Graphite Core Condition Monitoring through Intelligent Analysis of Fuel Grab Load Trace Data

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Abstract

As a graphite core ages, there is an increased requirement to monitor the distortions within the core to permit safe continued operation of the station. In addition to existing monitoring and inspection, new methods of providing information relating to the core are being investigated. Two systems are described in this paper to support the use of Fuel Grab Load Trace (FGLT) data, which has been shown to provide information relating to core distortions and brick cracking. The first system was designed and implemented to provide support to analyzing large volumes of fuel grab load traces for patterns and thereby increase the understanding of how FGLT relates to physical core distortions. The second system utilizes this developed knowledge to provide a method of automatically assessing new FGLT data for the presence of abnormal behaviour that is symptomatic of brick cracking.

INTRODUCTION

Information relating to the current condition of the core is very valuable as the nuclear stations within the UK enter the latter stages of their operational lives. There is a desire by the station operators to extend the station operational lifetimes beyond the initial predictions in order to drive more value out of them. This is balanced by the obligation to ensure that the station is being run safely. This paper describes the utilisation of fuel grab load trace (FGLT) data to provide additional information relating to the current condition of the core. FGLT data is captured and retained as part of station records for protection purposes, particularly for detecting faults such as a failure of the tie-bar load mechanism, ledging and false-bottoming of the fuel assembly within the channel during refuelling. An expert system was designed to analyse the last 50cm of FGLT data to assess the success of fuel touchdown and is reported in (Steele, 2003). It has been shown, however, that this data can also provide information relating to distortions within the core. There are two main objectives of this research, firstly to develop a method for exploring the underlying relationship between the data and physical core condition and secondly to develop a system for automatically assessing new FGLT data in a structured and repeatable manner so that any anomalous behaviour can be quickly identified, based on this initial understanding of the data. This paper is divided into four main sections. The first section provides a brief overview of the refuelling process and how FGLT data can provide information relating to core condition. The second section describes a process of data-mining the FGLT data in order to develop an understanding of how the data relates to the core condition, and also to develop an understanding of what a "normal" refuelling event should look like. This data-mining approach is supported by the development and implementation of a software system which will also be described. The third section describes taking this newly acquired understanding and implementing it within a system that can automatically interpret new fuel grab load trace data. Finally, the last section

discusses the future direction of this work, with reference to potentially supporting future core safety cases.

BACKGROUND

It is assumed that the reader is familiar with the design of AGR graphite cores. This section provides a very brief overview of the refuelling process and provides an explanation as to why the FGLT data can provide information relating to the reactor core brick condition.

Refuelling background
AGR refuelling takes place on a regular basis with about 60-70 channels per reactor refuelled each year. A single refuelling event involves the removal of the old, spent fuel and the replacement with new fuel. During the entire refuelling process, a load cell measures the apparent weight of the fuel assembly as it traverses the core. Traditionally this has been recorded using a paper plotter, though there is a move towards recording and storing this information digitally.

