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In vessel detection of delayed neutron emitters from clad failure in sodium cooled nuclear reactors: Information treatment

P. Filliatre [a,*], C. Jammes [a], J.-P. Jeannot [b], F. Jadot [c]

[a] CEA, DEN, DER, Instrumentation Sensors and Dosimetry Laboratory, Cadarache, F-13108 St-Paul-lez-Durance, France
[b] CEA, DEN, DTN, Instrumentation and Technological Testing Laboratory, Cadarache, F-13108 Saint-Paul-lez-Durance, France
[c] CEA, DEN, DER, ASTRID project group, Cadarache, F-13108 Saint-Paul-lez-Durance, France

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ABSTRACT

With appropriate techniques, the information brought by the in-vessel instrumentation of nuclear reactors may betray rather subtle departures from normal state indicating an abnormal situation at early stages, to improve both safety and availability. This paper takes the case of the detection of delayed neutrons released by a clad failure in sodium-cooled fast neutron reactors as an illustrative application of hypothesis testing. Two methods are discussed, seeking either for a counting excess of for a departure from stationarity, yielding similar results. The question of false alarms is addressed by a Bayesian approach that takes into account the prior probability of failure. The use of several identical sensors is shown to be effective.

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1. Introduction

The conception of the in-vessel instrumentation is to be considered right from the beginning of the reactor design. In addition to normal operation control, one of its goal is to detect any abnormal situation at early stages, to improve both safety and availability. Even if those incidents induce a variation of observables of interest (e.g. neutron flux, temperature), the impact on the sensor response is often rather subtle when compared to the noise, so devising an appropriate information treatment strategy to assess whether an abnormal situation occurred or not is an issue. This is the goal of this paper, which belongs to our research program dedicated to nuclear instrumentation (Jammes et al., 2005; Andriamonje, 2006; Jammes et al., 2006; Geslot et al., 2007; Filliatre et al., 2008, 2009, 2010a; Geslot, 2011; Filliatre et al., 2011a, 2012; Jammes et al., 2012b).

The detection of delayed neutrons released by a clad failure is taken as a working example. Although the equations are restricted to the case of sensors relying on a counting process (i.e. Poissonian), the methods discussed here can be applied to any situation inducing a variation of the response of the sensor, or, in other terms, into a departure from the expected stationarity of its signal. Clad failures are routinely searched for in the sodium-cooled fast neutron reactors (SFR) because they may complicate the maintenance through the contamination of large components, and even raise a safety issue if a loss of fissile material reduces the effectiveness of the cooling: indeed, as their predecessors, future SFR will comply with the "clean sodium concept", i.e. the amount of contaminant released in the primary vessel by a clad failure in an assembly must be kept as low as reasonably achievable. To illustrate our method, we use preliminary studies carried out on the ASTRID project (Advanced Sodium Technological Reactor for Industrial Demonstration) (Le Coz et al., 2011), led since 2006 by CEA in partnership with AREVA and EDF, as a working example.

The paper is organized as follows: the signal delivered by the sensors in case of a clad failure is derived in Section 2, summing up the results obtained in a previous publication (Filliatre et al., 2014); the main principles of hypothesis testing are recalled in Section 3; two different approaches, relying on count excess and departure of stationarity, are discussed in Sections 4 and 5; they are illustrated by numerical examples taken from the ASTRID project in Section 6; the problem of false alarms is discussed in Section 7; then we conclude.

2. Signal from a clad failure

The signal that is delivered in case of a clad failure has been modeled in (Filliatre et al., 2014). Only the relevant features for this paper purposes are reviewed here.

* Corresponding author. Tel.: +33 4 4225 7808; fax: +33 4 4225 7876.
E-mail address: philippe.filliatre@cea.fr (P. Filliatre).

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Without loss of generality, the detector is assumed to be a fission chamber, specially designed to endure the harsh environment regarding temperature and radiation level (Filliatre et al., 2010b, 2011b; Jammes, 2010; Jammes et al., 2012b). It may be operated in pulse, fluctuation or current mode, provided that the fission rate within its fissile coating can be easily retrieved from the data, and that the main noise is the shot noise coming from counting statistics. In the following of this paper, it assumed that those conditions are fulfilled and that the fission ratewithin the fissile coating of the chamber is equal to the count rate, hence neglecting self-absorption (Jammes et al., 2012b). In absence of clad failure, it is assumed that its signal is due to the neutrons coming from the reactor core, yielding a count rate λ_m that can be estimated either by calculation or measurement. In order to reduce λ_m, the detector is located at the rear side (as seen from the core) of an internal component, e.g. an internal heat exchangers (IHX), as demonstrated in SUPERPHENIX by Trapp et al. (1988).

