EXPERIENCE WITH NEUTRON FLUX MONITORING SYSTEMS QUALIFIED FOR POST-ACCIDENT MONITORING

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Abstract

In this paper we discuss the environmental requirements for ex-core neutron flux monitors that are qualified for use during and after postulated accidents in Pressurized Water Reactors (PWRs). We emphasize PWRs designed in the United States, which are similar to those used also in parts of Western Europe and Eastern Asia. We then discuss design features of the flux monitoring systems necessary to address the environmental, functional, and regulatory requirements, and the experience with these systems.

I. INTRODUCTION

In 1979 the Three Mile Island Unit 2 reactor experienced a Loss of Coolant Accident (LOCA). For several days after the accident, experts tried to assess the damage to the core and to predict if the core would once again become critical. Their efforts demonstrated the importance of the information they obtained from the neutron flux monitoring channels, some of which failed after the accident.

In December 1980 the U.S. Nuclear Regulatory Commission (NRC) published Revision 2 to Regulatory Guide (R.G.) 1.97, which addresses instrumentation for post-accident monitoring. This revision included the requirement that neutron flux monitoring systems be qualified for the accident and post-accident environment and that they cover the range from full power to 10^{-6} percent power. As discussed below, the guide also specified the systems to be "Category 1," which requires full environmental and seismic qualification, redundancy, continuous real-time display, and on-site standby power. Quality Assurance requirements were to be the same as for safety systems.

In May 1983 the NRC issued Revision 3 of the regulatory guide [1], which modified some of the earlier requirements for radiation monitors and meterological measurements. Requirements for neutron flux monitoring were not changed.

II. REQUIREMENTS

A. Environmental Requirements

Reference 1 classifies neutron flux as a "Type B" variable, one that provides information to indicate whether plant safety systems are performing their safety functions. One of these functions is reactivity control. Neutron flux monitoring is essential for this function, and carries the classification "Category 1." Other functions are cooling the core, maintaining reactor coolant system integrity, and maintaining containment integrity, including radioactive effluent control.

Category 1 systems require the full environmental and seismic qualification required for reactor safety systems. These requirements are invoked by other NRC Regulatory Guides and documents (R.G. 1.89, R.G. 1.100, NUREG-0588), which endorse industrial standards such as IEEE 323-1974 [2] (Environmental Qualification), IEEE 344-1975 [3] (Seismic Qualification), and numerous supporting standards addressing independence and isolation, criteria for type testing, application of single-failure criterion, criteria for periodic testing, general principles for reliability analysis, etc.

Moreover, Category 1 systems also require that the system be qualified, manufactured, installed, and maintained under a quality assurance program, specified by the legal requirements of the U.S. Code of Federal Regulations (specifically 10 CFR 50 Appendix B) and by various NRC Regulatory Guides that endorse industrial standards such as ANSI/ANS N45.2 and ASME NQA-1.