Relating FGLT data to physical core condition
It was recognised that the physical features, such as the piston seal bore, could be related to features within the fuel grab load trace. Further investigations revealed that changes in the channel diameter are also reflected in the trace. The fuel assembly usually has two sets of brushes which guide it through the reactor during refuelling. These brushes form an interface with the channel wall and changes in channel diameters are reflected in the FLGT data. It should be noted that there are slight differences in design of fuel assembly and is dependent upon the station. This work focuses on Hunterston B and Hinkley Point B stations, though the same principles are equally applicable to most of the other AGR stations. As the reactor ages the graphite bricks will deform, which may ultimately lead to brick cracking. It is currently thought that brick cracking will be reflected in one of two ways within the FGLT data, either as a distinct peak in the data, or as a step change in load across an entire brick. As FGLT data was not specifically collected for condition monitoring purposes, there is not the underlying years of experience with interpreting it for these purposes. Figure 1 shows a comparison between the FGLT data and a set of data measurements of channel diameter taken during an outage using a channel bore monitoring unit (CBMU). The similarities in the data can be clearly seen and in particular the peaks in the FGLT data correspond to the reductions in diameter at the brick layer interfaces. In addition, a suspected crack in the CBMU data can also be seen reflected in the FGLT data. This diagram also indicates the difference in data quality, with the CBMU data producing a cleaner profile of the channel, whereas the FGLT clearly has an element of noise introduced. However, the CBMU data is only gathered from a limited number of channels over an infrequent time period, whereas the FGLT is gathered on a much more regular basis.
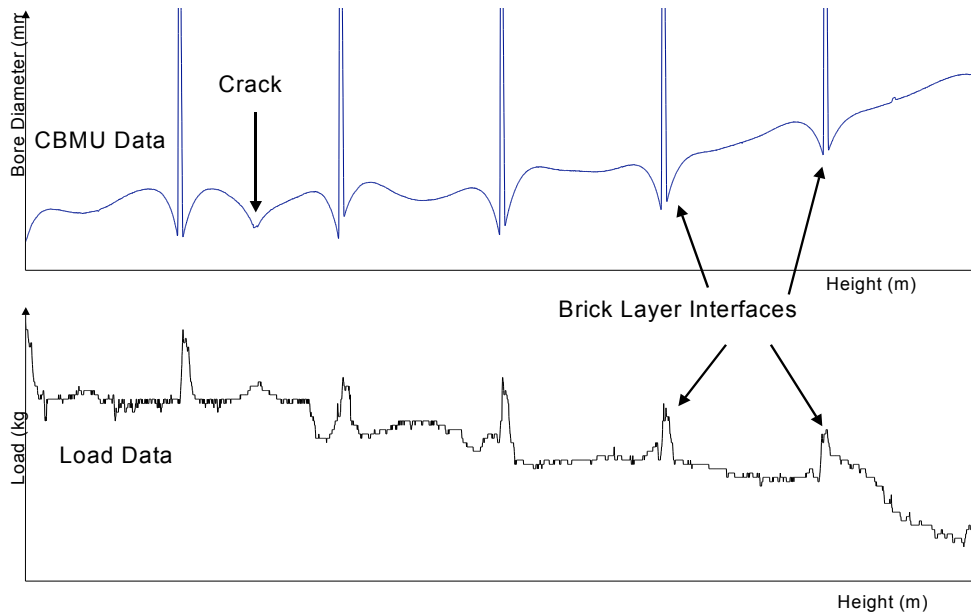
FIGURE 1: Diagram comparing FGLT data with channel diameters

Types of distortion

The objective of this research is to develop a system for detecting abnormal core distortions from the FGLT data. This process is difficult for two main reasons. Firstly, there are very few instances of brick cracking and secondly the exact nature of how these defects form and manifest themselves within the FGLT data is not fully understood. It is currently thought that there are two main modes of brick cracking, namely circumferential cracking and primary cracking. Circumferential cracking refers to cracks that propagate round the inner surface of the channel wall as shown in figure 2. The stresses built up within the brick cause it to distort at the crack interface, causing a restriction at the crack over time. This manifests itself as a peak within the FGLT data and has been corroborated with known cracks from CBMU data.
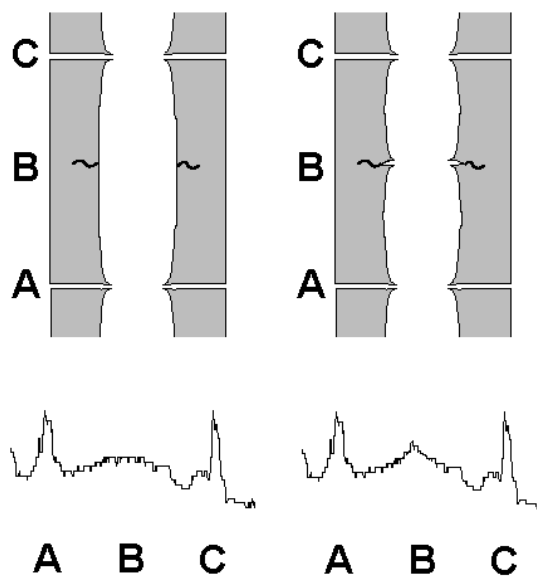

FIGURE 2: The development of a circumferential crack. The upper two diagrams show a cut-away of a graphite brick with points A and C illustrating the interfaces between two bricks. The lower two diagrams show the equivalent FGLT response.

