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Distributed Data Fusion for Condition Monitoring of Graphite Nuclear Reactor Cores

by

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Abstract

Nuclear power stations worldwide are exceeding their originally specified design lives and with only limited construction of new generation underway, there is a desire to continue the operation of existing stations to ensure electricity supply. Continued operation of nuclear power stations with degrading and life-limiting components necessitates increased monitoring and inspection, particularly of the reactor cores, to ensure they are safe to operate. The monitoring of a large number of components and their related data sources is a distributed and time consuming process for the engineer given the lack of infrastructure available for collecting, managing and analysing monitoring data. This thesis describes the issues associated with nuclear Condition Monitoring (CM) and investigates the suitability of a distributed framework utilising intelligent software agents to collect, manage and analyse data autonomously. The application of data fusion techniques is examined to estimate unrecorded parameters, provide contextualisation for anomalies in order to quickly identify true faults from explainable anomalies and to extract more detail from existing CM data. A generalised framework is described for nuclear CM of any type of reactor, specifying the required components and capabilites based on the design of a suitable Multi Agent System, including the interaction of the framework with existing CM systems and human users. A high level ontology for nuclear CM is proposed and is emphasised as a crucial aspect of the data management and extendability of the framework to incorporate further data sources and analyses. A prototype system, based on the generalised framework is developed for the case of the Advanced Gas-cooled Reactor, with new and existing CM analyses formalised within intelligent agents. Using real station data and simulated fault data, the prototype system was shown to be capable of performing the existing monitoring tasks considerably faster than a human user while retaining all data and analyses for justification and traceability of decisions based on the analyses.

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Groucho Marx once said "*Outside of a dog, a book is a man's best friend. Inside of a dog, it's too dark to read.*" This is good advice and relevant to this thesis.

This thesis represents the views of the author and not necessarily those of EDF Energy, EDF Group companies, or their employees.

Contents

List of Abbreviations

ACL	Agent Communication Language
AGR	Advanced Gas-cooled Reactor
AMS	Agent Management System
ANN	Artificial Neural Networks
APACS	Advanced Process Analysis and Control System
API	Application Protocol Interface
BDI	Belief Desire Intention
BE	British Energy
BETA	British Energy Trace Analysis
BWR	Boiling Water Reactor
CANDU	CANadian Deuterium Uranium
CBMU	Channel Bore Measurement Unit
CPD	Channel Power Discrepancy
CCPD	Change in Channel Power Discrepancy
CDF	Core Damage Frequency
CM	Condition Monitoring
COMMAS	COndition Monitoring Multi Agent System
CPD	Channel Power Discrepancy
DC	Data Collector
DF	Data Fusion
DFa	Directory Facilitator
DM	Data Mining
EDF	Electricite de France
FIPA	Foundation for Intelligent Physical Agents
FGLT	Fuel Grab Load Trace
HPB	Hinkley Point B
HNB	Hunterston B
HYA	Heysham 1
HYB	Heysham Stage 2
HRA	Hartlepool A

HSE	Health and Safety Executive
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
IA	Intelligent Agent
IAEA	International Atomic Energy Agency
IF	Information Fusion
IMAPS	Intelligent Monitoring Assessment Panel System
JADE	Java Agent Development Environment
JDL	Joint Directors of Laboratories
JSP	Java Server Pages
JVM	Java Virtual Machine
MAP	Monitoring Assessment Panel
MAS	Multi Agent System
NPS	Nuclear Power Stations
ODF	Optical Data Format
ONR	Office of Nuclear Regulation
PEDA	Power Engineering Diagnostic Agents
PWR	Pressurised Water Reactor
RMA	Remote Management Agent
RUL	Remaining Useful Life
SCADA	Supervisory Control And Data Acquisition
SQL	Structured Query Language
TOR	Torness
URL	Universal Resource Locator
WANO	World Association of Nuclear Operators

List of Variables

CPD	Channel Power Discrepancy value
$CCPD$	Change in Channel Power Discrepancy value
D	Estimated control rod drive order
F_{FGLT}	The measured Fuel Grab Load Trace force
F_{fr}	The frictional force component of the FGLT
g	Gravity
h	Height in the core
H	Row vector of heights in the core
K	Delta function of direction of motion
m	Mass of the fuel stringer
t	Time
δ	Change in height
Δ	Deviation between predicted and actual motion
ϕ	Fuel channel diameter
ρ	Correlation
μ	Coefficient of friction

List of Figures

Chapter 1

Introduction

1.1 Background To The Research

Increasing energy demand worldwide, coupled with an environmental need to move to low carbon electricity generation, has resulted in renewed interest in nuclear power in some countries. The construction of new Nuclear Power Stations (NPS) is politically and economically controversial and can take up to 10 years [Kennedy2007] to construct and begin generating electricity. In the meantime there is a desire to continue the operation of existing NPS, many of which are exceeding their original design lives.

Regular inspections of station components are required to ensure that equipment is in good condition, that safety systems are functional and that the facility meets the operating conditions of the license under which it operates. These inspections normally require the reactor to be offline, which is expensive to the operator and also results in a gap in generation for the duration of the outage, therefore in recent years there has been an increasing focus on Condition Monitoring (CM) of reactors during operation, to supplement inspections. Monitoring will normally not provide conclusive information or data of the same detail as inspections, however the impact on operation is comparatively lower, provides decision support and can often be automated in software.

A key problem associated with the addition of CM to existing nuclear facilities, as a result of tight regulation of the nuclear industry and the age of many existing nuclear facilities, is a limitation on the addition of new equipment or an onerous amount of work required to do so. Recent work on nuclear CM has included the application of intelligent analysis techniques to address particular analysis problems non-invasively, without directly interfacing with reactor systems. The application and integration of these analyses however normally occurs on an ad-hoc basis with little re-use of data and often limited consistency in approach across different analyses.

An example of this type of monitoring problem exists in the UK, which currently operates a fleet of Advanced Gas Cooled Reactors (AGR) at seven stations constructed between the late 1960s and the early 1980s. By increasing the volume and frequency of inspection, monitoring and materials research performed on the AGR stations, expanded safety cases have been developed to justify the continued operation of the stations however the retrieval and management of data and subsequent analysis is still largely performed manually. A formal CM scheme was introduced at the oldest AGR stations in 2005, which grades various core-related parameter observations at quarterly meetings. The CM analyses performed vary between stations and most consist of a visual inspection of manually collected data by an experienced engineer, with little storage and re-use of data, rather than automated and repeatable analyses. Indeed due to the number of data sources, the required data pre-processing and the various expertise required, CM of a nuclear reactor can be seen to be a highly distributed and time consuming process.

1.2 Justification For Research

To support continued operation of existing NPS, of any design, there is a need for a software framework which can implement intelligent analysis techniques such that maximum use is made of CM data, to gain as much information as possible about reactors between outages. Further, there is a desire for integration of existing monitoring systems to provide more detailed contextual information when performing CM and to provide external access to existing data. Previous online and offline CM applications in the nuclear domain have been based on single, centralised systems approaches, for one or more CM applications, however the distributed nature of the problem of NPS CM suggests that conventional software approaches may not offer the best solution for such a system, therefore the applicability of an agent-based system is investigated. Intelligent software agents can be encoded with knowledge and analysis abilities and distributed over several locations to provide capabilities and flexibility that a monolithic system cannot.

This thesis proposes a framework for automatically managing many distributed data sources, while minimising duplication of effort in data collection, management and analysis, allowing for future extension of the knowledge base and the development of new analyses. This framework, based on a distributed system of Intelligent Agents (IA), would allow the engineer to gain perspective of events across the reactor. Many reactor parameters are correlated and the analysis of multiple data sets, using Data Fusion (DF) techniques, is proposed to as a method to derive more detailed CM results. These techniques can be applied where knowledge exists which describes the causal relationship between multiple parameters or where a parameter is unknown, but can be estimated using related datasets. The deployment of a set of agents with these DF analysis capabilities, coupled with agents designed to access and store data in a common format, could allow for simplified development of further analyses with a particular emphasis on the use of multiple data sources to confirm and correlate events. Indeed, for the case of the AGR, many of the existing CM analyses are performed manually, and often not quantitatively which results in limited scope for trending and comparison between components. This thesis therefore investigates the use of a Multi Agent System (MAS) to develop these existing analyses algorithmically, to provide more useful CM information from the existing monitoring regime. Though the work described in this thesis is inspired by the existing AGR stations in the UK, the potential benefits of the research have applications in other reactor designs and even in the design of future reactors which are likely to incorporate monitoring systems from construction.

1.3 Thesis Overview

This thesis begins with a discussion of nuclear power, including a brief overview of the operation of common nuclear reactor designs and the key components and the roles they perform, describing in particular the safety and control systems. The particularly safety conscious nature of the nuclear industry is then reviewed as the basis for the increasing application of CM to critical components of NPS.

Chapter 3 introduces the Advanced Gas-cooled Reactor in more detail, including a review of the principal reactor components, their functionality and their impact on the safe operation of the reactors. The issues of ageing and degradation of the reactor are then discussed, describing the need for, and the current implementation of, a formalised monitoring regime for the AGR fleet, to compliment physical inspections. The challenges and limitations of the current AGR monitoring regime are compared to those discussed in the wider nuclear industry as described in Chapter 2, particularly the issues associated with the collection, storage and analysis of reactor data. It is argued that an extensible framework is required to perform these tasks in a more efficient and repeatable manner while combining datasets wherever possible to derive as much system health information as possible. Thus it is proposed that the application of DF techniques within a distributed system of intelligent software agents is a suitable method of solving this problem.

Chapter 4 reviews common approaches and techniques used in the field of CM and describes some relevant previous CM applications, including examples in the nuclear industry. The key characteristics of these examples are discussed with a specific emphasis on intelligent systems approaches and some of the issues encountered and lessons which can be incorporated into the design of a distributed monitoring framework.

Chapter 5 introduces the concept of intelligent, autonomous agents; describing aspects of agent architecture, design methodologies and inter-agent communication. The autonomous and social nature of agents is emphasised through the introduction of Multi Agent Systems (MAS) and a discussion of previous CM work, including nuclear applications, using Multi Agent Systems.

Chapter 6 introduces the principles of data and information fusion techniques, reviewing previous applications in CM and recent work in agent-based data fusion. A generalised framework is then described for the application of data and information fusion of nuclear reactors within a distributed, agent-based framework including a comparison of the attributes of such a framework with the requirements of nuclear CM.

Chapter 7 describes the creation, development and implementation of CM analyses implementing data and information fusion techniques for the specific case of the AGR. The analysis of some key reactor systems which are already considered in the AGR monitoring regime are formalised as analytical algorithms, suitable for deployment in agents. The correlation of disparate reactor events which can affect reactor power is automated, using periodic analysis algorithms which fuse multiple sets of qualitative event data. The existing manual analysis of control rod motion is replaced with a numerical CM analysis, which fuses sensor data from multiple rods to produce a new, quantitative CM parameter. Finally, an analysis is developed which attempts to trend the degradation of the graphite core based on the fusing of monitoring and inspection data, to provide a geometric estimate of channel distortion based on regularly available monitoring data.

The analyses developed in Chapter 7 are then implemented as intelligent agents, within a prototype distributed CM framework which is described in Chapter 8. Development of the ontology and the platform is described in detail. The implementation within the prototype framework is described for each analysis, using samples of real data from AGR stations and examples of analyses and results.

Chapter 9 summarises the research presented in this thesis, discussing the main contributions, the knowledge gained from the work, the potential practical use and value of the prototype system and possible future work.

1.4 Novel Contributions

- A critical review of intelligent CM of nuclear reactors, describing key conclusions from previous work, determining where further work is required and where limitations have previously been met

- Specification of a generalised framework for distributed CM incorporating DF techniques for nuclear reactors for decision support between inspections

- Development and testing of a prototype distributed Condition Monitoring for nuclear reactors and in particular for the AGR, to introduce greater consistency and efficiency to the existing monitoring scheme

- Integration of Data Fusion analysis techniques to Condition Monitoring of nuclear reactors to analyse and explain reactor events by combining and correlating disparate data sets from reactors

- Demonstration of the suitability of agent based systems for Data Fusion and other CM analyses in the nuclear domain

- An analysis of the operation of the AGR to determine suitable parameters for Condition Monitoring analysis and where Data Fusion techniques may be applied to enhance monitoring

- Implementation of existing Condition Monitoring analyses in the prototype agent based system for an AGR

- Development of new Condition Monitoring analyses, including:

    1. Creation of a quantifiable parameter for control rod Condition Monitoring and prognostics based on Data Fusion techniques
    2. Combination of refuelling data and control rod management data to automatically generate explanations for thermal and neutronic power analysis results

3. Combining physical inspection and monitoring data to enhance and refine refuelling CM and generate a geometric estimate of channel distortion

1.5 Related Publications

The following publications are associated with and have been published or accepted for publication prior to the submission of this thesis.

- *"Distributed Data and Information Fusion for Nuclear Reactor Condition Monitoring"* C. J. Wallace, G.M West, S. D. J. McArthur, D. Towle. IEEE Transactions on Nuclear Science Vol. 59, No 1. January 2012
- *"Integrated Condition Monitoring For Plant-Wide Prognostics"* C.J. Wallace, J.J.A Costello, G.M. West, S.D.J. McArthur, M. Coghlan. Chemical Engineering Transactions, Vol. 33, 2013
- *"Intelligent Distributed Condition Monitoring For Nuclear Power Plants"* C. J. Wallace, G. M. West, S. D. J. McArthur and M. Coghlan. Proceedings of Eighth American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, 2012
- *"Intelligent Graphite Core Condition Monitoring"* C. J. Wallace, G. M. West, M. Coghlan, D. Towle, S. D. J. McArthur. Proceedings of Modelling and Measuring Reactor Core Graphite Properties and Performance, 2011
- *"Data Fusion For Enhanced Condition Monitoring Of Nuclear Reactor Refuelling"* C. J. Wallace, G. M. West, S. D. J. McArthur, G. J. Jahn. The Eighth International Conference on Condition Monitoring and Machinery Failure Prevention Technologies, 2011
- *"Multi-Agent System For Nuclear Condition Monitoring"* C. J. Wallace, G. J. Jahn, S. D. J. McArthur. Proceedings of 10th Int. Conf. on Autonomous Agents and Multiagent Systems (AAMAS 2011)

- *"Control Rod Monitoring of Advanced Gas-Cooled Reactors"* C. J. Wallace, G. M. West, G. J. Jahn, and S. D. J. McArthur, D. Towle and G. Buckley. Proceedings of Seventh American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies, 2010
- *"The Effect of Reactor Parameters on AGR Refuelling at Hinkley Point B"* C. J. Wallace, G. West, S. D. J. McArthur, D. Towle, J. Reed. Proceedings of 'Securing the Safe Performance of Graphite Reactor Cores', Royal Society of Chemistry, 2008.

Chapter 2

Nuclear Power and Safety

2.1 Introduction

On December 2nd 1942, in a former Rackets court under the stands of the Alonzo Stagg Field stadium at the University of Chicago, Enrico Fermi and his team created the first artificial self sustaining nuclear fission reaction in a reactor called Chicago Pile 1 (CP-1) [Angelo2004]. The world's first nuclear reactor was primitive by modern standards, consisting of layers of graphite and uranium blocks, which was brought to criticality by slowly withdrawing cadmium coated control rods with a length of rope pulled by a researcher. It is interesting to note however that there are several key similarities between this first reactor and the current generation of civilian nuclear reactors operated in the UK. Though the CP-1 reactor wasn't used to produce any electricity and only achieved criticality for around 28 minutes, the use of a graphite moderator and uranium fuel shares some fundamental design principles with the AGR. Indeed it is interesting and relevant to this work to discuss the physical and technological reasons for particular design choices for nuclear reactors and where commonalities between different designs and general principles for engineering and problem solving in the nuclear domain exist. This chapter will therefore describe the basic operating principles of nuclear reactors, including a discussion of the most prevalent designs of civil reactor, and a description of the particularly prominent role that safety and regulation plays in the nuclear industry.

2.2 Nuclear Fission

The fundamental principle of nuclear fission is that by causing a large atom to break into smaller pieces (the net mass of which is slightly less than the mass of the original large atom), the change in binding energy, holding the large atom together, results in a release of energy [Stacey2007]. This is achieved by bombarding the large atoms with slow moving *thermal* neutrons until the balance of nuclear forces inside the atom becomes unstable, due to an excess of neutrons, and the atom splits apart, as illustrated in Figure 2.1.

An incoming thermal neutron combines with a large atom, causing it to fission and split into two other atoms and potentially another neutron. The released neutron may then go on to cause another fission, potentially releasing further thermal neutrons and continuing the cascade. Only certain isotopes of some atoms are fissile in this way, and are normally found in extremely low concentrations. Most civil nuclear fuel uses an isotope of uranium, U^{235} which on average composes 0.72% of natural uranium ore, therefore significant effort is required to enrich uranium materials to a sufficient level for the desired use. For civil nuclear re-

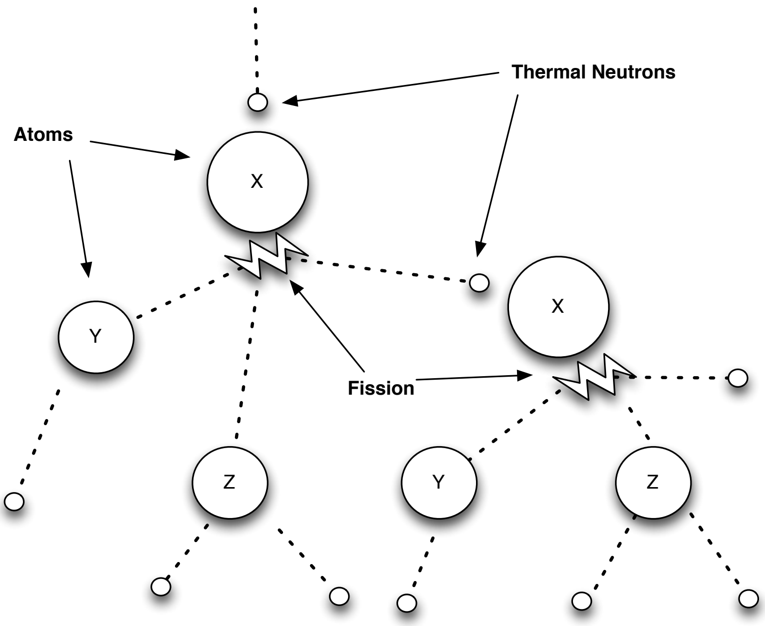

Figure 2.1: A schematic representation of a fission chain reaction.

actors this fraction is around 2%, for research reactors around 15% and close to 90% for weapons grade material. With a greater fraction of fissile U^{235}, fewer neutrons are required to achieve a self sustaining cascade of reaction known as criticality.

It is possible to manipulate the speed of neutrons through use of materials with moderating properties, which can slow down a fraction of the fast neutrons to create a larger number of thermal neutrons, that can cause fission reactions [Angelo2004]. Some materials, such as water, moderate neutrons slightly, while other materials such as graphite or heavy water (D_2O) moderate very strongly. The opposite of a neutron moderation is neutron absorbtion, whereby certain materials absorb neutrons and prevent them from interacting with fissile material and continuing the chain reaction. The absorbance or moderation of materials has an important influence on reactor design. Hydrogen for example is an excellent neutron moderator, but is also a neutron absorber, while Deuterium is not. The net result of which is that while water acts as a moderator, heavy water (where Deuterium replaces Hydrogen) is a much more effective moderator. Conversely, some metals such as boron or cadmium are very strong absorbers and are often used in reactors to control the fission reactions.

It is this complex relationship between fuel, moderator and control that dominates nuclear reactor designs, all of which aim to achieve criticality but with sufficient stability that they do not result in uncontrollable, runaway reactions. For the most part however, reactor designs have historically varied between countries due reasons of economics, expertise and availability of materials.

2.3 Reactor Design

As with conventional thermal power plants, the basic principle of a nuclear power reactor is to generate heat which is then transferred either directly or indirectly to a boiler which creates steam in order to drive a turbine and generate electricity. The choice of coolant, which takes heat away from the core, is therefore a convenient method of classifying the various types of reactors.