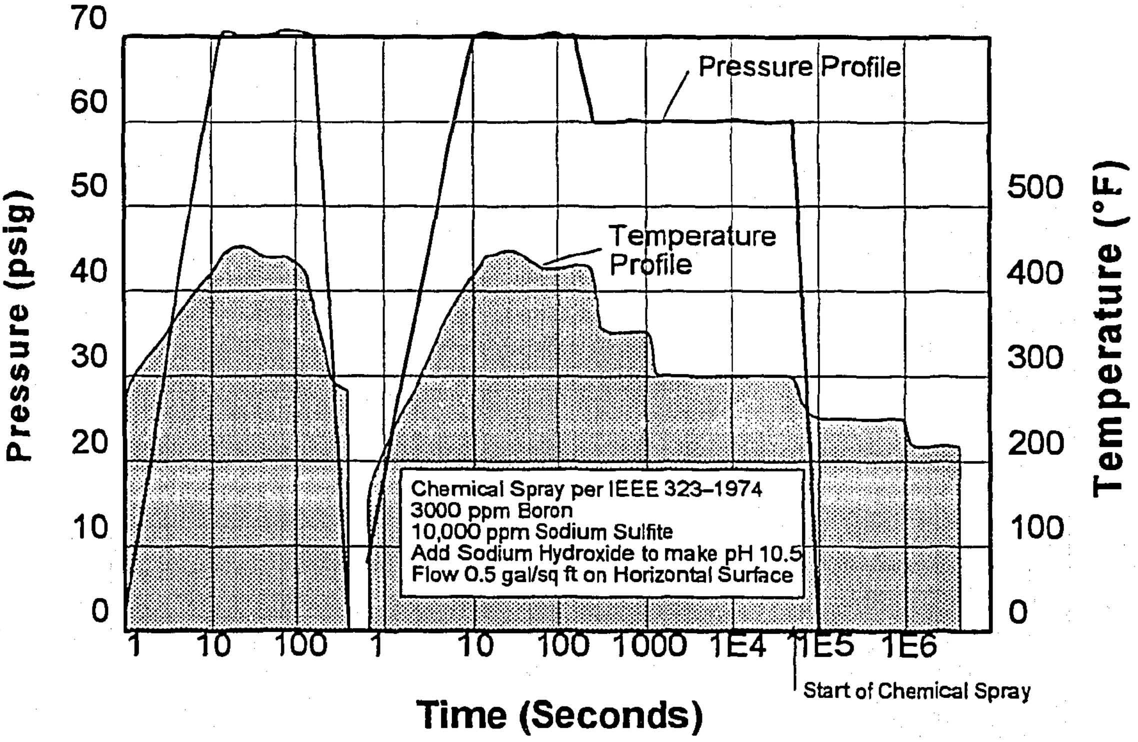
Ex-core neutron flux detectors in U.S. PWRs are typically installed in vertical wells that are exposed to the temperature, pressure, and humidity environment inside the containment. Most of these detectors are also exposed to chemicals that would be sprayed inside containment after a Loss of Coolant Accident (LOCA) or Main Steam Line Break (MSLB), although some well designs protect the detectors from this spray. Some detectors are installed inside wells in tanks of water (Primary Shield Tanks), but their associated cables may still be exposed to the post-accident environment. Thus the most common designs of the detectors and the other in-containment components (e.g., cables, penetrations, connectors, etc.) must withstand and operate during the harsh, accident and post-accident environment.

This environment depends on the specific plant design. However, a limiting, composite environment that envelopes the most severe conditions of typical PWRs is included for reference in Appendix A of Reference 2. A typical LOCA/MSLB qualification test profile, based on the reference, is shown below.

The detectors must also operate through and after a Safe Shutdown Earthquake (SSE), the motion induced at the detector's location by the design basis event. The magnitude and frequency of this motion depends both upon the specific plant design and its location.