Primary brick cracking occurs when the brick splits down its entire length. In addition, it is hypothesised that a second full-length crack can develop, breaking the brick into two parts. The results of primary brick cracking are not fully understood, though it is thought that both of these cracks would cause a step change in expected load across the entire brick layer. It is hypothesised that a single primary crack will cause the brick to open out slightly, producing a slightly wider channel diameter. As a result there will be less friction on the fuel assembly and overall a drop in load. In the situation of a double cracked brick, there may be no visible change if the brick is held in place by the surrounding bricks. However, if there were a shearing force between the two halves of the brick, then there would be a resulting reduction in the diameter seen by the fuel assembly, resulting in a step change in load across the brick layer. It should be stressed that this understanding at present is still being developed and while there are very limited instances of brick cracking the behaviour will be restricted to theoretical and experimental results.

Availability of data
FGLT data has been recorded for every refuelling event undertaken at every station and is kept as part of station records. Though there is a move to make the capture of this data electronic, the majority still is stored as paper traces. In an effort to provide a benchmark of FGLT data for future analysis, and to allow a greater number of these traces to be compared, a substantial number (approaching 1000 events) have been converted to electronic files through a process of scanning and digitisation. This has provided a large volume of data, but as a result, automation of the analysis is required in order to prevent the analyst becoming overloaded with data. The following section describes the data-mining approach adopted to analysing this data.

A FGLT PROFILING SYSTEM USING A DATA-MINING APPROACH

A profiling system was developed to explore the FGLT data, which allows engineers to identify outlying refuelling events from a user-defined set of events. It also allows the user to define a set of good behaviour based on a predefined set of known, acceptable refuelling events. In addition, relationships between the channel location, load status, date of refuelling and status of fuel stringer can be explored. The resulting profiling system is easy to use, provides a consistent method of comparing FGLT data, allows several hundred traces to be examined simultaneously and allows models of expected behaviour to be developed.

Data-mining approach
The approach adopted to the development of the system, and therefore the analysis of the FGLT data, follows the general Knowledge Discovery in Databases (KDD) process proposed by (Fayyad, 1996). The key stages of this are summarized in figure 3, and can broadly be separated into a preprocessing stage, where the data is selected and cleaned and a data-mining stage where the data is examined for underlying patterns.
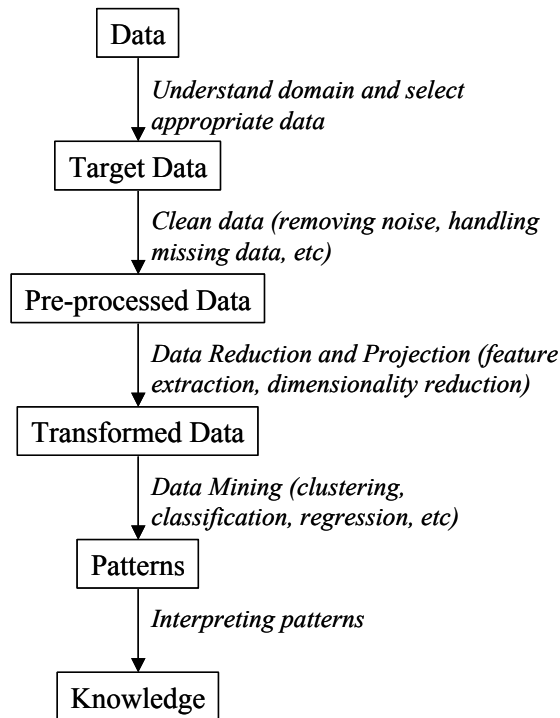
FIGURE 3: The key stages of the knowledge discovery in databases process.

