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# IN-CORE FLUX/POWER DISTRIBUTION DETECTORS: A COMPARISON OF TYPES

L. H. Thacker

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Instrumentation and Controls Division

# IN-CORE FLUX/POWER DISTRIBUTION DETECTORS: A COMPARISON OF TYPES

L. H. Thacker

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# IN-CORE FLUX/POWER DISTRIBUTION DETECTORS: A COMPARISON OF TYPES

L. H. Thacker

Abstract

Twelve important characteristics of five types of in-core neutron flux and/or power density distribution detectors are examined in some detail and compared in a summary table.

## 1. INTRODUCTION

This informal study compares the various types of in-core flux/power distribution detectors to accentuate the advantages and disadvantages of both self-powered and externally powered detectors. The detector types considered are fission counter/chambers, self-powered neutron and gamma detectors, and gamma thermometers. Twelve important characteristics of these detectors will be considered:

- the parameter actually measured
- sensitivity
- dynamic range
- response time
- operating temperature limit
- size
- multi-position configurations
- cable effects and requirements
- failure modes and operating experience
- burnup and lifetime
- disposal at end of service
- cost

These 12 characteristics are summarized in Table 1 at the end of this report.

All data in this report arise from a literature search on the subject, but specific references will not be cited aside from noting that much of the information was taken from the proceedings of two International Specialists' Meetings on In-Core Instrumentation and Reactor Assessment held in Fredrikstad, Norway in 1983 and in Cadarache, France in 1988. One direct quotation from the general summary of the Fredrikstad meeting seems appropriate here: "This session was notable for its discussions of the relative merits of various detection techniques, but unfortunately no very firm conclusions were reached."

Each detector type will be considered in some depth, followed by a tabular summary of the evaluations at the end of the report. However, some general considerations apply to all of the subject detectors. All are installed to help provide safe and/or efficient reactor operation, and the instrumentation system is likely to include a mixture of several detector types with complementary functions. In all cases, selection of an appropriate core instrumentation system ultimately depends on the properties and limitations of the specific reactor system, including maximum permissible total power, maximum permissible channel power, allowable limits on radial and axial power density distributions, and distribution and accounting for isotope production. While safe operation is the primary concern, it is very important that the instrumentation be sufficiently accurate and reliable to allow operation close to safety limits. Even a very small percentage of unnecessary power reduction due to instrument limitations produces a very large economic burden on the operator in terms of electric power generation and/or isotope production. In most cases the quantity of ultimate interest—the power density distribution and/or distribution and rate of isotope production—cannot be measured directly but rather must be inferred from measurements of a related parameter such as neutron or gamma flux through correlations based on 3-D reactor physics calculations and thermal hydraulic codes. These correlations involve uncertainties that must be taken into account when establishing reactor operating limits. However, the uncertainties can be reduced by improved accuracy of in-core measurements. To obtain this improved accuracy, a very detailed understanding of factors that affect the signal and its dynamic response—fuel enrichment, fuel burnout, neutron energy spectrum, spectral sensitivity of the detector, detector burnout, moderator properties, and void fraction—is required because one is generally trying to change margins by only a few percent.

With appropriate reactor physics analysis, power distributions can be mapped using either gamma or neutron flux detectors. However, because gamma flux gradients in the spaces between fuel elements are smaller than neutron flux gradients, gamma detector measurements are less sensitive to exact sensor position. On the other hand, neutron flux detectors are the most appropriate in cases in which isotope production accountability may require detailed data on the spatial distribution of product and/or burnout of sensitive target materials.

## 2. THE FISSION COUNTER/CHAMBER

### 2.1 GENERAL DESCRIPTION

Since a single well-designed detector can function as either a fission counter or a fission chamber, the two operational types will be evaluated together. Used as a fission counter, the detector is connected to an electronic system that detects and records individual fission events occurring within the counter as an indication of the neutron flux to which it is exposed. Used as a fission chamber, the same detector is connected to an electronic system that detects and records either the time average of the squared amplitude of voltage fluctuations (MSV mode) or the integrated current generated by the *rate* at which fissions occur in the chamber (current mode). Although the fission counter/chamber can be designed in a large variety of geometrical configurations to meet special requirements, the most common arrangement is that of two coaxial cylinders—with at least one of the two opposing surfaces coated with a fissionable material—separated by an annular space containing an appropriate counting gas at a predetermined pressure. A somewhat less common arrangement is that of a stack of parallel-plate electrodes with both sides coated with fissionable material and with alternate plates connected as high voltage and signal electrodes. This arrangement permits large surface areas and large fissionable material inventories with attendant high capacitance and high sensitivity.

To meet specific operational requirements, individual counter/chambers may be implemented in a variety of sizes and in arrays functioning as a single counter/chamber or even as a single counter with location-of-event sensing capability, depending on the type of signal-conditioning electronics employed. Strings of small-diameter fission chambers are often used as local power range monitors (LPRMs) for determining the power density distribution in power reactor cores.

### 2.2 PARAMETER ACTUALLY MEASURED

Aside from a very small and insignificant number of spontaneous fissions from $U^{234}$ and $U^{238}$ (about 24/h/g in the more active $U^{238}$), the properly adjusted fission counter operated in the pulse mode within its dynamic range responds only to neutrons. That is, the other (alpha and gamma) events occurring in the chamber can be discriminated against electronically. In the mean square voltage (MSV) mode the total response is weighted strongly in favor of neutrons, even with high alpha and gamma backgrounds. In the current mode several additional decades of flux measurement are provided in which the output is a mixed response to the neutron and gamma fluxes. The contribution of gamma rays to current mode operation can be essentially eliminated by using a gamma-compensated fission chamber.

### 2.3 SENSITIVITY

The sensitivity of fission counters usually is reported in counts per second per unit flux (cps/nv). The absolute limiting sensitivity is obviously the total fission rate of the amount of fissionable isotope in the counter in the existing neutron flux, divided by the neutron flux, or ~1.49 cps/nv/g of $U^{235}$ in a thermal flux for which the fission cross section of $U^{235}$ is 580 barns. The limiting value is reduced in practice by factors depending on thickness of the film of fissionable material, electrode geometry, counting gas characteristics, background alpha pileup, electrode capacitance, detector self-shielding effects, and characteristics and adjustment of the counting electronics. A good average value for a wide range of commercial and developmental detectors is about 0.5 cps/nv/g. Because of differences in the $U^{235}$ loading and in the efficiencies of detecting fission events in the counter, these detectors provide actual sensitivities ranging from 0.05 to 48.4 cps/nv.

