ADVANCED LIGHT WATER REACTOR REQUIREMENTS DOCUMENT

TOPIC PAPER

RELATIVE TO CHAPTER 4

REACTOR PRESSURE VESSEL LEVEL INSTRUMENTATION FOR PWR

Prepared For
Electric Power Research Institute
Palo Alto, California

Rev. 0, Issued October 1989

ALWR TOPIC PAPER

REACTOR PRESSURE VESSEL LEVEL INSTRUMENTATION FOR PWR

ALWR POSITION

It is the ALWR position that the advanced features of the ALWR plant, significantly upgraded operator training plus diagnostic tools provided to the operator, and symptom-oriented emergency operating procedures make it unnecessary to specify a reactor pressure vessel (RPV) level instrumentation system for the ALWR. The advanced features of the ALWR that eliminate the need for RPV level instrumentation are as follows:

- Larger pressurizer than most current PWRs, located above the RPV head;
- No automatic power operated relief valve;
- Improved head venting capability;
- Improved feed-and-bleed capability;
- Increased redundancy in emergency feedwater pumps;
- Emergency feedwater cavitating venturis to limit extent of overcooling transients;
- Improved engineered safety systems;
- Major improvements in the electrical systems;
- Shutdown RPV level indication system;
- Improved reactor system instrumentation.

The above ALWR features will make the occurrence of sustained voiding in the reactor pressure vessel during anticipated transients unlikely, will enhance the usefulness of the pressurizer level indicating system as a direct measurement of reactor coolant system inventory, will substantially reduce the likelihood of events leading to inadequate core cooling (ICC), and will improve the capability to deal with such events should they occur. The ALWR features, including a shutdown reactor vessel level indication system, will significantly reduce the likelihood that residual heat removal capability could be lost when the reactor coolant system level is lowered for steam generator or pump maintenance. Finally, the required ALWR reactor system instrumentation including subcooling margin monitors, core exit thermocouples, pressurizer level indicators, and reactor coolant pump status (motor current) will provide the necessary instrumentation for detecting voids in the reactor vessel head and other reactor vessel inventory deficits that could lead to inadequate core cooling (ICC), thus making it unnecessary to provide a separate system of reactor pressure vessel level instrumentation.

Elimination of the RPV level indicating system is consistent with the goals of the ALWR program in that it:

- Enhances plant safety by eliminating the diversion of operator attention from restoring reactor coolant system inventory and decay heat removal capability during core-threatening events to attempting to interpret ambiguous and unreliable RPV level indications;
- Eliminates the complexity an RPV level indicating system adds to the plant with no commensurate benefits;
- Eliminates the significant maintenance burden needed to maintain and calibrate the RPV level indicating system;
- Eliminates the need to disassemble and reassemble the RPV level indicating system for refueling;
- Eliminates reliability and maintenance problems associated with an RPV level indicating system, including sensor failure and leaks of boric acid from joints on the primary coolant system;
- Significantly reduces radiation exposure associated with disassembly, reassembly, and maintenance of the RPV level indicating system.

DISCUSSION

There is general agreement that the TMI-2 event got out of hand **not** due to an inadequate amount of instrumentation, but due to significant shortcomings in the training of operators; specifically, the operators were unable to recognize and interpret the indications on instruments which they had available during an abnormal event. The apparent inconsistency at TMI between the full pressurizer, the saturated conditions in the RPV and the vibrating (cavitating) main coolant pumps led the operators to take incorrect actions when responding to an event they had never before encountered or been trained to manage.