Data Pre-processing

The step of understanding the domain and selecting the appropriate data was straightforward, as there was only FGLT data available. It was, however, important to ensure that as much of the event specific information was preserved with the actual data. This included the station, reactor and channel relating to the refuelling event, as well as the date of refuelling. In addition information as to whether the reactor was online or offline was recorded as well as whether the fuel stringer had previously been shuffled from another channel, as it is suspected that this will have an effect on the load trace. Cleaning the data involved removing spurious data points from the digitised data during the digitisation process and also removing stoppages, where a fuel assembly is paused during refuelling to inspect the seals before being shuffled to another channel. Also, where relevant, the data was rescaled to a common sample rate to allow two or more events to be compared on a point-by-point basis. Finally, the data was segmented into individual brick layers to allow a more detailed brick by brick analysis to be undertaken. The resulting cleaned, pre-processed data was then stored in a database to permit fast access and searching, using the event information as the indexing terms.

Data-mining

Data-mining is the process of discovering new patterns and knowledge within datasets. For detecting abnormalities relating to circumferential cracking, brick layers were analysed on an individual basis. In addition, the shape of the brick profile, rather than the absolute values of load was found to be the important factor. Also, in order to identify a trace as abnormal, some measure of normality was required. As there was no definite knowledge of what a good and bad brick layer trace should look like, it was felt that selecting one event as a benchmark would not necessarily be the most optimal solution. Instead, it was decided that an average trace developed from all the traces in the data set would provide a good reference. The assumption here is that most of the events represent good behaviour and that there is only one single mode or shape relating to good behaviour. For the purposes of exploring the FGLT data, the method shown in figure 4 was developed and implemented within the profiling system.
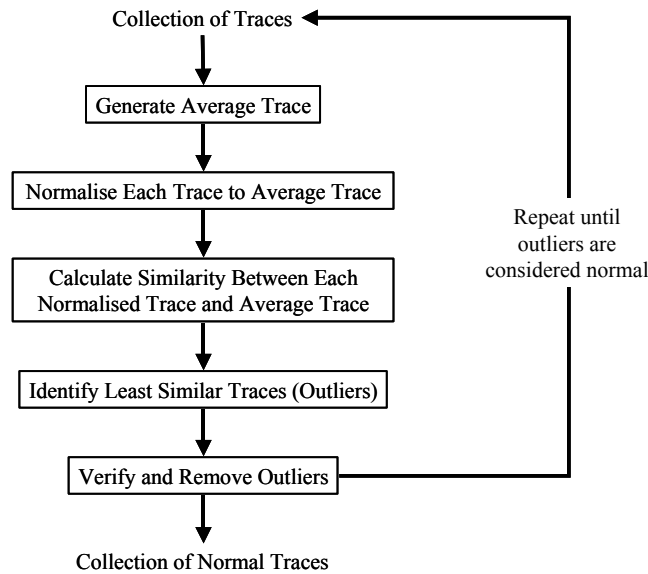
Collection of Traces

Generate Average Trace

Normalise Each Trace to Average Trace

Calculate Similarity Between Each
Normalised Trace and Average Trace

Identify Least Similar Traces (Outliers)

Verify and Remove Outliers

Repeat until
outliers are
considered normal

Collection of Normal Traces

FIGURE 4: Method of analyzing FGLT data

The steps from generate average trace through to identify least similar traces were automated within the profiling software. Human intervention is still required in order to make the judgement of which traces should be included in the initial collection of traces and also to assess those traces that are identified as least similar to the majority. The measure of similarity chosen was the root mean squared error between a trace and the reference trace. However, the manual tasks of plotting the graphs and calculating the similarities have been automated, resulting in a very quick way of comparing many traces. The repeatable nature of the software also makes it useful for providing a consistent, auditable measure of an anomaly as opposed to a more subjective, manual analysis.