In practice it has been difficult to obtain sensitivities above 1 cps/nv in individual counter tubes, regardless of the amount of fissionable material applied. However, careful optimization of all design parameters and use of 19 g of ultra-pure (99.97%) $U^{235}$ has allowed development of a stacked parallel plate fission counter with a sensitivity of 8.5 cps/nv (0.447 cps/nv/g). A much more exotic curved-parallel plate counter with 5 m of electrode surface area coated with 88 g of 93.15% $U^{235}$ and using a lumped delay line electrode hookup with both pulse height and time delay discrimination has produced a sensitivity of 48.4 cps/nv (0.59 cps/nv/g) in a gamma-free field.

The sensitivity of fission chambers for neutrons is usually reported in amps/nv and the sensitivity for gammas in A/R/h. Typical in-core chambers that might have a volume close to 1 $cm^3$ have neutron sensitivities of the order of $10^{-17}$ A/nv, while miniature or subminiature chambers with volumes as small as 0.06 $cm^3$ have reported sensitivities of the order $10^{-18}$ to $10^{-20}$ A/nv. A good average sensitivity for many typical fission chambers is about $2 \times 10^{-17}$ A/nv/$cm^3$ of chamber volume. Reported gamma sensitivities for the same instruments average about $5 \times 10^{-14}$ A/R/h/$cm^3$ of chamber volume. Typical in-core conditions at full reactor power include neutron flux values up to $10^{14}$ nv and gamma fluxes up to $10^8$ R/h, which would produce about 2 mA of neutron signal current and 5 μA of gamma signal current per cubic centimeter of chamber volume.

## 2.4 DYNAMIC RANGE

A single fission counter/chamber tube can be operated in at least three modes to provide many decades of neutron response. No other detector type can operate over such a wide dynamic range. The low end of the dynamic range of a fission counter/chamber operated in the counter mode is established by adjusting the counting electronics to discriminate against detection of alpha particles and pile-up of background gamma rays. Discriminators typically are adjusted to limit background counts to 1 cps, permitting a signal-to-noise ratio of 1 at a neutron count rate of 1 cps. The upper limit of the dynamic range in the counting mode is $\sim 10^5$ to $10^6$ cps. As the event rate exceeds the dynamic range of the device as a counter, the operational mode can be switched to MSV mode and cover perhaps 4 additional decades of flux with the total response weighted strongly in favor of neutrons, even with high alpha and gamma backgrounds. When the dynamic range of the MSV mode is exceeded, the sensor can be operated in current mode to provide ~2 additional decades of flux measurement in which the output is a mixed response to the neutron and gamma fluxes. It should be noted that gamma-compensated fission chambers, which have an additional sensing volume responding to gammas only, can be used in the dc current mode to effectively subtract out the contribution of gamma background, leaving for all practical purposes only the neutron-induced current. Saturation of the detector occurs at very high flux levels when the ionization density in the gas volume becomes so great that the ion recombination rate approaches the formation rate.

As an example of wide-range application of the fission counter/chamber, a fixed, in-core monitoring system supplied by Reuter-Stokes (General Electric) covers 11 decades by operating in the counter mode for the source and startup flux ranges, in the MSV mode for the intermediate range, and in the dc current mode for power-range operation. One of these systems has been in operation in Sweden since 1987 and one in Japan since 1989.

A different approach to wide-range flux monitoring is under development at Oak Ridge National Laboratory (ORNL) as the Wide-Range Single-Mode Flux Monitor, which will use a variable-threshold counting system to cover some 11 decades in the counting mode.

## 2.5 RESPONSE TIME

The time response of the fission counter/chamber to changes in neutron flux is limited only by statistical considerations as to how rapidly a change in count rate can be verified, and by detector capacitance and the timing characteristics of the associated circuitry for either counting or integrated current measurement. These fission detectors are intrinsically the fastest sensors of flux or power level changes.

## 2.6 TEMPERATURE LIMITS

The operating temperature limits for fission counters currently in use or commercially available range up to 800°C for the low-sensitivity (0.0004 cps/nv) Toshiba HS-3, whereas the Toshiba FX-3 operates to 600°C with a sensitivity of 0.3 cps/nv. The Toshiba HS-2 fission chamber has been tested to 1000°C by General Atomics; they found "high sensitivities" up to 800°C, and "a fairly reasonable sensitivity ... even at 1000°C."

In a June 1988 report the French describe an in-core fission counter/chamber used to follow core loading, first criticality, and neutron testing of the Super Phenix I fast reactor at full power. Prior to operation on the Super Phenix, the detectors were tested in the pulse mode for 1 year in the Phenix reactor at 550°C, and in the current mode at 560°C in the KNK II reactor. The system was kept in operation for more than 15 months. Pulse mode operation was completely satisfactory from source level to about 20-30 kW (a count rate of about $2 \times 10^5$ cps). Sensitivity (0.05 cps/nv) was such that a count rate of 17 cps was obtained early in the fuel-loading process with only the inherent neutron source of the seven central fuel assemblies (5 cps was the minimum requirement). Current mode operation was used to follow power ascension from 10% to full power; the signal current was proportional to reactor power.

A large amount of research and development has been invested in trying to develop high-temperature, high-sensitivity (>1 cps/nv) fission counters. A development program at ORNL is working on the High-Temperature High-Sensitivity Fission Counter that is designed to produce ~8 $cps/nv_{th}$ in a 550°C, in-vessel environment. Although much progress has been made, no known high-sensitivity fission counter has operated satisfactorily above 450°C.

## 2.7 SIZE

The sizes of detectors in present use or under development range from about 1 mm to over 5 in. OD, and in length from a few centimeters to at least 8 ft.