2.3.1 Water Cooled Reactors

Water cooled reactors are by far the most common types of reactors [Bodansky2007] and can be divided into two main types: Boiling Water Reactors (BWR) and Pressurised Water Reactors (PWR). The BWR, designed in the 1950s, is one of the oldest civil nuclear reactor designs and uses water as both coolant and moderator. The reactors are fuelled with bundles of slightly enriched uranium Dioxide (UO_2) ceramic pellets which undergo fission due to geometry of the core and the presence of water as a neutron moderator. The water in the core is allowed to boil due to heat from the fission reactions in the fuel and passes from the top of the reactor steam pipes to drive turbines before passing through a condenser and re-entering the bottom of the reactor. The generation of steam in the top of the reactor causes extreme variations in neutron flux in the region and as a result the control rods of BWRs are inserted from below the reactor to control the fission reactions. Control of the power of the reactor is achieved by altering the position of these control rods and varying the flow of water into the core. The simplicity of the BWR design has made it a popular choice in countries without a sophisticated existing nuclear industry.

Unlike the BWR, the PWR is designed to keep the water, which again acts as both coolant and moderator, in liquid state. This is achieved by including a pressuriser in the coolant loop which keeps the water at around 15MPa. Since the PWR does not create steam directly, a secondary stage is required through which the primary coolant loop passes, which is allowed to boil and create steam which drives the turbines. PWR power generation is controlled by varying the position of the control rods, inserted from above the core and through the addition of low concentrations of boric acid (a strong neutron absorber) into the core.

Variations of the BWR and PWR were constructed in several countries including the UK, France, Germany, United States and Japan while the Russian VVER reactor shares a very similar design to the PWR. The Russian RBMK (Russian acronym for High Power Channel-type Reactor), also utilises water as a coolant, however it uses graphite as the principal moderator.

2.3.2 Gas Cooled Reactors

Gas cooled reactors are less common than water cooled reactors and were developed mostly in Britain, France and Russia, with exported reactors in Italy, Japan, Spain and North Korea [Bodansky2007]. Most gas cooled reactors use Carbon Dioxide (CO_2) as a primary coolant and graphite as a moderator. As a much stronger moderator than water, the use of a graphite allows the use of lower enriched uranium or even natural uranium as a fuel, significantly lowering front-end costs of the fuel cycle at the expense of a generally larger core. Most gas-cooled reactors however use enriched fuel to achieve a higher power density and a smaller size than water-cooled reactors of comparable output.

The British Magnox reactor comprised the first generation of civil nuclear reactors in the UK, with 26 reactors constructed between the mid 1950s to 1970. A similar reactor, the French UNGG was developed around the same time, however only 10 were constructed as water cooled reactors became dominant. While most countries moved towards operating water cooled reactors, the UK continued to develop gas cooled reactors with the Advanced Gas-cooled Reactor fleet, an evolution of the Magnox design. The AGR generates comparable electricity outputs to modern water cooled reactors, with a slightly greater thermal efficiency and the ability to refuel at power. The AGR is discussed in greater detail in Chapter 3.

2.3.3 Other Civil Nuclear Designs

Although water and gas cooled reactors dominate the civil nuclear industry for the purposes of electricity generation [Bodansky2007], other distinct designs of reactor are in use. The CANadian Deuterium Uranium (CANDU) reactor for example uses pressurized heavy water as a moderator, which allows the reactor to be run using cheaper, natural (i.e. non-enriched) uranium fuel. The CANDU reactor, like the AGR, was also designed for at power refuelling and has been exported to several countries including India, Pakistan and South Korea.

For several decades there was strong interest in the possibility of the use of so-called breeder reactors, which could generate more fissile material than was burned during fission, by surrounding the core with suitable breeding material (which was otherwise un-fissionable) which could be bred into fuel by exposure to neutrons from fission reactions inside the core. Complexities of design, including the need to use liquid metal coolants and the changing economics of uranium based fuels resulted in a drop in interest in such reactors in recent years for power generation, however they remain a potentially relevant technology for future nuclear reactors due to their ability to extract greater amounts of energy from fuel than existing reactors.

2.4 Nuclear Safety

By virtue of the way that energy is released in a nuclear reactor, through a controlled chain reaction, and the huge amount of energy potentially available, safety concerns are particularly acute in the nuclear industry. The decay heat, for example, the power generated in a reactor core when the reactor has been shut down, can continue to be as much as 1% of normal output, several hours after the reactor has shut down. Nuclear safety can be separated into two main classes, *Safety Design* [Petrangeli2006], where some aspect of the design of a nuclear reactor component performs a safety function and *Regulation* [Walker2000], which ensures that a safe operating environment is maintained and that correct procedures are followed.

2.4.1 Safety Design

The design of specific safety systems of nuclear reactors depends to a large extent on the reactor type, but there are some general concepts of safety systems that are common to most reactor types, albeit in varying implementations. Safety design can be further divided into *active safety*, where some machine automation or operator action performs a safety function, and *passive safety*, whereby some design feature of the reactor provides safety functionality without any externally driven action occurring.

2.4.1.1 Active Safety

Managing the reactivity, or how close the reactor is to a self-sustaining chain reaction, is the most important control priority of any fission reactor, with loss of reactivity control potentially resulting in excessive generation of heat within the core [Bodansky2007]. Most reactor designs therefore incorporate control rod systems based on high redundancy and immediate access to the core. More specifically, there will normally be more rods available than are strictly required (to accommodate possible failures) and entrance to the core will be controlled by a simple system with high reliability. For reactors where the control rods enter from above the core, this system will normally drive some rods into the core mechanically and allow others to fall under gravity into the core. In the case of the BWR, where the neutron flux at the top of the core is too erratic (due to steam bubbles) the control rods are inserted from the base of the core. The BWR rods are held under constant pneumatic pressure during normal operation, keeping them outside the active core region, while in an emergency the pneumatic system is disabled and the rods automatically drive into the core.

Depending on the reactor type, there are various other methods of managing core reactivity, including altering the chemical composition of the coolant — for example, in the case of a PWR, by adding various concentrations of the neutron absorber boric acid. Other reactor designs, such as the AGR, include the capability to rapidly inject nitrogen, a strong neutron absorber, directly into the core to quench the fission reactions.

The dynamic relationship between fuel, coolant and moderator forms a complex and highly responsive system where small perturbations can be amplified massively and feed back into the system in a very short time. It is therefore essential that sufficient coolant, in any reactor design, is available. Consider for example, a water-cooled reactor where the coolant supply has been interrupted to some extent and the core begins to overheat. Some of the water will begin to boil, resulting in small voids forming in the moderator which can have very large effect on the reactivity of the core, as the voids will interact with the available thermal neutrons very differently to the moderator. While such a situation can potentially be dealt with by having backup coolant supplies available, such hazards are also considered in the design of modern reactors by incorporating passive safety.

2.4.1.2 Passive Safety

To continue the previous example of a water-cooled reactor with an interrupted coolant supply, we shall assume that no backup coolant supply is available and that the evaporation of the coolant water causes it to become less efficient at transferring heat away from the core, creating a feedback loop which causes the core to rapidly overheat. This situation may appear unrecoverable, but in fact by exploiting the fuel-coolant-moderator relationship, it is possible for a passively safe design, such as exists in the PWR, to stabilise this situation. Noting that the coolant of a PWR acts as both the moderator and the coolant, as the coolant becomes less effective (due to evaporation), so does its ability to moderate, resulting in a decreasing number of fission reactions. It can be seen therefore that such a reactor design is passively safe by design in such a circumstance. More formally, the International Atomic Energy Association (IAEA) classifies the passive safety of components, based on the absence of: "*moving working fluid*, *moving mechanical parts*, *signal inputs of 'intelligence'* or *external power input or forces*" [IAEA1991]. Passive safety design is therefore normally found in some geometric, structural or chemical property of a component and is almost always used in concert with active safety systems. Indeed a lack of passive safety in some designs can be a key driver for additional active safety.

2.4.1.3 Defence in Depth

Modern NPS are designed using a mixture of active and passive safety systems, with higher levels of redundancy in components than is found in almost any other field. In order to minimise the risk from potential hazards, it is standard practice to use multiple, overlapping safety systems — commonly called 'Defence In Depth' in the UK nuclear industry. The basic concept involves using multiple layers of independent and diverse redundant safety systems, each designed in such a way that a factor which causes one layer to fail will not cause another layer to fail, also known as a common mode failure. In other words, the process is designed to ensure that a single failure of a safety critical system will not cause a catastrophic event.

The risk associated with a particular reactor design is quantified statistically as a Core Damage Frequency (CDF), which is based on the predicted failure rates of components and estimated likelihood of particular events, such that damage is caused to the core which inhibits the safety systems from operating. A typical CDF for a modern reactor is around 5×10^{-5} per reactor year[Gaertner2008], across the entire fleet of a particular reactor design. For a fleet of 500 reactors for example, this would correspond to a core damage event once in 40 years. Such probabilistic qualifications are required at the design stage of reactors' construction, as part of the justification to the government regulator that reactors are safe to construct and operate. Regulation continues however, throughout the operating life of a NPS and indeed even after shutdown, as it is decommissioned, due to the hazardous materials which remain in the core.

2.4.2 Regulation

Given the strong emphasis placed on safety at NPS, regulation at every stage of construction, operation and decommissioning is a prominent feature of the nuclear industry. Though the remit and operations of regulators vary between countries, they will generally have a major say in, or even the final decision as to whether NPS are allowed to operate.

2.4.2.1 United Kingdom As An Example

In the United Kingdom, civil nuclear facilities are regulated by the Office Of Nuclear Regulation (ONR), a division of the Health and Safety Executive (HSE), based on the principle of making risk 'As Low As Reasonably Practicable' (ALARP) [UKHSE2009a]. This principle states that *"measures should be taken to reduce the risks unless the costs of doing so are disproportionately high compared with the risk averted"*. The purpose of the regulator therefore is to ensure that the operators are fulfilling this obligation. Existing NPS in the UK operate subject to conditional, renewable licenses, provided that the operator can demonstrate that the reactors continue to be safe to operate. These ‘safety cases’, produced periodically by the operator, collate evidence from monitoring, inspection, research and analysis of the reactors since the submission of the last safety case to argue for continued operation [UKHSE2013]. As the AGR fleet in the UK has largely exceeded the originally specified design lives, the safety cases have become increasingly stringent in their required safety margins, with significantly more inspections and monitoring [UKHSE2009b] than earlier in their operating lives.

The ONR in the UK, and regulators in other countries, also regulate the operation of other civil nuclear sites that do not generate power, such as fuel manufacture, re-processing sites or decommissioned stations. These sites, much like operating NPS, must carefully control the transport and storage of nuclear materials which carry both safety and security concerns if not managed properly. The acutely serious concerns associated with materials involved in the nuclear industry can be considered the main reason that the regulation and inspection of nuclear facilities is normally delegated to a government agency rather than to the private sector.

2.4.2.2 International Regulation

As well as regulation within each country which operates NPS, there are several international organisations and standards that, though not legally binding, provide guidelines for the operation, maintenance and regulation of the nuclear industry. The World Association of Nuclear Operators (WANO) for example, created after the Chernobyl accident, regularly inspects NPS all over the world, using a pool of experts drawn from within the organisation and publishes regular reports on the state of industry[WANO2011]. Other organisations, such as the IAEA generate reports and reviews of instrumentation and control of nuclear power systems as well as guidance on the state of the art monitoring and inspection technologies[IAEA2011a].

2.4.3 The Need For Nuclear Condition Monitoring

Noticeable surges in interest in nuclear safety occur after high profile events, most recently the Fukushima accident[IAEA2011b], after which the IAEA published their 'Action Plan On Nuclear Safety'[IAEA2011a]. This advisory paper calls for *"research and development in nuclear safety, technology and engineering, including that related to existing and new design-specific aspects"*. The response to events such as these combined with an ageing global fleet of NPS is causing an accelerated move towards increasing use of CM in the nuclear industry [IAEA2008]. In the United States, there is a government led scheme to manage the continued safe operation of the civil nuclear fleet [DepartmentofEnergy2008], the 'Life Beyond 60' program, which places particular emphasis on the need for monitoring of key components while standards agencies, such as the Institute of Electrical and Electronics Engineers have also published guidelines for monitoring of reactor systems [IEEE2012] based on the expectation of a large future increase in such monitoring.

In the UK, the knowledge that the graphite bricks of which the AGR reactor cores are constructed are experiencing cracking has led to an increase in monitoring for the oldest stations. The requirement to justify to the regulator, through periodic safety reviews [UKHSE2013] that the reactors are safe to continue operating, is a key driver for nuclear CM.

2.5 Discussion

This chapter has discussed the fundamental principles of a nuclear power station, touching on how key systems relate to the safe operation of a nuclear reactor. The powerful and complex nature of a nuclear reactor requires equally robust and reliable safety systems, the maintenance and operation of which must be properly regulated. The application of safety and regulation in the nuclear industry was shown to take several forms, with particular interest recently, for a number of reasons, in the application of CM in the nuclear industry, described in more detail in Chapters Three and Four. The background to this thesis is the UK fleet of AGR stations, which in the next section shall be described in more detail and will be used as an example to illustrate the safety and regulatory issues associated with operating a fleet of ageing reactors described in this chapter.

Chapter 3

Advanced Gas-cooled Reactor

3.1 Introduction

The Advanced Gas-Cooled Reactor (AGR) is the second generation of British civil nuclear reactors, based on the previous Magnox design [Steer2005]. The Magnox reactors were so called because of the MAGNesium OXide fuel cladding they employed, which was later replaced with a stainless steel cladding in the AGR design, to allow higher temperatures and greater thermal efficiency. The Magnox reactor and the AGR share many features, most importantly Carbon Dioxide (CO_2) coolant and a graphite moderator, but due to the AGR's use of enriched fuel and higher coolant temperature and pressure, the power density is much larger and as a result, the core is significantly smaller.

A total of seven AGR stations were constructed, each configured with two reactors contained within a single building. With the exception of Dungeness B, the AGR stations were constructed in pairs as Hunterston B (HNB) and Hinkley Point B (HPB), Heysham 1 (HYA) and Hartlepool (HRA), and Heysham Stage 2 (HYB) and Torness (TOR). Figure 3.1 shows the main core structure and some of the key systems of the AGR, which vary slightly between station pairs. The vertical penetrations at the top of the core allow refuelling and the insertion of control rods, while the horizontal insertions at the bottom of the core connect to the eight gas circulators that supply coolant to the core.

3.2 AGR Design

The AGR uses a graphite core as a moderator and CO_2 as a primary coolant [Steer2005]. The fuel, normally $2.5\% - 3.5\%$ enriched uranium dioxide (UO_2) in the form of ceramic pellets, is used to heat coolant to produce around $1600MW_t$ of thermal power per core, to generate a nominal $660MW_e$ of electrical power per core. Control rods of boronated steel are used to control the reactivity of the core and quench the fission reactions and shut down the core in an emergency. A nitrogen injection system can also be used for long term hold-down in the event that an insufficient number of control rods can be inserted into the core.

3.2.1 Graphite Core

The core of an AGR is composed of several thousand[1] interlocking graphite bricks [Steer2005, MPP1992], a schematic of which is shown in Figure 3.2. These hollow, cylindrical bricks form fuel channels into which fuel stringers are inserted. The smaller interstitial channels formed by the spaces between adjacent fuel channels contain smaller square hollow bricks, which are used as control rod channels, although only every second interstitial channel actually contains a control rod. The graphite bricks form concentric circles which form a total of around 320 fuel channels, though only slightly over 300 are used to hold fuel, in 10 or 11 layers, each of which is typically 825mm in height. The remaining channels consist of solid graphite bricks which act as neutron reflectors. A layer of graphite also exists at the top and the bottom of the core to act as a reflector to increase the thermal flux at the edge of the core. This cylindrical graphite core structure measures approximately 11m in diameter and 9.8m in height and weighs around 1300 tonnes. The graphite core is not replaceable, and is therefore a life limiting feature of the AGR.

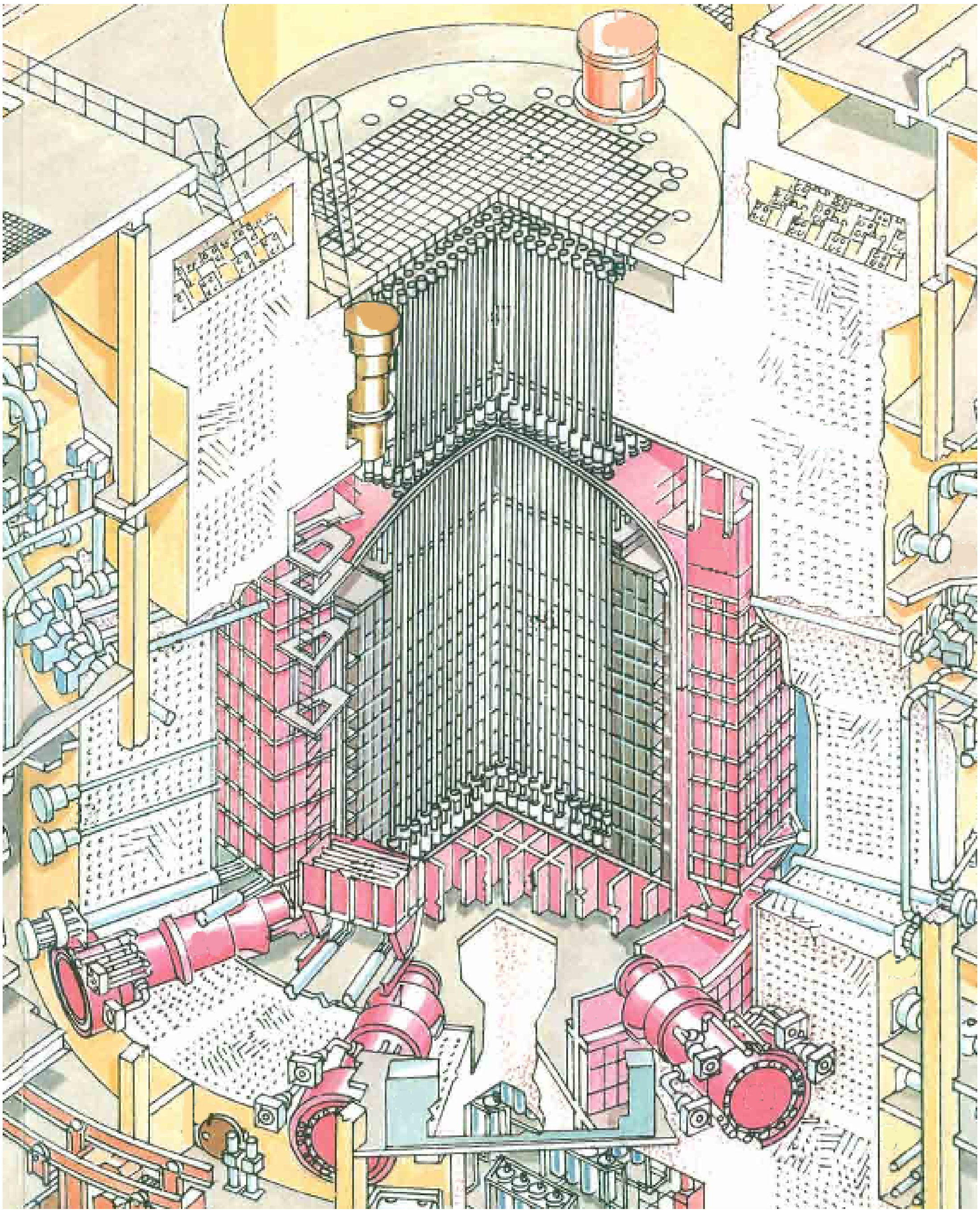

Figure 3.1: A cutaway drawing of an AGR core, with the graphite core in the centre, surrounded by the pressure vessel. Diagram courtesy of EDF Energy.

