Graphite core brick crack detection through automated load trace analysis

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Introduction

It is impossible to repair or replace the graphite core of an AGR, and therefore the graphite core is one of the main components that determine the operational life of a nuclear station. The reactor core is composed of hundreds of hollow graphite bricks. The graphite ages because of neutron irradiation and radiolytic oxidation causing distortion and potentially cracking of the bricks towards the end of reactor life. Monitoring the integrity of the core is undertaken on a routine basis during planned station outages. These outages occur roughly every three years and result in a large volume of detailed information from a few selected channels (normally eight) collected by a Channel Bore Monitoring Unit (CBMU). This data consists of accurate measures of the channel bore diameter and tilt angles. The information from these few channels is used to provide an overall assessment of the health of the core. Gathering this detailed information is time consuming due to a number of factors:

- The channel being inspected must be emptied of fuel prior to monitoring, in order for the monitoring device to be inserted into the channel,
- To capture the level of detail that is required, the monitoring device is raised very slowly through the entire length of the reactor. This can take several hours.
- Once the monitoring is complete, the fuel needs to be reinserted into the channel.

This process needs to take place during a station outage, when the reactor is off-line. While the reactor is off-line, it is not generating electricity. Therefore, it is important that the reactor is not off-line for any longer than is necessary.

In addition to the detailed data gathered during the outages, data is also gathered during routine refuelling operations. Height and load measurements are taken during refuelling and are used for control and protection purposes.

It has been proposed that this routine refuelling data could be interpreted to provide additional information relating to the presence of cracks within the reactor core, thus supporting the safety case for the continued operation of the station. Manual interpretation of this data would be too laborious and time consuming so an automated approach utilising Intelligent System (IS) techniques is described in the remainder of this paper. A number of Intelligent Systems techniques utilise encoded expert knowledge to reason about a particular situation in order to provide the same conclusion as a human expert, given the same set of inputs. The main IS technique discussed in this paper is rule-based reasoning, which uses expert knowledge in the form of rules to derive a conclusion.

To summarise, there are two sets of data available that can provide information relating to the condition of the graphite bricks within the reactor core:

- A low volume of very detailed channel information from a small number of channels. This data is gathered during planned station outages, which occur every few years.
- A high volume of less detailed information relating to height and load of a fuel assembly during a refuelling event. Refuelling events take place on a weekly basis.

The aim of this research is to utilise IS techniques to interpret this high volume of lower quality data in order to drive out additional information relating to the condition of the reactor core.

Previous work in this field has seen the application of IS techniques to support the analysis of fuel assembly set-down during reactor core refuelling [1]. The developed ALTA system, employs three techniques, K-means clustering, C4.5 rule induction and Kohonen networks to identify and classify features of interest within the data. A majority voting system involving the three techniques increases the confidence in the results and provides redundancy should one of the techniques fail. Diagnostic rules elicited from fuel route engineers and implemented in ALTA are used to provide an assessment of whether the fuel assembly has seated satisfactorily or if there is a situation that requires further analysis, such as a fuel ledging within the channel. This work demonstrated the applicability and practicality of IS techniques for data interpretation relating to the core. It also proved that such IS applications can be justified for safety-related implementation.

Background to Nuclear Refuelling

Refuelling a power station reactor is an ongoing process and the refuelling of individual reactor channels takes place on a regular basis, with around 60 to 70 refuelling operations annually. A refuelling operation consists of removing the old fuel and fuel assembly from a channel, moving it to storage for future reprocessing, and inserting new fuel and fuel assembly into a channel. During this refuelling process, data relating to height and load of the fuel assembly is recorded. Engineers interpret this data to ensure that the fuel has been correctly inserted into the reactor and has settled correctly on the support stool at the bottom of the reactor. This height and load data is captured on a pen and paper plotter, although the newer stations also capture this data electronically. In addition, there is a programme in place to fit most of the remaining stations within the UK with electronic data capture devices.