## 2.8 MULTIPOSITION CONFIGURATIONS

Arrays of fission counter/chambers are sometimes assembled to obtain increased sensitivity or to obtain information on neutron flux distributions. One example is the ORNL high-temperature, high-sensitivity developmental counter, which consists of 19 individual counter tubes in a hexagonal array within a common gas envelope. It has been designed with a goal of about 8 cps/nv at 550°C. Another example is the Reuter Stokes High-Sensitivity Position-Sensitive Fission Counter for subcriticality measurements in spent fuel storage racks. It consists of eight 1-ft counter tubes stacked in an 8-ft-long array in a common gas envelope to obtain neutron flux levels and distribution with 1-ft resolution at ambient temperature. Both of these counter arrays are connected in a lumped delay line configuration with special electronics that allow either accumulation of total counts from all chambers or accumulation from individual chambers with resulting positional information.

Assemblies of multiple individual (usually miniature) chambers are used in light water reactors (LWRs) to implement local power range monitors (LPRMs), usually in a single thimble with accommodation for a traveling in-core probe (TIP) for in situ calibration.

## 2.9 CABLES: EFFECTS AND REQUIREMENTS

Good electrical engineering practice must be maintained in the selection and installation of cables, particularly for operation in the counting mode. Most in-core applications require metal-sheathed, mineral-insulated cables. Both magnesia and alumina are widely used for insulation, but there have been some reports of magnesia breaking down in pressurized water reactor (PWR) service. In high-temperature applications such as liquid metal fast breeder reactors (LMFBRs) and high-temperature gas-cooled reactors (HTGRs), signal shunting due to temperature-induced loss of insulation resistance (about one decade per 100°C rise for $Al_2O_3$) may become a significant problem. For this reason in-vessel cable runs should be minimized, and routing should be selected carefully. In severe cases re-entrant instrument thimbles with cooling might be required. Care must be exercised to ensure impedance matching in order to avoid pulse reflections and compromised results. Cable hot-end seals should be used to isolate the chamber gas from any residual gases in the cable insulation, and cable sheaths integral with the chamber are preferred in many applications. The large signal of the fission chamber at high power avoids the necessity for the cable compensation required by most self-powered detectors.

## 2.10 FAILURE MODES AND EXPERIENCE

One statistical analysis of data from 268 in-core regenerative fission chambers in 10 different boiling water reactors yielded a mean-time-to-failure (not considering physical damage from maintenance procedures) of over 30 effective full-power years.

Another study presents a list of important causes of failures of in-core fission chambers which includes the following:

1. Failures or inadequacies of the hot-end seals between the fission chamber and the mineral-insulated (MI) cable, allowing migration of the chamber gas into the insulation with the attendant change in pressure of the fill gas, or leakage of contaminating gases from the cable into the chamber.

2. Degradation of the insulation resistance (IR) of the fission chamber/MI lead cable/connector system, including the following:

    a. Shorts or open circuit conditions, often caused by physical damage to cables and connectors during maintenance procedures on nearby equipment under the reactor, or from malfunctions in chamber or cable construction.

    b. Reduction in the dc resistance values from typically $10^8\ \Omega$ down to $10^2$ to $10^4\ \Omega$, often caused by external moisture ingress to cable insulation from seal failures, sheath penetrations, or residual moisture from time of cable manufacture.

## 2.11 BURNUP AND LIFETIME

Relatively rapid burnup of the fissionable isotope in fission counters and chambers in high neutron fluxes, with the attendant loss of sensitivity, is unavoidable and has been one great disadvantage of these detectors. This characteristic makes some method of in situ calibration essential for long-term, fixed, in-core applications. However, the advent of the regenerative fission chamber, in which the fissionable isotope is mixed with a fertile isotope, has provided detectors with greatly increased lifetimes. For example, the General Electric regenerative fission chamber used in the wide-range neutron monitor described earlier can be installed fixed in-core and provide a useful life of about 7 full-power years in a 51 kW/liter plant. The specific life extension can be tailored by the selection of the fertile-to-fissionable ratio: The Japanese report that test irradiations to $10^{21}$ nvt have shown that a $U^{234}$:$U^{235}$ mixing ratio of 3:1 extends detector life by a factor of 4, while a ratio of 6:1 extends useful life by a factor of 9. The useful life of fission counters is often considered to be that fluence at which sensitivity is reduced by burnup to 10% of the initial sensitivity; for fission chambers, end-of-life may be defined as that fluence at which neutron response has been reduced to five times the gamma response.

## 2.12 DISPOSAL

The disposal of used-up or failed fission counters and chambers is complicated by both the highly radioactive fission products from operation of the chamber and by the residual fissionable material remaining in the exhausted detector. The extra care and the accounting for the special materials are in addition to the problems associated with disposal of other exhausted neutron-activated sensor assemblies.

## 2.13 COST

The cost of fission counters and chambers has been their main limitation. They are expensive to manufacture compared to other detector types, and even with the advent of regenerative fission chambers they have shorter service lives than most alternatives. One should note that the expense is well justified in meeting the need for rapid response 10-11 decade neutron flux level measurements for safety and control systems, although it is perhaps not justified in fixed arrays of many detectors for high-resolution neutron flux distribution measurements in the power range.

# 3. THE SELF-POWERED NEUTRON/GAMMA DETECTOR

## 3.1 GENERAL DESCRIPTION

Most self-powered detectors (SPD) are structurally very similar to a length of small-diameter, metal-sheathed, mineral-insulated thermocouple or coaxial cable. An axial emitter wire of a carefully selected material is separated from a coaxial collector or sheath by a thin, compacted annulus of mineral insulation. The emitter wire material is selected to emphasize particular interactions with neutrons and gamma rays as described later. The detector is powered by these interactions and performs as a current source, with its output functionally related to the neutron and/or gamma flux so that no external power supply is required. Self-powered neutron and gamma detectors (SPND and SPGD) cannot be separated cleanly because all SPDs have an output signal that is some combination of responses to both neutrons and gamma rays. Proper design and selection of materials allows one or the other parameter to be emphasized. One of the two principal forms of the SPD, the delayed SPND, directly measures the beta decay current resulting from (n, $\beta$) reactions; the other principal form, the prompt SPD, uses the current generated by (n, $\gamma$, secondary electron) reactions for detecting neutrons, or simply ($\gamma$, secondary electron) reactions for detecting gammas. SPDs have the advantages of small size, low cost, an extensive history of successful use in commercial power reactors, and the relatively simple electronics required to measure the output signal. However, extensive analog electronics, software, and computer hardware may be required to compensate dynamically for long sensor time constants and to relate sensor output data to in-core neutron flux and power density distributions. The disadvantages include delayed response times (for delayed SPNDs), limitation to the current mode of operation, mixed response to neutrons and gamma rays, and sensitivity of the output current to changes in the neutron energy spectrum.