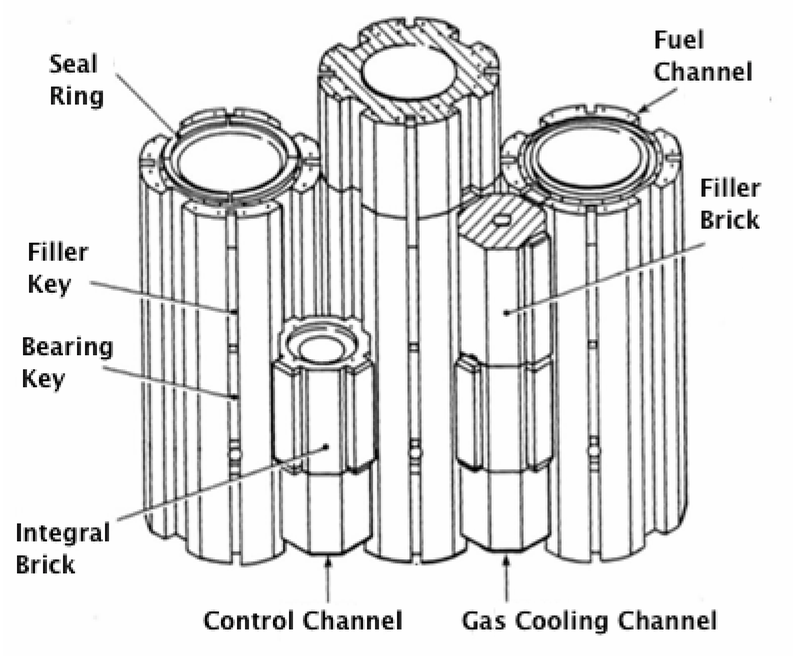

Figure 3.2: The interlocking graphite brick arrangement, which forms the core structure and moderator. Diagram courtesy of EDF Energy.

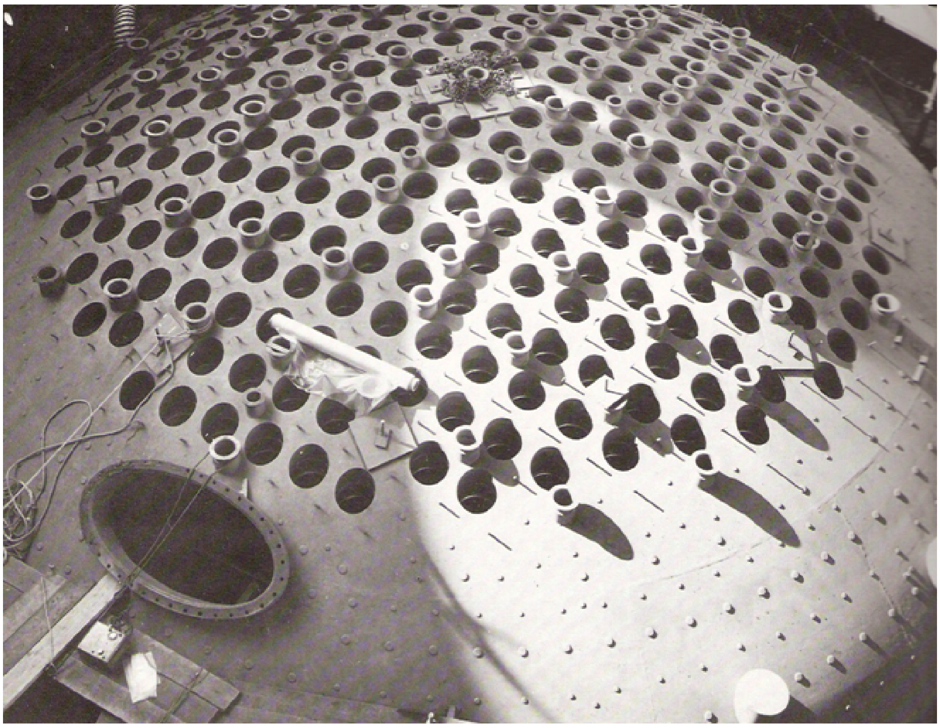

Figure 3.3: The gas baffle dome, above the active core, during construction showing the control and fuel penetrations. Diagram courtesy of EDF Energy.

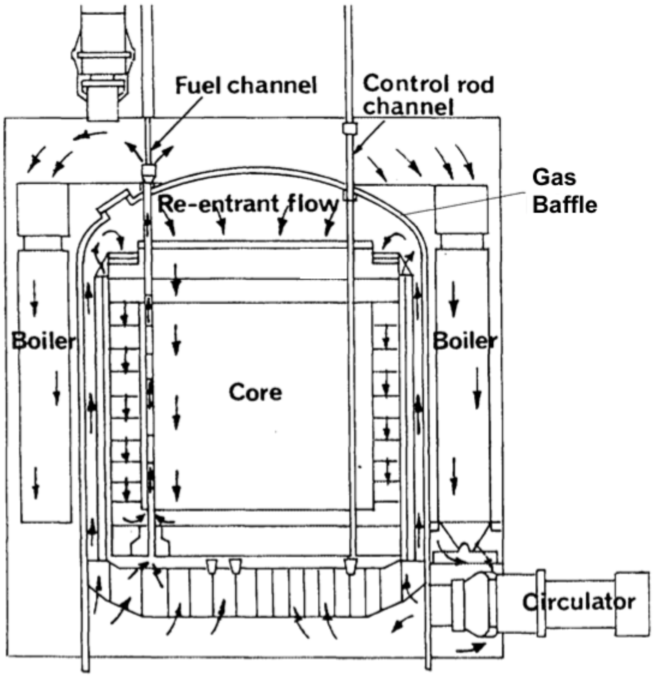

Figure 3.4: The coolant flow within the AGR core. Diagram courtesy of EDF Energy.

3.2.2 Cooling

A steel structure surrounds the graphite core known as the gas baffle which directs the coolant through the core, the dome of which is shown in Figure 3.3 with penetrations for fuel and control assemblies.

The AGR coolant is CO_2, which was selected because of its low neutron capture cross section (which limits chemical reactions with the graphite), availability and cost. Eight gas circulators are attached to each core, as shown in Figure 3.1, and pump coolant at around 40bar into the reactor at a combined flow rate of 4000kg/s. The circulators operate with variable Inlet Guide Vanes (IGV), so that the coolant flow rate into the reactor, the primary loop, can be controlled. The coolant enters the bottom of the core and is separated into two flows, as shown in Figure 3.4, part of which travels up the side of the core, while the other flow travels up the outside of the core and re-enters the core at the top of the gas baffle passing down through the fuel before being passing through the boilers.

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[1] The number varies from station to station as designs differed slightly

When the coolant has been heated to around 600°C by passing the fuel, it passes through one of four boilers, each of which contains three elements, installed between the gas baffle and the pressure vessel, transferring the heat to a secondary water loop containing economizers, evaporators and superheaters which create high pressure steam in order to drive turbines and create electricity. The boilers, like the graphite core, are non-replaceable and are therefore also a life limiting feature of the AGR.

3.2.3 Pressure Vessel

The entire graphite core structure is contained within a pre-stressed concrete pressure vessel [Steer2005, MPP1992], with walls 5.8m thick containing around 3600 post-tensioning steel tendons in a helical formation, designed to withstand high gas pressure through the core and to provide a shield against gamma and neutron radiation. The inner surface of the pressure vessel is gas sealed which provides some protection to the concrete from the otherwise corrosive effects of high temperature and pressure gas flow. The pressure vessel is designed to operate up to 49.5bar, to maximise thermal efficiency, above which a safety release valve system, which is connected to the coolant circuit, can release coolant to lower the pressure. The steam pressure in the boilers is maintained at a higher pressure than the gas circuit, which is an example of a passive safety feature, as any leak from the gas circuit will not result in the release of radioactive material.

3.2.4 Fuel

Ceramic pellets of enriched UO_2 in batches of 60 are sealed in a stainless steel ‘pin’, 36 of which are inserted into a graphite sleeve to form a fuel element, as shown in Figure 3.5. Eight fuel elements are arranged between reflectors and form a fuel stringer, as shown in Figure 3.6. The stringer has stabilising brushes at the top and bottom, to allow the fuel to move smoothly through the channel. Around 300 fuel assemblies will be in an AGR core during operation, with fuel remaining in the core for 5–7 years. The original design intention of the AGR was that fuel would be replaced during normal operation, however problems with coolant impacts have limited this to partial load refuelling at some stations[2]. Shuffling of fuel, generally from a channel near the edge of the core to a channel at the centre, occurs at some stations in order to maximise fuel burn-up and efficiency. Refuelling is performed in batches of 5–7 assemblies approximately every 4–6 weeks.

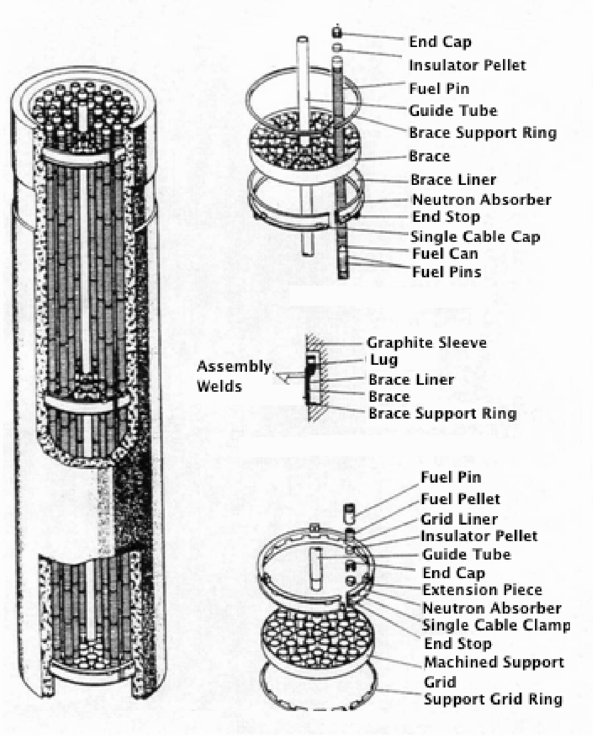

Figure 3.5: The arrangement of fuel pins in a fuel element, wrapped by the sleeve. Diagram courtesy of EDF Energy

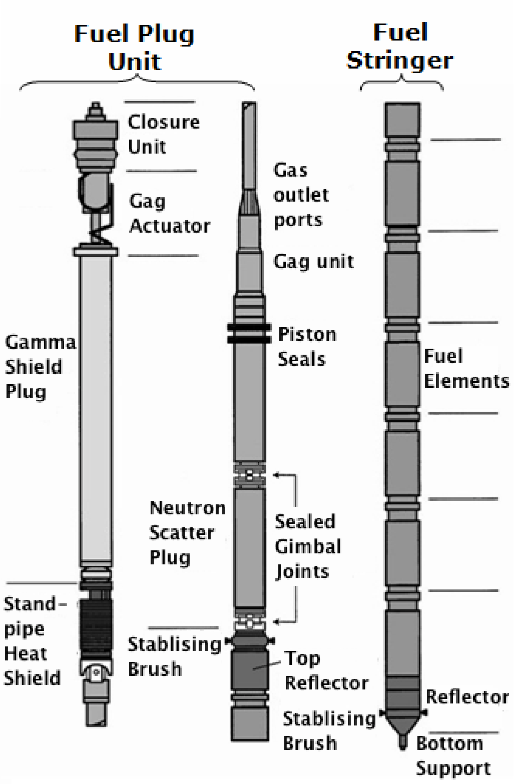

Figure 3.6: The fuel stringer, combining eight fuel elements and shielding and seals with the plug unit sitting above the stringer. Diagram courtesy of EDF Energy.

3.2.5 Control

The primary control system of an AGR is achieved by positional manipulation of articulated, boronated steel control rods, which can be inserted to different depths in the core to control the rate of fission and as a result, the thermal power

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[2] Hinkley Point B, Hunterston B, Heysham Stage 2 and Torness

created in the core. The rods, shown in Figure 3.7, are controlled by a drive system above the core with a chain connecting the drive system to the rod. An electromagentic clutch holds the rod in the required position and in the case of an emergency, the clutch is de-energised and the rod falls into the core. The rods are divided into two main classes: *bulk* rods and *regulating*.

3.2.5.1 Bulk Rods

The bulk, or black, rods are full neutron absorbers and are held above the core during normal operations and in the event of a reactor trip are allowed to fall under gravity into the core. Periodically, some bulk rods are partially inserted into the dome above the core in order to determine that the path through the dome to the control channel is clear and that the rods can be inserted into the core without obstruction.

3.2.5.2 Regulating Rods

The regulating, or grey, rods are partial neutron absorbers and are partially inserted into the core during normal operation and are moved automatically to balance the flux profile and the power of the core. The rods are driven with reference to the outlet coolant temperature from the reactor, commonly known as T_2, in order to keep the reactor at the required power level. The control systems vary somewhat between stations, with some AGR variations driving groups of regulating rods in groups of six or seven, while at other stations each of the regulating rods moves independently.

3.3 Ageing

The graphite core is the principal life-limiting feature of the AGR, with prolonged exposure to high pressure CO_2 and neutron irradiation gradually reducing the structural strength and integrity of the core while removing some of the mass. At the beginning of the operating lives of the stations it was known that graphite experiences radiolytic oxidation, resulting in weight loss in a CO_2

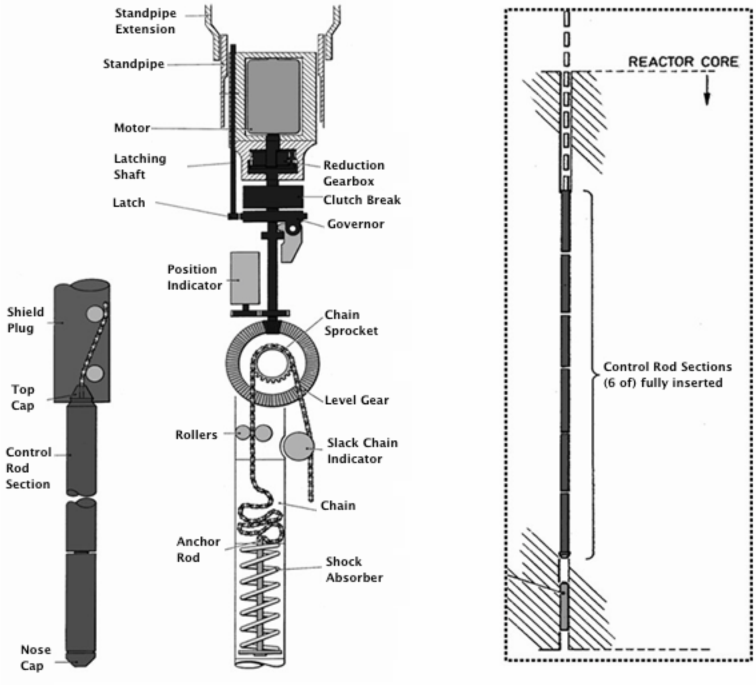

Figure 3.7: The control rod drive mechanism and the control rod, formed by six articulated sections of boronated steel. When released, the rods fall into the core under gravity. Diagram courtesy of EDF Energy.

environment, however the stations were not expected to operate beyond their original design lives of aproximately 35 years, therefore significant research is underway to determine empirically and theoretically the likely state of the graphite. Weight loss limits are revised as new safety cases are developed for individual stations in preparation for the next license period, as the operator demonstrates through research[Maul2010], modelling[Tsang2010] and testing[Ramsay2010] that the graphite is capable of fulfilling its structural and moderating requirements for that license period. Determining the mechanical properties of the graphite core has become key to the safety case as the stations enter a regime of operation with irradiated graphite about which there is a limited knowledge base.

It is thought that the graphite bricks in the longest operating stations have reached what is known as stress reversal, as shown in Figure 3.8, where the dominant mechanical forces acting on the inner surface of the graphite bricks change from tensile to compressive on the inner surface of the brick and from compressive to tensile on the outer surface of the brick. Current work[Maul2010]

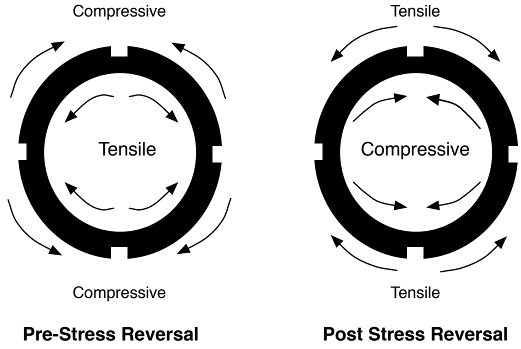

Figure 3.8: A schematic view of the changing mechanical forces acting on the graphite bricks, which can cause the graphite bricks to crack and potentially distort the channel shape.

attempts to estimate where cracking will occur in the brick and what types of crack will form. Circumferential cracks (where a crack consists of a horizontal ring round the inner surface of the brick) and axial cracks (vertical cracks on the inner surface of the brick) have already been observed at some stations.

As stress reversal occurs however, it is expected that keyway root cracks (where a crack initiates at the keyway — the notches visible in the simplified schematic of a fuel brick in Figure 3.8) will occur, which could potentially result in sufficient channel distortion so as to inhibit or disrupt fuel movements or control rod insertions.

3.4 Monitoring

As the AGR stations continue to operate with evolving damage due to ageing as discussed in the previous section, the operator must maximise the knowledge available about the state of the core, to justify that the reactors are safe to continue operating. Between inspections of the core, monitoring provides the sole source of supplemental information about the core, resulting in safety and economic drivers for increased CM. The potential for damage to the graphite, such as a sheared brick or fully open crack, to cause fuel to become stuck or to inhibit the control rods from being inserted has resulted in the main focus of CM being on the graphite core. Other monitoring exists, albeit on a somewhat limited scale, with the boilers also potentially considered to limit the operational life of the AGR and recent work investigating the structural integrity of the helical windings in the pressure vessel [Irving2000].

In exceeding the original specified life of the AGR, it was recognised that a formal monitoring regime would be required in order to support the development of safety cases to continue the operation of the reactors. To that end, a collection of CM analyses were identified at the oldest stations that could be performed on a regular basis and reported on. This collection of analyses and the discussion thereof, forms the Monitoring Assessment Panel (MAP) and is currently in operation at HNB, HPB, HYA and HRA.

3.4.1 Monitoring Assessment Panels

The MAP meets quarterly to consider the monitoring data from the period and grades the observations according to a predefined set of rules as:

- **Red** - An observation which is likely to be a direct indication of adverse core condition
- **Amber** - An observation which could be related to adverse core condition
- **Green** - An observation which is not thought to be directly related to adverse core condition, but when considered with other factors, could provide useful information
- **Blue** - An observation which has the potential to indicate adverse core condition, but in this case has not.

The MAP is primarily concerned with classifying the observations under this scheme, and any that cannot be downgraded by explanation of some other factor are classified as amber or red and are to be investigated further outside the MAP. The MAP consists of discussion of two sets of parameters, known as Class 1 parameters and Class 2 Parameters. Class 1 parameters are the primary source of monitoring information that may indicate adverse condition of the core, therefore are treated with higher importance than other parameters. As a result of this emphasis, this thesis considers only the Class 1 parameters, however the work developed in this thesis can be readily extended to incorporate other parameters.

Class 1 parameters include

- **Fuel Grab Load Trace (FGLT)** - Analysis of the weight of fuel during insertion or removal from the core to infer, through frictional load, fuel channel distortion
- **Channel Power Analysis** - A comparison of the measured thermal and the calculated neutronic power values for each fuel channel
- **Control Rod Analysis** - Analysis of control rod movements and alarms
- **Fuel Movements** - Review and discussion of fuel movements and any issues associated with refuelling

The class 1 parameters are now described in more detail, so as to illustrate how they are used to support the safety case by adding to the knowledge of the state of the core.

3.4.2 Fuel Grab Load Trace

During insertion (charge) or removal (discharge) of fuel from the core, the load of the fuel stringer is recorded as it moves through the core to the refuelling machine. This measurement, the Fuel Grab Load Trace (FGLT), provides a description of the frictional forces acting on the stringer, via the contact of the stringer's stabilising brushes (shown in Figure 3.6) with the channel wall, as shown in Figure 3.9. The design geometry of the interior of the fuel channel causes characteristic and identifiable features on the FGLT as the diameter of the channel changes and alters the coefficient of friction.