Currently no routine examination of this refuelling data is undertaken for the purposes of graphite brick crack detection. Manual interpretation of this data has been performed on an *ad-hoc* basis and is a time consuming process, which requires a significant amount of expertise. The individuals with this expertise do not have the time to spend manually examining all the load traces that are produced during refuelling. Therefore, to reduce the burden placed on these experts, methods of automatically interpreting this data using intelligent system techniques are being investigated.

Graphite Core Construction

The core of a nuclear reactor is constructed from hundreds of interlocking cylindrical bricks of graphite. Each brick is hollow, and a number of bricks, normally eleven, are stacked on top of each other, leaving deep channels the length of the core into which the fuel is inserted. A simple diagram of one reactor core brick is shown in figure 1. Due to the heat and radiation that the core is subjected to during operation, individual bricks can distort and may eventually develop cracks over time [2].

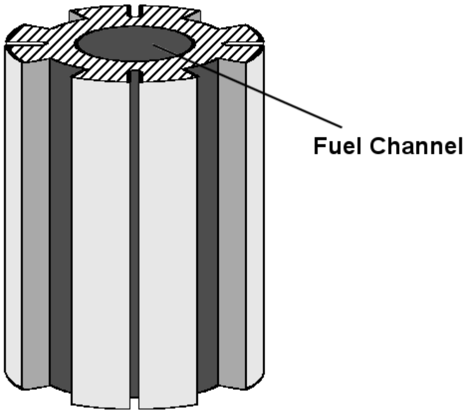

Figure 1: Diagram of graphite core brick

Fuel assembly exchange

A fuel assembly, which holds the fuel used to generate the heat within the reactor core, is inserted into the fuel channel during refuelling. This is not a single solid device, it consists of four sections separated by telescopic and compression joints. The sections are: the gag unit which seals the fuel assembly into the fuel channel; an upper plug unit which contains the biological and heat shields; a lower plug unit containing the radiation shield and the fuel stringer for housing the nuclear fuel. Two sets of brushes, one at the bottom of the assembly, and one at the top, guide the fuel assembly down the channel into the core of the reactor. These brushes set up a frictional interface with the wall of the reactor channel. Interfaces between adjacent brick layers result in changes to the bore diameter of the channel. As the brushes pass through these features, there is an equivalent change in the frictional forces between the walls and the brushes, which correspond to an apparent change of load on the fuel assembly. This change in load manifests itself as peaks within the refuelling load trace. Figure 2 shows a sample load trace, with the peaks representing the brick layer interfaces highlighted on it. Other known features can also be seen as peaks or sets of peaks within the load trace. A set of peaks caused by the fuel assembly passing through a restriction in the fuel channel is also highlighted on figure 2 as the upper stabilising brush passing through the piston seal bore. In addition, certain types of brick crack will also appear as a peak in the load trace.