The materials of construction for the delayed SPNDs are selected to provide an emitter (the central electrode in the coaxial structure) that has a relatively high cross section for (n, $\beta$) reactions, leading to a beta-emitting isotope with a short half-life. Excessively high cross sections lead to early burnup in high fluxes, while low cross sections lead to low sensitivity. The sheath and insulator are chosen for a minimal absorption cross section among materials having adequate temperature, insulation, and corrosion characteristics. In practice, the two most popular emitter materials for this detector type have been rhodium and vanadium. Note that large numbers of these delayed SPNDs are used in-core as local power range monitors (LPRMs) in commercial power reactors. However, because of the delayed response characteristic they are unlikely candidates for use in reactor safety systems.

The prompt SPDs are based on the emission of fast secondary electrons produced by prompt capture gamma rays from neutron captures in the emitter, or by the absorption of gamma photons directly from the reactor prompt gamma flux. This type is generally less sensitive but has the advantage of fast time response compared to those depending on beta decay half-lives. Because the output signal depends on secondary electron emission from gamma ray interactions with the emitter, emitter materials can be selected to produce mainly neutron or mainly gamma response. Among the fast-response neutron sensors, cobalt and cadmium have been the emitters most extensively used; however, platinum, osmium, cerium, hafnium, erbium, and gadolinium have also been used. A zirconium emitter produces an almost pure gamma response.

Self-powered in-core detectors are used extensively in PWRs and in PHW reactors. The CANDU PHW reactors use SPDs for a variety of functions in the regulating and protection systems; 102 vanadium SPNDs provide input for an on-line flux-mapping system and data for an off-line power-mapping system; 71 prompt platinum detectors provide inputs to regulation and protection systems. As early as 1982 an estimated 5000 SPNDs were in service in PWRs manufactured by Combustion Engineering, Babcock & Wilcox, Kraftwerk Union, and AEE (Finland).

## 3.2 PARAMETER ACTUALLY MEASURED

The parameter actually measured with any self-powered detector is some combination of the responses to neutrons and gamma rays. The relative contributions of the two components depends on the emitter material of the SPD and on the neutron energy spectrum of the flux being measured. The gamma responses of rhodium, vanadium, and cobalt are typically less than a few percent of the neutron response. On the other hand, zirconium emitters have an almost pure gamma-ray response, while platinum, osmium, and cerium have a mixed response. Of these, the most data are available for platinum detectors. Because of the sensitivity to neutron energy spectrum, the relative responses to neutron and gamma fluxes will depend on the type of reactor in which the sensor is installed. For example, a platinum detector in a CANDU $D_2O$-moderated reactor will have a neutron:gamma response of ~50:50, while in a PWR the same detector would have a ratio of ~20:80.

When neutron detectors are used for power density distribution measurements in fuel assemblies, the power calibration constant must be corrected continuously for the changing distribution of fissionable material as fuel burnup proceeds. Gamma detectors detect the prompt fission gamma photons *from* fissions rather than the neutrons which *cause* fissions, and thus are nearly independent of the distribution and density of fuel material. For this and other reasons, many operators prefer to make power density distribution measurements with gamma flux detectors.

## 3.3 SENSITIVITY

Reported sensitivities for vanadium and rhodium delayed SPNDs, per centimeter of length, for typical diameters are as follows:

| Emitter | Sensitivity (A/nv/cm) |
|---|---|
| Vanadium | $5 \times 10^{-23}$ |
| Rhodium | $1 \times 10^{-21}$ |

Actual vanadium detectors in maximum reactor fluxes in the CANDU-600 reactors produce output currents of about 3 μA which decrease with burnup by about 50% over 20 years of service.

Sensitivities reported for prompt SPNDs include those in the following table of theoretically calculated values, which have been cross-checked with earlier results from measurements in different reactors. The sensitivity values are amperes per centimeter of emitter length. Note that the gamma response for cobalt in the specific detector geometries used is of the opposite polarity to the neutron response, and thus diminishes the total signal. The nature of the changes in relative outputs with the reported change in emitter diameter suggests that it may be possible to tune the gamma output to a minimum relative to the neutron response by adjusting emitter size.

| Detector material | Emitter Diam. (mm) | Thermal flux (A/nv/cm) | Fast flux (A/nv/cm) | Gamma flux (A/cm R/h) |
|---|---|---|---|---|
| Co | 1.0 | $6.0 \times 10^{-23}$ | $5.9 \times 10^{-24}$ | $(-)2.0 \times 10^{-18}$ |
| Co | 1.45 | $1.15 \times 10^{-22}$ | $1.2 \times 10^{-23}$ | $(-)1.3 \times 10^{-18}$ |
| Er | 1.45 | $5.7 \times 10^{-22}$ | $9.9 \times 10^{-23}$ | $8.3 \times 10^{-18}$ |
| Gd | 1.0 | $5.65 \times 10^{-22}$ | $3.9 \times 10^{-23}$ | $8.0 \times 10^{-18}$ |
| Hf | 1.0 | $9.4 \times 10^{-23}$ | $7.3 \times 10^{-23}$ | $1.0 \times 10^{-17}$ |
| Hf | 1.45 | $2.2 \times 10^{-22}$ | $1.5 \times 10^{-22}$ | $8.3 \times 10^{-18}$ |

Since detector lengths range up to about 100 cm, typical neutron sensitivities of the order $1 \times 10^{-20}$ A/nv may be obtained, giving a signal the order of several microamperes for a thermal neutron flux of $1 \times 10^{14}$ nv. For an associated gamma flux of $1 \times 10^{8}$ R/h, the current will be of the order of a fraction of a microampere.