If an open clad failure occurs in an assembly, fission products are released in the primary sodium and transported within the vessel. In the following, the failure is assumed to occur at time $t = 0$, and to remain stationary $t > 0$: as a failure cannot spontaneously shrink, this is a conservative hypothesis. Non gaseous fission products can be considered as tracers: if they were stable, their concentration in a given point $\vec{r}$ and time t with respect to their concentration at the clad failure $\vec{r}_0$ would be given by the hydraulic transfer function (HTF) $F(t,\vec{r},\vec{r}_0)$, which can be regarded as the step response of the system to a failure. Some fission products, called the delayed neutron precursors (DNP), yield a delayed neutron that may be detected provided that the β-neutron decay process occured sufficiently close to the fission chamber. The fission rate in the chamber due to those delayed neutrons is thus given by:

$$\tau(t,\vec{r}_d,\vec{r}_0) = \rho_0\bar{\nu}\sum_i \int_V \mathcal{F}_i(t,\vec{r},\vec{r}_0)\epsilon_i(\vec{r},\vec{r}_d)\,d^3V \tag{1}$$

where $\bar{\nu}$ is the average number of neutrons (delayed or not) per fission within the fuel, ρ_0 is the concentration of fission products at $\vec{r}_0$, $\epsilon_i(\vec{r},\vec{r}_d)$ is the dimensionless efficiency of the sensor with respect to a neutron released by the DNP i at $\vec{r}$. Since each DNP has its own decay dynamics represented by λ_i, its decay probability to β-n decay per second, a summation over the different DNP is introduced in Eq. (1). DNP decay dynamics also affects the transportation terms $\mathcal{F}_i$ that are given by:

$$\begin{aligned}\mathcal{F}(t,\vec{r},\vec{r}_0) &= \sum_i \mathcal{F}_i(t,\vec{r},\vec{r}_0)\\ &= \sum_i \lambda_i\beta_i\left[F(t,\vec{r},\vec{r}_0)e^{-\lambda_i t} + \lambda_i\int_0^t F(u,\vec{r},\vec{r}_0)e^{-\lambda_i t}\,du\right]\end{aligned} \tag{2}$$

where β_i and λ_i are the delayed neutron fraction. The concentration ρ_0 is given by:

$$\rho_0 = \frac{\alpha}{d}\sum_i\left(\int_{V_f} p_i(\vec{r})\,d^3\vec{r}\right) \tag{3}$$

where d is the sodium flow at the failure location, α the fission rate per volume unit of the fuel, p_i the probability that a DNP i produced within the fuel volume V_f reaches the sodium. Its computation requires to model the failure. It is proportional to a surface S, which would be the area of the failure if DNP could only escape within the sodium by recoil, neglecting diffusion. This surface must be considered as a handy parameter to make computations and comparisons between assemblies. The genuine area of the failure is smaller (Gross and Strain, 1980) and may be obtained by calibration on the real reactor, after the removal of the faulted assembly and its examination.

It is customary not to consider the DNP individually, but to regroup them onto groups, e.g. the 8 group scheme of the JEFF3.1 library (Konig et al., 2006), validated for the SFR (Tommasi et al., 2010). In practice, for a ^{235}U fissile coating, the efficiency depends loosely on the group i. The integration volume V is limited by internal components and the vessel itself. Furthermore, the contribution of neutrons released farther than 2.4 m from $\vec{r}_d$ is less than 10% (Filliatre et al., 2014): assuming that the HTF is spatially constant in this volume, Eq. (1) becomes:

$$\tau(t) = \rho_0(\bar{\nu}/2)\times\mathcal{F}(t,\vec{r}_d,\vec{r}_0)\times E(\infty) \tag{4}$$

where $E(V)$ the efficiency (in m^3·s^{-1}) of the detector integrated over the relevant volume V. It is noteworthy that $\mathcal{F}$ increases with T up to an asymptotic value, so does $\tau(T)$: the system has reached its permanent regime, the sensor being constantly flooded by particles coming from a stationary clad failure.

3. Hypothesis testing

In this section the procedure of hypothesis testing is recalled. It is supposed that only two mutually exclusive hypotheses can be made:

H0 there is no open clad failure; H0 is referred as the null hypothesis.
H1 there is an open clad failure; H1 is referred as the alternative hypothesis.

It is thus implicitly assumed that any other cause of detector count increase or departure from stationarity (e.g. a variation of the reactor power, or a detector failure) has been eliminated by other means. A statistical test is performed to decide whether H0 is false or not, i.e. whether a clad failure has been detected or not. For that, the following quantities are needed:

(1)A measurement, e.g. a count, or any relevant quantity constructed with the data, referred as the statistic.
(2)A probability law, the previous measurement can be considered as a realization of this law if H0 is valid. With this, the p-value is computed, i.e. the probability that of obtaining a measurement at least as extreme as the one that was actually observed if H0 is valid.
(3)An arbitrary parameter s_α, which is p-value below which it is decided to reject H0. This parameter is referred as the significance level. It corresponds to the probability, if H0 is true, to take the wrong decision of rejecting it (a situation called a type I error, or false positive).
(4)An arbitrary parameter s_β, which is the probability, if H1 is true, to decide that H0 is true (type II error, or false negative). Conversely, it can be used if H0 is rejected at the previous step to put a constraint on the fraction of the measurement that can be attributed to the clad failure, and eventually, with a proper modelling of the clad failure, to its minimal surface.

Depending on the truth of H0, the decision of retaining or rejecting H0 falls into one out four possibilities, the probabilities of which are given on Table 1. It reflects the impact of the choice of s_α and s_β: the lower they are, the lower is the risk of having made a wrong decision, the larger the risk of missing small clad failures. Usual choices are 10%, 5% or 1%, corresponding roughly to 1.6, 2 and 1.6σ for a Gaussian statistic. It is noteworthy that the probabilities given in Table 1 are conditional: s_α is not the probability of making a type I error, it is the probability of making it if H0 is true. The issue of false alarm is discussed in Section 7.

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