regulatory aspects for existing and new power reactors and other nuclear installations, and the regulatory implications of new designs and new technologies of power reactors and other types of nuclear installations consistent with the interests of the members. Furthermore, it examines any other matters referred to it by the NEA Steering Committee for Nuclear Energy. The work of the committee is collaborative with and supportive of, as appropriate, that of other international organisations for co-operation among regulators and consider, upon request, issues raised by these organisations. The Committee organises its own activities. It may sponsor specialist meetings, senior-level task groups and working groups to further its objectives.

In implementing its programme, the committee establishes co-operative mechanisms with the Committee on the Safety of Nuclear Installations (CSNI) in order to work with that committee on matters of common interest, avoiding unnecessary duplications. The committee also co-operates with the Committee on Radiological Protection and Public Health (CRPPH), the Radioactive Waste Management Committee (RWMC), and other NEA committees and activities on matters of common interest.

Foreword

The Nuclear Energy Agency (NEA) Working Party on Boiling Water Reactors (WPBWR) was created in 2018 by the Committee on Nuclear Regulatory Activities (CNRA), which is responsible for the NEA programme concerning the regulation, licensing and inspection of nuclear installations and it reviews practices and operating experience.

The working party is responsible for establishing: 1) an international forum to exchange information and experience specifically on regulation issues regarding boiling water reactors (BWRs), including those in design, construction, commissioning, operation and decommissioning; 2) a way to identify international safety challenges within BWRs to share national perspectives; and 3) a range of appropriate opportunities for international collaboration on regulatory activities related to BWRs that will lead to improvements in the nuclear safety areas.

This report outlines first the safety concerns and the regulatory basis for reactor water level measurement diversity and reliability in participating countries. After that the measurement methods and their diversification efforts are presented, followed by a discussion on the measurement reliability based on operating experience.

This report was approved by the CNRA at the 47th CNRA meeting on 2-3 June 2022 (NEA, 2022) and prepared for publication by the NEA.

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List of abbreviations and acronyms

ARI	Alternate rod injection
CNRA	Committee on nuclear regulatory activities
BWR	Boiling water reactors
BWROG	BWR Owner's Group
CCF	Common cause failures
GDC 22	General Design Criterion 22
GE	General Electric
I&C	Instrumentation and control
KEV	Nuclear Energy Ordinance (Switzerland)
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
PRA	Probabilistic Risk Assessment
RPV	Reactor pressure vessel
STUK	Radiation and Nuclear Safety Authority (Finland)
TMI	Three Mile Island
WPBWR	Working Party on Boiling Water Reactors (NEA)

Executive summary

Reactor water level is a critical safety parameter in boiling water reactors (BWRs). If the reactor core is covered with water, severe core damage can usually be avoided, but if the core becomes uncovered, the situation deteriorates quickly. A water level that is too high could also cause safety concerns as water could enter the steam lines, possibly damaging valves or steam-driven emergency feed water pumps, or fill up the reactor pressure vessel.

This report outlines the safety concerns and the regulatory basis for reactor water level measurement diversity and reliability. Based on the review of international standards and national regulations, there are no specific requirements for the diversification of BWR water level measurements. However, there are general requirements for a high reliability and diversity in reactor protection system designs. In the end, the need for diversification of the reactor water level measurement, and the required level of this diversification, remains to be judged on a case-by-case basis, taking into consideration national regulations, existing plant designs, the complexity of required plant modifications, other measures to achieve high levels of reliability and plant-specific safety analyses.

Information on past efforts to diversify reactor water level measurements in BWRs, including explanations for why these efforts were mostly unsuccessful, was collected from the countries participating in the Working Party on Boiling Water Reactors (WPBWR). Participating countries also provided information on operating experience and technical difficulties with reactor water level measurement accuracy and reliability, as well as the technical solutions implemented to improve the water level measurement.

The WPBWR concluded that, overall, the reliability of reactor water level measurements has been good during the decades that BWRs have been in operation. The most significant issues encountered have been false water level indications caused by the release of non-condensable gases or boiling in the reference leg in connection with reactor pressure decrease. These issues have been solved by plant modifications, together with operator guidance and training.