## 3.4 DYNAMIC RANGE

The residual in-core gamma field from the decay of fission products limits SPGDs to a range of 1 to perhaps 2 decades and SPNDs to a range of only 2 to 4 decades.

## 3.5 RESPONSE TIME

The inherent response time of the delayed SPNDs is established by the half-lives of the neutron-induced beta activities, aside from a small prompt component (between 5 and 10%) from (n, $\gamma$, secondary electron) reactions. Vanadium has a single beta decay with a half-life of 3.76 min, while rhodium has a more complex decay scheme with half-lives of 42 s and 4.4 min. The response time of these detectors can be decreased to a value adequate for load following by using analog or digital dynamic compensation; however, it is doubtful that they can be shortened enough for use in reactor safety systems.

The prompt component of prompt SPDs (e.g., about 0.85 for platinum) has a time constant of a fraction of a second (as compared to the tens of seconds to minutes of delayed SPNDs), making them fast enough for use in control and safety systems of some reactors.

## 3.6 TEMPERATURE LIMITS

The temperature limits are established by properties such as the temperature coefficients of resistance of insulators and the thermoelectric characteristics of materials, and by mechanical details such as electrode spacing and length in the hot zone. Tests performed in France by the CEA showed that thermoelectric noise voltages, arising in the detector and in the thermocouple-like lead cable, seriously degrade the signal-to-noise ratio for neutron flux measurements (and presumably also for gamma flux measurements) at high temperatures. A program for development of self-powered detectors that function adequately in high temperature applications would seem to have potential for a significant return on investment (for example, in the NPR-MHTGR project).

To avoid degraded time response performance in prompt SPDs, temperature effects should not reduce insulation resistance below about $10^8$ Ω.

## 3.7 SIZE

Small size is one of the major advantages of the SPDs. Typical outside diameters are 1 to 3 mm, with active lengths from a few to ~100 cm or longer. The sensors are manufactured with an integral metal-sheathed cable, which may be many meters long.

## 3.8 MULTIPOSITION CONFIGURATIONS

Most in-core SPDs are used in strings or in linear arrays of detectors in a single, usually small-diameter, rod or tube.

## 3.9 CABLES: EFFECTS AND REQUIREMENTS

For all types of SPDs, neutron and gamma interactions in the mineral-insulated, metal-sheathed cables can cause significant interference with the measuring process. Lead cable signals presently limit the inherent accuracy of SPND flux-mapping detectors to about 1%. Cable effects can be alleviated by appropriate choice of cable construction materials and by use of an extra conductor in the cable, parallel to the signal lead but not connected to the emitter, to generate a compensating signal that can be subtracted from the emitter/lead signal. The difference signal is approximately free of cable response. Thermoelectric noise voltages arising in the detector and in the thermocouple-like lead cable may seriously degrade the signal-to-noise ratio of these detectors at high temperatures. Degradation of performance ranging from slowed time response to complete failure may result from degradation of insulation resistance in sensors and mineral-insulated cables as discussed in the following section. Major problems also may be encountered in high-temperature applications due to the temperature-induced loss of insulation resistance caused by the high negative temperature coefficients of resistivity of mineral insulators. These problems usually are not evident below about 500°C; however, the temperature limit depends on the cable diameter and the thickness of the insulator annulus as well as the specific insulator material.

## 3.10 FAILURE MODES AND EXPERIENCE

As of mid-1988, KWU had some 1200 detector years of cumulative operating experience with SPNDs (cobalt). Aside from one bad manufacturing batch, nearly all of which suffered an unspecified systematic failure, they have observed a failure rate of approximately 3%/year, most of which developed in less than 1 hour. Most failures were attributable to moisture-induced loss of cable insulation, a very small minority were caused by lead breaks, and only a few developed slowly with loss of sensitivity or buildup of excessive background signals.

Recent Canadian experience shows that prompt SPNDs with a low insulation resistance are also slow to respond to sudden changes in flux, even if the steady-state response still appears normal. The effect is attributed to contamination of the insulation in the detector and/or lead cable, possibly through failure of the detector or cable sheath with attendant water leakage and chemical corrosion. The effective capacitance of the cable is increased by an amount so large that electrolytic effects from a corrosion reaction are suspected. The adverse effect on the response time is most severe when amplifiers of high input impedance are used.

## 3.11 BURNUP AND LIFETIME

Designers must choose appropriate emitter materials for each specific application because there is a significant trade-off between high sensitivity and long service life. Some German experiments in PWRs with gadolinium and hafnium detectors have shown burnup of gadolinium detectors to 50% of initial sensitivity after only 5 months of service, and the same reduction for hafnium in 7 months of service; both are very high cross section materials. On the other hand, the vanadium detectors exposed to maximum fluxes in the CANDU-600 reactors produce output currents of about 3 $\mu$A, which decrease with burnup by about 50% over 20 years of service. Operational corrections for sensor burnup are done both experimentally by using traveling in-core probes (TIPs) and analytically based on the lifetime integrated current output of the sensor.

The German experiments also found that some detectors experienced loss of insulation resistance by as much as 50% after 2 months of service. The rate of loss appears to decrease with time, but "the observed tendency is a continuous decrease into a range where the measuring fault caused by the leaking current cannot be neglected anymore." (It is highly probable that these resistance losses were due to moisture in the insulation.)

## 3.12 DISPOSAL

The disposal of used SPDs is the same as disposal of any highly irradiated structural material or medical isotope. It is not complicated by the presence of special nuclear materials.

## 3.13 COST

In terms of direct detector cost, SPDs are the least expensive of the in-core flux/power distribution detectors. A final comparison of the cost of a specific total system will depend on the analog and digital hardware and software necessary to obtain the desired dynamic performance and to derive the required output.

