POST-IMPLEMENTATION REVIEW OF INADEQUATE
CORE COOLING INSTRUMENTATION

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Instrumentation Needs for Detection of
Inadequate Core Cooling

Studies of the Three Mile Island (TMI) accident identified the need for additional instrumentation to detect inadequate core cooling (ICC) in nuclear power plants. Industry studies by plant owners and reactor vendors¹ supported the conclusion that improvements were needed to help operators diagnose the approach to or existence of ICC and to provide more complete information for operator control of safety injection flow to minimize the consequences of such an accident. In 1980, the U.S. Nuclear Regulatory Commission (NRC) required further studies by the industry² and described ICC instrumentation design requirements that included human factors and environmental considerations.³ On December 10, 1982, NRC issued to Babcock & Wilcox (B&W) licensees' orders for Modification of License and transmitted to all pressurized water reactor (PWR) licensees Generic Letter 82-28 to inform them of the revised NRC requirements. The instrumentation requirements for detection of ICC include upgraded subcooling margin monitors (SMMs), upgraded core exit thermocouples (CETs), and installation of a reactor coolant inventory tracking system (RCITS). NRC Regulatory Guide 1.97, which covers accident monitoring instrumentation,⁴ was revised (Rev. 3) to be consistent with the requirements of item II.F.2 of NUREG-0737.³ Following are some of the more significant requirements specified in that item.

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1. Instrumentation should provide an unambiguous indication of the approach to and existence of ICC.
2. Reactor water level measurement is to be considered.
3. The system must indicate the existence of ICC caused by various phenomena (e.g., high void fraction pumped flow and stagnant boil-off).
4. The presence of an unrelated phenomenon must not cause the system to erroneously indicate ICC.
5. Advance warning of the approach of ICC must be given.
6. Instrumentation must conform to Appendix B (Class 1E) of NUREG-0737.
7. Alarms and displays should be selected based on a human factors analysis.
8. Instrumentation indications must be integrated into emergency procedures and operator training programs.

Review of RCITS

The NRC, with assistance from Oak Ridge National Laboratory, reviewed generic RCITSs proposed by reactor vendors, instrument manufacturers, and individual utilities. Two water level measurement methods were developed by vendors and approved generically by NRC for application in nuclear power plants: the Westinghouse differential pressure (dp) system and the Combustion Engineering heated junction thermocouple (HJTC) system. Both of these systems were tested extensively under simulated accident conditions, including extremes of temperature and two-phase flow, and the results have been reviewed.^{5,6} Both systems were shown to have adequate response to the accidents simulated. In addition to the generic reviews, the plant-specific installations at 66 PWRs were reviewed for conformance to NUREG-0737 requirements. Of these, 48 plants use one of the generic vessel water level measurement systems, 18 plants have unique designs, and 2 plants (3 units) use a gamma-thermometer (GT) level measurement scheme very similar in principle to the HJTC system. The remainder of the unique designs use dp measurement schemes with various configuration differences.

ICC Instrument Performance

Subcooling margin monitoring provides an early indication of potential voiding but does not of itself provide any additional information about the possible approach of ICC. Sometimes the reactor vessel head water level monitor provides an initial indication of voiding at the same time that the hot-leg resistance temperature detectors (RTDs), or even the CETs, indicate that subcooling still exists. This situation has occurred in steam generator tube rupture events and could happen in any overcooling event that results in loss of pressurizer water level. The upper head can be the region of highest temperature, thus acting as the system pressurizer. In addition, a small-break loss-of-cooling accident (SBLOCA) with a leak in the upper head of the reactor vessel can result in upper head voiding. Small line breaks or faulty valves can lead to such accidents.

CETs provide perhaps the most reliable indication of the existence of ICC during stagnant boil-off when superheated steam conditions are present. However, some loss-of-fluid tests (LOFT)⁷ suggest that during reflood or coolant injection, CETs may be subcooled while the core remains voided. There is some indication from LOFT that CETs can be cooled by water falling back from the steam generator. A serious condition can occur if the loss of pumps in a highly voided situation permits the water level to collapse below the bottom of the core. The core can then heat up without detection by the CETs because there is no coolant in the core to boil, and thus no superheated steam is generated to flow past and heat the CETs. A diverse measurement system that includes measurements of other parameters, such as coolant inventory or water level, is needed to complement CET measurements under abnormal conditions. When the primary coolant pumps are running, the voids tend to be distributed throughout the system, and the resulting "froth" can provide adequate cooling when high void fractions exist. However, if pumping is continued, high void fraction mixtures ($> \sim 25\%$) are likely to cause pump damage.

The problems of ambiguities in water level measurement and the difficulties of achieving adequate accuracy with water level or inventory tracking systems are considerable. Some of those problems and the current status of industry efforts to achieve a reliable and unambiguous indication of water level were discussed recently in another paper.⁸ The possible effects of level measurement uncertainty for a typical small-break transient are shown in Fig. 1.

Generic RCITS

The Westinghouse Reactor Vessel Level Instrumentation System (RVLIS) uses redundant sets of 3 dp cells to measure pressure drop from the bottom to the top of the reactor vessel and from the hot legs to the top of the vessel. A wide-range transducer includes the pump dynamic head and is used to infer void fraction with the pumps running. A narrow-range transducer is calibrated to indicate full-scale with the static head across the vessel and pumps off, and the output is conditioned to display the equivalent collapsed liquid level in the vessel. The head-to-hot-leg measurement is used for head venting operations during long-term recovery. For plants with upper head injection, the measurement from the bottom to the top of the vessel is omitted. The Westinghouse RVLIS dp system uses hydraulic isolators and sealed lines compensated for temperature and density effects inside containment, with the transmitters located outside containment to achieve an accuracy of better than $\pm 6\%$ ($\sim \pm 2.5$ ft) under degraded environmental conditions in containment.