As a result, one of the most significant outcomes following the TMI-2 event was the introduction of symptom-oriented emergency operating procedures, which ensure that operators focus on maintaining critical safety parameters with appropriate bounds, and a dramatic upgrading in the training of operators to enable them to recognize, diagnose, and mitigate transient conditions. The advent of full scope replica simulators has provided utilities with an extremely effective training tool to enable the operator to experience and respond to events which the plant will likely never encounter. Of particular value is the ability of the simulator to display the response of instruments which the operator relies on in normal operation during the off-normal or transient event. In addition to the system-oriented procedures and the major upgrade in training, operators were provided with additional tools to aid them in responding to transient events, especially those which were not anticipated. The tools which have been added for PWR operators include:

- **Subcooling Monitors:** An instrument to enable an operator to quickly correlate the indicated RCS temperature and pressure to assess the degree and trend of subcooling present in the RPV, to diagnose the nature of the transient event, and to select the proper action or actions to mitigate the transient.
- **Reactor Level Instrumentation:** A totally independent system consisting of multiple reactor vessel penetrations, differential pressure and/or temperature sensors, power supplies, electronics, and displays. The system is intended to provide an indication of the coolant level in the upper part of the RPV, thereby enabling the operator to confirm that a transient has progressed to the point that voiding is present in the RPV and to determine the trend.

In conjunction with symptom-oriented EOPs, the subcooling monitors have proven to be very useful to operators, providing them with: (1) effective insight and guidance, (2) the means for rapidly interpreting the instrumentation which they routinely use in operating the plant, and (3) the ability to keep aware of all the options available to them to respond to and mitigate an unanticipated event.

In theory, reliable, unambiguous reactor vessel level indication should add to the operator's knowledge of one of the most critical parameters to the status of core cooling and thereby provide the operator with a confirmation that the mitigating actions already initiated are having the desired effect. Unfortunately, reliable and accurate measurement of the fluid level in an operating PWR reactor vessel is a very difficult technical undertaking.

Because a PWR reactor is intended to be full for every normal operating condition, the usefulness to an operator of a level indicating system must lie in its use as an aid in diagnosing and mitigating off-normal and high unusual **transients**. Level measurement in a PWR is particularly difficult during transients when the fluid is flashing, operating status of equipment is changing, and temperatures are fluctuating. Reactor safety research programs, including some sponsored by the NRC, have recognized that no single "level instrument" is capable of obtaining a meaningful level indication in the reactor vessel under transient conditions. It may be possible to obtain some indication of level by cross-checking and comparing the outputs of several instruments; however, this results in a complicated level indicating system that may not provide accurate level indication. In fact, there is disagreement on whether "level" is a meaningful parameter to be measured in a PWR.

Furthermore, when a transient has progressed to the point where subcooling margin is lost, the operator's responsibilities consist primarily of monitoring the performance of the safety systems which should already be operating and the trends of key reactor coolant system parameters. All possible steps are taken to ensure that the appropriate safety systems are operating. If subcooling is not recovered, additional actions are taken, such as lowering RCS pressure to enhance delivery of emergency coolant. No significant operator action is taken on the basis of reactor level instrumentation alone. For those plants where EOPs provide guidance on the use of RVLIS indications, they are employed only as a confirmation of information obtained from other instrumentation.

In summary, the RVLIS which has been added to current plants, while promising potential benefit, has not proven to be useful. The reverse has been the case; such instrumentation has added to the plant maintenance burden and has been unreliable so that operators tend not to believe the level indications.

The ALWR will benefit from the significant improvements in operator training and procedures and will, in addition, contain numerous features which substantially reduce the likelihood of inadequate reactor vessel inventory during transients, accidents, and shutdown maintenance operations. The ALWR will be a safer plant. An RVLIS is not required to achieve this enhanced safety and has not been specified for the ALWR. Subsequent paragraphs of this section discuss:

- Regulatory guidance for current plants;
- Current plant approach;
- ALWR approach;
- Problems with current plant approach.

Regulatory Guidance for Current Plants: NUREG-0737 indicates that an unambiguous indication of inadequate core cooling (ICC) should be provided, that the indication should give advanced warning of ICC and notes that water level instrumentation may be part of the ICC detection system. Regulatory Guide 1.97 indicates that coolant inventory should be measured from the bottom of the hot leg to the top of the reactor vessel, and also indicates that a measurement should be provided to detect the trend of voids in the reactor coolant system with the reactor coolant pumps running. In addition, Regulatory Guide 1.97 indicates that measurement should be provided of core exit temperature and the degree of reactor coolant system subcooling. These two measurements may also be part of the ICC system.

