Annals of Nuclear Energy 69 (2014) 1–6

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Estimating the occurrence of foreign material in Advanced Gas-cooled Reactors: A Bayesian Monte Carlo approach

Paolo Mason *

EDF Energy, Barnwood, Gloucester, United Kingdom

ARTICLE INFO

Article history:
Received 15 November 2013
Received in revised form 13 January 2014
Accepted 16 January 2014
Available online 18 February 2014

Keywords:
Nuclear safety
Bayesian inference
Monte Carlo methods

ABSTRACT

The current occurrence of a particular sort of foreign material in eight UK Advanced Gas-cooled Reactors has been estimated by means of a parametric approach. The study includes both *variability*, treated in analytic fashion via the combination of standard probability distributions, and the *uncertainty* in the parameters of the model of choice, whose posterior distribution was inferred in Bayesian fashion by means of a Monte Carlo route consisting in the conditional acceptance of sets of model parameters drawn from a prior distribution based on engineering judgement.

The model underlying the present study specifically refers to the re-loading and inspection routines of UK Advanced Gas-cooled Reactors. The approach to inference here presented, however, is of general validity and can be applied to the outcome of any inspection campaign on any plant system, and indeed to any situation in which the outcome of a stochastic process is more easily simulated than described by a probability density or mass function.

1. Introduction

The graphite core, i.e. the channels in which the fuel assemblies (also called ‘stringers’) are lodged, represents an irreplaceable, and therefore potentially lifetime-limiting, component of the Advanced Gas-cooled nuclear Reactor (AGR). For this reason a considerable effort has been spent by EDF Energy, operator of the UK AGR fleet, on the assessment of the current and future structural integrity of the cores of its seven twin-reactor AGR power stations (Maul et al., 2011; Bradford and Steer, 2008; Maul and Robinson, 2006). The monitoring of graphite cores involves regular visual inspections of the inner surface of the channels, performed by means of remotely operated cameras.

In the course of two channel inspections at Heysham 2 power station in 2011 (channels 7R23 and 7J25) the unusual observation was made of some small pieces of material, trapped between graphite blocks, compatible in dimension and shape with the *petals* of a specific component of the AGR fuel assembly at Hinkley Point B (HPB), Hunterston B (HNB), Heysham 2 (HYB) and Torness (TOR) power stations, namely the *anti-gapping unit* (AGU) *shim* (AGU shim petals are thin metal foils of dimension $\sim 25 \times 25$ mm, see Fig. 1). Three fragments were observed in both channels; one of the fragments in channel 7R23, however, may consist of two adjacent petals (see Fig. 2), so that it is here conservatively assumed that the number of fragments observed in the two inspections is respectively four and three.

The possibility was soon recognized that the fragments may accumulate in particular locations and hinder the flow of the coolant around the fuel assemblies. Studies were therefore undertaken in order to

- estimate the occurrence of loose AGU shim petals in the reactor;
- assess the effect on the coolant flow of the supposed presence of AGU shim debris;
- put in place measures for the mitigation of a possible fault.

The present work represents the fulfillment of the first bullet point above, i.e. it aims to estimate the current fouling of the HPB/HNB/HYB/TOR reactors due to AGU shim debris. For this purpose, a model was set up of HPB/HNB/HYB/TOR with respect to the generation, detection and removal of AGU shim debris in fuel channels (Section 2). The model was implemented by a Monte Carlo route by means of which the posterior distribution of the model parameters (PDMP) given the historical record of AGU shim debris detection in fuel channels was sampled via the conditional acceptance of sets of model parameters drawn from a prior distribution based on engineering judgement (Section 3). From this distribution the amount of AGU shim debris currently fouling the

* Tel.: +44 01452653418.
E-mail address: paolo.mason@edf-energy.com

http://dx.doi.org/10.1016/j.anucene.2014.01.028
0306-4549/

Fig. 1. A photograph of the AGU shim. Each stringer carries two shims, that carry 60 overlapping petals each.