Damage to the graphite bricks, such as some types of cracking, is visible on the FGLT as a step change in load as the stringer brushes pass cracks in the brick and the diameter of the channel is momentarily altered. Only circumferential cracks can currently be detected in the FGLT because the change in channel diameter

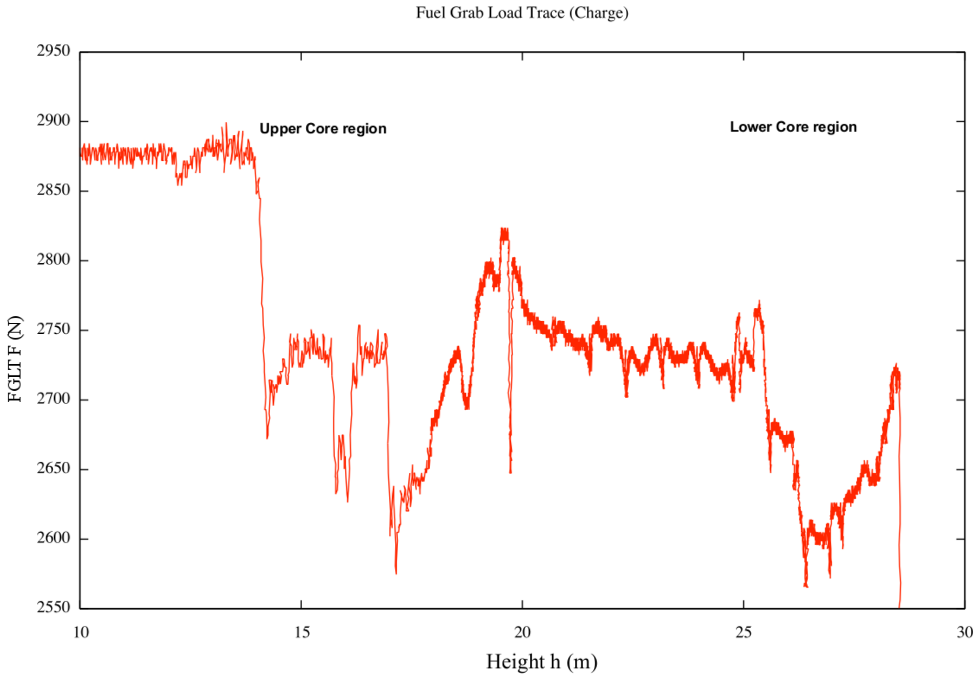

Figure 3.9: An example Fuel Grab Load Trace of a fuel insertion (charge), where the peaks and troughs indicates features in the channel, such as brick layer interfaces

is perpendicular to the motion of the fuel stringer. Less common axial cracks which do not separate the bore of the brick cannot currently be inferred from the FGLT, however research is underway to attempt to achieve this.

Experimental rig work has been used to benchmark expected FGLT responses to a variety of cracked brick configurations. This knowledge is used by engineers to manually assess the FGLT produced at refuelling, originally using paper trace FGLTs. Within the last few years some stations have installed digital logging equipment[3] which records electronic copies of FGLT. Initially bespoke systems, which varied significantly between stations, were used, however as the prominence of CM has increased with respect to the safety case and after some system failures, matching commercial data loggers have been installed at HNB and HPB. These new loggers record the height and load data using industry accepted standards.

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[3] The youngest AGR station, Torness, has had digital FGLT logging installed from construction

3.4.2.1 The BETA System

The British Energy Trace Analysis (BETA) software developed at the University of Strathclyde has been developed to perform an automated and numerical analysis of the FGLT using a rule-base of known crack signatures[West2006]. The system was initially developed to analyse the height and load data from the bespoke systems but has since been adapted to utilise the data generated by the digital loggers[West2009]. While the existing analysis uses a set of rules which look for characteristic features in the FGLT, other work has considered use of hidden Markov models to detect anomalies in the FGLT data[Stephen2009].

The current analysis detects where certain types of anomalies exist, but does not generate any geometrical information about the anomaly. Such information can only currently be derived from inspection equipment, described later in this chapter.

3.4.3 Fuel Movements

During refuelling, a log is kept of the operation, including the insertion or removal of the fuel, the state of the refuelling machine and the state of spent fuel on removal. Every time fuel is inserted or removed from the core, an inspection is made of the fuel stringer. Any change in the shape of the stringer on removal could indicate distortion of the fuel channel however the stringer is highly radioactive on removal from the core and only a limited visual inspection is possible before it is disassembled.

3.4.4 Channel Power Analysis

Separate computational methods are used to model the thermal and neutronic power of each fuel channel in the core. The enrichment and predicted burn-up of the fuel is used to calculate the neutronic power of the channel, while the temperature of the coolant in the channel is used to calculate the thermal power.

Regular comparisons of the thermal and neutronic channel powers are made, and any deviation therein is known as a Channel Power Discrepancy (CPD). The

CPD is calculated for every fuel channel on a weekly basis, and consecutive weeks are compared to calculate the Change In Channel Power Discrepancy (CCPD). CPD and CCPD values above certain limits are noted by the engineer and reported at the MAP for later investigation. Larger than normal CPD and CCPD values can be caused by a number of factors including:

- **Modelling Errors** - The neutronic model used may include errors compared to the actual core state
- **Refuelling** - The change in neutron flux in a region near a refuelled channel (due to the presence of new fuel) can alter the thermal power of the channel by 'burning' slightly hotter. This is a short-lived effect.
- **Control Rod Exchange** - The replacement of a control rod with one of a slightly different neutron absorbance strength to the previous rod can affect the heat generated by adjacent fuel channels. This is a short-lived effect.
- **Fuel Sleeve Gapping** - The most severe though unlikely danger, and the main reason for channel power monitoring, is that damage to the core or the fuel could result in the sleeve on the fuel becoming damaged and the fuel overheating due to insufficient coolant passing over the fuel elements

Determining which of these causes has resulted in the anomalous CPD or CCPD value requires an engineer to collate the relevant data and correlate the events which may explain the anomaly.

3.4.5 Control Rod Analysis

As the primary shutdown mechanism of the AGR, monitoring of the ability of the control rods to properly function is key to safe operation of the reactor. There are several control rod analyses, of various styles, which describe the behaviour of the control rods.

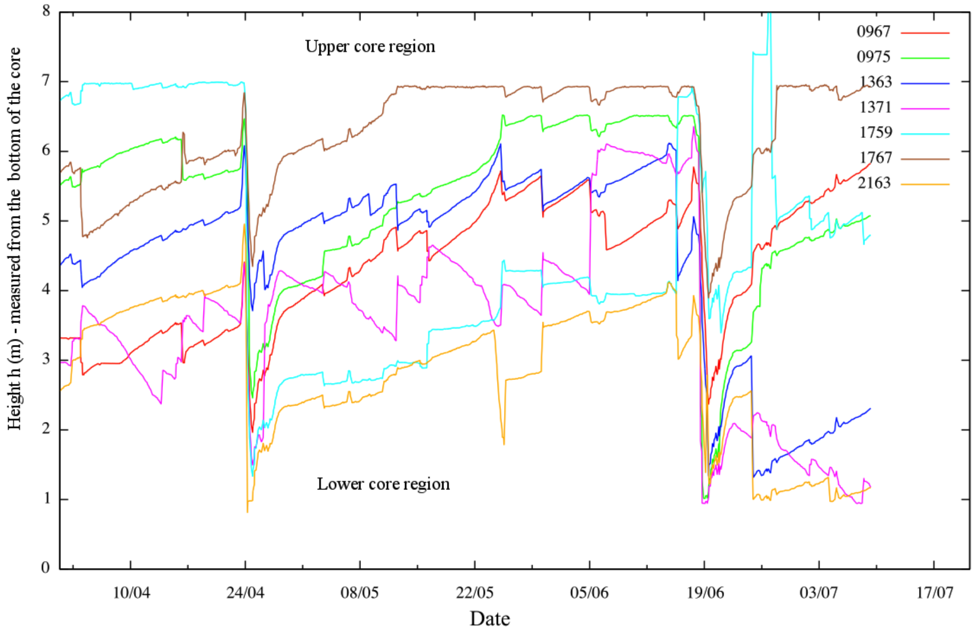

Figure 3.10: The motion of a sector of regulating control rods, with channel identifiers noted on the right of the graph. The rods are inserted at refuelling then slowly withdrawn

3.4.5.1 Regulating Rods

The regulating rods of an AGR are constantly in motion and are therefore analysed as a potential indicator of core distortion. A visual inspection of the height data of sets of regulating rods with time, as in Figure 3.10, is performed in preparation for each MAP meeting. The engineer attempts to visually detect evidence of ‘plateauing’, where it appears that the rods remain at a particular height (that is not the upper or lower limit) and may indicate restricted rod motion due to core distortion. A large number of, indeed almost certainly all to date, observations of rods ‘sticking’ are in fact the result of mechanical failures in the driving equipment housed above the core that moves the rods, as the clearances between the rods and the channel walls are considerable and the rods themselves are articulated, to accomodate some channel distortion.

3.4.5.2 Rod Drop Times and Braking

Whenever the reactor is tripped, the full set of control rods are dropped into the core. Sensors which record the height motion in a similar manner to Figure 3.10, but at much higher resolution, record the time taken for the rods to enter the core. Design and safety case guidelines determine a minimum speed at which the rods must be partially and fully inserted, and the resulting drop times are assessed after every reactor trip at the next MAP.

3.4.5.3 Rod Alarms

There are various alarms associated with the control rods, most of which activate when some potential problem with the motion of the rod are detected, for instance if the chain which holds the rod becomes slack or a fuse on the drive mechanism fails. These alarms are reviewed at the MAP and discussed where they are relevant to other observations.

3.4.6 Class 2 Parameters

Class 2 parameters are of secondary importance and MAP members discuss, where relevant, control rod exchanges, moderator temperature and test insertions of control rods known as sensor rods. The class 2 parameters refer to sets of data which are available that may provide supporting evidence of core damage or distortion, however on their own do not, due to either the limited scope of the data (the parameter may not be directly related to the physical state of the core) or the low quality or availability of the data (the sensor population may be unreliable). The parameters include:

- **Moderator Temperature** - Several thermocouple sensors were embedded in the graphite at construction, however a large fraction have failed and many others give unreliable readings

- **Control Rod Exchanges** - Control rods are replaced according to a maintenance schedule, or for more immediate maintenance reasons, however the rods do not interact directly with the graphite core structure

- **Sensor Rod Tests** - A rod from the bulk group is regularly inserted a small distance into the top of the core to ensure the dome on top of the reactor is in the correct position. These very small insertions provide very little indication of the state of the core underneath.

3.4.7 Intelligent Monitoring Assessment Panel System

The storage and management of the large amount of information generated by and for the MAP, as well as the need for a historical perspective on the observations has resulted in the development of Intelligent Monitoring Assessment Panel System (IMAPS) [Jahn2007]. The system is designed to allow engineers to add, manage and view observations relevant to the core based on the MAP discussions. A web-based application, which users can access through their desktop browser, IMAPS is now deployed on the operators' network and is used by station staff and engineers company-wide to manage core monitoring observations. At MAP meetings the system is used to provide context for the discussions of the current monitoring data and provides decision support[Jahn2010] that is recognised by the regulators. IMAPS also contains details of known cracks or damage within some channels that have been inspected. This knowledge assists engineers performing other CM analysis, such as of the FGLT, in identifying causes of anomalous data, however in order to maintain monitoring as an independent aspect of the safety case, IMAPS is not used as a storage facility for inspection data.

3.5 Inspection

Each reactor in the AGR fleet is required to undertake outages every 2–3 years in order to perform physical inspection of key reactor components. These outages are expensive, as they require the reactor to be offline hence not generating electricity and require considerable man-power resources. A principal inspection task performed during the outage consists of the direct measurement of the internal structure of the core by inserting a device known as the Channel Bore Measure-

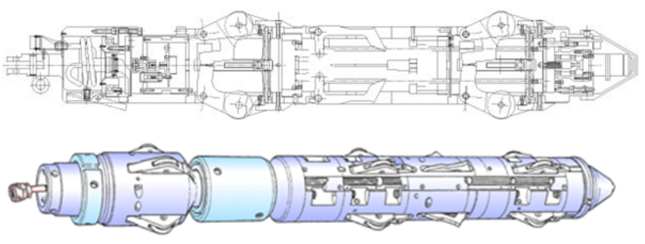

Figure 3.11: The CBMU device. The ‘feelers’ which measure the channel diameter are visible aswhite protrusions from the device. Diagram courtesy of EDF Energy.

ment Unit (CBMU) into a selection of fuel channels, as shown in Figure 3.11.

3.5.1 CBMU

The CBMU is an inspection tool developed to measure the interior geometry of the fuel channels during inspections when the reactor is offline. There have been several evolutions of the device, shown in Figure 3.12, each of which contain two sets of feelers, which apply a constant force perpendicular to the main axis of the device and based on calibration, can determine the diameter of the channel. As the device is moved through the channel, the small variations in channel diameter are detected as a result of the change in restorative force acting on the feelers. The CBMU is capable of detecting deviations of as little as 0.5mm in the channel wall. By measuring the diameter of a fuel channel, then performing the same measurement under a rotation of the device, it is also possible to calculate the ovality and bow of the channel while two gyroscopes at the top of the CBMU allow the calculation of the tilt of the channel.

3.5.2 TV

In order to visually inspect channels, a TV camera unit can be inserted into fuel channels and record videos or still images of any features of note. The camera is used to systematically inspect entire channels or to perform inspections of known features or anomalies. Recently, a new tool known as the New In Core Inspection Equipment (NICIE) has been introduced, shown in Figure 3.14, which combines

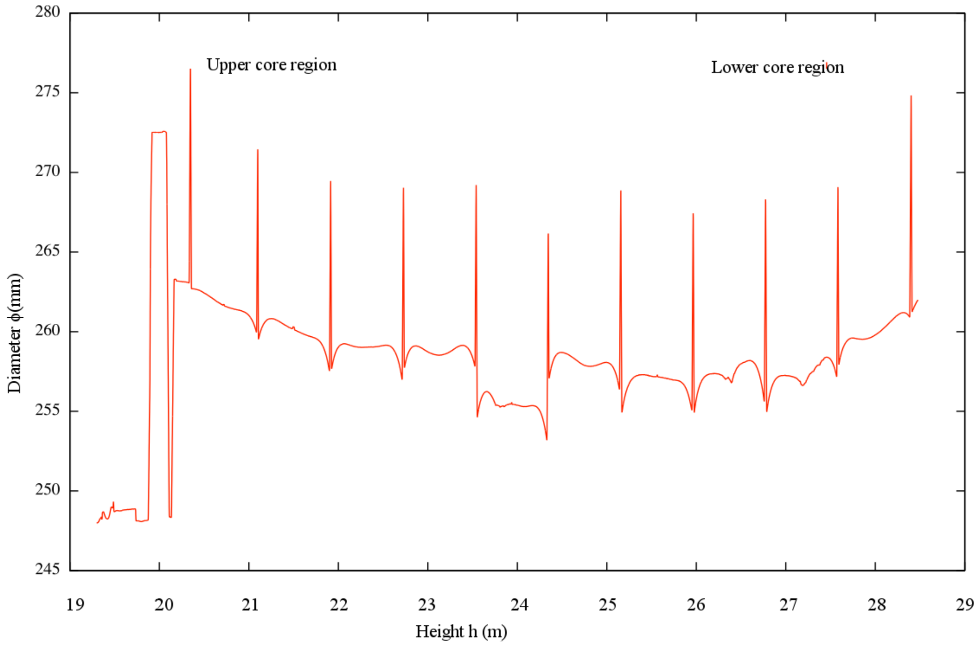

Figure 3.12: The variation of fuel channel diameter with height, as measured by the CBMU. The peaks correspond to the gaps at the chamfered brick interfaces, with the bricks slightly narrower near the edge of the brick.

the functionality of the CBMU with the TV equipment.

3.5.3 Trepanning

Analysis of the material properties of the graphite core is a key aspect of the AGR safety case, and in order to determine the structural properties of the graphite, small samples are periodically trepanned from the core. The trepanning tool, shown in Figure 3.15, cuts small sample of graphite, a few centimetres in diameter from pre-selected sites, during outages. The graphite samples are analysed in order to estimate the mechanical properties of the graphite, such as weight loss and Youngs Modulus.

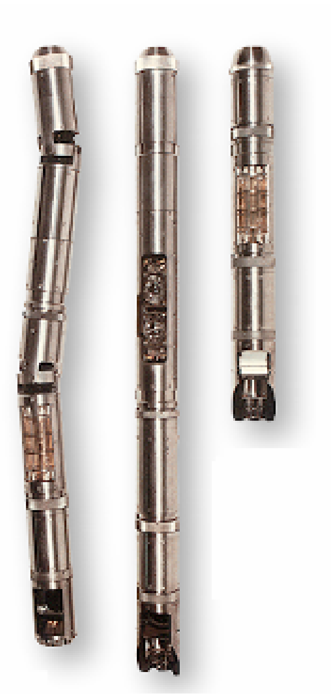

Figure 3.13: The articulated camera which can be inserted to visually inspect fuel channels. Diagram courtesy of EDF Energy.

3.6 Discussion

This chapter has described the main design features of the AGR, with particular emphasis on safety related systems and the evolving state of the graphite core as the reactors exceed their originally specified design lives. An overview was described of the existing monitoring regime, highlighting analyses of particular interest which supply information about the state of the graphite core between inspections and the limitations which currently exist in these analyses.

The large volume of data, of various physical parameters, available for monitoring is not directly comparable in resolution or conclusiveness to the data available from inspection, discussed towards the end of the chapter, however with appropriate rigour it will be shown in the next chapter that by adopting modern CM techniques, more detailed and more confident conclusions can be drawn from the monitoring data.

Figure 3.14: The NICIE inspection unit, which combines the capabilities of the CBMU and the camera. Diagram courtesy of EDF Energy.

Figure 3.15: The trepanning tool, which can cut small cylindrical samples of irradiated graphite from fuel channels, for testing. Diagram courtesy of EDF Energy.

Chapter 4

Nuclear Condition Monitoring

Nuclear reactors have been shown in the preceding chapters to be highly complex, dynamic systems where the vast amount of energy which can potentially be released in the core has resulted in a strong focus on safety. However while the incorporation of safety into the design and operation of reactors provides initial layers of security, further safety is required to protect against the occurrence of events outside the normal operating state of the reactors. The condition, or health of industrial equipment in general — whether it is a nuclear reactor or a valve, and the knowledge of that state of that component, is key to determining whether the system is safe to operate. The MAP scheme which exists at certain AGR stations, introduced in Chapter 3, is an example of a domain specific implementation of Condition Monitoring (CM) for safety purposes.

This chapter describes CM in the wider context of the nuclear industry, reviewing some standard approaches and techniques from the literature, such that an approach to formalising and extending the existing MAP analyses can be identified. From a safety and a business perspective, a highly coveted goal of CM can be found in the drive towards condition based maintenance and prognostics — the process of determining the remaining safe or useful life of a component. To that end, this chapter reviews the characteristics of different CM systems, highlighting some particularly relevant examples of previous work in the area, describing benefits that can be derived from the use of CM but also some important limitations which exist.

4.1 Condition Monitoring

Condition Monitoring is a process of measuring and analysing a parameter or set of parameters related to a component or system, so as to enhance the knowledge of the state of that system. CM is used in a wide variety of domains, wherever a piece of equipment experiences, or is expected to experience, degradation due to repeated use, a hostile environment or some other factor. In fields such as civil construction [Brownjohn2007] and aviation [Tumer1999], CM has been applied to monitor the state of various structural and electro-mechanical components [Nandi2005] using a diverse set of artificial intelligence techniques including neural networks, fuzzy logic and expert systems among others. The initial task for any CM application is to determine the characteristics of the problem and to determine which set of techniques, from a multitude of approaches, best suits the scenario.

4.1.1 Approaches to Condition Monitoring

The design of a particular CM application depends entirely on the system to be monitored, the availability of data and the available knowledge of the system. The degradation path of a component may be well known and very predictable, in which case minimal, infrequent monitoring may be required before the component is replaced. In other cases however, knowledge of the degradation may be very sparse or even non existent, in which case more regular, detailed monitoring and analysis may be required.