1. Introduction

Reactor water level is a critical safety parameter in boiling water reactors (BWRs). If the reactor core is covered with water, severe core damage can usually be avoided but if the core becomes uncovered, the situation deteriorates quickly. On the other hand, a high water level could also cause safety concerns through water entering the steam lines, possibly damaging valves or steam-driven emergency feed water pumps, or through filling up the reactor pressure vessel (RPV).

Some countries have direct requirements for diversity in the measurement of such essential parameters, while others have more general requirements aiming to prevent the loss of critical functions by common cause failures (CCF).

However, obtaining diversified reactor water level measurements has proven difficult in practice. In the past, different methods have been investigated to achieve this diversity, but most of these efforts have failed for various technical reasons.

Reactor water level instrument accuracy and reliability is a related topic with considerable operating experience available across participating countries. While some of the operating experience may be dated (10 years old or more), an investigation of the historical technical challenges faced by participants and their generic solutions to these challenges is still informative.

This report outlines the safety concerns and the regulatory basis for reactor water level measurement. It includes a summary of past efforts to diversify reactor water level measurement in BWRs, explains why these efforts were unsuccessful and discusses the ensuing regulatory response. In addition, the report covers the historical technical difficulties participating countries have experienced with reactor water level measurement accuracy and reliability and the technical solutions implemented to improve the water level measurement.

2. Standards and regulations concerning diversity and reliability of measurements

There are no regulations or standards in the participating countries that specifically require the diversification of BWR water level measurements. However, there are general requirements for high reliability and diversity in reactor protection system designs as stated in IAEA and national regulations, standards and requirements. As a summary of the various regulations, it can be stated that diversity is one of the methods to achieve high reliability in reactor protection system design. Ideally, two different physical parameters would be available to generate the reactor protection signal in each accident scenario. Diversification can also mean measuring the same parameter in two different ways, or diversifying only the measurement and I&C equipment.

Below is a list of IAEA standards and national requirements that touch on this issue:

- IAEA SSR-2/1 Requirement 62 (IAEA, 2016) "Reliability and Testability of Instrumentation and Control Systems"
- United States, 10 CFR Part 50 Appendix A General Design Criterion 13 (GDC 13), GDC 20, GDC 21, GDC 22, GDC 23, and GDC 24
- USNRC ATWS rule (10 CFR 50.62) (NRC, 2017)
- Finland, Section 11 of the Regulation STUK Y/1/2018 (STUK, 2018) and in YVL Guide B.1 (STUK, 2019)
- Sweden, SSMFS 2008:17 Section 10 (SSM, 2008)
- Switzerland, Article 10 of the Swiss Nuclear Ordinance (KEV)

In many national regulations, the diversification of the measurement of the main reactor parameters is only required if reasonable or practical. The most notable exception is the Finnish regulatory guide YVL B.1 (STUK, 2019), where there is no such wording.

Indirectly, these requirements can also result in the need for a comprehensive analysis to demonstrate that the design is good enough without a diversified reactor water level measurement function.

After the Fukushima Daiichi accident, Japan introduced a requirement to have alternative measures to calculate or estimate critical reactor parameters, such as the reactor water level, in severe accident situations if the principal parameters cannot be measured. Such guidelines for severe accident management are also used in other countries.

Finally, there is the question of requiring the backfitting of operating nuclear power plants. In most countries relevant laws allow this when it is well justified, reasonable and practically possible, as can be seen in e.g. 10 CFR 50.109 of the US Code of Federal Regulations (NRC, 2007), The Finnish Nuclear Energy Act Section 7a, and The Swiss Nuclear Energy Act.

In the end, the need for diversification of the reactor water level measurement, and the required level of this diversification, remain to be judged on a case-by-case basis, taking into consideration national regulations, existing plant designs, the complexity of required plant modifications, other measures to achieve high levels of reliability and plant-specific safety analyses.

3. Principal measurement method

All boiling water reactors use the same principal method for measuring the reactor water level. The level measurement systems are based on pressure difference between the reference leg and the reactor downcomer (variable leg). Each reference leg has two connections to the reactor pressure vessel. One connection penetrates the reactor vessel in the steam area and is connected to a condensing chamber. The reference leg maintains a relatively constant height of water for comparison to the variable leg. This height of water is maintained constant as excess water, condensed in the condensing pot, spills over back into the reactor pressure vessel. The lower penetration enters the reactor vessel in the downcomer annulus region. Since the reference leg water level remains constant, changes in the downcomer annulus water level produce a differential pressure proportional to the reactor vessel water level. Variations in water density caused by temperature and pressure conditions inside the pressure vessel can be compensated with the measurement system.