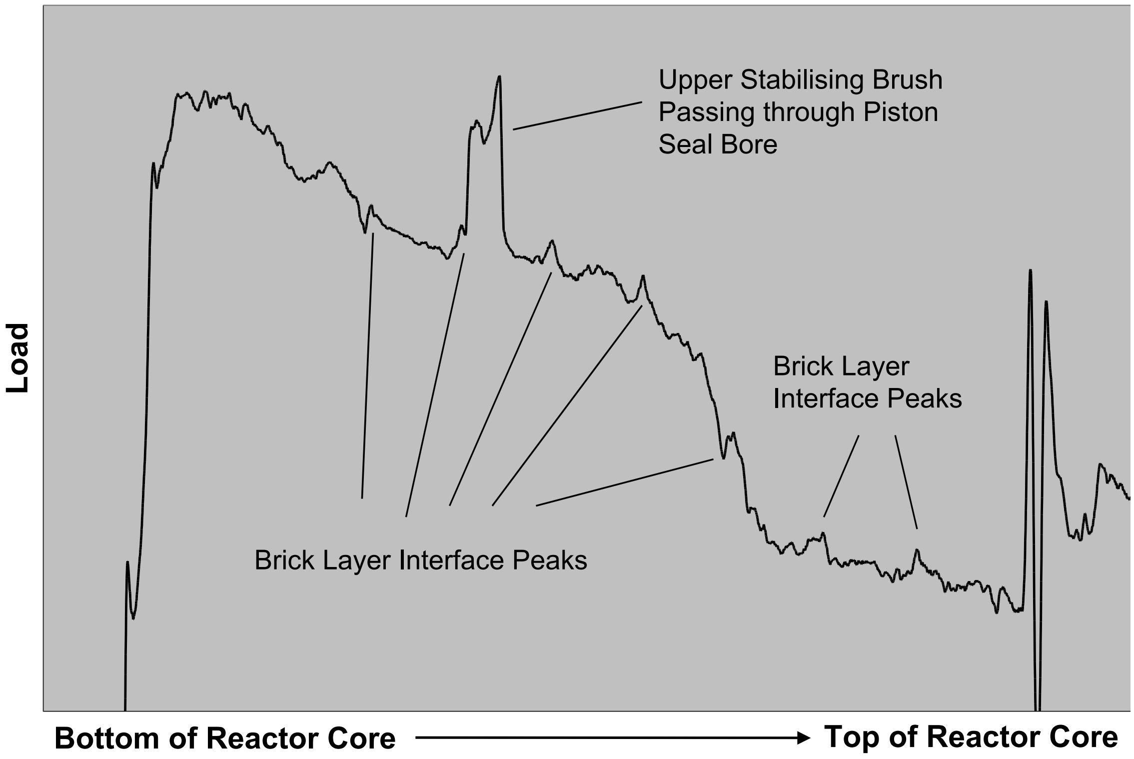

Figure 2: Example load trace for removal of a fuel assembly from the core illustrating the brick layer interfaces

Types of crack

This work focuses on two of the major types of brick cracking that can occur in a reactor core, early life cracking and primary cracking. Early life cracking occurs circumferentially and its appearance on a load trace plot is a peak, similar to that of a brick layer interface. Primary cracking occurs when a brick splits from top to bottom, which results in an increase in bore diameter of the brick as it separates at the crack. This corresponds to a step change in load across the brick layer with the crack, which can be detected in the load trace. Though brick cracking sounds serious, the design of the reactor core and keying system allows safe operation of the reactor to be continued in the presence of brick cracking. It is, however, very important to be aware of the nature and location of any cracking within the core.

Refuelling trace analysis

In order to demonstrate that reactor core brick cracking could be detected from the load trace produced during refuelling a number of channels containing known cracks were examined. The CBMU data was compared with load trace data from each refuelling event associated with that channel. Figure 3 shows the comparison between a load trace and a CBMU trace of bore diameter of the channel. Due to the effects of radiation, areas of a graphite core brick will shrink at different rates, leaving the top and bottom of the brick channel narrower than the middle. This effect can be seen on the CBMU trace in figure 3 with the reduction in channel diameter towards the interfaces between brick layers. Due to the large volume of data, it would be impractical to undertake a manual examination of the data for each refuelling event for evidence of brick cracking. The automation of load trace data analysis through the use of IS techniques could provide useful additional information relating to core integrity. The remainder of this paper describes a proposed system for the automatic detection of brick cracking from routine refuelling event data.