The frequency and detail of CM analysis also depends on the criticality[1] and value of the component to which it is applied. For example a non-critical, inexpensive piece of equipment may be allowed to fail, while degradation in a more expensive or more critical piece of equipment may require detection of a fault before failure and subsequently, unscheduled maintenance. The use of informa-

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[1] This use of criticality should not be confused with the earlier definition describing the conditions for a self sustaining fission reaction. Criticality is also commonly used to describe the impact of failure of a component, expressed in loss of life, injury, system damage or economic cost for example, using techniques like Failure Mode, Effects and Criticality Analysis [NASA1995]

tion derived from CM to inform maintenance regimes, more commonly known as Condition Based Maintenance, allows the operator to plan maintenance more efficiently with more accurate knowledge of the state of components, which creates an obvious economic benefit of CM.

A large amount of recent work [Jardine2006] has discussed the application of software based CM solutions, particularly through the application of intelligent systems techniques. An Intelligent System [Rudas2008] is "a system that emulates some aspects of intelligence exhibited by nature.", specifically, systems which are characterised by their "flexbility, adaptability, memory, learning, temporal dynamics, reasoning, and the ability to manage uncertain and imprecise information". The application of intelligent systems to perform CM tasks, using model based, data driven, knowledge based or hybrids of several types of techniques [Russell2005] is now widespread.

4.1.2 Model Based Condition Monitoring

In some cases, a model of the physical system can be incorporated into the design of the CM system, with analyses geared towards classifying behaviour based on known states of the system. This style of CM is more commonly referred to as a Model Based approach [Jardine2006, Dvorak1989]. Detailed physical models, using available data as inputs to estimate the state of components, are possible where the complexity of the system is limited. More commonly however, a simplified model of the system is created and then using available data as an input, tuned to better reflect the behaviour of a real component. Model based approaches have the benefit of explicability based on the domain knowledge used to create the model, however it is often necessary to simplify the model (compared to the physical behaviour of the component) which can limit the applicability of the model outside of certain regimes of operation.

4.1.2.1 Tiger

The use of model-based monitoring is particularly suitable when detailed domain knowledge is available, as well as modes of behaviour and known fault conditions.

Trave-Massuyes and Milne [Trave-massuyes1997] developed a model-based CM system, Tiger, for gas turbines, which runs continuously and incorporates existing knowledge to estimate which component of a gas turbine, based on measured outputs, is the source of the fault. The model-based approach in this case was selected to allow a decoupling of the knowledge of the physical system and of the diagnosis. Tiger features three distinct diagnosis tools:

- **Kheops** - a rule based system which applies diagnostic rules to turbine parameter outputs,
- **IxTeT** - a software module which analyses the progression of anomalies and records where safety systems acted,
- **CA-EN** - a model-based supervision system which combines mechanical knowledge of the system with recorded data from the turbine

CA-EN contains two modules: one which simulates the expected output from the turbine given the current parameter measurements and another which performs the actual diagnosis. The three diagnosis tools above feed into a Fault Manager which determines what information and which faults to report to the user, in order of criticality. The use of three tools running in parallel performing fault detection and simulation, allows for the creation of predictions of future state of parameters, which are constantly updated based on new information. Such predictions, through the use of a model-based approach, can provide valuable information to the engineer viewing a fault in real time and this example in particular highlights some of the benefits of modularising components of a CM system. Perhaps the most interesting characteristic of TIGER is the ability of the system to continuously run simulations based on new data and identify anomalies or potential anomalies at an earlier stage than would be possible if anomaly detection was performed in real-time.

4.1.3 Data Driven Condition Monitoring

An alternative approach, in situations where domain knowledge is lacking or the system is too complex to feasibly model accurately, is to use a data driven approach. Common techniques such as cluster analysis, where data measurements sharing some common characteristic are grouped together, or artificial neural networks, where a mapping of inputs to outputs is estimated in a system mimicking a set of biological neurons as in the brain, have been successfully used in many CM applications [Nabeshima2002, Uhrig2005, Jahn2011]. The flexibility of such techniques allows them to be applied in a very large range of CM applications, however the *black box* nature of many of these techniques limits the explicability of the results produced compared to model based approaches.

4.1.4 Knowledge Based Systems

There are some other approaches to CM, such as expert systems, where sets of rules based on detailed domain knowledge are used to classify data sets, part of a class of techniques known as Knowledge Based Systems. There have been some examples of expert systems used in the nuclear industry however typically only for classification of known faults as in [Nelson1982a]. The need to have knowledge formalised in a rule based system for example, requires a very large and complex tree of possible conditions and the limited knowledge of certain types of faults or conditions related to faults which haven't been experienced, limits to ability of such systems.

4.1.5 Hybrid Systems

More recently, some CM applications have blended aspects of model based and data driven approaches [Nabeshima2002, Zio2012, Liu2013]. In the nuclear industry, with a high level of importance placed on the decision support information proved by CM systems, it is common [Nabeshima2002, Xing1996] to find many nuclear CM applications featuring some level of model based approach, to help provide explicability to the results produced or for verification of the technique used.

4.1.5.1 Hybrid Data Driven and Rule Based Nuclear Monitoring

Nabeshima et al [Nabeshima2002] have developed a nuclear CM system which combines these two different classes of analysis techniques. A hybrid monitoring system for a PWR was designed which includes a neural network approach to model the plant dynamics and a rule-based system which can diagnose faults, using both an a priori knowledge-base as well as the outputs from the neural network. The neural network consisted of 22 input nodes, 25 hidden nodes and 22 outputs, corresponding to 22 key parameters required to monitor the core. The outputs correspond to the predicted values of the parameters at the next time step, based on the relationship between the parameters that the neural network has identified. The network was trained on an initial set of data, and then during operation continually trained on new data which was deemed by the system to be normal. This continual learning of the network allows it to refine its ability to detect faults as it runs. The expert system, using a rule base, determines which of five states the plant is in from: *start-up*, *transient*, *steady-state*, *shutdown* and *unstable*. Based on the operational mode detected, the level of severity of potential faults detected from the outputs of the neural network are classified and presented to the user.

With definite parallels to Tiger, described earlier, this hybrid system uses data driven techniques to analyse numerically intensive problems which are impractical for a human to process in real-time, but contextualises the outputs of the neural network for use as a decision support tool.

4.1.6 Prognostics

In some situations, certain components cannot be allowed to fail for the system to operate safely or cannot be replaced. In this case, the output of CM can become an indicator of the Remaining Useful Life (RUL) of a component [Jardine2006], the study of which is known as prognostics. The additional information made available to the engineer through any form of CM is normally of some benefit to the engineer, either for safety considerations, output optimisation or for maintenance planning. An increasingly common goal of CM however, is to extend the analytical power of such systems to introduce prediction, such that future states of components can be estimated. There has been a large amount of research [Jardine2006] into the application of prognostic algorithms which extend existing CM for the application of condition based maintenance. There are already several examples of how prognostic systems for power systems can be developed and installed [Sharp2009], including in the nuclear industry [Coble2009] where concerns due to ageing equipment are becoming a particularly acute problem, for example in materials where fatigure crack growth [Zio2012] can affect RUL of reactors.

4.2 Nuclear Condition Monitoring

CM has arguably been employed in the nuclear industry to varying degrees since the construction of the first reactors, however the use of computational CM has increased significantly in recent years[Uhrig2005] for two main reasons. Firstly, the broadened availability of advanced computers in nuclear facilities (albeit often retrofitted onto existing equipment), frequently connected to live reactor data sources, has provided a means to present the engineer with ever more refined views of plant data and information. Secondly, the ageing of the existing worldwide nuclear fleet, given that new reactor construction virtually halted after the Chernobyl accident, has resulted in many reactor designs exceeding their originally specified lifetimes, with potentially degraded components. This increase in nuclear CM [IAEA2008] has therefore sought to increase the knowledge of the state of these components and as a result, provide justification to regulators that existing reactors are safe to operate and potentially allow operators to run reactors more economically [Heo2008].

For CM of safety critical systems in the nuclear domain, almost without exception, degradation of components must be detected as early as possible in order to properly qualify the safety function of that piece of equipment. In some cases, the failure of certain components may result in the end of the life of the reactor, with the replacement of the component either not practical or uneconomic. There are various examples of CM in the nuclear industry [Uhrig2005, IAEA2011a], used to perform different types of monitoring, which can be broadly split into two categories: online monitoring and offline monitoring[2].

There are some aspects of the nuclear industry which make nuclear CM somewhat unique compared to monitoring of other industrial equipment. The strict safety environment in which the reactors operate make it very time consuming and expensive to fit new equipment, therefore limitations often exist as to the availability of data or in the case of adding new equipment, there is a strong need to justify the potential benefits. This safety requirement also results in a lag in the deployed technology in NPS, compared to the state of the art. The criticality of failure is also an important aspect in the consideration of CM as a safety precaution. Apart from perhaps the airline industry, the nuclear industry requires considerably higher levels of reliability of assets compared to other industries, therefore proven technologies are invariably preferred for NPS application. Coupled with the fact that the nuclear industry has a relatively small fleet, within which very few components can acceptably fail, failure modes often require more modelling and simulation than may be required in other industries where components can be tested to destruction.

4.2.1 Online Monitoring

Online monitoring generally involves the monitoring of particular set of parameters, such as pressure or temperature, to ensure that a system is functioning properly in real time and is often designed to provide the engineer with a diagnosis of detectable faults and potentially a solution. As described in earlier chapters, transients in nuclear reactors due to failures of equipment or materials can occur very quickly, therefore the ability to rapidly process large quantities of data in a suitable amount of time has proven to be a major asset in the use of computational CM. There are several examples [Ma2011] of online monitoring of reactor

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[2] To avoid any confusion in the definition of online and offline, in this thesis, online monitoring is taken to mean data recorded and analysed in real time, whereas offline monitoring corresponds to any analysis of data that is not performed using a real time system.

subsystems such as motors, compressors and pumps [Koo2000][Porcheron1997] which employ model based, data driven and signal driven techniques to perform automated fault detection and fault diagnosis [Xie2005]. The retrofitting of modern AI based analyses to online monitoring is well established [Hashemian2010, Hashemian2011] and has become an area of intense research focus as part of an effort to extend the operational life of existing reactors.

4.2.2 Neural Network Peak Power Estimation

Souza and Moreira [Souza2006] demonstrated that Artificial Neural Networks (ANN), a black box technique, could be used in an online environment for reactor core CM. By using knowledge of the control rod positions within the core and with a set of training data, a model was created to predict the peak power within the core to within 5% accuracy. Though a relatively conventional application of an AI technique to a data analysis problem, this work as well as other examples, highlight the applicability of such techniques to provide decision support information to the operator. In this case, the information derived from the ANN could potentially be used to predict future peak powers and allow operators to adjust their actions accordingly, while the reactor is online.

4.2.3 Intelligent Vibration Analysis

Some features of reactor operation such as vibration have been used to perform online monitoring to detect transients. Koo et al [Koo2000] coupled a conventional Fourier Transform analysis with a neural network to develop a monitoring system for reactor coolant pumps on BWRs. The use of Fourier analysis to detect anomalies in vibrational data was used as the basis to develop a neural network which could recognise particular types of anomalies and provide advanced indication to engineers of a problem with the pumps, which can then be shut down to limit damage. This example in particular highlights the application of intelligent systems techniques to not only rapidly perform analyses, but to gain knowledge of the system through learning new behaviours as more data becomes available.

4.2.4 Offline Monitoring

Offline monitoring typically consists of analyses that are not related to the real-time decision making process of the engineers operating a reactor and are more commonly used to support long term maintenance planning [IAEA2007], output optimisation [Yoon2004, IAEA2008] and estimation of component health [Jahn2011] where transients occur more slowly. Mechanical properties of reactor components, such as strength or material density, or performance and reliability of electro-mechanical systems, can be the source of slow developing faults or degradation of the reactor as a whole.

Offline monitoring can sometimes be implemented as a less invasive alternative to online monitoring, potentially as a result of restricted access to data over safety concerns or because of a limited IT infrastructure for deploying a real-time system. The retrofitting of new equipment onto existing plant equipment is often very expensive and complex, therefore providing secondary data access to an offline monitoring system can often be a more attractive solution to the operator, providing the required functionality (e.g. suitably fast response to events) is still provided. The analysis of slower evolving trends, such as materials degradation, can be considered within the scope of offline monitoring, where movements between different behaviour modes can take months or years, rather than seconds or less for some transients.

4.3 Benefits And Limitations Of Nuclear Condition Monitoring

Some aspects of nuclear CM, particularly offline monitoring, overlap to an extent with what was described as inspection in Chapter 3, as applied to the AGR. More generally, the ever increasing age of the existing worldwide nuclear fleet and the comparatively lower cost of deploying a CM system (compared to more frequent physical inspections and the loss of revenue from generation) has been one of the main drivers for an increase in installed nuclear CM. The use of CM systems to inform maintenance regimes, optimise performance and provide a source of evidence of safe operation to regulators between statutory outages has been of benefit to the nuclear industry, however there are some limitations which face monitoring which can often hamper deployment and restrict the usefulness of CM systems.

All of the examples of nuclear CM discussed in this chapter were implemented for individual reactor systems or groups of related systems with a specific set of parameters to analyse. The addition of systems in such a piecemeal approach can result in fragmented CM systems across even a single station, with multiple CM systems performing analyses on different parts of the plant, but without any overarching framework. The use of many CM applications, distributed across a station can introduce duplication of effort (several systems performing the same data pre-processing task for example) and provides little or no scope for correlation of events or analyses to provide a more holistic view of the state of a reactor.

Limited IT infrastructure within plants constructed as long ago as the late 1960s can also inhibit the usefulness of CM. Though increasingly powerful computers are now installed in nuclear power stations, the infrastructure within which they reside is often based on the original design topology of individual systems relative to the control room and the core at the time of construction. Exactly such problems can be found in the UK's AGR fleet, where, for example, bespoke systems have been installed to *join-up* gaps that exists between a source of data and the interface to a CM system designed specifically to analyse that data or where data sets describing related physical systems are analysed in isolation, or manually by an engineer which can be extremely time consuming.

4.4 Discussion

This chapter has described the principles of CM and the various approaches which can be taken and were shown to be highly dependent on the system to which they are applied. The suitability of model based and data driven CM systems were shown to each have their merits and some limitations which have particular relevance to the nuclear industry and the requirement for some level of explicability. The development of prognostics, as a means of determining the RUL of components, along with many examples of existing nuclear CM has shown the field to be very active. Some important limitations to monitoring in the nuclear industry in general were highlighted, and parallels drawn to the problems facing the monitoring regime in the AGR fleet. In particular, the lack of connectivity and communication between CM applications and the limited re-use of data for correlation and corroboration of events and anomalies, limits the usefulness of nuclear CM. It will be shown in the next chapter that a solution to these problems in the form of a distributed framework, combining data sources to derive more useful CM information, could contribute to solving some of these problems for the AGR fleet and for nuclear CM in general.

Chapter 5

Intelligent Agents and Condition Monitoring

Some of the key problems associated with the use of CM in the nuclear industry have been shown to be caused by piecemeal implementation of CM systems of varying design onto legacy equipment which is often distributed across nuclear power stations. A modern approach to solving distributed analysis problems of this type is possible through the use of intelligent software agents. These agents can be distributed over several locations, each incorporating some type of intelligence or functionality which can then be exploited by the community, providing a more flexible software solution than a traditional, centralised system could offer. Such a system designed with a common language, or ontology, would allow the sharing and common understanding between different system components as to how to interpret concepts such as data or analyses. While distributed software components, such as web services could potentially form such a system, previous work in the CM field has highlighted intelligent agent based systems as a proven, flexible approach [Mangina2001, McArthur2007a, Wang1996] for use in CM and may provide a new approach to the problem of nuclear CM. This chapter introduces the concept of an intelligent agent, describing common attributes of agent based systems and illustrates the suitability of agents to CM. Generic agent concepts are introduced, to illustrate the design principles of agent-based systems, with more detailed, agent-platform specific discussion in Chapter 8, which describes the development of a prototype system based on these ideas. Some particularly relevant example of prior research are introduced and discussed, so as to identify the benefits and limitations of previous application of MAS to CM.

5.1 Intelligent Agents

Traditional software programming is based on the creation of a set of algorithms which are performed as a sequence or procedure by the computer, based on a human user's requests or until some end condition is met. Normally the intelligence, or knowledge base for a program will be in a single location, with relevant knowledge (in code) employed as required as the program runs. This approach has been used successfully for decades as it allows the programmer to design specific tasks and ordering for the software to perform.

There are certain problems however, where such a monolithic design can be unsuitable, such as where there are a large number of parallel tasks occurring and where some independence within the software — to act, or prioritise actions — may help achieve a global goal (the overall problem to be solved) albeit possibly at the expense of local goals (sub-parts of the problem).

Arguably since the development of the earliest computers and software, there has been an interest in the ability of a mechanical or algorithmic entity to behave autonomously, even independently of its designer – indeed many consider this to be a key aspect of intelligence. A system of multiple independent agents has a vastly greater number of potential configurations than a system consisting of a linear sequence of actions performed by a single agent and can potentially provide a more flexible and robust approach to solving distributed problems.

5.1.1 Intelligent Agency

There are several definitions as to what characteristics qualify an entity as an agent as compared to an Intelligent Agent (IA) [Russell1999], with Wooldridge and Jenning's *weak notion of agency* [Wooldridge1995] one of the most commonly referenced. This description requires that to be considered an IA, an entity must exhibit:

- **Autonomy** - The ability to perform actions without input from an external source
- **Social ability** - The ability to interact with other entities
- **Reactivity** - The ability to respond to changes in environment
- **Pro-activeness** - The ability to perform action independent of external factors to achieve a goal

This definition of intelligent agency is used in this thesis, as it provides a relatively clear definition of where traditionally programmed systems differ from agent based systems [Franklin1996][Jennings2001] and it is these characteristics which will be exploited to design a nuclear CM framework based on MAS technologies. For simplicity, the word 'agent' is will henceforth be used to mean IA for the remainder of this thesis, with the characteristics described in [Wooldridge1995]. In the structure of intelligent systems techniques as described in the previous chapter, agents can be considered an intelligent systems, with the capability to incorporate other intelligent systems techniques within the agents.

5.1.2 Is It An Intelligent Agent?

The characteristics of the weak notion of agency, given above, help classify where pieces of software should be considered IA, and where they should not. An operating system service, such as a printer daemon for example, is reactive to requests and continues to run without the supervision of a human user, giving an appearance of some independence, however it will only perform an action based on a request from the user and is therefore not autonomous or proactive. Careful consideration must be given to whether a task or behaviour is suited to an agent based design or whether a conventional programming approach will suffice. In the context of this thesis, particular emphasis is placed on the occurrence of dynamic and irregular events (and associated data), which require sequences of actions and responses from a number of different analyses, rule sets and data sources.

A logical extension of the use of an agent-based approach for such problems, as sociable entities, is the concept of a Multi Agent Systems (MAS).

5.2 Multi Agent Systems

When a group of agents, more commonly known as a Multi Agent System (MAS) is assembled, the social aspects of an agent can be exploited so as to offer the capabilities of each agent to the whole system. A MAS can perform tasks in sequence by passing consecutive parts of analysis between different agents with different capabilities or, potentially more efficiently, performing several parts in parallel, with one or more agents assembling analysis results or conclusions to return to the user. This decentralisation of expertise or capabilities within the MAS need not be restricted to software components, indeed it is possible to federate groups of agents, or MAS, in different physical locations to create a larger, distributed MAS. Such a system has the benefit of allowing the MAS designer to have greater flexibility over the management of resources of the larger system. Management of storage and computational power capabilities and requirements can be encoded into the agents themselves, with the agents aware of their current resources and able to offer services to the MAS on a basis that helps optimise the speed with which tasks can be completed. An agent in a particular location for example may be aware that the analysis of a dataset will take a longer than acceptable time[1] and may request that a different agent in the MAS perform the analysis. Communication between agents to determine available resources and transfer information, requests and data, to a large extent defines how a MAS functions.