In most operating BWR plants this is the only method of reactor water level measurement, which means it is critical that the measurement be highly reliable. Usually there are several reference legs and measurement channels to ensure redundancy and separation of various safety and operational functions.

The diversification of the water level measurement is not explicitly required in any country; as such using one measurement method can meet a strict interpretation of the regulations and be consistent with assuring reactor safety. However, this should be supported with a deterministic safety analysis for the specific plant design that demonstrates for each initiating event and accident scenario that there are at least two different signals as input into the reactor protection system that will initiate a reactor trip and start other essential safety functions.

4. Diversification efforts

Over the decades, several ideas have been proposed to diversify the measurement of the reactor water level. Most active discussions and investigations on the subject seem to have taken place in Sweden.

Float switches for a diverse safety system actuation from the water level were part of the original design in the earliest BWR plants in Sweden. Operating experience from these switches was good, but this feature was abandoned in later designs. Requiring backfitting level switches to operate plants in Sweden is deemed unpractical, as it would require new connections to the reactor pressure vessel.

There is a well developed and tested design of float switches to be implemented at the Olkiluoto plant in Finland. The switches would be connected to existing pipelines so that no new connections to the reactor pressure vessel itself would be needed. However, the licensee has proposed to halt the project for several reasons, including the potential increase in the probability of loss-of-coolant accidents and risks related to modifying the analogue-technology based reactor protection system. The licensee has proposed compensatory measures to improve safety in case of a CCF in the water level measurement:

- implementing a possibility to bypass an erroneous high water level signal preventing water injection to the reactor;
- several new alarms, for example if feedwater flow is not in line with reactor power;
- operator training to recognise incorrect water level measurements.

STUK has so far not accepted the proposal, as there are open questions concerning a postulated CCF of the low water level signal and the very short time available to operators.

In Germany, the PRA showed that a CCF of the non-diverse RPV water level measurement was a dominant path for a core melt sequence in German BWRs, for example in case of the event "failure of the feed water supply with CCF of the water level measurement." After measures that increased the reliability of RPV level measurements, which are discussed in the next section, a CCF of the non-diverse RPV level measurement was not categorised as a design basis accident, but as a beyond design basis accident.

A diverse signal for reaching a low coolant level in the reactor pressure vessel was implemented by retrofitting three in-core lances equipped with thermocouples in the RPV. When defined limits are reached (50 K above the saturation temperature during normal operation), the reactor is automatically shut down by a separately installed safety control system. RPV pressure relief, steam line isolation, auxiliary steam and feed water, and core flooding are actuated. This way, the failure of the RPV level measurement is controlled with completely independently triggered measures.

The lances for the in-core temperature measurement are located between the fuel channels, approximately 0.4 m below the upper core boundary. Once the water level has dropped, the thermocouples heat up by the thermal radiation of neighbouring fuel channels.

In addition, an indirect, diverse RPV level detection was introduced via the flow monitoring of the coolant cleaning pumps. At an actual reactor level < 12.15 m, only steam is sucked in by the coolant cleaning pumps, which leads to a pump failure and is reported accordingly at the control room and indirectly allows conclusions to be drawn about the level in the reactor pressure vessel.

Core thermocouples were also introduced in Sweden in Barsebäck 1 and 2 and Oskarshamn 2 and 3. Low reliability and difficulties with testing and calibrating resulted in the removal of the system. After the German experience, the core temperature measurement method was also discussed in Switzerland for the Leibstadt nuclear power plant, but in the end the installation was considered unjustified.

Other level measurement methods discussed in Sweden include ultrasound measurement in the reactor downcomer. This was considered unreliable in BWR conditions. Differentiation of process flows in and out of the RPV in combination with the reactor power was also considered unreliable with the given tolerances and calculation methods, since relatively small differences in process flows could give a false indication, leading to failures impacting the safety functions. Weighing the reactor tank with the help of wire strain sensors was tested; however, thermal stresses and similar variations contributed to excessive measurement errors. Finally, it was proposed to have cavitation measurement in a system that is connected to the RPV at a suitable level and is normally in operation. The method is based on gas being sucked into the system at low reactor water levels. It has not been demonstrated that this method can be made sufficiently reliable to be used for safety functions.