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REACTOR PRESSURE VESSEL LEVEL INSTRUMENTATION FOR PWR

Current Plant Approach: To meet post-TMI-2 instrumentation requirements, a subcooling monitor was installed at all U.S. PWR plants, and some form of reactor vessel level indication was installed at many plants. Because a direct means of monitoring level in the RPV does not exist, the reactor vessel level instrumentation has typically consisted of: (1) differential pressure indicating instruments connected to capillary tubes which penetrate the RPV or (2) a series of heated-junction thermocouples mounted above the core, within the reactor vessel. Core exit thermocouples were already employed at essentially all plants and, following TMI-2, were made a part of the ICC system.

The installed reactor vessel water level instruments typically are intended to indicate water level within the reactor vessel head, down to the bottom of the hot leg, and in some cases down to the core region. Thus, they are intended to serve two basic functions. One function is to detect the presence of head voids which can occur during transients such as natural circulation cooldowns and overcooling events or as a result of non-condensible gas accumulation such as occurred during the TMI-2 accident. The second function in some plants is to measure water level above the core and, in conjunction with subcooling margin monitors and core exit thermocouples, provide indication of approaching ICC and aid in ICC mitigation strategy.

ALWR Approach: The ALWR will provide enhanced capability compared to current plants for maintaining adequate RCS inventory during anticipated transients, accidents, and maintenance operations without using a reactor vessel level instrumentation system. This approach is summarized below, including how the advanced features of the ALWR provide the means to effectively establish the status of RCS inventory and provide all necessary information for safe operation of the plant in the absence of the level instrumentation.

(1) Void Management/RCS Inventory Control During Transients: The specific features which have been specified for the ALWR reactor coolant system which reduce the susceptibility of the RPV to voiding in the head are as follows:

- A larger pressurizer than most current PWRs ensures that a water level remains in the pressurizer, covering the heaters for most anticipated transients and delays uncovering the heaters for the most severe transients.
- Improved head venting capability with either an active system discharging to the in-containment refueling water storage tank (IRWST) or an alternative continuously open vent from the reactor vessel head to the pressurizer. Head venting assures that a single RCs water level can be quickly re-established if head voiding occurs, e.g., during natural circulation cooldowns.

- The pressurizer is arranged high in the system above the RPV head. In conjunction with head venting, this feature ensures that pressurizer level and subcooling monitors are a positive indication that the reactor head is free of voids.

- Cavitating venturis in the emergency feedwater system delivery lines limit the extent of overcooling transients.

For all anticipated overcooling transients, including natural circulation cooldowns, pressurizer level indication, in conjunction with reactor coolant temperature indication and the above advanced ALWR features, is sufficient to detect and trend reactor vessel head voiding. The onset of head voiding would be indicated by an increase in pressurizer level. The effectiveness of head venting to eliminate the void would be indicated by a decrease in pressurizer level followed by stabilization at or near its original level plus indication of subcooling from the subcooling monitors.

(2) Inadequate Core Cooling: Numerous features have been specified for the ALWR to reduce the likelihood that an inadequate core cooling condition could be reached. The major features are summarized as follows:

- Engineered safety systems and reactor coolant systems are designed to ensure **no** fuel damage for the range of small break LOCAs up to 6 inches in diameter, with 12-inch diameter an objective (Chapters 1, 4, and 5).

- The reliability of the reactor coolant pumps (RCP) seals has been significantly improved (Chapter 5), reducing the probability of losing the services of an RCP or of a LOCA through a failed seal.

- Four mechanical trains of the safety injection system are provided to decrease the probability of severe core damage during LOCAs (Chapter 5).

- The engineered safety feature pumps are continuously aligned to the in-containment refueling water storage tank, which improves reliability as compared to current plants which must switch suction from an outside tank to the containment sump (Chapter 5).

- The pressurizer is large enough to ensure that primary safety valves remain closed during all anticipated transients, and an automatic power operated relief valve is not needed. This greatly reduces the probability of a TMI-2 type event (Chapter 3).