# 4. THE GAMMA THERMOMETER

## 4.1 GENERAL DESCRIPTION

In its basic form the gamma thermometer consists of a thermally isolated mass that is heated by absorption of gamma radiation and fast neutrons, connected through a thermal resistance to a heat sink, and instrumented to measure the temperature difference between the mass and the heat sink (or a point of the thermal resistance near the heat sink). Heat generated in the mass is permitted to escape to the sink only (to a first approximation) through a controlled heat path of closely held dimensions. The temperature drop along that heat path is directly proportional to heat rate (watts per gram) deposited in the mass and therefore proportional to power, not flux, in adjoining fuel rods. Typical heat rates in masses fabricated of stainless steel range at full reactor power from 0.5 to 7.5 W/g of absorbing mass. The sensitivity of the gamma thermometer to local fuel power changes is found to be proportional to its thermal response time constant.

In practical designs thermal isolation of the sensing mass is most often obtained by supporting it in a blanket of argon which, while not as low as vacuum, has a very low thermal conductivity combined with greater ease of application in this service than vacuum. Typically, power distribution monitoring gamma thermometers [specifically Radcal Gamma Thermometer Assemblies (RGTAs)] are fabricated in "strings" of six to nine detectors in small diameter stainless steel rods, which also contain an axial electrical heater for both in-core and ex-core calibrations. Some gamma thermometers take the difference between two separate thermocouple readings while others use differential thermocouples, sometimes with a separate absolute thermocouple.

Single-unit gamma thermometers have been in use as local power monitors at the Savannah River Plant for over 32 years and at Halden (Norway) for 27 years. Use of multisensor RGTAs in LWRs began in France in 1979. In August 1982 the NRC approved RGTAs for local fuel power monitoring in PWRs; also a number of BWRs (1983) are equipped with gamma TIPs. In 1988 the Swedish State Power Board began replacement of existing TIP instrumentation in Westinghouse PWRs with eight fixed in-core RGTAs to measure local power and provide input to computer programs performing on-line evaluation of core power distributions and thermal margins. International theoretical studies have verified the firm relationship between local fuel power and gamma flux for LWRs, and it is estimated that raw, uncorrected signals from an RGT-based in-core system would predict the local fuel power within ±10% regardless of fuel burnup, core configuration, and control rod positions. French experience shows that corrected signals can provide 1 to 1.5% accuracy.

Advantages of the gamma thermometer include an output proportional to local fuel power density, a large signal with an extremely high signal-to-noise ratio, sensitivity independent of fluence, simplicity, ruggedness, independent electrical heating for calibration and standardization in place, low cost, and long service life. Disadvantages include power density averaging over a large volume because of the longer range of gamma radiation, sensitivity to movements of nearby control rods, and possible errors from thermocouple drift.

## 4.2 PARAMETER ACTUALLY MEASURED

The parameter actually measured is a differential temperature that is proportional to the rate of absorption of both gamma radiation and neutrons in the thermally isolated mass of the detector. The relative contributions of neutrons and gamma rays depends on the heater material and the specific reactor type. Typically, gamma thermometers produce about 10% of the total signal from neutron absorption, 60% from fission gammas, and 30% from fission-product gammas. Since the differential temperature measured is directly proportional to energy absorption *rate* in the mass, it is therefore proportional to the power in the adjoining fuel rods. Experimental results (1983) from a 4-year test at Halden clearly show the local power proportionality of the gamma thermometer response vs the burnup-related thermal neutron flux response of vanadium SPNDs. Later Swedish work (1988) shows a power proportionality constant that is a linear function of burnup but that is nearly independent of other core parameters.

There has been some concern that self-powered detector effects in the mineral-insulated thermocouples may contribute a small, unwanted component to the signal.

## 4.3 SENSITIVITY

The sensitivity of the gamma thermometer to local fuel power changes is found to be proportional to its thermal response time constant. Design trade-offs are therefore possible to get very high sensitivities for steady-state power distribution measurements, or to get improved time response at lower sensitivity. Precision manufacturing processes allow all sensors in a multi-position RGTA rod to have sensitivities within ±1.5% of the assembly average.

Sensitivity calibration can be accomplished ex-reactor by either "Joule calibration," in which the whole RGTA is electrically heated by passing large currents through the body of the RGTA, or through use of the internal heater cable. In-core calibrations are accomplished with the heater cable only, and they may be done automatically under computer control. Swedish studies have shown that the two methods give results identical within 0.3%, and that both calibration methods facilitate determination of sensor heating with an accuracy of ~1%.

The sensitivity is not the same at the high temperatures of power reactor operation as at lower temperatures because the thermal conductivity of the stainless steel is reduced (30% between 20°C and 300°C) and the thermal conductivity of the argon increases. Thermal radiation loss across the gas gap, which depends on differential temperature within the sensor, can degrade performance even at low *ambient* temperatures, whereas the stainless steel and argon conductivity changes become significant only at high *service* temperatures. The change in sensitivity with increasing temperature is well predicted by 2D thermal codes.

(See the discussion of operational experience with sensitivity variations in RGTAs in BWRs and PWRs in Sect. 10.)

## 4.4 DYNAMIC RANGE

The dynamic range of the RGT is at most 2 decades.

## 4.5 RESPONSE TIME

The thermal response time constant of an individual Halden type gamma thermometer is about 110 s, which is quite long but still shorter than that of the vanadium SPND. Typical hot junction time constants measured for RGTs are in the range 15 to 25 s, cold junction time constants typically range from 2 to 5 s, and in-core (BWR) time constants range from 2 to 50 s.

The most significant response time problem is a characteristic of the fission process, which is unavoidable for any gamma-sensing LPRM (i.e., the long time constant of the delayed fraction of fission-product gamma radiation). Following a step change in power in a PWR, about 72% of the gamma flux response is prompt, 18% of the response has a time constant of 1 min (fast dynamics), and 10% of the response has a time constant of 90 min (slow dynamics); thus it takes hours to approach within 1% of the final value. A very much faster effective response can be obtained by applying dynamic feedback approaches in processing the RGT signal.

Successful German attempts to improve gamma thermometer time response in BWRs to step changes in nuclear power level up to a speed acceptable in their protection systems (99% response in 0.25 s) consist of the following procedure. First, on-line time constants necessary for speed-up are identified and automatically verified every 2 h (time constant drifts of 1 to 2 s are common); then the delayed gammas and thermal inertia of the RGTs are compensated. Finally, a digital filter suppresses noise. The RGTs used have a separate absolute thermocouple for transient response in addition to the steady-state differential thermocouples. Measurements have shown that this analytically speeded up RGT response signal will meet BWR protection system requirements; also, the noise figure of these RGT signals is not greater than that of neutron detector signals.