As the differential pressure reactor water level measurement is considered sufficiently reliable, especially considering the improvements mentioned in the next section of this report, a very high level of reliability would be required from the diverse measurement if it was to be relied upon as an input for automatic protection functions. This would be the case especially if, for example, the diverse low-level signal was given priority over the existing principal water level measurement.

Another way to improve safety in the case of a water level measurement system failure would be to have the diverse measurement as an alarm to the operators or to develop operating procedures and operator training to detect incorrect water level information.

After the Fukushima Daiichi accident, guidance was developed in several countries, especially Japan and the United States, on how to infer levels from other indications (e.g. core steam flow, containment pressure, hydrogen concentration and injection flow). Such methods could be used in severe accident situations to determine adequate core cooling when level indication is not available. This kind of approach has also been proposed in Finland as an alternative to implementing a diverse water level measurement system.

5. Operating experience and improving reliability and accuracy

As discussed in the previous section, if no diverse method to measure the reactor water level is available, ensuring the reliability and accuracy of the principal method increases in importance. Much of the operating experience, discussions and solutions to improve the measurement method are from the United States, which is natural considering the size of the US BWR fleet.

In Generic Letter 84-23 (NRC, 1984) the NRC discussed the generic evaluation of water level instrument adequacy for BWR 2-6 designs. It identified improvements in level measurement and instrumentation systems to increase their reliability and accuracy. The NRC staff concluded that Emergency Procedure Guideline changes were adequate in the short term while licensees determined how to make permanent physical plant improvements. The issues in question were:

- Reducing level errors caused by high drywell temperatures which could cause reference leg flashing. These were to be mitigated by having a maximum drop in the reference leg, which would cause the level to indicate at the bottom of the normal operating range.
- For plants with mechanical level indicating systems that experience reliability issues, mechanical level indicating equipment should be replaced by analogue level transmitters.
- Consideration of changes to the protection system logic to mitigate negative effects of a break in a reference leg along with a single failure in a protection system channel associated with an intact reference leg.

The first two issues were post-Three Mile Island (TMI) action items and the associated changes were implemented at any plants that identified the vulnerability. The third issue became Generic Issue 101 (NRC, 1989), and the NRC determined that no action was necessary because the BWR design and operator training provide adequate protection from instrument line breaks. Generic Issue 101 was summarised in NUREG/CR 5112, "Evaluation of BWR Water Level Sensing Line Break and Single Failure." No action was required by the NRC.

NRC Generic Letter 92-04 (NRC, 1992), Information Notice 92-54 (NRC, 1992), and Bulletin 93-03 (NRC, 1993) all addressed concerns with water level instrument inaccuracies related to the flashing of the reference leg, whereby non-condensable gases would come out of solution during a rapid plant depressurisation, cause water to be expelled from the reference leg and result in inaccurate high water level indication.

The NRC concluded that interim plant operation was acceptable based on: 1) the observation that level instruments would initiate safety systems prior to reactor depressurisation; 2) the adequacy of emergency procedures combined with operator training; and 3) the unlikelihood of a sudden depressurisation to result in common mode, common magnitude errors. Based on diverse designs in the United States, the NRC requested that licensees review the analyses in Generic Letter 92-04. Licensees were requested to analyse their plant design and ensure continued compliance with the General Design Criteria for instrumentation control and protection system independence. In Generic Letter 92-04, the NRC requested BWR licensees to:

- provide the impact of potential level indication errors on automatic safety system response, operators' short and long-term actions in an accident and operators' actions prescribed in the emergency operating procedures;
- notify the NRC of short-term actions taken in response to the generic letter;
- provide any plans and schedule for corrective actions (e.g. modifications to ensure level indication reliability).