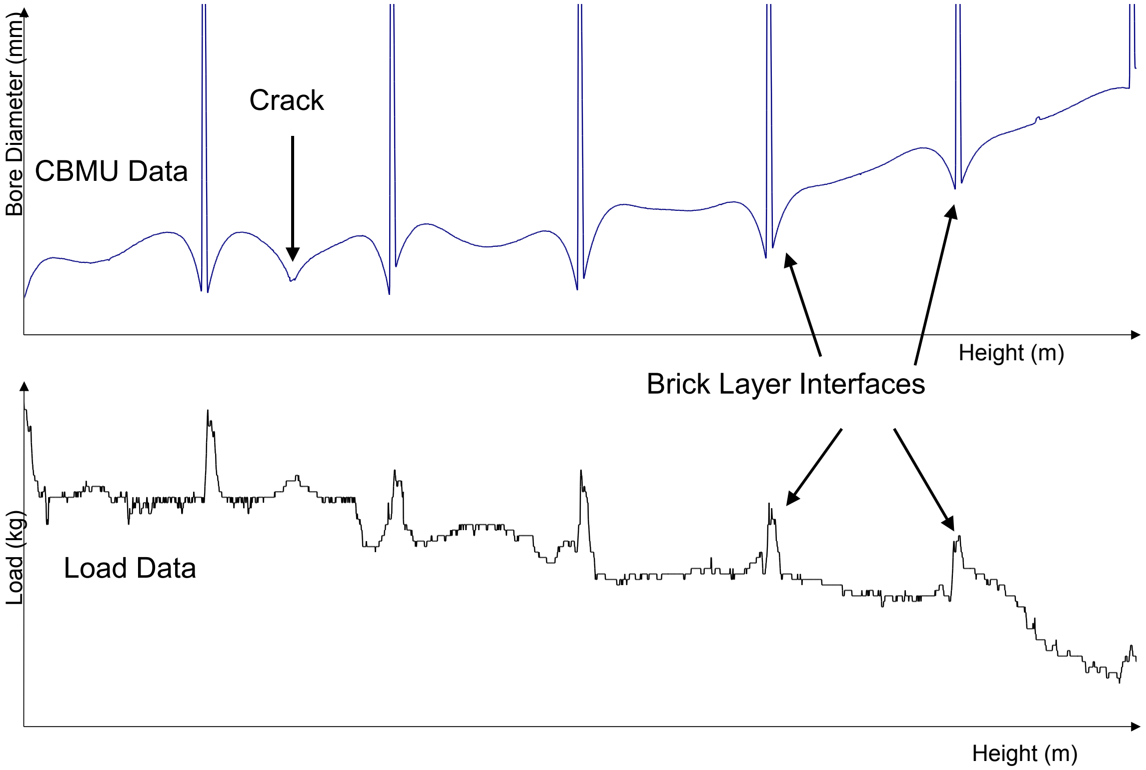

Figure 3: Comparison of a channel bore monitoring unit trace of channel bore diameter and a refuelling load trace from the same channel.

Intelligent Crack Detection System

The key activities undertaken within the crack detection intelligent system are shown in figure 4. The load trace data is fed into the system where initial data validation is carried out. This ensures that a refuelling event, as opposed to an on-line plug unit (OLPU) insertion event, is being examined and that the data is of suitable quality. The next stage is to extract the data relating to the region of interest, namely the core region containing the brick-layers, and discard the unnecessary data. The core region data is then examined for peaks, as these are used to identify the locations of the brick layers within the load trace. Peaks in the data can also indicate the presence of cracks within the core. Once the peaks have been identified, they are classified as either brick-layer interfaces, other known features, potential cracks or noise. Rule-based techniques are then employed to analyse the resulting conclusions to determine the likelihood of a crack being present in the channel. Following this analysis, a report summarising any findings is produced and the results of the analysis archived. At this stage of the research, the data validation, data preparation and peak identification modules have been demonstrated, using data from a single station.