Implementation and use of the profiling system
The system was implemented using a client-server architecture. The system is accessed through a web-based front end where the user selects the appropriate files for analysis using a number of search criteria such as station, reactor and refuelling date. This dataset is then queued on the server for analysis which is undertaken by the processing engine at the next opportunity. The user can monitor the progress of the analysis from a web-page and is informed when the analysis is complete. When the software is used to perform the analysis as shown in figure 4, there are two outcomes. The first is identification of those traces that differ significantly from the majority of the other traces, which can then be examined in greater detail, perhaps in conjunction with other sources of data such as inspection records from outages or with further historical data from the station. The second is to identify a set of traces that the user considers to be normal. This data set can then be used to derive a set of envelopes of expected behaviour against which new refuelling events can be compared. In this way, a set of envelopes for each reactor in each station can be defined.

Case Study
This case study demonstrates the use of the profiling system to define a set of envelopes for brick layer 7 in Reactor 3 for Hunterston B, and four screenshots from this process are shown in figure 5. Firstly, the user enters the search criteria and is presented with a list of matching files. This is shown in the top left screenshot. The user then selects those files to include in the analysis. The analysis is then queued on the server and undertaken automatically when it reaches the top of the queue. The top right screenshot shows a plot of the raw data, while the bottom left screenshot shows the data normalised to the average trace, indicated by the thick black trace. The bottom right screenshot shows a plot of the RMS errors from this average

trace for each trace. An ordered list of traces, from highest to lowest RMS error is also provided. Finally, the maximum and minimum envelope, along with the average trace can be saved to an external file for incorporation into the intelligent analysis system.
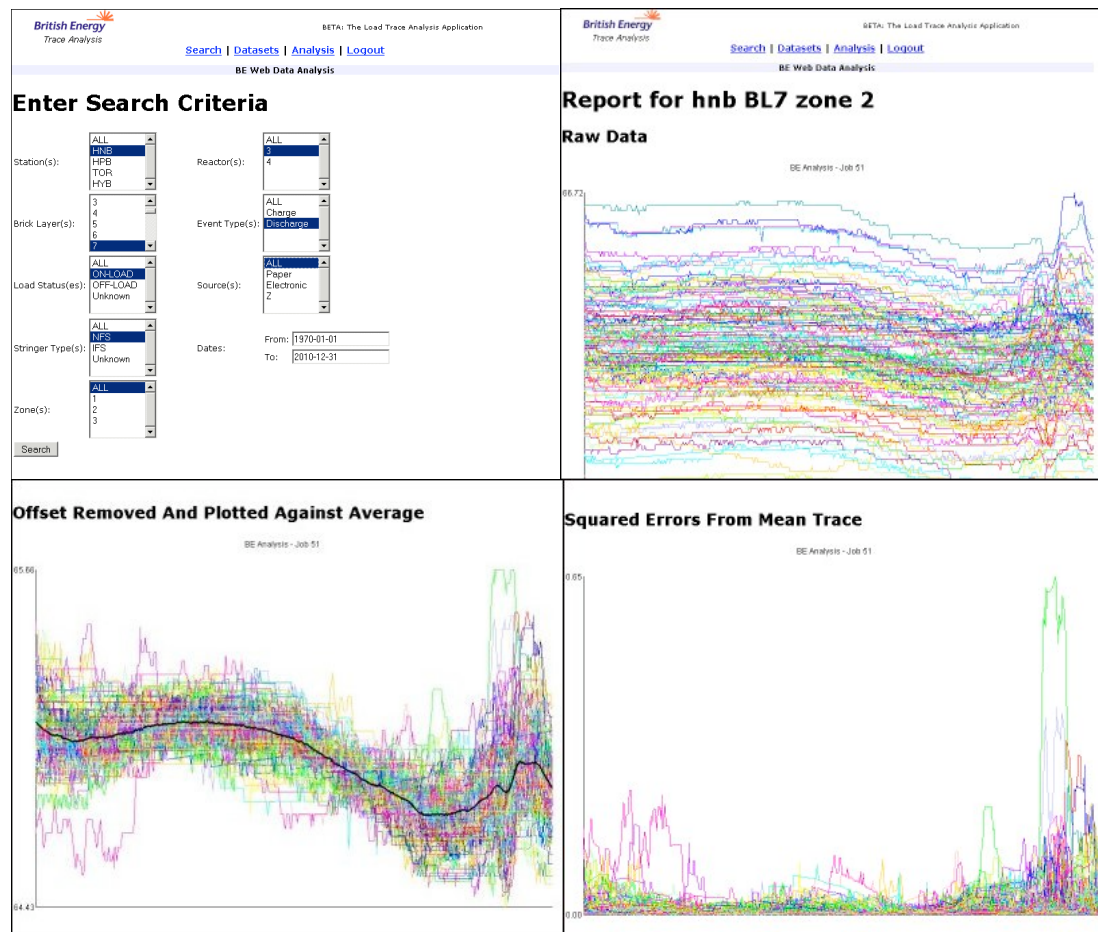