At high temperatures the thermal time constant is reduced by about the same amount as the sensitivity (~30%) by the same changes in the physical characteristics of the detector.

## 4.6 TEMPERATURE LIMITS

Gamma thermometers of conventional design are degraded in high-temperature operation by the fact that the argon gas (and gases in general) used to create a highly resistive heat flow path has a positive temperature coefficient of thermal conductivity. This means that the thermal isolation of the hot thermocouple is decreased at high temperature and the output signal for a given gamma field is decreased. Given some design changes such as use of vacuum instead of argon for thermal insulation and use of the high-temperature heat conduction coefficients of materials at the application temperature, it is not evident why gamma thermometers cannot be developed for use up to the thermal limits of the structural material and the thermocouples.

In the design of gamma thermometers, *differential* temperatures usually are selected in the range from 15 to 250°C for full-power operation; above ~500°C, the instruments remain reproducible but tend to become nonlinear with power because of thermal radiation losses across the gas gap to the coolant. Note that thermal radiation losses depend on differential temperature in the sensor (a design parameter), not on the application temperature. However, the temperature-induced loss of insulator resistance in small-diameter thermocouples and cables above ~500°C will also degrade performance at these temperatures.

(See discussion of the temperature dependence of sensitivity in Sect. 4.3. See also the discussion on temperature dependence of thermal time constant in Sect. 4.5.)

## 4.7 SIZE

The sizes of Scandpower RGTA strings of 6-10 detectors range from 7.5 to 10 mm diam. with an active length of 4 m and a total length of 15 to 35 m. Individual sensors may be about 30 mm long with an annular argon gap 0.5 mm thick between the core tube and the sheath. In this configuration ~20% of the heat generated in the absorbing mass is lost by conduction across the thin argon annulus.

## 4.8 MULTIPOSITION CONFIGURATIONS

Most applications of gamma thermometers are in multiposition RGTA configurations as described above. These assemblies consist of a small-diameter core tube with accurately machined reductions in outside diameter spaced along its length to create annular gaps between the core tube and the outer sheath, which is drawn tightly over it. The gaps are filled with argon to establish thermal isolation of the active sections of the core tube. The bore of the core tube contains a differential thermocouple for each RGT spaced along its length and an electrical heater for calibration of the assembly.

## 4.9 CABLES: EFFECTS AND REQUIREMENTS

The cables are stainless steel sheathed, mineral-insulated (usually alumina) thermocouples. Because of the low impedance voltage source of the thermocouple junctions, the signal is relatively insensitive to variation in cable resistance. It has been suggested that self-powered detector effects in these cables may contribute minor signal components, and electrical shunting in small-diameter mineral-insulated thermocouples at high temperatures is a well-known effect that should be evaluated for each application.

## 4.10 FAILURE MODES AND EXPERIENCE

Experience with 227 gamma thermometers in the Halden Boiling Heavy Water Reactor showed an "average defect rate of ~9%." The usual cause of failures was thermocouple cable defects. Gamma thermometer performance (1983) as a local power indicator was shown to be independent of fuel burnup after a limited start-up period, whereas neutron detectors tended to indicate too high a local power with increasing burnup. However, apparently conflicting results (1988) show a linear dependence on burnup of the power density proportionality constant.

A series of Swedish tests in a 1000-MW(e) BWR led to the following conclusions:

a. All RGTs show a 3 to 5% initial decrease in sensitivity.

b. Sensors of normal (30-mm) chamber length stabilize during the first cycle and stay constant.

c. Long chamber length (e.g., 63-mm) sensors exhibit a slow downward drift in sensitivity even after four cycles.

d. Measured time constants of normal length sensors are constant.

A concurrent series of tests in an 800-MW(e) PWR showed the following:

a. Sensitivities relative to high-temperature loop calibration results are lowered 10 to 15% before stabilizing.

b. Some data suggest that the downward drifts observed may be the result of the temperature history of the sensor rather than reactor exposure. (This suggests that preconditioning at high temperature might eliminate the drift in service.)

c. After shutdowns, sensitivities at restart were higher than before the shutdown.

d. Time constant measurements confirmed the measured decreases in sensitivity.

Despite considerable study, no real explanation has been found for the observed difference between sensitivity characteristics in a BWR and in a PWR; however, the observed sensitivity variation presents no problem because periodically the sensors are recalibrated in-core using the heater cable.

## 4.11 BURNUP AND LIFETIME

Gamma thermometers installed in heavy water reactors have exhibited constant calibration over fast fluence corresponding to several years of PWR operation. Preliminary results of a series of irradiations at the Oak Ridge National Laboratory showed no change in the long (dominant) time constant of RGTs after exposure equivalent to 3 years in a PWR. The stable time constant implies a constant sensitivity. One expert at Halden estimates service lives of up to 10 years.

## 4.12 DISPOSAL

Gamma thermometers contain no special nuclear materials; therefore, disposal problems are limited to only those associated with any irradiated structural material.

## 4.13 COST

The cost of gamma thermometers falls between that of self-powered detectors (low) and fission counter/chambers (high).