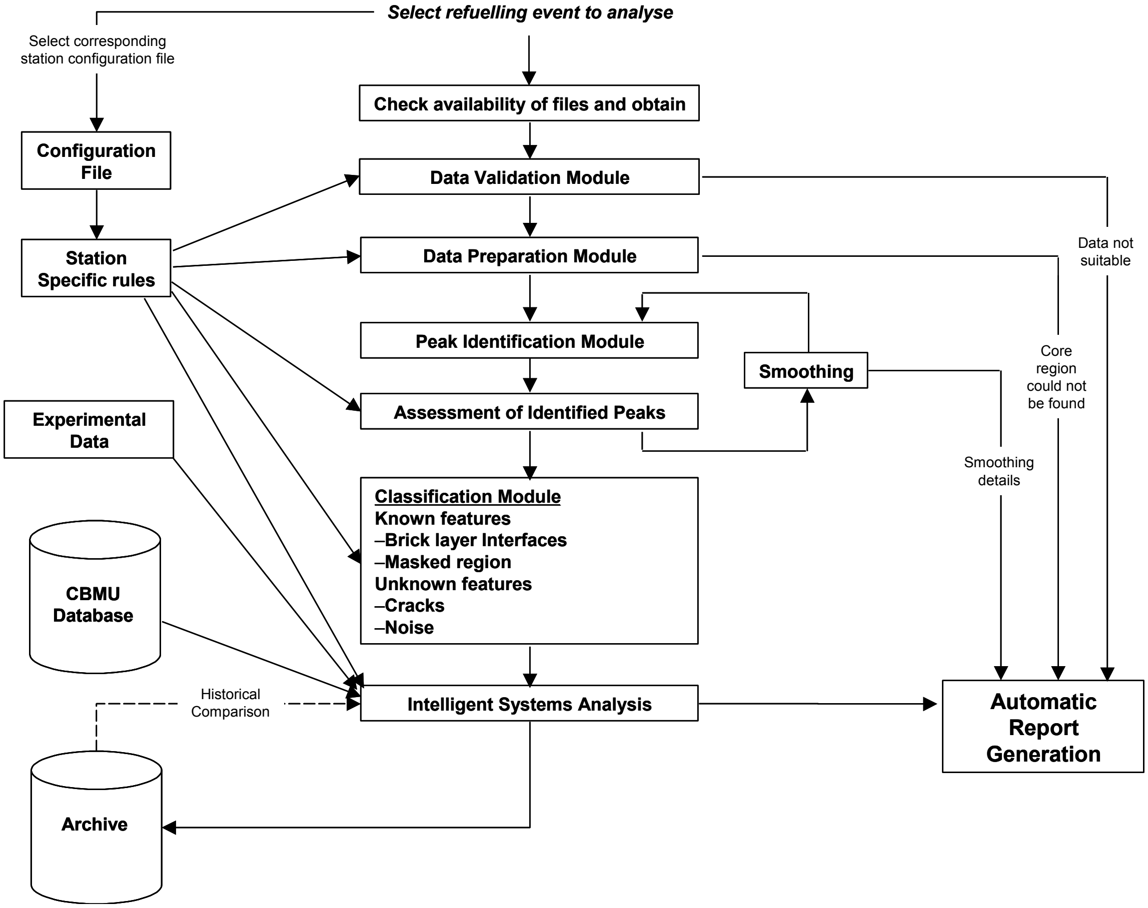

Figure 4: System description showing the key modules required for graphite brick layer crack detection

Data Validation Module

The data validation module ensures that the data refers to the refuelling process, as opposed to the insertion of a control device such as an on-line plug unit (OLPU) and that the data is not corrupt. This is an important stage of the analysis as the knowledge used in the feature classification module assumes that a standard fuel exchange event is under examination. Multiple elements are used to assess the file, namely:

- Size of the data file. A refuelling operation normally takes about an hour to complete. As the data is recorded at a constant rate, the channels are the same length and the speed of the hoist is consistent, the size of the resulting data file should also be consistent between refuelling operations. Events, such as re-seating of the fuel or delays in the fuel exchange process can prolong the refuelling operation and therefore result in a larger file. This may need to be factored into any future analysis.
- Date and time of refuelling. Occasionally the refuelling event may be split across two files. If there is another refuelling file for the same channel within a 30 minute time period from the first, this can indicate such an event. When this occurs, the two files will need to be combined into a single file for analysis

- Maximum, minimum and average values of load and height. These statistical measures can indicate data corruption or loss of signal.
- Shape of refuelling trace. A human can quickly identify events involving OLPUs from the overall load trace. An equivalent measure can be obtained by assigning each data point to one of four value bands and examining the points where the data changes from one band to another.

These elements are formatted into a set of rules that are applied to any new trace, to ascertain whether it is suitable for further analysis. These rules include supporting evidence used to justify any outcomes of the analysis to the user at the reporting stage of the system. An example rule relating to the file size is shown below.