5.2.1 Communication And Ontology

Communication between agents allows the social actions and reactivity of a MAS to occur, however for agents to effectively communicate with each other, a common language is required such that concepts and information can be interpreted

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[1] Acceptable time as deigned by the system designer

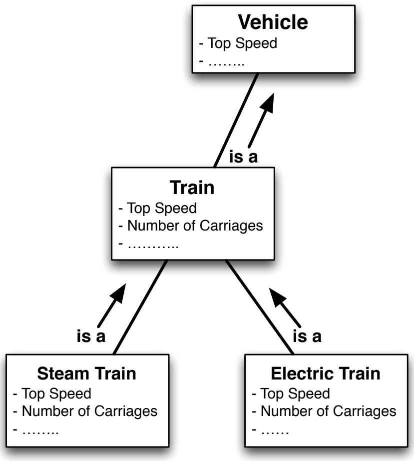

Figure 5.1: An example from an excerpt of an ontology

and stored within the system. The creation of a well defined ontology is crucial to the ability of the agent system to share resources or knowledge [Tamma2002], offer services and provide a flexible approach to computational problems. There are a large number of styles and formats of ontologies, often based on predicate logic (where statements are evaluated to be true or false) or other logical formalisms [Huhns1997][Williams2004]. An ontology is a model of some aspects of the physical world or abstract concepts and the relationships between them. The ability to arrange concepts into generalizable types, allows the creation of representations of concepts with different slots, or properties, as in Figure 5.1.

For example, a concept ***Train*** may have certain attributes, or slots, such as *Number Of Carriages* or *Top Speed*. The concept ***Train*** is related to similar concepts such as ***Steam Train*** or ***Electric Train*** which can then inherit the slots of *Number Of Carriages* or *Top Speed*, which are common to all trains, as well as other attributes unique to those types of trains. Similarly, the class ***Train*** may be a subclass of a larger class ***Vehicle*** from which it inherited the attribute *Top Speed*, which is an attribute of all vehicles. The relationships between different concepts can be formalised using predicates, a simple example of which might be '*Train* **is a** *Vehicle*', where the predicate '***is a***' describes one relationship between the two concepts and can be evaluated to a Boolean value. This representation, which has strong parallels with Object Oriented (OO) programming, is discussed in more detail in Chapter 8 and provides a formalism within which domain knowledge can be stored and reasoned against.

5.2.2 Design Methodologies

There are several established design methodologies for MAS[Wood2001], and in particular for power systems[McArthur2007a]. Most approaches can be categorised as top-down, where the needs of the global system are the basis of design, or bottom up, where individual component requirements are designed for and global behaviour emerges from the system[Crespi2008]. The use of a design methodology encourages a regimented design process such that the complexity of the system (from a design perspective) will be limited and the development of new agents is simplified. A design methodology is selected based on the requirements of the system and will ideally complement the conceptual agent model that the designer has chosen. one of the most well known of which is the Belief-Desire-Intention (BDI) model[Georgeff1998], which models internal states of the agent as beliefs (things the agent believes to be true), desires (the end state that the agent seeks) and intentions (functions that the agent will undertake to reach its goals).

The work described later in this thesis followed the same general path as McArthur et al[McArthur2007a] and several aspects of the Gaia[Wooldridge2000, Zambonelli2003] methodology, in particular for the development of a Service Model, which defines the roles for which agents are created and the capabilities they can offer the system. The emphasis on defining the services offered by the agents reflects the desire for the system, initially at least, to automate the tasks and procedures already defined and performed by engineers.

5.2.3 Platforms

Typically the creator of a MAS will employ an existing middleware as a framework, using a pre-specified programming language, coding style or deployment format. There are a large number of different platforms[Bordini2006], categorised by the design approach, the programming language used to construct the agents and the level of integration provided by the framework. Some fully integrated environments such as Java Agent Development Framework[Bellifemine, Tilab2010] or the Jack agent platform[AOS2013] use Java as the programming language and provide base classes and utilities for agent design. Jack also implements its own agent language to implement the BDI model, an example of one of several different languages and programming styles[Bordini2006] which are used among one or more frameworks. Many frameworks such as ABLE[IBM2013] or ZEUS[Nwana1999] also provide toolkits to create agents and automatically generate code which can be compiled and run by the user.

The Foundation for Intelligent Physical Agents (FIPA)[FIPA2013] is a standards agency, associated with IEEE, which is tasked with defining the standards for 'Intelligent Physical Agents', which are published to encourage interoperability between different platforms. Different platforms however have varying levels of compliance with the FIPA standards, a feature that can be an important factor in selecting a platform. It is also interesting to note that many agent platforms are the result of industrial research, often with academic collaboration, which, it can be argued, reflects the desire for such systems in industrial applications, rather than purely for research purposes. This supports the case for agent-based systems as an established and suitably robust candidate technology for use in the nuclear industry, the importance of which was discussed in Chapter 2.

5.3 Multi Agent System Condition Monitoring

Intelligent systems are, by their nature, ideally suited to data intensive, analytical tasks that involve repetition that is too time consuming for a human. The extension of intelligent systems to an agent-based approach allows a level of independence to be introduced to the software, to increase flexibility and meet the requirements of distributed problems, that conventional software does not offer. The discussion of CM in Chapter 4 highlighted similar requirements for automated, intelligent CM systems and so perhaps unsurprisingly, there are several example of MAS in a variety of CM related roles, in fields as diverse as structural health monitoring [Yuan2006], wind turbine monitoring[Zaher2007], process automation[Pirttioja2005] and even healthcare[Laleci2007].

5.3.1 Distributed Monitoring

Yuan et al [Yuan2006] made use of sensors with microprocessors, to turn the health monitoring of a structure into a distributed parallel system, rather than a centralised processing problem. This work, as well as other research with intelligent sensors [Baker2010] has shown the practicalities of using low-power computing to make use not only of sensing capabilities, but also of analytical capabilities of such devices and the intelligence that the designer imbues them with. A distributed system can potentially be more efficient and robust than a centralised system, with Yuan et al [Yuan2006] for example, applying data fusion algorithms to optimise the efficiency of data and information transfer.

5.3.2 Multi Agent Systems For Power Systems Condition Monitoring

One industrial area where MAS have been used to great effect is the power industry, which has embraced the use of MAS based CM[McArthur2007a, McArthur2007b], in particular for monitoring of power transformers [McArthur2004, Catterson2005, Catterson2006, Rudd2007] and for fault diagnosis in electricity distribution and transmission [McArthur2004].

5.3.3 PEDA

The Power Engineering Diagnostics Agents (PEDA) system [Hossack2003, McArthur2004] combined several sets of intelligent analyses into a MAS for analysing post-fault analysis of Supervisory Control And Data Acquisition (SCADA) data and Digital Fault Recorder (DFR) data from electrical substations. Using knowledge based and model based approaches, PEDA provides customised analyses to the engineer in a timely manner after a fault has occurred in the network. PEDA features a rule-based expert system to analyse alarms and fault data and a model-based reasoning engine to analyse the protection applied on the power system.

5.3.4 COMMAS

The COndition Monitoring Multi Agent System (COMMAS) [Mangina2001, Catterson2006] was designed as a MAS to perform CM analyses, in particular the analysis of partial discharges within power transformers, using a variety of analysis techniques including:

- C5.0 Decision Trees
- Back Propagation Artificial Neural Networks
- K-Means Clustering

Each analysis agent in the COMMAS system performs a different type of analysis, each of which performs slightly differently in different circumstances. To make the analysis process more robust, COMMAS has the ability to reflect on different analysis results within the system and determine which was most likely to be accurate based on the situation.

The integration of PEDA and COMMAS[Catterson2005] highlighted important issues common to other MAS, including the management of multiple ontologies and the lack of an upper ontology, under which domain specific systems (like PEDA and COMMAS) can sit, such that interoperability between different systems is simplified. More recent work on the COMMAS system included the integration of a wireless sensor network to the system [Baker2009], further emphasising the suitability of agent based systems to distributed monitoring problems.

5.4 Nuclear Applications Of Multi Agent Systems

There are some limited examples of MAS in the nuclear domain, including the Advanced Process Analysis and Control System (APACS) [Wang1997, Wang1996], developed by the University of Hong Kong which used a MAS to manage real-time data collection and analysis of faults on the feed-water pump systems of CANDU reactors.

5.4.1 APACS

In contrast to the work described in this thesis, APACS was designed to interface a single, centralised data source and provided interpretation and analysis of data in real-time. As the first example of a deployed MAS in a nuclear power station, there are however some useful lessons to learned from APACS, including the importance of a well designed data repository and the importance of knowledge sharing. APACS was built as a knowledge-based system with agents forming APACS components which perform:

- Data Acquisition of real-time data
- Tracking of a real-time simulation of the plant
- Monitoring of sensor data to detect the state of the plant
- Diagnosis of monitoring data to generate explanations of behaviour
- Verification of the diagnoses in faster than real-time
- Human-computer interface to interact with data and models

These agents are managed by a knowledge server agent, which has a global view of the system. A particular problem considered in the development of APACS was that of knowledge representation and use of ontologies within the system, which was addressed through the use of multiple ontologies stored in a repository. For reasons of efficiency and complexity of design, a common knowledge representation for the repository agent and the knowledge server agent was created, while client agents (Monitoring or Diagnosis agents for example) use their own internal ontology.

The APACS agents therefore are limited in their sociability by the use of different ontologies, while the knowledge server agent, in managing the system, is effectively synchronous and performs the translation of communication between the client agents and the information repository.

5.4.2 Other Applications Of Nuclear Agents

The use of MAS has also been proposed for the automated control of generation IV nuclear reactors [Uhrig2003], which would be expected to operate for long periods in a relatively constant state. Generation IV reactor are conceptual designs for future reactors, compared the current Generation II, III and III+ reactors, based on high temperature or fast reactor designs to maximise use of fuel. In such a proposed application, it is suggested that a MAS would be able to act proactively to anticipate potential problems far more rapidly than human operators could hope to. In the UK, some work [Jahn2011] has investigated the use of MAS for management of CM observations for the AGR, indeed an early protoype of the IMAPS system described earlier implemented an agent-based approach however for performance reasons, speficically the rendering of a large number of objects on-screen in an acceptable amount of time, a different approach was adopted for deployment. It is worth noting that though agent-based systems were found not to be suitable for live user interfaces, work which can acceptably absorb small delays (of the order of seconds) could potentially be performed by an agent-based system in the background.

5.5 Discussion

This chapter has introduced the concept of an agent and a MAS, describing the flexible and distributed approach they bring to certain types of computational analysis problems. The design approach and requirement for the creation of an ontology for a MAS, was shown to be conducive to a strong focus on organisation and structure, which was earlier argued to be lacking in many applications of nuclear CM. Indeed it was shown through several examples that MAS are well suited to CM applications, particularly for data-intensive background work and it is on this basis that the next chapter describes a generalised framework for distributed nuclear CM. In order to achieve this, whilst maximising the use of available data and identifying correlated events in data sets, an approach incorporating analyses which emphasise the combination of information and data, based on a MAS structure and a common ontology, is proposed.

Chapter 6

Distributed Nuclear Condition Monitoring Using Data and Information Fusion

The importance in the nuclear industry of multiple distinct layers of safety (or defence in depth) manifests itself, in CM, through several parallel analyses on connected subsystems to monitor the larger core. An agent-based system for CM would complement this approach by providing a framework for parallel, distributed tasks while being extensible enough to grow with the requirements of the monitoring regime as the plant ages. One of the key benefits of CM is the ability to extract useful information about plant components from data which is already recorded for fault detection or post fault analysis, rather than for continuous trending and analysis. Though this provides a useful source of CM data, under-use of this data is common and coupled with the frequently isolated nature of many CM analyses, as described earlier, emphasises the potential for more detailed CM by incorporating more data sources into analyses and comparing analysis results. To that end, this chapter introduces key concepts from the field of Data and Information Fusion, such that they can be used to increase the utility and flexibility of CM and data management. The chapter will then go on to propose a generalised model for a distributed nuclear CM system incorporating data and information fusion inspired analyses based on a MAS architecture.

6.1 Data And Information Fusion

Data Fusion (DF) was originally conceived as a method of combining data from a number of sources, initially for military applications [Llinas2004]. It was often the case for decision support hardware and software in the field, that several sources of sensor data required some combination and contextualisation before an analysis could be performed and appropriate action taken. A framework was therefore devised to describe the process of combining data from multiple sources and analysing it, such that it could be used as the basis for a decision. This original model was known as the Joint Directors of Laboratories (JDL) fusion model [Llinas2004] which has since undergone several revisions. This model defined DF as a *"multilevel, multifaceted process dealing with the automatic detection, association, correlation, estimation and combination of data from single and multiple sources"* [Mandic2005]. There are now several DF models [Esteban2005] and many applications of DF, based on a variety of techniques, in fields such as science and engineering [Mandic2005], business [Qiu2002], marketing [Haas2009] and medicine [Aerts2006].

6.1.1 Generic Data Fusion Techniques

There are a variety of types of problems and data types to which DF techniques can been applied, with no single approach or model suited to all types of problems. In general these problems may be classed as the fusion of:

- temporal data - where older data must be combined with new data
- multiple source data - where different sources of similar data describing the same parameter must be combined
- multiple representation data - where different parameters of an object or environment must be combined

DF is better viewed as a general set of techniques, often involving common steps or types of analysis, which can derive a single conclusion or parameter from multiple sets of data. These techniques, variously called Data Fusion[Llinas2004], Data

Integration[Iyengar2001] or Information Fusion[Xiong2002] can be performed in a number of ways, but generally involve some or all of the following key stages (where DF is the complete process of these stages):

- Data collection - Raw data is retrieved from a sensor or a database
- Data refinement - Data is converted into an ontology format for further use
- Application of knowledge - A model or analysis is applied to the data
- Feature detection - Analysis results are compared to expectations and classified

Most DF techniques make use of statistical analysis of sensor data to derive information and perform some classification or make a decision. There are several examples [Punska1999, Cou2002, Orton2001] of previous work based on the use of Bayes theorem for DF for example.

Combining existing knowledge of the world with new observations in order to generate new and better estimates of the environment is the basis of DF. As such, DF is often used in situations where operation of equipment depends on interaction with the environment, for example in robotics [Durrant-Whyte2001] or for controlling autonomous vehicles [Bento2005]. It is interesting to note the parallels between the use of DF for autonomous applications and the autonomous nature of intelligent agents described in the previous chapter, which suggests that such techniques could be well suited to application in an agent-based system.

6.1.2 Data Fusion Example

A simple example which illustrates the basic principles of DF is shown in Figures 6.1 and 6.2. Consider an aircraft that is being tracked by a ground based radar station as shown in Figure 6.1 where, by means of projecting a signal onto the surface of the aircraft and detecting the reflected signal, it is possible to estimate the position and speed of the aircraft. Using several radar stations however, as in Figure 6.2 and projecting and detecting multiple signals, it is possible to achieve a higher resolution measurement of the aircraft's position and speed.

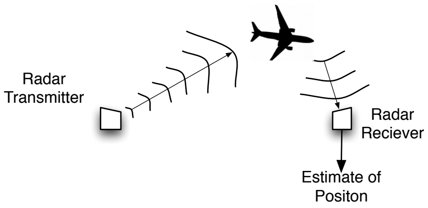

Figure 6.1: A single source of radar data used to estimate the position of an aircraft

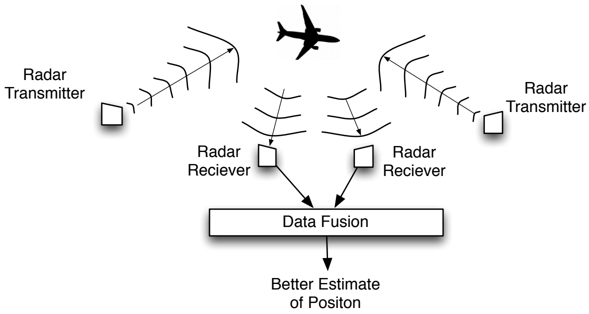

Figure 6.2: Multiple sources of data combined to create a better estimate of the position of an aircraft

This technique is known as Multistatic radar [Farina1986], and to achieve the increased resolution gained by the addition of further data sources, DF is required. In the case of Multistatic radar, the DF analysis is concerned principally with the timing of the signals and the geometry of the radar station configuration, however the general concept of combining data sources to derive a measurement of an unknown, or coarsely measured parameter, can be extended to a great number of different scenarios.

6.1.3 Information Fusion

While it is possible to combine data at the lowest level with raw data from a sensor or a database, fusion can also occur at higher levels, including Information Fusion (also known as Information Integration). Information Fusion (IF) is the process of combining information from different sources which describe different characteristics or conceptual representations of some aspects of related data sets. In some cases, this could involve the combination of different pieces of evidence, such as in Dempster-Schafer theory [Dempster1967], to determine a degree of belief based on available, even conflicting, evidence. In other examples, IF can be used to describe the mechanism through which information about a system is shared and consolidated, so as to allow more efficient or detailed analyses. Such processes are now commonplace in business and retail as knowledge of consumer behaviour becomes an increasingly sought after commodity[Haas2009] and even in science and engineering, the benefits of combining data sets has become apparent[Mandic2005]. Indeed the use of Dempster-Schafer evidence combination for example, as a means of an intelligent analysis system internally comparing and reflecting on analysis results in power transformer CM, has been shown to be a task well suited to a MAS, as in COMMAS[Catterson2006].

6.1.4 Data Fusion For Condition Monitoring

Recent work on CM[Niu2010] and prognostics[Roemer2001] has suggested that the combination of data and information from multiple sensors or sources can provide significantly more detailed information about the state of a system than conventional CM. The apparent simplicity of the collection, refinement, knowledge application and feature detection tasks described above however belies the considerable amount of effort required at each stage. It is proposed that an agent based approach to this distributed problem could provide sufficient flexibility to allow several parallel tasks to be performed in different locations, including CM analyses and pre-processing and correlation of different events in datasets.

6.1.5 Distributed Data Fusion

There has been significant interest recently in IA based DF [Das2010], highlighting the parallels between the characteristics of an IA as described in the previous chapter, with common features of DF algorithms. The use of agents to perform tasks where bandwidth or computational power may be limited in one location but not elsewhere in the MAS, and potential for specialised sensor placement and the use of intelligent sensors [Xiong2002] amongst others have resulted in the creation of distributed DF frameworks such as DFuse[Kumar2003].

6.1.5.1 DFuse

DFuse was designed to support DF applications across wireless sensor networks with limited resources and demonstrated that the distribution and topology of the DF scheme across the network was critical to efficient operation. The DFuse framework however is based on the premise of a physical network of components each with computational capabilities, rather than a virtual topology implemented as a MAS, on top of an existing infrastructure.

6.1.5.2 Sensor Networks

Other work [Maranenko2004] has emphasised the importance of the communication between different sensors in *Active Sensor Networks* to perform data gathering tasks in a decentralized manner which is scalable. This approach utilised Bayesian IF algorithms, however like DFuse was based on the use of autonomous physical sensors, which in this case could be reconfigured dynamically to improve data collection tasks. Other examples include a framework for DF using a MAS applied to visual sensor networks [Castanedo2010]. This system uses multiple sources of data, each assigned to an agent, which then interact to attempt to estimate the most likely position of objects in the scene by attempting to eliminate measurement errors.

6.2 Distributed Nuclear Condition Monitoring Framework

The capabilities and benefits provided by the application of DF techniques in a distributed system, as well as the experience of agent-based CM described in the previous chapter provide the basis for the contributions presented in this thesis. The remainder of this chapter therefore describes a model for distributed CM of nuclear reactors using an agent-based approach, showing where the benefits of DF techniques can be introduced and exploited. A general model [Wallace2012] is presented, describing the key features and requirements of such a system, before the next chapter introduces a prototype system designed on these principles.

6.3 Agent Design

Earlier chapters introduced the idea of design-methodologies as a technique to simplify the creation and development of agents. It is proposed that as the desired system for nuclear CM will effectively attempt to perform tasks that are currently or could in principle be performed by plant engineers, a strong emphasis should be placed on roles. Three broad classes of agent have therefore been identified in this thesis, with characteristics reflecting the roles that they serve: *Interface Agents* for managing the communication and access to CM systems and data sources, *Analysis Agents* for performing CM analyses or deriving information from data and *Archive Agents* for storing and structuring CM data and information. The names of these roles describe the broad functionality of that class of agent, in particular the type of task the engineer currently undertakes which it is desired for the agent to perform. These classifications are not based on a particular design methodology, however some of the classes such as 'Archive Agent' are used elsewhere [Jahn2011].