- Two turbine-driven emergency feedwater pumps plus two motor-driven pumps provide substantial reduction in the likelihood of severe core damage compared to current plants (Chapter 5).

- Improved feed-and-bleed capability, i.e., bleed to the in-containment refueling water storage tank, provides a backup to the unlikely event of complete loss of feedwater, which the operator could use without the concern in current plants of contaminating containment. It is noted that for ALWR, feed-and-bleed is **not** an automatic function (Chapter 5).

- The design pressure of the residual heat removal system has been increased to at least 900 psig to significantly reduce the risk of an interfacing system LOCA (Chapter 5).

The electrical systems have been significantly improved. The frequency of loss of power to auxiliary loads has been reduced to 1.8×10^{-3} events per year, an alternative on-site ac power supply has been added in addition to the two safety dedicated emergency sources, and functionally redundant batteries with 8-hour capacity provide reliable and extended dc power capacity.

Accordingly, there is substantial reduction for an ALWR of the probability that an inadequate core cooling condition could be reached. Additionally, adequate instrumentation is available in the ALWR, without an RVLIS, to ensure that appropriate operator actions will be taken for the events with the potential for insufficient RCS inventory, such as small break LOCAs (at the top of the pressurizer or elsewhere) and complete loss of feedwater. In particular:

- Pressurizer level would provide early indication of such events by either (1) anomalous high level indication, coupled with decreased subcooling, for inventory loss through the top of the pressurizer, or (2) low level, for inventory loss other than from the top of the pressurizer.

- The subcooling monitors would indicate onset of RCS voiding. This would be backed up by RC pump operating status indication, i.e., motor current for operating pumps. If subcooling is lost, the operator will be directed to take all possible measures to restore reactor coolant system inventory and decay heat removal capability. Trending information such as might be provided by an RVLIS would have no effect on the steps undertaken by an operator once subcooling is lost.

- ICC will be detected by the core exit thermocouples and subcooling monitors when superheat temperatures are reached. ICC will be detected by these instruments approximately 15 minutes later than reactor vessel level instrumentation would indicate ICC. However, no operator actions would depend on the ICC as detected by the reactor vessel level instrumentation alone, i.e., the 15-minute delay would not affect operator action. The reactor level indication does not contribute any unique information or insights that would lead to a more effective ICC mitigation strategy.

Utilities have trained their operators to recognize the onset of voiding in the RPV and ICC without dependence on a reactor vessel level indicating system. They primarily rely on subcooling monitors and core exit thermocouples. Probabilistic risk assessments on current plants have shown that the use of the RVLIS in conjunction with subcooling monitors and core exit thermocouples provides no significant reduction in risk compared to providing only subcooling monitors and core exit thermocouples. The RVLIS does not contribute any unique information or insights that would lead to a more effective ICC mitigation strategy. Emergency operating procedures typically do not initiate any additional actions for ICC mitigation until the subcooling monitors, thermocouples, or other supporting instrumentation also indicate core cooling. Thus, there is not significant difference in recovery from such sequences, whether or not reactor vessel level indication is provided. Furthermore, there is a potential for delaying operator action due to inconsistent indications.

The real risks of ICC have been addressed for the ALWR by substantial improvements to the reactor and engineered safety systems. An RVLIS does not address such risks.

(3) Monitoring RCS Level During Maintenance: The ALWR will incorporate various features that prevent or mitigate the effects of losing suction to the residual heat removal (RHR) pumps when the RCS level is lowered for steam generator or pump maintenance. Most importantly, the ALWR design requires redundant and permanently installed RCS shutdown level instrumentation to indicate level during these maintenance activities. Range overlap is provided with the pressurizer level instrumentation so operators can verify that the shutdown level system is operable before RCS level is completely lowered. This instrumentation operates with the reactor head removed and provides accurate indication of hot leg level during mid-loop operation. Currently installed RVLIS systems do not provide such indication.

Problems with Current Plant Approach: Problems experienced in current PWRs demonstrate the disadvantages of reactor vessel level instrumentation.