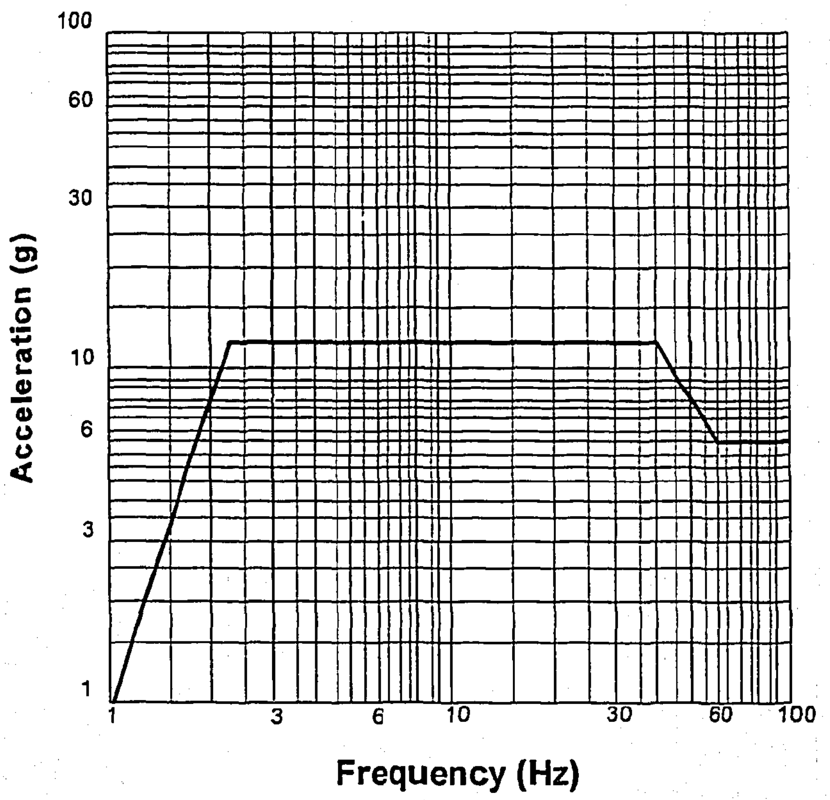
Again however, a seismic response that envelopes the most severe earthquake has been developed, and a typical seismic qualification test profile based on this response is shown below.

PWR LOCA/MSLB Test Profile



Chemical Spray per IEEE 323–1974
3000 ppm Boron
10,000 ppm Sodium Sulfite
Add Sodium Hydroxide to make pH 10.5
Flow 0.5 gal/sq ft on Horizontal Surface

Seismic Profile – SSE



Tested Profile, Horizontal and Vertical Directions, 1% Damping

Less well defined is the neutron flux and gamma radiation following an accident. In general, the thermal neutron flux in the ex-core wells at full power is between 3×10^9 to 1×10^{10} n/cm^2-sec. The actual value depends on the core and fuel design, the burnup, and to some extent the physical design of the well.

Gamma radiation at full power is approximately 10^5 R/hr. Gamma radiation after an accident can be assumed to be higher, and at least one system design assumes 10^6 R/hr. Measuring neutron flux accurately in gamma radiation this high poses problems for the system designer, as discussed below.

B. Functional Requirements

The neutron flux monitoring system must cover at least a flux range corresponding to an upper level of full power and a lower level of 10^{-6} percent power. Systems typically provide an output proportional to the logarithm of the neutron flux. In general, accuracy, drift, and response times are not defined specifically for post-accident monitoring; however, when the post-accident monitoring channel replaces the original channel, the functional design of the original channel apply. Typical accuracy requirements for original Intermediate Range instrumentation (channels with range comparable to that required by Reference 1) was ±5 percent equivalent full scale linear. Advances in technology incorporated into modern systems have improved that accuracy to as great as ±1 percent equivalent full scale linear.

Response times vary, depending on the application of the channel in reactor safety systems. In general, response times at low flux levels are long, to allow sufficient time for "meaningful" readings (i.e., slow enough for the operator to read but fast enough to follow expected changes in flux). At higher flux levels the response times are short, compatible with requirements of protection functions that may depend on signals from the channels.

C. Requirements of Other Industrial Standards

Other industrial standards not written specifically for Nuclear Power Generating Stations are now frequently applied to modern neutron flux monitoring systems. These include IEC 801-3 for immunity to electromagnetic radiation and IEC 801-2 for immunity to electrostatic discharge. Others are sometimes applied to establish predicted reliability.

D. Integration into Plant Designs and Operations

In most U.S. PWRs, the original design of the Intermediate Range or Safety Channel neutron flux monitors was not and could not be qualified for the post-accident environment, for reasons discussed below. Most plants had been designed, and many were in operation before post-accident qualified systems were required. Therefore the new systems had to be integrated into existing plant designs and operating practices.