6.3.1 Interface Agents

The number and variety of data sources associated with nuclear reactors results in the need for a significant volume of domain knowledge just to extract meaningful information from data. Different designs, formats or sample rates of data loggers (and the data they produce) can be encoded as knowledge in an agent. The agent can then re-use the knowledge of how to access, parse and interpret data from that source whenever data is available. Given the previously discussed common limitations on access to reactor related systems, this is likely to be a file drop location, network share or access to a database rather than direct access to a data logger.

The sociability of an agent, as discussed earlier, allows the interface agents to act as proxy agents for other agents that may wish to query or retrieve data from a source that has particular access requirements. The concept of an interface need not be restricted to a data source; other CM systems or even human user-interfaces can interact with the MAS either for analysis or to access some resource for which the MAS contains the appropriate knowledge. A database structure for example may be encoded in an interface agent, which can then translate suitably structured requests into an appropriate database query and can then return the resulting data in a structured form. The extensibility of such a system can be emphasised here, since the identification of new interfaces and the addition of new interface agents to the MAS allows the system to continually improve its ability to respond to generic external requests.

6.3.2 Analysis Agents

New and existing CM analyses can be encapsulated in modular pieces of code which can be executed at regular intervals, at the request of a user or at the request of another agent. Agents can be programmed to recognise when suitable data is available and perform analyses automatically. These analyses could be numerically intensive calculations such as trending control rod positions or reactor power levels, or simply recording particular events in incoming data, such as refuelling or maintenance. As a result of their sociability and reactivity, a key aspect of a MAS is the ability of agents to make requests of each other. This allow sequences of CM analyses to be automated, triggered and synchronised and results shared without the need for any user interaction.

Providing access to different data sources and CM systems through agents promotes the use of multiple datasets in analyses which can be encoded in the agents as DF analyses. Also, analyses where event or component information from multiple sources can be used to correlate or confirm anomalies for example, could be implemented as IF analyses which can request any type of available information from the MAS.

6.3.3 Archive Agents

It could be argued that an Archive Agent is actually an Interface Agent and to a large extent this is true; the actual storage of data is likely to be performed by database software. It is particularly important however, when working with large volumes of data and potentially conflicting analysis results, that careful control is exerted over any data that is archived. For storing data and analysis results, persistent storage, such as a database should be made available through at least one agent, that manages the storage and retrieval of objects defined by means of the system ontology. Since the goal of any CM system is to provide information about a system to the user, ultimately analysis results and conclusions should be available as facts which can be reasoned against. To achieve this however requires a detailed, carefully structured ontology that incorporates knowledge of the physical nature of the system to which the CM is applied.

6.4 Ontology

In order for agents to communicate, a common language known as an ontology, as discussed in Chapter 5, is required. An ontology for CM can be considered to be a hierarchy of physical components, such as reactor components or sensors as well as more abstract concepts such as data associated with sensors or analysis results and agent actions. With sufficient detail and consistency, the development of analyses, once physical relationships have been identified, is significantly simplified. As mentioned earlier, one of the key problems with nuclear CM can be the lack of consistency between different CM systems, and while the distributed system proposed cannot bring uniformity to these systems themselves, it can bring some consistency to the future storage of data and information about the components which are being monitored. The need for a formal ontology is beneficial therefore not just to the MAS but to future work where properly structured data and concepts can help accelerate the development of new tools.

6.4.1 Components

The ontology must be able to describe reactor components including where possible how a component relates to other components. For example the position of a fuel channel in the core or which sector of the core a particular gas circulator cools will be important relationships when analysing the performance of and interaction between different components. Clear distinction should be made between data from a sensor in a location and the physical component that may occupy the same location. For example a thermocouple sensor on a fuel assembly describes a parameter of that fuel channel, but not nescessarily the state of the fuel channel itself.

6.4.2 Sensors And Data

Data that is stored and analysed within the system must be structured such that subsequent retrieval and analysis can be performed efficiently. Structurally, a class based system can organise data by type or parameter. For example there may be several types of time series data which are all stored in a similar manner in the database and extend a base type of 'time series' data. This will aid in the extendability of the system and the addition of new data types. Data should always be associated with a component or sensor within the system subject to the conditions described previously.

6.4.3 Information

As a result of existing CM, there can be significant volumes of qualitative CM information, where a CM observation has been described, often without any associated measurement or where the analysis of a measurement has not been standardised. The current control rod analysis at AGR stations for example includes datasets of time-height data, however the judgements made on the data are qualitative. All available information should continue to be recorded, potentially for later semantic analysis [Hofmann2001] such as searching for the frequency of particular words or phrases. All descriptive content should be associated with a component or sensor and identified spatially and temporally as far as possible. It is important for later analyses, which are often reduced to search problems, that information is properly structured.

6.4.4 Events

Information describing events must be clearly and uniquely identified spatially and temporally, and be labeled in relation to the component with which they are associated. For CM, events should be considered instances of non-continuous information, that is an event may occur frequently or rarely and may have data associated with it or be purely descriptive, but it is to be distinguished from a continually measured parameter. This distinction is particularly important given the discussion in previous chapters of the effect of transient events which can perturb operational parameters often used for CM, where the dismissal of certain anomalies due to mitigating events can often drastically simplify the analysis.

6.4.5 Analyses, Observations and State

While information and data require processing to a structured format, they both remain objective descriptions of parameters. Other concepts, such as analysis results, engineers' observations or estimates of state or health can be more subjective — either as a result of the analysis used or due to normal human subjectivity. These concepts should be stored separately and clearly identified in an ontology as representing only abstractions or interpretations of data and event information. In the case of a faulty measurement, it should be considered that the sensor is un-reliable but that the data produced contains the normal level of precision, even if it is not accurate. An analysis can be re-performed using better classifiers or cleaner data but data can in general not be re-recorded.

6.4.6 General Nuclear Ontology

Based on the results of previous work [Catterson2005, Shvaiko2013], it was identified that relationship between ontologies of different systems in the same field is

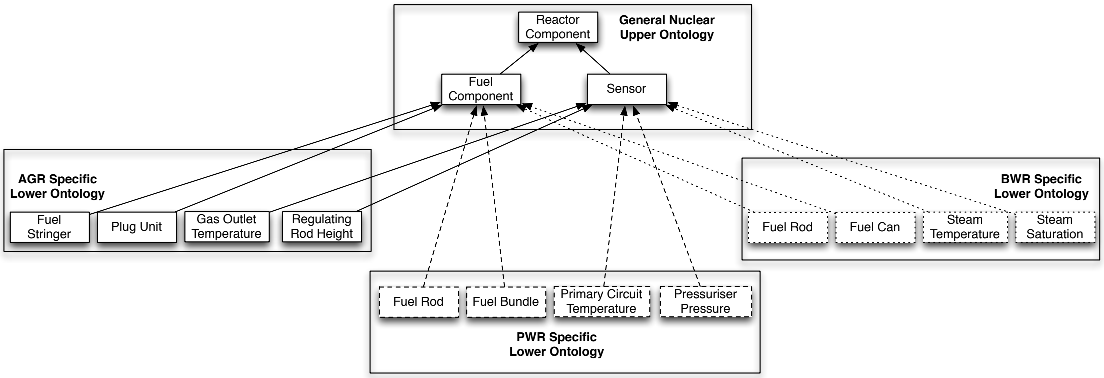

Figure 6.3: An example of different lower ontologies with a shared upper ontology. In this case, the upper concepts are common to AGR, PWR and BWR stations, while lower concepts are specific to a particular reactor type.

a crucial aspect in the extensability and interoperability of any MAS. It is therefore proposed in this thesis, that to maximise interoperability and re-use of data and analysis algorithms, and for simplifying design interfaces for future systems, common features of nuclear power stations should be identified and described using a common upper ontology. Specific features of different reactor designs and different stations necessitate the use of differing concepts at a detailed level, however at a high level, all nuclear power stations have some common features, such as physical objects including reactors or sensors, but also abstract concepts such as maintenance or RUL. Figure 6.3 illustrates how a shared upper ontology can describe broad concepts, which at lower levels introduce concepts specific to a particular reactor design.

To this end, Figure 6.4 contains a proposed upper ontology for nuclear CM containing concepts which can be extended to describe the key concepts of nuclear CM for any reactor design.

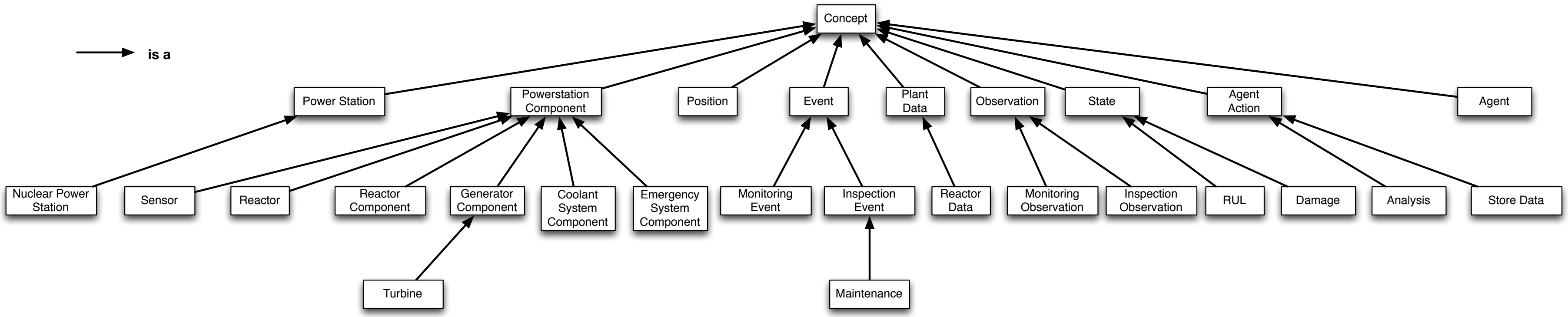

Figure 6.4: A general high level ontology proposed in this thesis for nuclear condition monitoring. The concepts are intended to be generic enough that they can be extended (downwards) to include other concepts required for specific CM implementations.

6.5 Decentralisation

One of the primary reasons for using a distributed agent-based system is the capability to manage resources on the network of connected data sources, storage and users. Design of a distributed CM system must consider the available resources and encode as appropriate in agents which tasks can only be performed in particular locations. Agents can themselves manage which tasks are performed locally by being aware of the current available resources or if available, estimates of future resources. An agent in a particular location for example may be aware that there is relatively high utilisation of CPU time locally during business hours, however at night there is greater availability of CPU time and computationally intensive tasks, where suitable, may be postponed.

6.6 Interoperable Condition Monitoring

Where multiple CM systems exist, with overlapping scope, a distributed agent-based framework for monitoring may also be beneficial in retrieving data, adding functionality or providing access to data stored in existing systems. CM systems are to a large extent characterised by the information and data available to them, in order to make diagnoses and generate models of behaviour. Where additional relevant data or information exists it seems logical to incorporate this into the existing CM analysis. It may be the case however that the source of additional data or information is another CM system, which therefore requires consideration of the integrity and independence of each system before any integration is applied.

It is important that the there is no increased dependency of one system to another, as the standalone integrity of each system is crucial to their continued use and the reliability placed on their conclusions. That is, a failure in one system may be allowed to remove some functionality from another system (the functionality provided by the failed system), however the failure of one system must not compromise the complete functionality of another system.

Similarly, the sharing of information or data between two or more CM systems must be carefully analysed in order to check for logical consistency and to ensure

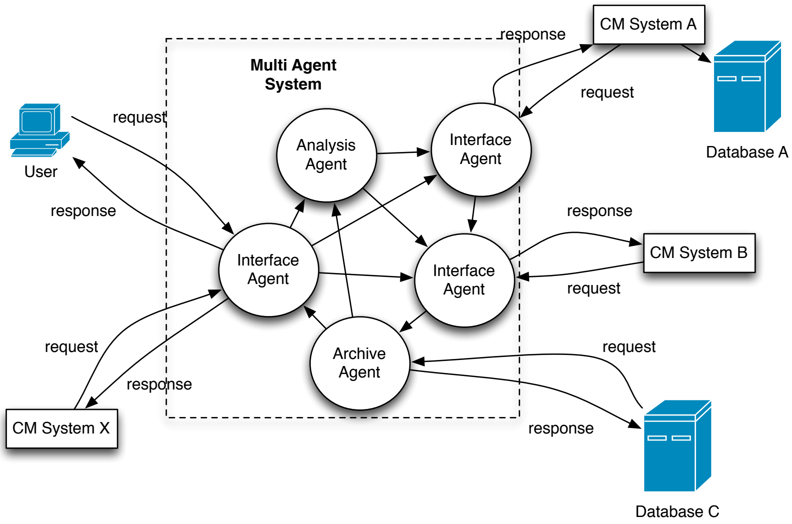

Figure 6.5: A proposed model whereby multiple CM systems and users can interact through a single, well defined interface.

that the conclusions made by systems are not unduly affected by potential errors in other systems. For example, an error in one system may lead to a particular bias in one type of conclusion, which is used as as a fact[1] by another system which then alters its own conclusions, which then may feed back into the system which made the original error, amplifying the original error.

As discussed earlier, the fragmentation of different CM systems is an important issue when considering the application of CM to a complex system such as a nuclear reactor. The lack of interoperability between existing CM systems is a problem of design, and it is proposed that a distributed agent-based architecture could provide a solution to this. Figure 6.5 shows an example of a structure which would simplify the querying of multiple CM systems and sharing of information and data, viewed from an external perspective. In this model, an agent provides a single interface which handles and routes requests while other agents handle communication and translation between existing CM systems and databases.

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[1] 'fact' in this sense is meant to mean something which is accepted to be true

6.6.1 A Generic Condition Monitoring Interface

The variety of techniques and designs used for CM applications often makes it difficult or impractical to directly interface two or more CM applications, especially where a system is used for safety critical decision support and modifications are unwanted or time consuming to achieve. For this reason it is proposed that a middleware agent-based framework, incorporating the features already described, could be used to open up access to existing CM and even provide new functionality to these systems. Using an agent encoded with the appropriate knowledge to access an existing system, and making use of the defined ontology used by the MAS, access can be provided externally to the information, knowledge and data in existing systems. Similarly an agent with knowledge of the structure of the underlying database of a CM system could perform supplementary analyses without affecting the core operation of the existing system. The creation of such an interface, potentially implemented using web-based technologies to maximise usability, based on the MAS ontology of a distributed CM system would allow for more rapid development of new analyses and maximise the use of existing data. It should be noted that given the tasks with which such an agent would be assigned, they would have comparably less autonomy than other agents in the system. Typically, this agent would simply be fulfilling and routing requests, albeit through communication with the rest of the MAS, therefore this application highlights the flexibility, sociability and benefits of a distributed structure, rather than the intelligent aspects of agency.

6.7 Distributed Structure

The existence of different agents in different locations requires that each agent platform is connected as part of a larger, distributed system. Figure 6.6 shows an example of such a generic structure, within which the agent types described above could be arranged. These individual groups of agents, known as a container, are connected, or federated, to create what is effectively a single system, distributed over several locations [Bellifemine]. Within the system the capabilities of each

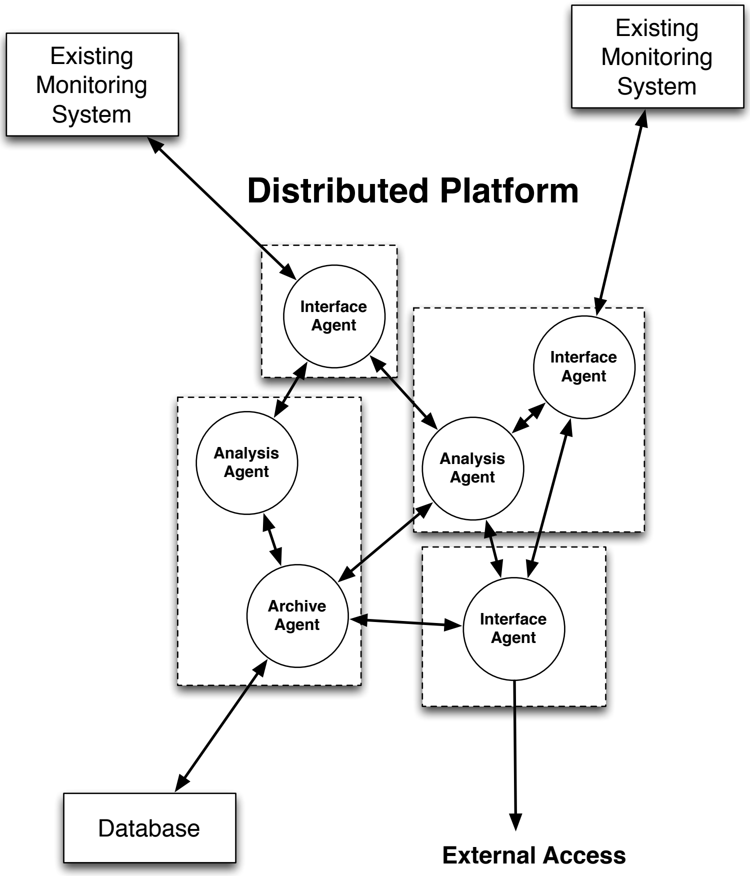


Figure 6.6: A generic structure for a distributed CM framework proposed in this thesis.

agent are available to the community by advertisement and request, but from outside the system, external requests see only a single interface.

6.8 Discussion

This chapter has introduced basic concepts from the fields of DF and IF, highlighting aspects of these approaches which would be beneficial to a distributed CM framework for application to a nuclear power station. The basis of such a framework was then described as a generic approach to applying a MAS to a CM problem, including descriptions of types of agents which are required and the requirements of a well defined ontology and strucutred storage and manipulation of data. It was proposed that with such a generic framework, other CM systems could be integrated by means of agent interfaces and that external access to users and other systems could be provided via an agent-based interface. A system based on this model, containing analyses for the AGR monitoring regime developed in the next chapter, will be described in Chapter 8.

Chapter 7

Development of Class 1 Condition Monitoring Analyses

7.1 Introduction

This chapter describes the development of specific AGR related CM analyses, based on the requirements of the MAP, the availability of data and the flexibility provided by an agent-based framework as described in the previous chapters. The analyses therefore introduce, where possible, formal rules and numerical calculations, the application of DF techniques and make use of the flexible autonomy of agents to share data and to perform correlative analyses and data management tasks.

Each of the developed analyses, including regulating rod monitoring, channel power analysis and channel geometry estimation are described and placed in context in the monitoring regime. As described in Chapter 3, the class 1 parameters are the most important indicators of core state, therefore the analyses concentrate on only the class 1 parameters. The analyses developed in this chapter will then be implemented in a distributed framework of the type described in the previous chapter.

7.2 Regulating Control Rod Monitoring

The regulating control rods, as described in Chapter 3, are part of the primary shutdown mechanism of the AGR, however by virtue of their function, they remain within the core structure at all times, providing a potentially valuable source of CM information. Previous research on control rod monitoring is limited, but includes work on the monitoring of the drive mechanisms of BWR [Greene1994] reactors, that contains parallels to this work. Indeed, the two potential CM applications for control rod monitoring can be divided into:

- **Graphite core state** - the possibility of exploiting the fact that rods are within the core and may provide some indication of the core state potentially affecting the control rod system effectiveness
- **Control rod mechanism state** - analysis of the control rod drive mechanism, which is also important for the safe operation of the reactors

7.2.1 Control Rod Motion

The control rods are driven by a mechanical system, wherein a signal is transmitted from outlet gas temperature sensors, through a control system with the specific task of maintaining a target core temperature. Should the sensor indicate that the temperature is too high, the rods can be slightly inserted in order to lower the reactor power, by absorbing a greater fraction of the free thermal neutrons. Should the temperature be measured to be too low, the rods are withdrawn slightly, in order to allow a greater number of the thermal neutrons to cause fissions and increase the reactor power.

This operation of balancing rod position with temperature, results in a pattern of the rods progressively moving out of the core over a period of one to two months between refuellings, as shown in Figure 7.1 as the rods move between pre-defined upper and lower limits, of around 7m and 0m respectively. This movement reflects the burnup of the fuel and the decreasing number of available thermal neutrons to cause fission, negating the need for the absorbtion provided by the control rods.