NRC Bulletin 93-03 was a follow-on to Generic Letter 92-04 and Information Notice 92-54. In January 1993, Washington Public Power System Unit 2 (WNP-2) had sustained a 0.81-metre level indication error that gradually recovered over approximately 2 hours. This occurred during a normal plant cooldown. The NRC issued Information Notice 93-27 (NRC, 1993) to discuss the level indication errors possible during normal plant depressurisation. As a result of this event, the NRC requested that the BWROG evaluate the effect of level indication errors on events such as reactor pressure vessel drain-down that are initiated from low-pressure conditions. The concern was that there are several paths with the potential to drain the vessel and there is operating experience of several events of this type at BWRs. Automatic isolation signals based on a low RPV level are credited with terminating such events, but the isolation signals would not occur if there are large errors in multiple level instruments. The result of Bulletin 93-03 was a request by the NRC for BWR licensees to immediately begin enhanced monitoring for similar phenomena, provide training to their operators on potential vulnerabilities in Mode 3 resulting from erroneous level measurements, and to continue implementing the hardware modifications discussed in Generic Letter 92-04.

Information Notice 93-89 (NRC, 1993) discussed potential vulnerabilities discovered by several US BWRs related to their reference leg backfill systems, and Information Notice 2002-06 (NRC, 2002) reported a design vulnerability of the backfill system related to system interactions between the backfill system and the control rod drive hydraulic control units.

The solutions to BWR water level indication errors implemented by the United States can be summarised as follows: in addition to the hardware modifications (most plants chose to install a reference leg backfill system), significant operator training was carried out to ensure awareness of potential inaccuracies in level indication, their causes and how to use multiple indications to properly determine reactor water level. Through a combination of hardware modifications, operator training and the sharing of operating experience via generic communications and other means, the US nuclear industry has had success in improving the reliability and accuracy of reactor water level measurement.

A similar approach following the US experience and decisions has been taken in most BWRs of the General Electric (GE) design operating worldwide, and a continuous reference leg backfill system by the control rod drive water supply system has been implemented.

In Switzerland, after a scram in one BWR caused by a deflagration of the hydrogen and oxygen gas in the condensation chamber of the reference leg, the condensation chamber and connecting pipes of the RPV level measurement were redesigned. In Mühleberg, which had only two condensation chambers and four reference legs, a computer system was installed to identify leaks or breaks in the piping of reference legs based on temperature measurement. As the Leibstadt BWR had five condensation chambers and connecting reference legs, such a leak detection device was not required.

In Sweden, non-condensable gases dissolving in reference legs or reference vessels and creating an incorrect reactor water level indication has also been an issue at Oskarshamn 1.

Boiling can also occur in reference piping or reference vessels in the event of a pipe break and create an incorrect reference level. Both these issues have been solved by having a degassing pipe from the reference vessel to the steam line and by installing a cooling system connected to the reference leg. In Oskarshamn 1 the licensee installed a feature to provide water to the reference piping from the demineralised water distribution system.

In Finland, there were false high water level signals during temperature decreases at Olkiluoto 2 from 1991 onwards, after the reference lines had been thermally isolated to prevent the lines from overcooling. This was first interpreted to be caused by the dissolution of non-condensable gases based on the US experience discussed above. Later, it was shown that this was caused by boiling in the isolated reference legs. The possibility to fill up reference tubes with water during power operation was added to remove non-condensable gases, which did not remove the false signals. The second action was to cool the reference line with airflow after shutdown. This was successful and solved the issue.

In Germany, the following measures to increase the reliability of the water level measurements have been implemented:

- use of diverse signal transmitters (converters);
- installation of temperature measurements in the reference tube for the detection of small leaks that lead to an increase in temperature and thus to falsification of the measured value;
- stripping the level measurement standpipes isolation to stabilise the level measurements in case of pressure changes due to subcooling and thus prevent evaporation;
- annual, redundant flushing and filling of all differential pressure lines to flush out non-condensable gases and to check for blockages or clogging;
- monthly recurrent testing of the level measurements to verify the function of the measurements and to detect clogging of the measuring lines due to clogging or foreign objects.

The measures presented in this section are based on overall good operating experience and the reliability and accuracy of the reactor water level measurement system has been considered sufficient by the majority of national regulators.

6. Conclusion

All boiling water reactors use the same principal method for reactor water level measurement. The method is based on differential pressure between the reference leg and the reactor downcomer. In most, probably all, currently operating BWRs this is also the only method to measure the reactor water level.