Table 1
Brief Comparison of Detector Characteristics

| | Fission counter | Fission chamber | Self-powered neutron detector | Self-powered gamma detector | Gamma thermometer |
|---|---|---|---|---|---|
| 1. Parameter actually measured | Detects fission events, internal alphas and gamma pileup pulses. Discriminator limits output to count of neutron induced and spontaneous fission events. | In the MSV mode, detects the time average of the squared amplitude of voltage fluctuations. In the current mode, detects integrated current from fission event rate. | Detects the current generated by neutron-activated beta decay and by high-speed electrons from Compton and photoelectric gamma interactions. Rhodium, vanadium, cobalt, and cadmium emitters emphasize neutron response. | Detects the current generated by neutron-activated beta decay and by high-speed electrons from Compton and photoelectric gamma interactions. Zirconium, platinum, osmium, and cerium emitters emphasize gamma response. | Detects a differential temperature arising from flow of gamma- and neutron-generated heat through a precision resistance. Typical signal ~60% from fission gamma, ~30% from fission product gamma, and ~10% from neutrons. |
| 2. Sensitivity | Limiting value is 1.49 cps/nv/g U-235 loading (in a thermal flux). Typical values are 0.3–0.6 cps/nv/g and high values are ~0.8 cps/nv/g. | Typical neutron current mode sensitivities are on the order of $10^{-17}$ A/nv/cm$^3$ of chamber volume. Gamma sensitivity tends to be ~2 to $4 \times 10^{-14}$ A/R/h/cm$^3$. | Typical vanadium sensitivity is $5 \times 10^{-23}$ A/nv-cm, rhodium is $1 \times 10^{-21}$ A/nv-cm, and cobalt is $1 \times 10^{-22}$ A/nv-cm. | Typical sensitivities for the above emitters are not at hand but should be comparable to that for cobalt, $-1 \times 10^{-18}$ A/cm-R/h. | Sensitivity in °C/W/g is proportional to the thermal-response-time constant and is temperature dependent because of material temperature coefficients. |
| 3. Dynamic range | Typically 5–6 decades. | The MSV mode adds ~4 decades above the counting range. The current mode adds ~2 more for a total of about 11 decades for all three modes. | Residual in-core gamma field limits SPNDs to a range of only 2–4 decades in the power range. | Residual in-core gamma field limits SPGDs to a range of 1 to perhaps 2 decades. | The dynamic range of the gamma thermometer is only 2 decades. |
| 4. Response time | Limited only by statistical considerations as to how rapidly a change in count rate can be verified. | Limited by chamber capacitance and timing characteristics of associated circuitry. | Vanadium has a single half-life of 3.76 m, rhodium has two half-lives of 42 s and 4.4 m, and prompt SPDs such as platinum have prompt time constants of less than 1 s. | The SPGDs have prompt time constants of a fraction of a second. | In-core time constants (BWR) range from 2 to 50 s. A German system has been developed to speed effective RGT time response to 99% in 0.25 s. |
| 5. Temperature limits | Highest known temperature ratings are 800°C for the Toshiba HS-3 low sensitivity counter (0.0004 cps/nv), and 600°C for the 0.3 cps/nv Toshiba FX-3. | The Toshiba HS-2 fission chamber is rated at 800°C. | Established by insulation temperature coefficient of resistance and thermocouple effects in detector and cable in hot zones. | Established by insulation temperature coefficient of resistance and thermocouple effects in detector and cable in hot zones. | High-temperature use is limited by the thermal coefficient of resistance of the materials used. High-temperature versions should be possible. |
| 6. Size | The sizes of detectors in present use or under development range from about 1 mm OD to over 5 in., and in length from a few centimeters to at least 8 ft. | See entry for fission counter. | Typically 1–3 mm OD with active length from a few to over 100 cm. | Typically 1–3 mm OD with active length from a few to over 100 cm. | RGTA strings of 6 to 10 detectors are 7.5 to 10 mm diam with an active length of 4 m and a total length of 15 to 35 m. Individual sensors are typically 30 to 60 mm long. |
| 7. Multiposition configurations | Multiple detector bundles may be assembled to increase sensitivity. "Strings" or arrays of single detectors measure neutron flux distributions at low power. | Multiposition arrays may be used to obtain flux distributions at high power. | Most in-core SPDs are used in "strings," or linear arrays of detectors in a single, usually small-diameter, rod or tube. | Most in-core SPDs are used in "strings," or linear arrays of detectors in a single, usually small diameter rod or tube. | Most applications are in multiposition configurations as described above. The bore of the core tube contains the thermocouples and a heater for calibration. |
| 8. Cables: effects and requirements | Good electrical engineering practice for fast pulse response and environment. See text. | Good electrical engineering practice for environment. See text. | Neutron and gamma interactions and thermocouple effects at high temperature in metal-sheathed mineral-insulated cables cause spurious signals. Reduced insulation resistance from any cause may degrade time response or cause complete failure. | | Cables are metal-sheathed, mineral-insulated thermocouples. Shunting at high temperature may be a problem, and self-powered detector effects in cables are possible. |

**Table 1** (continued)

| | Fission counter | Fission chamber | Self-powered neutron detector | Self-powered gamma detector | Gamma thermometer |
|---|---|---|---|---|---|
| 9. Failure modes and experience | Cable hot end seal failures. Degradation of insulation resistance. Physical damage from maintenance in proximity. | See entry for fission counter. | One set of 1200 detector-years data showed 3%/year failure rate, most developing in less than 1 h. Most due to moisture-induced loss of cable insulation; a few caused by lead breaks. Only a few developed slowly with loss of sensitivity or buildup of excessive background. | | Halden experience with 227 GTs shows average defect rate of 9%/year. Usual cause of failures was thermocouple cable defects. |
| 10. Burnup and lifetime | Rapid burnout of nonregenerative detectors in high neutron flux vs high alpha background of regenerative detectors. In situ calibration probably necessary. | Useful life extended by factors up to at least 9 by use of regenerative techniques. Commercial chambers up to 7 full-power years in 51-kW/liter core. | Essential tradeoff between high sensitivity and low service life. Vanadium detectors in CANDU-600 lose 50% in 20 years. Gadolinium and hafnium in PWR lost 50% in 5–7 months. PWR experiments showed some sensors lost 50% of insulation resistance in 2 months service. | | Halden estimates service lifetimes up to 10 years. GTs in HWRs have shown constant calibrations over the equivalent of several years of PWR operation. |
| 11. Disposal | Disposal is particularly complicated by the accountability as well as the radioactivity of the residual fissionable material in the exhausted detector. | See entry for fission counter. | Disposal is not complicated by the presence of special nuclear materials. | Disposal is not complicated by the presence of special nuclear materials. | Disposal is not complicated by the presence of special nuclear materials. |
| 12. Cost | The high initial cost, relatively short service life, and high disposal cost have been a significant limitation on the use of fission counter/chambers. | See entry for fission counter. | Sensor cost is the lowest of any of the in-core flux/power distribution detectors. | | The cost of gamma thermometers is intermediate between that of self-powered detectors and fission counter/chambers. |

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