Considerations for installing new channels into an operating plant include:

- Design features to minimize the time that construction workers must handle the equipment inside containment, to reduce radiation exposure to workers
- Design features that increase flexibility in choosing a location to install the new cables and electronics. For example, a system that permits the first stage of electronics to be as far as 300 m (of cable length) from the detector simplifies the plant-specific engineering needed to install the new system.
- Design features that minimize the risk of damage during handling, especially given the concern about speed when installing the equipment
- Design features to minimize the time required to connect cables inside containment, yet allow for secure, reliable connections

E. Reliability and Maintainability Issues

Closely related to plant integration are issues of reliability and maintainability. These include design features to minimize the number and frequency of adjustments, to minimize drift (closely associated with minimizing adjustments), and to minimize the amount of time needed to perform those tests and calibrations that are necessary. Such features include self monitoring, built-in test and calibration circuits, and careful component selection.

Component selection not only can improve reliability and drift performance, it also can extend the life of the system by avoiding components that are likely to become obsolete. Many of the plants' original flux monitoring channels contain components for which spare parts are either not readily available or which have unacceptable delivery times.

III. SOLUTIONS

The basic approach taken to date has been (1) to discriminate strongly against signals from gamma radiation; (2) to seal the in-containment equipment against the harsh environment; and (3) to place electronics outside containment. Original plant equipment often could not meet the third requirement, but advances in technology have allowed some system designs to place the first stage of amplification 300 m (of cable length) from the detector, easily meeting this requirement.

Systems use uranium-coated fission chambers to provide the following advantages:

- The fission process provides high discrimination against signals caused by gamma from those caused by neutrons.
- The integration of the above detector property with the design of the electronics permits some channels to cover the entire operating range of neutron flux with only one detector assembly. Using the counting and Campbelling (mean square voltage) modes of detector operation avoids having to use two monitoring channels (one for each of two detector types commonly found in earlier operational channels), which was the traditional practice and a result of limitations of the technology at that time, as discussed in Reference 4. The combined range exceeds the requirements of Reference 1 and reduces overall costs of equipment replacement.

- Counting and Campbelling, both A.C. phenomena, are exploited to avoid the D.C. signal changes caused by the effects on cables (e.g., decreased insulation resistance) of high temperature and gamma flux. There is uncertainty in accounting for these changes in D.C. signals, especially at low levels of neutron flux. (Counting and Campbelling are discussed extensively in References 5 through 9.)

- The high inherent discrimination in the fission chamber eliminates the need for compensating voltages (which are required for boron-lined compensated ion chambers). There is uncertainty on how to adjust the compensation for boron-lined chambers to account for the effect of both normal and post-accident gamma flux, and the compensating voltage adjustment adds to the complexity of the system's design, maintenance, and operation.

- Minimal degradation of sensitivity with use of the detector. Depending on the design of the detector, sensitivity changes are minimal over forty years of normal plant operation. Also with proper design, saturation characteristics change minimally for a specified range of high voltage, and detector's gas properties are chosen so that they also change minimally during operation. These latter two characteristics preclude the need for high voltage adjustments (e.g., the "plateau curves" common with Source Range proportional counters). Instead, the value of the high voltage can be monitored to ensure it stays above a level that might affect system accuracy.

- When the post-accident system also replaces the Source Range channel, these detector characteristics also preclude the need to replace the Source Range every three to five years (or more frequently in some cases).

In summary, with one replacement channel, the performance of the original Source Range channel (typically using a boron-lined or boron-gas proportional counter) and the Intermediate Range channel (typically using boron-lined CICs) can be matched or exceeded. The detector properties allow the balance of the design to be less complex, which helps to improve reliability and reduce costs.

However, the choice of fission chambers as the sensing element, combined with keeping the electronics outside containment, presents other challenges to the designer. Cabling and penetrations must be designed and proven to prevent electromagnetic fields from corrupting the small signals that come from the detector. And the detector itself must show reliable and consistent performance for all modes of operation employed (as a minimum, counting and Campbelling but at times also including linear current operation).