High reliability as well as redundancy and diversity are generally required as necessary principles in reactor protection system design, but there is no standard or regulation internationally or in individual countries that specifically requires the diversification of boiling water reactor water level measurements. Furthermore, using two separate physical parameters would be preferable for starting safety functions in the postulated accident scenarios. If this can be achieved, there is no need for the diversification of the water level measurement. The backfitting of new measurement and I&C systems in operating plants requires strong reasonable justification and must demonstrate clear nuclear safety benefits.

In the past, efforts were made to diversify the protection signals from reactor water levels. Some methods were implemented in BWRs, while others were theoretical studies. Most of these methods were rejected, usually because they were considered unreliable compared to the principal method, and reactor vessel and reactor protection system modifications were considered unjustified and, in some cases, risky. The most notable exception to this is the core temperature measurements that were implemented in Germany. However, diversification of the sensors and other I&C equipment used in the differential pressure measurement has been widely implemented. Dependence on the one water level measurement method has also decreased through developing operating guidance and operator training to detect incorrect water level information, and to infer levels from other indications to determine adequate core cooling.

Overall, the reliability of reactor water level measurements has been good during the decades that BWRs have been in operation. The most significant issues encountered have been false water level indications caused by the release of non-condensable gases or boiling in the reference leg in connection with reactor pressure decrease. These issues have been solved by implementing reference leg backfilling and/or cooling. These plant modifications, together with operator guidance and training, are considered sufficient by most regulators in the countries participating in the WPBWR to ensure the reliability of water level measurements. However, while not explicitly required, diversification of reactor water level measurements is an approach that can contribute to enhanced reliability of the reactor protection system by reducing the likelihood of common cause failures. For example, in Finland, the issue of how to deal with a common cause failure of reactor water level measurements is still under discussion between the utility and the regulator.

References

IAEA (2016), Safety Standards - Safety of Nuclear Power Plants: Design - Specific Safety Requirements SSR-2/1 (Rev.1)

NEA (2022), "Summary Record of the 47th Meeting of the Committee on Nuclear Regulatory Activities (CNRA)", OECD Publishing, Paris. (not publicly available)

NRC (2017), 10 CFR Part 50 Appendix A *"General Design Criteria for Nuclear Power Plants"*, United States Nuclear Regulatory Commission, Rockville.

NRC (2007) CFR 50.109 "Backfitting", International Atomic Energy Agency, Vienna.

NRC (2006) Information Notice 2002-06, Design vulnerability in BWR reactor vessel level instrumentation backfill modification, United States Nuclear Regulatory Commission, Rockville.

NRC (2002), Information Notice 2002-06, Design Vulnerability in BWR Reactor Vessel Level Instrumentation Backfill Modification, United States Nuclear Regulatory Commission, Rockville.

NRC (1993), Information Notice No.93-89, Potential Problems with BWR Level instrumentation backfill modifications, United States Nuclear Regulatory Commission, Rockville.

NRC (1993), Information Notice No. 93-27, Level Instrumentation Inaccurancies Observed During Normal Plant Depressurization, United States Nuclear Regulatory Commission, Rockville.

NRC (1993), Bulletin 93-03, Resolution of issues related to reactor vessel water level instrumentation in BWRs, United States Nuclear Regulatory Commission, Rockville.

NRC (1992), Generic Letter 92-04, Resolution of the issues related to reactor vessel water level instrumentation in BWRs pursuant to 10 CFR 50.54(F), United States Nuclear Regulatory Commission, Rockville.

NRC (1992), Information Notice No. 92-54: Level Instrumentation Inaccuracies Caused by Rapid depressurization, United States Nuclear Regulatory Commission, Rockville.

NRC (1989), Generic Letter 89-11, Resolution of Generic Issue 101 "Boiling Water Reactor Water Level Redundancy", United States Nuclear Regulatory Commission, Rockville.

NRC (1984), Generic Letter 84-23 *"Reactor Vessel Water Level Instrumentation in BWRs"*, United States Nuclear Regulatory Commission, Rockville.

SSM (2008), Swedish Radiation Safety Authority Regulatory Code, The Swedish Radiation Safety Authority's regulations and general advice concerning the design and construction of nuclear power reactors, Swedish Radiation Safety Authority, Stockholm.

STUK (2019), *Safety design of a nuclear power plant*, Radiation and Nuclear Safety Authority, Vantaa, Finland.

STUK (2018), *Regulation on the safety of a nuclear power plant*, Radiation and Nuclear Safety Authority, Vantaa, Finland.