The Combustion Engineering HJTC system measures reactor coolant liquid inventory using discrete HJTC sensors located at different levels within a separator tube that extends from the reactor vessel head to the top of the core. The separator tube allows any steam-water mixture to collapse and hence provide a steam-water interface at the collapsed liquid level. Heated thermocouple sensors at discrete axial levels within the tube indicate the presence of water at the measurement level. The HJTC system claims very high accuracy (within a few inches), but resolution is limited to 2 to 4 ft because of the spacing between the limited number of discrete measurements points (typically 8). Additional uncertainty may be introduced during rapid level change caused by sensor response time delay (15 to 60 s).

RCITS Installation Experience

Fifty operating power plant units have installed one of the two generic RCITS. The operating experience obtained so far has been generally satisfactory, although a number of early failures and problems occurred in both system types, some of which necessitated field design changes. Most plants now have received final NRC approval and have declared their systems operational. Three units have chosen to use a GT level measurement scheme very similar in principle to the HJTC system. Eleven units have chosen to design their own dp measurement systems or use other vendors. Most of these systems use dp transmitters located inside the containment vessel, where they tend to give larger errors when subjected to SBLOCA conditions and can trap noncondensable gases in their impulse lines. Measurement uncertainties claimed for these systems range from $\pm 10\%$ to $\pm 30\%$, even with density compensation schemes. NRC has accepted most of these systems with some reservations about procedural guidance even though the guidelines of $\pm 6\%$ were exceeded. One unit, Yankee Rowe, was granted exemption from the vessel water level measurement requirement because of its small size and other features. B&W type reactors, because of their geometry, were required by NRC to have level measurement from head to hot leg and additional measurement of hot-leg (candy cane) level. Thirteen additional units included ICC instrumentation in their initial licensing submittals and were reviewed separately within NRC.

Operating Experience

All but a few of the PWRs have completed installation of the ICC instrumentation systems and have acquired operating experience with them over 1 to 3 fuel cycles. A number of early failures and problems occurred in both the generic and the unique systems types, some of which necessitated field changes. While ICC instrumentation was intended primarily for accident monitoring, expanded uses have been found to improve routine operation as operators develop confidence in the indications. Vendors and utilities have cooperated to make significant improvements in reliability and accuracy. A post-implementation review is being conducted of selected plants representative of most of the different types of systems in service. The reviews concentrate on performance factors, integration into the emergency procedures, control room and human factors considerations, and operator acceptance. The results are to be issued as a NUREG/CR report.

The SMM and CET system requirements were rather explicit in NUREG-0737. Conformance to these requirements has been good, and both performance and acceptance have also been good. More latitude was allowed in inventory trending or vessel level requirements to permit innovation and improvement. As a result, there has been much more variation in design, performance, conformance, and acceptance.

Accuracy and Procedures

NRC requirements have not included an absolute accuracy specification for water level measurements. Analyses based on SBLOCA scenarios suggest that $\pm 6\%$ is acceptable for procedural action requirements dealing with ICC. Larger uncertainties of $\pm 15\%$ or more may still be useful, but require more careful interpretation and integration into action procedures. Because the ultimate indication of the approach to ICC is expected to come from the CETs, it is argued that diagnosis of the transient does not depend on the absolute accuracy of the level measurement system and that only a correct indication of the trend of the coolant inventory is required. Typically the operator is not instructed to take action on the basis of level measurement system indication alone. Procedures were developed for some units with "conservative" decision points which, coupled with appropriate operator training, purportedly would not mislead operators into initiating inappropriate action. "Conservative," in this case, means that the measurement uncertainty would be added to the water levels requiring operator action to mitigate the consequences of accidents or transients. This procedure may cause problems in the case of events that call for a strategy of keeping the core covered while maintaining the water level below the vessel nozzles to reduce the flow of water out of the nozzles where a break may exist in the hot leg.

Although the NRC position has not ruled out an alternative procedural approach to dealing with uncertainties in level measurement, the concern remains that operators will not have confidence in a system with large uncertainties.

Human Factors

Most utilities have done a good job of integrating ICC information displays into already full control rooms. An appropriate choice taken by many is to incorporate the primary ICC display in the safety parameter display system (SPDS) or other advanced information display systems.

Conclusions

The addition of inadequate core cooling accident monitoring instrumentation to all PWRs is nearing completion after more than eight years. The direct cost is \$2M to \$10M per unit. Indirect costs for items such as procedures and maintenance may add another \$2M to \$4M. Cost effectiveness cannot be measured directly, but must be judged subjectively in relation to the socioeconomic impact of another accident similar to the one at TMI. The response and acceptance of the utilities has been largely positive, with only a few holdouts. The systems developed, while not providing the precision that might be desired, are sufficient to provide vital information for accident avoidance and recovery. In addition, unexpected benefits for normal operation have resulted, and operator acceptance and confidence have been good.

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Fig. 1. Predicted response of vessel level to a 0.1-ft² break.

Mixture Height (ft)

Temperature (°F)