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Industrial implementation of intelligent system techniques for nuclear power plant condition monitoring

G.M. West [a,*], S.D.J. McArthur [a], D. Towle [b]

[a] Institute for Energy and Environment, University of Strathclyde, 204 George Street, Glasgow G1 1XW, UK
[b] EDF Energy Barnett Way, Barnwood, Gloucester GL4 3RS, UK

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ABSTRACT

As the nuclear power plants within the UK age, there is an increased requirement for condition monitoring to ensure that the plants are still be able to operate safely. This paper describes the novel application of Intelligent Systems (IS) techniques to provide decision support to the condition monitoring of Nuclear Power Plant (NPP) reactor cores within the UK. The resulting system, BETA (British Energy Trace Analysis) is deployed within the UK's nuclear operator and provides automated decision support for the analysis of refuelling data, a lead indicator of the health of AGR (Advanced Gas-cooled Reactor) nuclear power plant cores. The key contribution of this work is the improvement of existing manual, labour-intensive analysis through the application of IS techniques to provide decision support to NPP reactor core condition monitoring. This enables an existing source of condition monitoring data to be analysed in a rapid and repeatable manner, providing additional information relating to core health on a more regular basis than routine inspection data allows. The application of IS techniques addresses two issues with the existing manual interpretation of the data, namely the limited availability of expertise and the variability of assessment between different experts. Decision support is provided by four applications of intelligent systems techniques. Two instances of a rule-based expert system are deployed, the first to automatically identify key features within the refuelling data and the second to classify specific types of anomaly. Clustering techniques are applied to support the definition of benchmark behaviour, which is used to detect the presence of anomalies within the refuelling data. Finally data mining techniques are used to track the evolution of the normal benchmark behaviour over time. This results in a system that not only provides support for analysing new refuelling events but also provides the platform to allow future events to be analysed. The BETA system has been deployed within the nuclear operator in the UK and is used at both the engineering offices and on station to support the analysis of refuelling events from two AGR stations, with a view to expanding it to the rest of the fleet in the near future.

1. Introduction

As the AGR stations in the UK age, there is an increasing need to understand the condition of the reactor core, the major life-limiting component in an AGR station. Inspections undertaken during routine outages, every two-three years, provide high fidelity information on a limited number of channels. Additional information about core condition can be gained from monitoring data obtained during refuelling operations. These refuelling events occur much more frequently than outage inspections, but the raw data requires significant interpretation effort to provide meaningful results. The application of intelligent systems can aid this process, providing a repeatable and reliable method of automatically assessing refuelling data. In addition, intelligent system techniques can be applied to large volumes of this data to uncover trends, which relate to the age and degradation of the graphite core. These trends can be used to supplement existing understanding of the ageing process of nuclear graphite and supports the case for continued and extended operation of the AGR NPPs.

This paper is split into the following sections. Firstly a brief introduction to Nuclear Power Generation in the UK is given along with more technical detail concerning the refuelling process and the associated monitoring data. The ageing process of nuclear graphite, from which the major components of the reactor core are constructed, is also described. The second section deals with the use of intelligent analysis techniques to support various aspects of analysing refuelling data, and how the application of these techniques can also provide valuable understanding into long-term trends in the data. These trends can then support continued operation and lifetime extension of the Advanced Gas-cooled Reactor (AGR) Nuclear Power Plant (NPP) fleet in the UK. The final section

* Corresponding author.
E-mail address: graeme.west@strath.ac.uk (G.M. West).

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describes the industrial implementation of these techniques in a decision support system that aids the analysis of refuelling event data for two NPPs in the UK.

2. Background

2.1. Condition monitoring of nuclear power plants

Within the UK, the existing fleet of AGR NPPs are approaching the end of their originally anticipated design lifetimes. Condition Monitoring (CM) of the reactors is playing an increasing role in the continued safe operation of the plant as well as contributing to the safety case made for extended operation beyond the original design lifetimes. This increase in condition monitoring activity generates a large volume data that must be analysed. The expertise required to analyse this data is limited to just a few experts and therefore the use of intelligent system techniques to provide automated decision support ensures that this expertise can be utilised more widely, and that some of the routine, labour intensive analysis can be reduced.