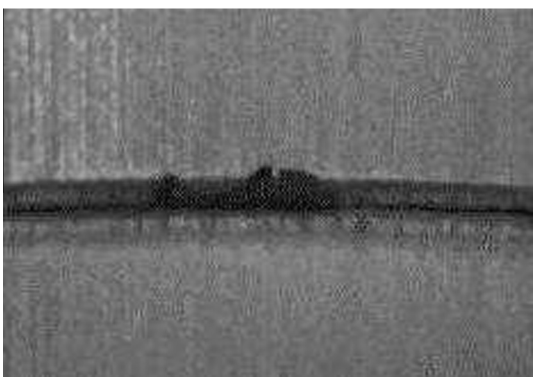

Fig. 2. One of the fragments, believed to originate from the AGU shim, observed in HYB channel 7R23. This fragment was conservatively assumed to consist of two adjacent AGU shim petals.

HPB/HNB/HYB/TOR reactors was subsequently estimated via a deterministic (as opposed to Monte Carlo) route (Section 4).

2. A model

Fuel assemblies include AGU shims at four stations, namely HPB/HNB (308 channels per reactor) and HYB/TOR (332 channels per reactor); each shim carries 120 petals. To date, 627 fuel channel inspections have taken place across HPB/HNB/HYB/TOR and ~12,360 stringers have been discharged from these stations' reactors. The (non-normalized) probability mass function (pmf) of the number of discharged stringers per channel at HPB/HNB/HYB/TOR as of May 2013 is given in Table 1.

The following modelling simplifications were adopted.

- The four stations (i.e. eight reactors) under examination were modelled as one reactor of $308 \cdot 4 + 332 \cdot 4 = 2560$ channels.
- Inspections are performed after the extraction of a stringer and before the loading of a new one with the following limitations:
  - A stringer cannot be placed back into the channel of origin, or any other channel, after it has been extracted from its location.
  - A maximum of one inspection can be performed in an empty channel before a new stringer is loaded into it. Note that this implies that $k \leqslant n$, where
    - k is the number of inspections carried out in the channel from reactor start of life to the present day;
    - n is the number of stringers discharged from the channel from reactor start of life to the present day.
- 627 inspections are randomly distributed across the channels.
- 12,360 stringers are randomly distributed across the channels as in the rightmost column in Table 1, with the constraint that in every channel $k \leqslant n$ (see above).
- At reactor start of life all channels are free of AGU shim debris.
- Whenever a stringer is extracted from a channel:
  1. Each detached AGU shim petal present in the channel is removed with probability P_0.
     Note that, as the model does not track events happening between the loading and the discharge of a stringer, P_0 actually represents the sum of the probabilities that each detached petal is swept away by the gas flow or wiped away during the extraction of the stringer.
  2. An event happens with probability P_1 that makes possible the release of petals from the stringer.
  3. If such an event happens, each of the 120 petals has a probability P_2 of being torn off the shim and being retained in the channel.
- All possible schedules for performing k inspections in n time slots following stringer removal are equally probable.
- Whenever an inspection takes place each of the detached petals present in the channel is detected with probability P_3.
  Note that the inspections are *not* primarily aimed at detecting AGU shim debris.

Table 1
The (non-normalized) pmf's of the number of discharged stringers per channel at HPB/HNB/HYB/TOR as of May 2013. Normalizations are obtained dividing the entries in each column by the number of channels in the reactor, namely 308 in the HPB/HNB reactors, 332 in the HYB/TOR reactors and 2560 in the HPB/HNB/HYB/TOR model reactor (rightmost column).

Discharges per channel	Number of channels								
	HYB		TOR		HPB		HNB		All reactors
	R7	R8	R1	R2	R3	R4	R3	R4	
0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0
2	0	0	0	8	0	0	0	0	8
3	184	231	241	270	0	0	0	0	926
4	148	101	87	54	0	0	0	0	390
5	0	0	3	0	9	16	31	70	129
6	0	0	1	0	114	124	155	178	572
7	0	0	0	0	143	121	87	34	385
8	0	0	0	0	40	36	25	21	122
9	0	0	0	0	2	10	8	4	24
10	0	0	0	0	0	1	1	1	3
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	1	0	1