FIGURE 5: Four stages of using the profiling system

AUTOMATED INTELLIGENT ANALYSIS SYSTEM

In addition to the profiling system for exploring the FGLT data, a second system was developed to automatically analyse FGLT data taken from new refueling events. This system uses sets of acceptable envelopes derived using the profiling system to make an assessment of any new trace. In addition to assessing the shape of each brick layer, thus identifying possible circumferential cracking, it also assesses the average load of each brick layer and compares it with a set of expected brick averages. A step change in load across a brick layer, therefore a similar step change in average load value for the brick layer may indicate the presence of primary brick cracking. The automated intelligent analysis system has a simple front end. The user selects a refuelling event file or files to analyse. The system obtains some key configuration information from the filename, such as the station and reactor and loads the appropriate rules and envelopes of expected behaviour. The raw data is then segmented into individual brick layers by identifying the brick interfaces, characterized by peaks in the data. This identification is undertaken using a rule-based engine that classifies each peak within the data according to its shape, relative location within the load data stream and its associated height value, if available. These underlying rules are generic to all the stations, though the individual limits are specific to the station to which the event being examined belongs. Once the brick layers are identified, they are compared to the pre-defined

envelopes in order to identify any that breach the bounds of the envelope. A report is automatically generated which provides the results of each brick layer analysis, both in terms of any breaches of the expected envelope and also a comparison to the expected average load. Summary results of the analysis are also stored within a database to be retrieved by future analyses of that channel.

FUTURE WORK AND CONCLUSIONS

Both systems are installed and are undergoing an evaluation period at the engineering offices in Barnwood. Currently, the analysis undertaken by the automated intelligent analysis system is restricted to making statements about whether the expected envelopes have been breached or not. A further area of research is to characterise these deviations and this will hopefully become possible as deeper understanding of FGLT data applied to core condition monitoring is developed. There is also scope for including historical analysis of tie-bar load trace data with the ultimate goal of deriving a model of how graphite core bricks distort over time, based on previously observed behaviour. This raises interesting questions about how and where the data should be stored.

This paper has described the use of FGLT data to provide information relating to core condition from a source not originally intended to provide condition monitoring information. This has resulted in the development and implementation of two supporting systems. The first system importantly allows a deeper understanding of the behaviour of FGLT data to be developed through a data-mining approach. It provides the means to visualize and explore large volumes of FGLT data in a quick and repeatable manner and as a result define models of expected behaviour. The second system uses these models of expected behaviour to automatically assess FGLT data gathered from new refueling events, quickly identifying potential instances of brick cracking. The user is provided with a detailed summary of the analysis on a brick by brick basis. Both these systems allow existing data sources to be leveraged to provide information relating to the condition of a channel following a refueling event, which occur with a far greater frequency than the existing detailed inspections undertaken during outages. In addition, gathering existing and historical data in a single location and through the use of the profiling software, patterns and relationships between different refueling events can be rapidly and consistently be explored to determine whether time, location, stringer condition and load conditions have an effect on the trace, ultimately increasing the understanding of the existing, and possibly future, condition of the core.

References
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Steele, J.A., Martin, L. A., McArthur, S.D.J, Moyes, A., McDonald, J.R., Howie, D., Elrick, R. and Yule, I. (2003) "An Intelligent System for Interpreting the Nuclear Refuelling Process within an AGR". Proceedings of the Institution of Mechanical Engineers Part A, Journal of Power and Energy, Vol. 217, 2003