2.2. Nuclear power generation in the UK

Currently, approximately 20% of the UK electricity demand is met by generation from NPPs. The vast majority, seven out of the eight NPPs, are the second-generation AGR designs. These NPPs are approaching the end of their initially intended design lifetimes of 35 years, though some of them have been granted a lifetime extension of a further 5 years. Part of this process of obtaining a license to operate past the initial design lifetimes is the presentation of a safety case to the regulator, the Nuclear Installations Inspectorate (NII). According to NII technical guidelines (Boyle, 2002), the safety case is described as:

> "... the totality of documented information and arguments developed by the licensee, which substantiates the safety of the facility, activity, operation or modification. It provides a written demonstration that relevant standards have been met and that risks have been reduced 'so far as is reasonably practicable' (SFAIRP)"

One method to ensure risk reduction is to undertake analysis of condition monitoring data to provide an improved understanding of the current health of the NPP, and in particular the graphite core. The work described in this paper aims to support this goal.

2.3. Reactor core construction

With AGR nuclear power plants the dominant life-limiting feature is probably the condition of the graphite core. The function of the graphite core is to act as a moderator for slowing the fast neutrons during the nuclear reaction and to provide a structure that allows un-impeded movement of both fuel and control rods as well as adequate cooling of both the fuel and the graphite moderator. The core is constructed from columns of graphite bricks that form vertical channels for fuel assemblies, control rods, instrumentation channels and coolant flow. Though the exact configuration changes from station to station, approximately 19,000 bricks comprise the core, which are spread over 12 layers, resulting in over 300 fuel channels per core. Fig. 1 shows a photograph showing the arrangement of the graphite fuel bricks during construction. The material properties of graphite change due to neutron irradiation and radiolytic oxidation encountered in the reactors, during normal operation. This affects the dimensions, internal stress and integrity of the graphite bricks, which in turn could impede the movement of fuel, control rods and coolant through the core. Knowledge of the current dimensions of the graphite bricks that comprise the core is therefore a key requirement of understanding the current condition of the core. These dimensions are routinely obtained from inspecting the core during outages. Typically, every three years a reactor will undergo an outage where a limited number (currently 31 for the oldest reactors, though much less for the younger reactors) of fuel channels are inspected. Inspection includes visual inspection of the channel walls using special TV camera equipment, accurate measurement of the diameter and tilt of the channel bore across the fuel height of the channel, and trepanning small samples of the core which are then subject to a series of material properties tests. Selection of these channels for inspection is undertaken to ensure a representative subset of the whole core is obtained, as well as targeting individual channels which may contain known issues. The inspection campaign provides very detailed information on the health of the core, but based on a limited number of channels.

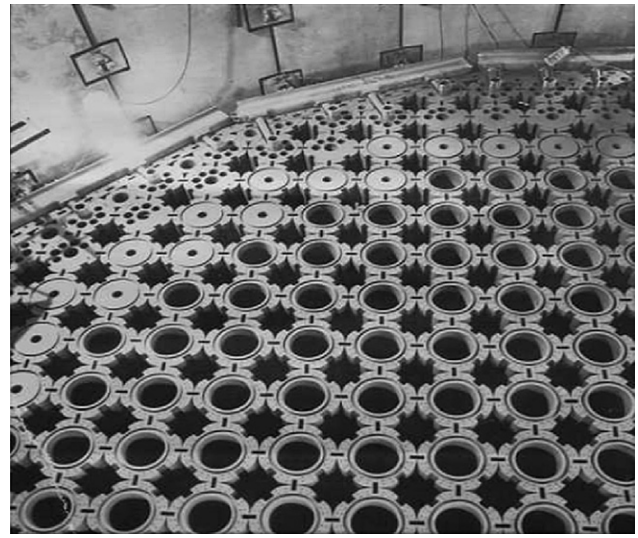

Fig. 1. Photograph showing the layout of the reactor core during construction showing the arrangement of a layer of graphite fuel bricks. Picture courtesy of EDF Energy Ltd.

As the nuclear power plant ages, there is a greater pressure to increase the volume and periodicity of these inspections. Inspections are costly, however, as the reactor must be offline (and thus not generating electricity) and the fuel channel to be inspected temporarily emptied of fuel. Limitation on buffer storage space restricts the number of channels that can be empty at a given time and movement of fuel between the reactor and the store is a time consuming process. One approach to mitigate the need for some of the increased inspections is to increase the amount of online monitoring that is undertaken. One existing source of monitoring data that can provide information relating to the current channel dimensions is fuel grab load trace data, gathered during refuelling operations. This condition monitoring data needs to be analysed to provide meaningful results, which is a labour intensive process requiring specialised knowledge. IS techniques have been successfully applied to address this issue and is a key contribution of this work.

2.4. Fuel grab load trace online monitoring data

AGR stations are refuelled on a regular basis, with the fuel for a single channel lasting approximately 6–7 years. The uranium fuel is housed within refuelling assemblies that are inserted into a fuel channel that has been evacuated during the refuelling process.