If **File Size** < 620000 (bytes) then **Non-standard refuelling event**

Supporting Evidence: 699 traces from over a 7-year period were examined. The smallest standard refuelling operation file examined so far is file xxxx_yyyy (reference to smallest file) at 694341 bytes. The limit for this rule has been set lower than this value to allow a margin of error. It is assumed that a file of less than 620000 bytes will not refer to a standard refuelling operation, as no evidence of such an event has been encountered to date.

This supporting evidence can then be returned to the user if the rule is fired during analysis, providing a more complete explanation than an ordered list of the rules fired. This approach will also benefit the maintenance of the system, by providing an auditable trail of the knowledge used by the system to make its decision. For example, consider the situation where a data file of 610000 bytes relating to a standard refuelling operation was presented to the system. Without the supporting evidence, the output from the analysis would be restricted to:

*File is a **Non-standard refuelling event (If File Size** < 620000 (bytes) then **Non-standard refuelling event)***

Though this provides an explanation as to why the file is non-standard, it provides no explanation as to how the rule was defined when the system was constructed. With the supporting evidence, the user would be aware of the reason for setting the limit and could propose that a revision to the rule be made. This is important in software within a safety-related domain, such as nuclear power generation, as clear and transparent justification is provided for any decisions made.

The rules are stored using an XML format to allow them to be parsed and read by a user in a web browser. The same file is used by the intelligent system to perform the diagnosis. This ensures that a single common set of rules is used and maintained.

A key question arising from this is how much explanation to offer the user. Too little explanation then the user may distrust the result provided by the system. Too much explanation and the user may be overwhelmed. This issue will be investigated further during the course of this research.

Data Preparation Module

Data is recorded throughout the entire refuelling process, however, the data of interest corresponds to the fuel assembly passing through the graphite brick layers in the core. This occurs twice during refuelling, as the old fuel assembly is removed from the core and as the new fuel assembly is inserted into the core. The analysis focuses primarily on the fuel assembly removal as, due to the physical interactions between the fuel assembly and channel wall, features such as brick layer interfaces and cracks are more prominent. The data relating to fuel insertion is not discarded but used to provide corroboratory evidence for the location of features of interest.

This module requires the start and end points of the region relating to the graphite brick layers to be identified. The height signal can be used to determine the start and end points of the data as the height of the core is constant and will not change over time. In addition, a distinct set of peaks appears in the load trace as the stabilising brushes pass through the piston seal bore. This feature can be used to corroborate the height data, or can be used as an alternative should the height signal be unavailable.

Peak Identification Module

As described earlier, both early-life cracks and brick layer interfaces manifest themselves as peaks within the load trace. In order to automatically identify these peaks from the data a peak identification algorithm is required. Once all the peaks within the load data have been identified, each peak is classified as either:

- A brick layer interface
- A known physical feature within the channel, such as a brush passing the piston seal bore
- A potential crack.