IV. EXPERIENCE

Fission chambers have extensive operating experience, as discussed in Reference 4. One U.S. PWR manufacturer originally employed fission chambers for the Intermediate Range and, in their later plants, also for the Power Range. Fission chambers had also been employed in the U.S. in high temperature gas-cooled reactor, research reactors (where some have operated for 30 years), and as in-core detectors in Boiling Water Reactors (BWRs) and some PWRs.

Physical features included to meet the post-accident requirements have allowed the channels to survive mistakes during plant maintenance and refueling, mistakes that have damaged detectors and cabling of earlier, non-qualified designs. These problems include water in detector wells and extremes of temperature following refueling and maintenance.

A result of the detector and physical design features discussed above is that the post-accident channels have proved to be more reliable than the original channels. Since 1986, almost every PWR that has installed post-accident flux channels has used these channels to replace the original equipment. This results in fewer channels to be maintained, more reliable equipment, and constant operator involvement with the new channels. Other benefits include reduced maintenance costs, elimination of noise on Source Range signals (especially during refueling outages, where noise in the Source Range can halt fuel movement, often a critical-path activity), and readily available replacement parts.

Although there may be concern in general about using post-accident monitoring instrumentation as the normal instrumentation, for neutron flux monitoring the post-accident instrumentation can meet or exceed the original performance requirements and historical reliability. Moreover, there are advantages to using the channels for both purposes: Reference 1 states in part

> Normal power plant instrumentation remaining functional for all accident conditions can provide indication, records, and (with certain types of instruments) time-history responses for many variables important to following the course of the accident. Therefore, it is prudent to select the required accident-monitoring instrumentation from the normal power plant instrumentation to enable operators to use, during accident situations, instruments with which they are most familiar. Since some accidents could impose severe operating requirements on instrumentation components, it may be necessary to upgrade those normal power plant instrumentation components to withstand the more severe operating conditions and to measure greater variations of monitored variables that may be associated with an accident. It is essential that instrumentation so upgraded does not degrade the accuracy and sensitivity required for normal operation. In some cases, this will necessitate use of overlapping ranges of instruments to monitor the required range of the variable to be monitored, possible with different performance requirements in each range.

Experience has shown that separate post-accident monitoring instrumentation is sometimes not adjusted as frequently as the normal power plant instrumentation (to maintain the correspondence of neutron flux to indicated reactor power), nor are operators as well aware of the significance of the indications of the supplementary instruments as they are of the operational channels. When the post-accident channels replace and become the operational channels, these issues disappear.

In summary, experience has shown:

- Systems using fission chambers have been designed and qualified by testing to meet the requirements for post-accident monitoring
- The performance of these systems can meet or exceed the performance of the original Intermediate Range channels
- With careful design, the performance of these systems can also meet or exceed the performance of the original Source Range channels
- The ruggedness of the systems, intended for the post-accident environment, also benefits the owners during unusual events during or after maintenance.

V. REFERENCES

[1] U.S. Nuclear Regulatory Commission Regulatory Guide 1.97, Revision 3, May 1983, "Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident."

[2] IEEE Standard 323-1974, "Qualifying Class 1E Equipment for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers (Piscataway, New Jersey)

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[4] Miller, James F., and Shugars, H. Gordon, "Applying Ex-Core Fission Chamber Technology to Reactor Protection Systems in European Pressurized Water Reactors: A Comparative Analysis," Presented at the 1992 IEEE Nuclear Science Symposium, Sessions on Nuclear Power Systems, October 27-30, 1992, Published in the Conference Record.

[5] Gwinn, David A., and Trenholme, William M., "A Log N and Period Amplifier Utilizing Statistical Fluctuation Signals from a Neutron Detector," Vol. NS-10, IEEE Transactions on Nuclear Science, April, 1963.

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[9] Knoll, Glenn F., Radiation Detection and Measurement, Second Edition, John Wiley & Sons, 1989 (New York).