- Reactor vessel level instruments have proven to be unreliable. As a result, operators tend to disbelieve the level indications. This detracts from the confirmatory benefits of the instrumentation. It is possible that ambiguous level instrumentation readings could delay operator action since the operator must spend time sorting out inconsistent indications before taking action.

- The RVLIS is not available during refueling outages. For a refueling outage, the reactor vessel head is removed. To do so, the reactor vessel level instrumentation must first be removed. This removal procedure is involved and complex, adding significantly to the radiation exposure for plant operation personnel. Additionally, the chances are high that the instrumentation system could be damaged during the removal process.

- Experience in operating plants has shown that present reactor vessel level indication systems adversely affect plant availability and personnel radiation dose. They represent an additional set of unique components which must be calibrated, maintained, and repaired over the life of the plant and thus add unnecessarily to the maintenance burden and radiation exposure for plant operation and maintenance personnel.

- The level indications from currently installed systems have poor human factors and are potentially confusing to the operators. In particular, they require very careful consideration of the context of plant operation. As an example of this, the differential pressure level instruments employed to measure vessel head level above the hot legs read off-scale low with the reactor coolant pumps running. Similarly, heated junction thermocouples have read erroneously high, due to turbulence associated with the reactor coolant pumps running. It is considered poor practice from a human factors standpoint to rely on such instruments during a stressful accident situation. The instruments, by their nature, do not meet the NUREG-0737 requirement of unambiguous indication.

- Reactor vessel level instruments have experienced numerous operating and maintenance difficulties. For example, differential pressure instruments require very long filled reference legs (about 100 feet) which require RTDs for fluid density compensation. Initial and ongoing calibration has been difficult. Leaks in the reference legs in some plants have been common, e.g., four or five per year, and have sometimes requires plant shutdown for repair. Such repairs have been time consuming; much time is required to drain and refill the reference legs. These problems have been costly in terms of both lost operating time and personnel exposure. No specific seal leaks have occurred with the heated thermocouple systems, but leaks and damage have occurred with other in-vessel level indicating systems which penetrate the head and which are not different in principle from those used in the RVLIS.

Research and development of an improved reactor level instrumentation system would be very costly. The ALWR approach avoids this cost as well as the disadvantages described above without sacrificing safety by excluding a level instrumentation system from its requirements.

ASSESSMENT

With hindsight, it is apparent that real improvements to the safety of reactor have been achieved following TMI-2, **not** by installation of RVLIS, but by the introduction of symptom-oriented operating procedures and dramatic upgrading in the training of operators. These lessons have been learned and will be available for the ALWR. The ALWR goes significantly further in improving safety, both through decreasing the challenges to safety systems and by improving the safety systems themselves. Substantial reductions in core melt frequency have been achieved in ALWR. Furthermore, safety grade instrumentation, such as pressurizer level, subcooling margin monitor, core exit thermocouples, and RCP status indication, can give all the information necessary for the detection of voids and ICC and for an effective ICC mitigation strategy in the ALWR. Hence, the level instrumentation can be deleted with no significant impact on core melt frequency. This simplifies the plant, eliminates unnecessary vessel penetrations and seals which can become safety concerns in their own right, and reduces the maintenance and personnel exposure burden.

REACTOR PRESSURE VESSEL LEVEL INSTRUMENTATION FOR PWR

The advantage of the ALWR features alleviate the concerns which led to the requirement of reactor vessel level measurement. Furthermore, they support the elimination of the practice in current operating plants of meeting regulatory guidance by providing safety grade reactor pressure vessel level instrumentation. Specifically, in the ALWR, the confirmatory benefits of the reactor vessel level instrumentation would be significantly outweighed by the disadvantages. The ALWR approach will decrease plant complexity, maintenance, and personnel exposure. Deletion of the reactor pressure vessel level instrumentation may improve plant safety because experience has shown that this instrumentation can be unreliable, strongly affected by changing plant conditions, and therefore confusing to operators. Subcooling margin monitors and core outlet thermocouples have proven to be reliable and unambiguous, and are adequate for detection of voids and the onset of inadequate core cooling (ICC).