The following outlines the peak identification algorithm:

```
Get Data
Repeat the following until no data is left

        Read in load data point (x)
        If x > (x-1)
                •  Values still increasing (no turning point reached)
        If (x-1) – (x-2) > 0 and x < (x-1)
                •  Turning point (peak) identified
                •  Store point (time, load) and peak start point (time, load) in array
        Count peaks in array
        If greater than acceptable number and smoothing limit has not been reached
                •  Perform smoothing operation
                •  Report smoothing operation
                •  Return to start using smoothed data
        If 3 smoothing operations have been carried out
                •  Report limit has been reached

Proceed to peak classification
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The data is then reversed and the algorithm re-applied. The two arrays are then compared for common peaks that are over a predefined length and height. This ensures that the major peaks, which correspond to the features of interest, rather than the smaller peaks, which are caused by noise, are identified. If the number of major peaks exceeds an upper limit of suspected peaks, the data is smoothed and the above procedure of peak identification is repeated. If there are still too many peaks after a third smoothing operation, the analysis continues, but a comment is added to the final report.

Identifying the brick layer interfaces permits the average load across the brick layer to be calculated. Values that fall outside a pre-defined limit can indicate the presence of the second type of crack, primary brick cracking. This module is still in the early stages of development.

Classification Module

Following the identification of all the peaks within the load trace, each peak needs to be classified in order to identify those peaks referring to brick layer interfaces or other known features and those which may relate to cracks within the core. The approach adopted is to firstly identify those peaks relating to the brick layer interfaces, followed by those caused by other known features within the channel, such as the upper stabilising brushes of the fuel assembly passing the piston bore seal. Finally, the remaining peaks are examined to determine whether the peaks are likely to have been caused by a crack in the brick.

In order to identify the brick layer interfaces within the load trace, each peak is examined in relation to its absolute position (from height measurements) and its relative position to the other peaks identified. The height of each brick layer remains constant, therefore the relative distance between adjacent brick layer interfaces on the load trace should also remain constant. This information is used to identify the set of peaks most likely to correspond to the brick layer interfaces. In addition, there are a few peaks that correspond to known physical features within the channel. Knowledge about the location of these features and their associated shapes within the trace are used to identify the peaks relating to these features. This information is currently being developed as a set of rules, similar to those described in data validation, to be implemented in a rule-based system. Each rule also contains an associated rationale used to provide an explanation of the analysis at the reporting stage of the system.

Once the peaks relating to known features have been identified the remaining peaks need to be examined to see if they result from a crack. In order to determine the likelihood of a crack, a number of factors are considered, namely:

- Historical data – does this peak appear in earlier refuelling events on this channel?
- CBMU data – has detailed channel bore monitoring been carried out on this channel and if so, was there any evidence of brick cracking within this data?
- Simulated crack profiles – a number of data profiles of cracked bricks are being generated through a full-size experimental rig. These data profiles will be compared with the actual data to look for possible matches.

Care must be taken when classifying each feature so that mis-classification does not take place. Mis-classified cracks may result in a decision to undertake CBMU analysis on that channel, which could prolong an outage. Therefore, proper justification for identifying a peak resulting from a crack must be given.

Primary Brick Crack Detection

Once all the brick layers have been identified, the average load across each brick layer can be calculated. These values can be compared to known values for uncracked brick layers in order to determine whether primary brick cracking has occurred. This module is currently under investigation as the process of primary brick cracking is not yet fully understood.

User interface and reporting results of analysis

The user will be able to select any completed refuelling operation in order to perform crack detection analysis on it. The system will perform the analysis and automatically produce a report highlighting any potential cracks identified through the analysis.

The report will consist of a summary page detailing any potential cracks. This will be supported through plots of the data, indicating the features on the trace that are suspected cracks. The user will then be able to select any of these potential cracks and view the supporting evidence for the analysis. This supporting evidence will be in the form of a list of any rules that applied to the data, and the order they were executed in, with the option to view the original rule definition with rationale. Each stage of the analysis process, from data validation to crack identification will be reported upon. This will be supported through evidence from historical data, through reports from previous analyses, and CBMU data where available. Finally, access to the original raw data will also be made available, should the user wish to perform any further, manual analysis on the data.

This report will allow the engineer to identify potential cracks within the reactor core during routine plant operations, rather than waiting until an outage. This will provide a more complete view of the reactor core by supplementing the existing, highly detailed, analysis carried out during an outage on a limited number of channels, with a broader, less detailed but more complete view through the use of routine refuelling data.

Conclusions and future work

This paper has described a proposed system for analysing routine load trace data for evidence of core graphite brick cracking. This system leverages existing data and data capture methods and supports the detailed analysis undertaken during an outage. This system offers a more complete and up-to-date view of the reactor core as refuelling is undertaken on a much more frequent basis than channel bore monitoring. This additional information could also be used to target areas of interest during an outage, though this may impact on the existing process of channel selection, which is designed to ensure that a set of channels which is representative of the whole core are chosen. An automated approach to the data analysis is required due to the volume of data involved. In addition, an explanation of any output produced by the approach is required, due to the safety-related nature of the domain. Both of these requirements can be met by the application of

IS techniques. Future work will result in the development of a prototype IS system that will automatically interpret the load trace data from a single station. This will then be expanded to include interpretation of data from other nuclear generating stations.

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