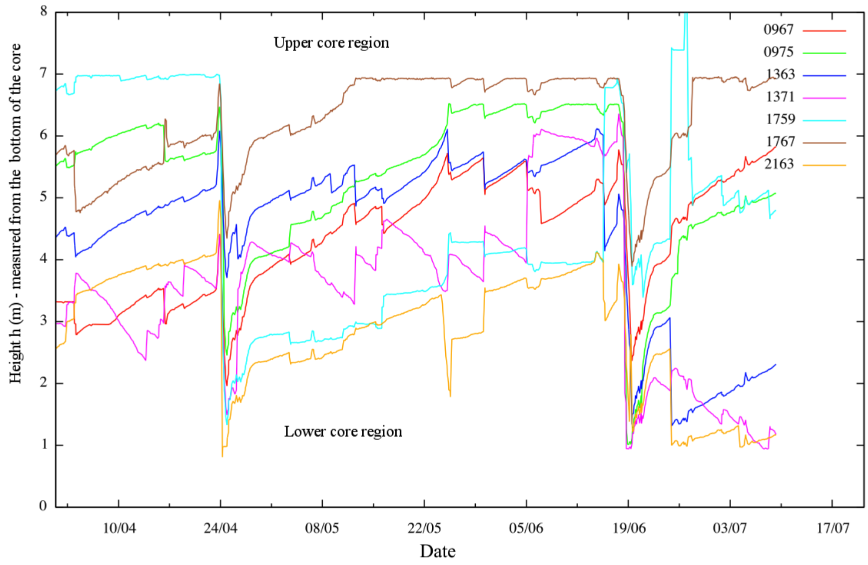


Figure 7.1: The motion of a sector (approximately 1/5th) of regulating control rods over a single MAP period. The rods are inserted at refuelling then slowly withdrawn

On a shorter time-scale however the rod motion is considerably more varied, as the auto-controller system attempts to meet the temperature requirement. Occasionally the control room operator can also 'deselect' a rod from the auto-controller system, fixing it in position while the other rods continue to move, or shifting the rod up or down in a step change.

Identifying the sources of all of these motions is key to determining whether the graphite core is distorted in such a way that it is inhibiting the motion of the rods, or whether mechanical imperfection in the drive mechanism is causing behaviour that could be misinterpreted as the effect of core distortion.

7.2.2 Rod Motion As An Indicator Of Core State

Previous work by AMEC[AMEC2008], investigated the level of distortion which would be required for the motion of control rods to be restricted. By considering a finite element model of a variety of channel distortion configurations, the difference in drop time for a clear and a distorted channel was calculated and used to determine which distortions and dimensions would be of most concern.

The report concluded that distortions of between 28–70mm would result in the motion of the rod becoming sufficiently restricted that it would not enter the core with sufficient speed and a slack chain alarm would be activated.

The MAP currently attempts to determine visually, using time-height data, whether there is any indication of regulating rods being restricted axially, as they move through the core. This is performed by considering the motion of each rod and estimating whether a rod shows any indication of limiting in an axial band (i.e. at a particular height). At some stations, rods are driven in notional sectors, so the task is slightly simplified by the ability to compare rods in sectors, all of which received the same drive order. In either case however, the analysis is prone to normal human subjectivity, limitations in consistency and no comparison with historical data.

These visual examinations of the data have not yet revealed any clear evidence of instances of rod motion being restricted in the core, however the large amount of data presented in a single plot, an example of which is shown in Figure 7.1, makes it difficult to determine where anomalous data might exist.

7.2.2.1 Actuator Performance

The control rods of an AGR are driven by motors above the core, acting on drive signals from an auto-controller. The movement of the rods therefore, excluding any external or core related effect such as distortion, is a composite of the drive order and the efficiency and reliability with which the drive order was executed. There are several possible mechanical sources of deviation from perfect behaviour for the drive action of the rod, including:

- Driving the rod requires the brake to be disengaged and can result in the rod slipping before it drives
- Some rods have motor brakes that are ‘tighter’ than on other rods which can result in the actual movement for a given drive being slightly less than the movement for a rod that has a ‘loose’ brake

- Variations in calibrations could result in some rods driving slightly more than other rods in response to the same drive order

These factors can affect the motion of a control rod in such a way that the anomalous behaviour exhibited by the rod may be misinterpreted as due to the effect of some interaction with the core.

7.2.3 A Quantitative Monitoring solution

A straightforward solution would be to compare the drive orders to the motions of the rods and determine where a rod was not moving as directed. With this knowledge, and by comparing the height at which the anomalous motion had occurred, it would be possible to determine whether the behaviour occurred only at a particular height, suggesting the rod is interacting with the core, or whether the anomalous behaviour existed at all heights, suggesting actuator performance is the source of the problem.

Unfortunately the drive orders to neither the sector, nor the the individual rods are recorded, therefore there is no immediate way to determine the source of any anomalous motion. The situation is complicated further by the lack of a ‘normal’ or ‘benchmark’ set of data which would describe how the rods should move, as the motion is dynamically related to the state of the core. To solve this problem, for the slightly simpler situation of reactors where the rods drive in sectors, an approach of combining control rod sensor data was adopted.

7.2.4 Algorithm

A method of estimating the unknown drive orders has been developed [Wallace2010], which fuses the motions of multiple control rods in order to estimate the drive order they were estimated to have received. This method consists of four main steps:

- Identify the direction in which the majority of the rods moves
- Select the rods which moved in this direction

- Calculate the average motion of the rods which moved in this direction, which is considered to be an estimate of the sector drive order
- Compare each rod to this average motion with performance based on similarity to the estimated sector drive

The comparison of each rod with the estimated drive order, which they all should have recieved and attempted to act on, is proposed to be a measure of that rod's performance and is described by a correlation at each time interval.

More formally, for a set of rods $X : \{x_1, x_2 ... x_n\}$ consisting of n rods and an associated set of time series heights H at a particular time t as shown in Figure 7.2, we define

$$H_x : \{h_1, h_2 ... h_n\} \tag{7.1}$$

The movement of each rod between each recorded sample time t is defined as

$$\delta_{n,t} = h_n(t+1) - h_n(t) \tag{7.2}$$

By applying a simple delta function to determine the nature of the net direction of movement of the rods, $K(\delta)$

$$K(\delta_{n,t}) = \begin{cases} +1, & \delta_{n,t} > 0 \\ 0, & \delta_{n,t} = 0 \\ -1, & \delta_{n,t} < 0 \end{cases} \tag{7.3}$$

For the case of non-stationary net motion, that is $\sum_1^n |K(\delta_{n,t})| > 0$, we create a subset of rods, X' containing the rods where

$$sgn(\delta_{n,t}) = sgn\left(\sum K(\delta_{n,t})\right) \tag{7.4}$$

That is, every rod in X' moves in the same direction as the majority sector motion. From this subset of rods, an estimated drive order D is obtained by taking the mean movement for each time step of the rods in X' for each time intervals. These estimated drive orders can then be compared to the actual rod motions, as in Figure 7.2.

Using a moving window of a variable selection of time-steps, the correlation ρ between each rod movement $\delta_{n,t}$ and the estimated drive order D_t is calculated using the Spearman's Ranking Correlation[Ostle1988] as

$$\rho = 1 - \frac{6\Sigma\Delta_i^2}{n\left(n^2 - 1\right)} \tag{7.5}$$

where Δ is the difference between the estimated drive order motion and the actual motion of each rod. The Spearman's correlation coefficient was used rather than the more common Pearson's due to the comparison of small subsets of the control rod height data, where the rods are either montonically related or they are not (i.e. driving up or not, or driving down or not). This correlation can be

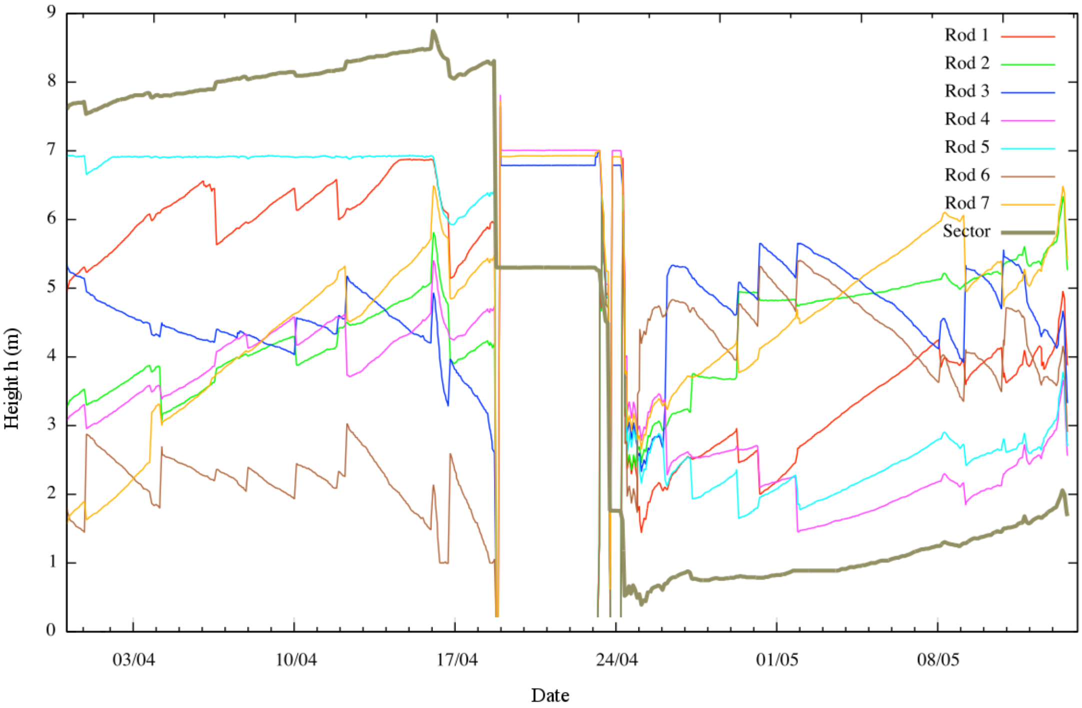


Figure 7.2: Motion of a sector of regulating control rods with the estimated drive order shown as a hypothetical rod, labeled 'sector', which indicates the trend of the drive order, but not the absolute height, since the actual rods are occasionally re-inserted and 'reset', while the drive order is effectively continuous

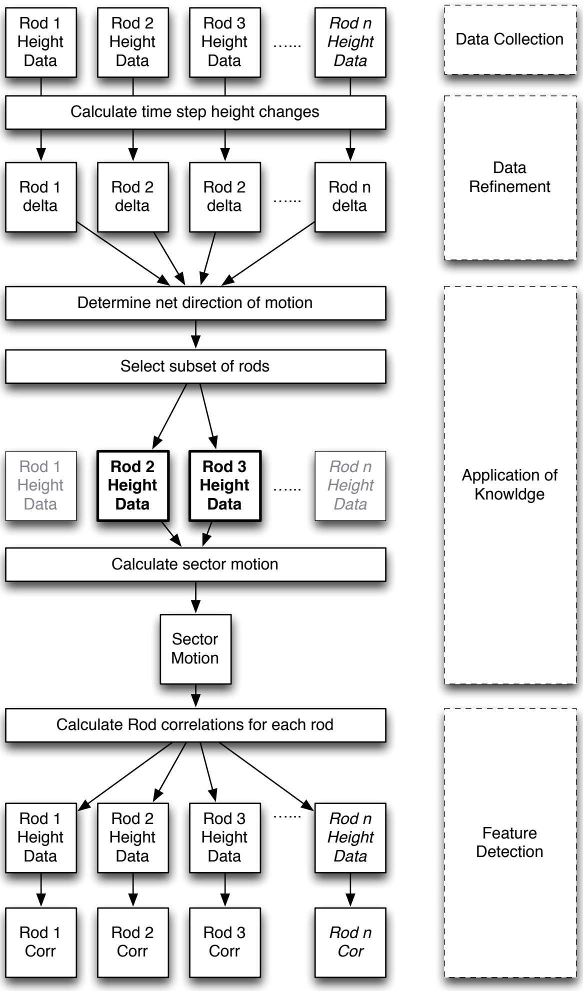


Figure 7.3: A schematic view of the fusing of multiple control rod height sensor data, in order to estimate the performance of each rod

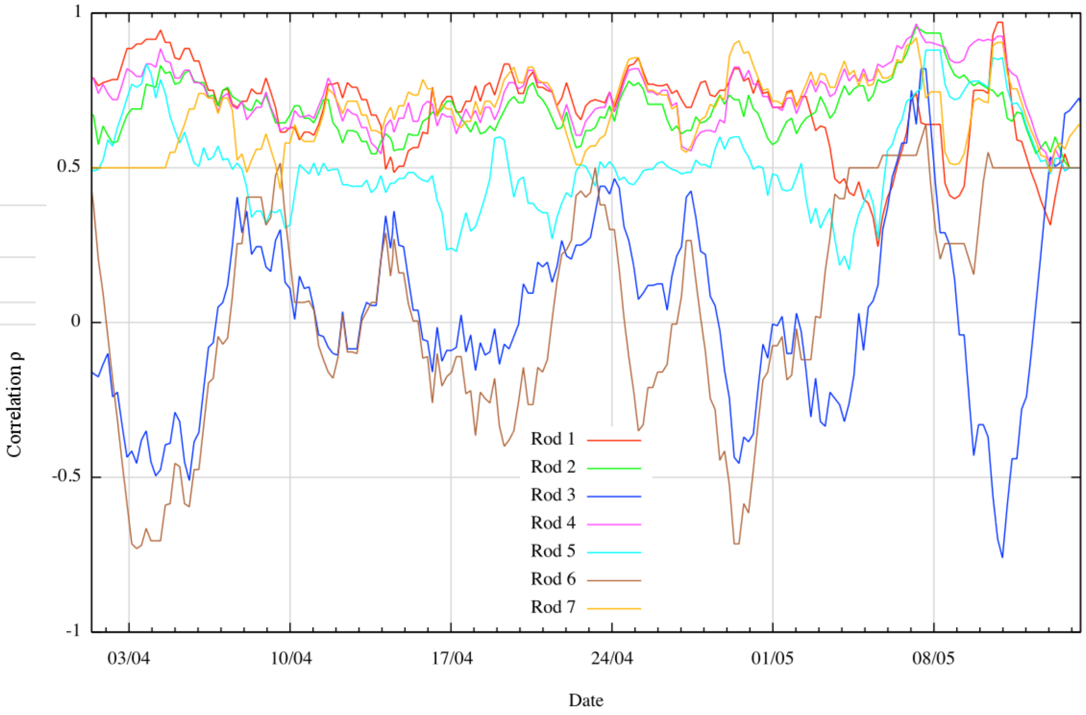


Figure 7.4: Correlations of a sector of regulating control rods, generated from the control rod motions shown in Figure 7.2

interpreted as describing how closely the actual movement of the rod compared to the estimated sector drive order. Using this correlation as a measure of how well each rod responded to the estimated drive orders, these can be plotted, as shown in Figure 7.4, showing in this case two rods (Rod 3 and Rod 6) with significantly lower correlations than the other rods in the sector. Some interpretation of these correlations is required in order to relate them back to the physical system which they describe.

7.2.5 Interpretation

The correlations shown in Figure 7.4 indicate how similar the motion of each rod is to the drive order D, and therefore provides a quantitative measurement of performance. The following rules are proposed as a guide for interpreting the calculated correlations for each rod:

- $\rho < 0$: The rod does not respond to drive orders and is slipping.

- $\rho = 0$: The rod does not respond to drive orders.

- $\rho > 0$ and $\rho < 0.5$: The rod responds to drive orders however has limited performance.

- $\rho > 0.5$: The rod responds relatively well to drive orders.

In this interpretation, 0.5 was arbitrarily selected as the cut-off for the rod to be performing well, based on the data available. In practical use, this cut-off could be set by the engineer or determined using statistical methods.

7.2.6 Example Analysis

Whereas the motion of the rods considered in isolation left some ambiguity as to when the rod was moving correctly, the correlation parameter allows the engineer to clearly see how the rod is behaving relative to the rest of the sector. The use of the correlation measurement is particularly useful over longer periods, where consistently poor behaviour or degrading behaviour is more evident. Figure 7.5 shows a clearer comparison of an example of rod motion and the calculated rod performance correlations, over a longer period than the previous examples. Some interesting features to note include:

- When the rod reaches its upper or lower limits (7m and 0m respectively), the correlations are constant, reflecting the lack of automated motion in the rods — that is, they are not expected to move with the rest of the sector outwith these limits

- When rod motion is static or downwards, but within the operating limits, between July 2007 and January 2008, the correlation is highly negative, indicating that the sector was driving while this particular rod was not.

- When the rod is manually driven, which is visible in the height data as step changes in height, the correlation tends towards +0.5, a value which was preselected for the algorithm in order to distinguish between a rod with

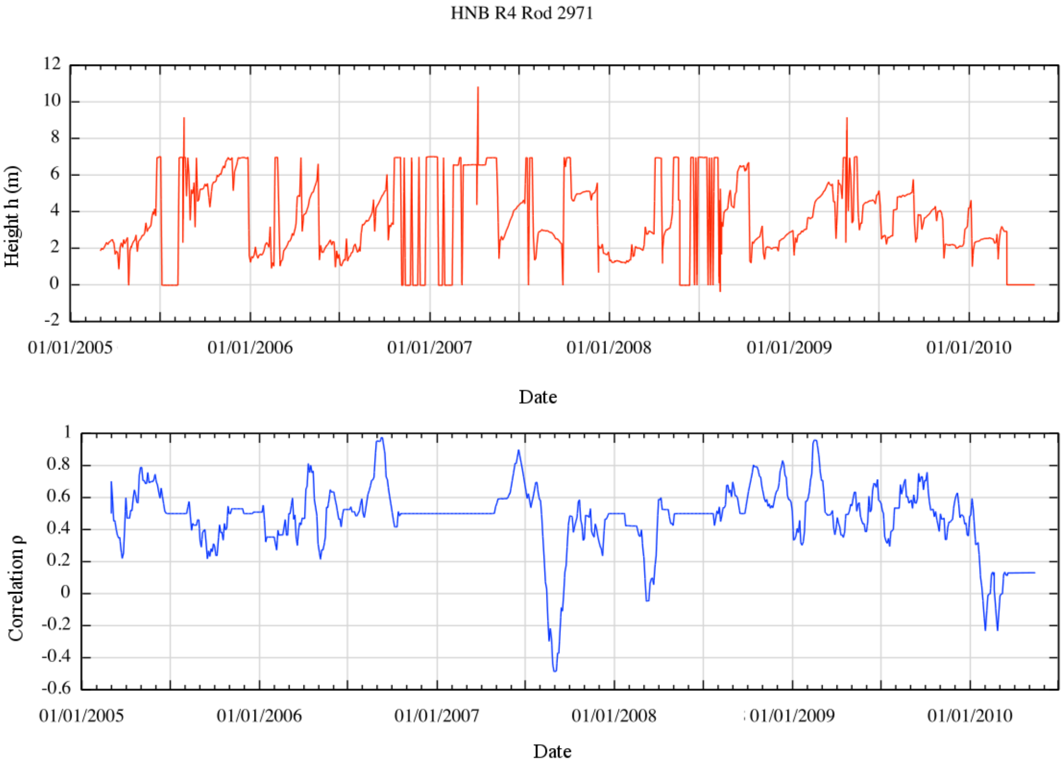


Figure 7.5: The height data of a single rod and the corresponding correlations (a measure of performance) over several years.

a genuine fault (and incorrect motion) and a rod which has merely been deselected.

While the performance correlations on their own do not describe directly whether a rod requires maintenance or has become stuck in a distorted graphite channel, the quantitative measurement that they provide does allow for further analysis and trending of the state of the regulating rods over longer periods.

7.2.7 Prognostics

Longer term trending of performance correlations, provided sufficient data is available, may allow for more accurate estimations of when maintenance is required. Maintenance regimes which are guided or informed by estimates of the future performance or health of the system, can introduce efficiency savings and help avoid failures in components which do not follow fleet average behaviour.

7.3 Thermal To Neutronic Power Ratios

7.3.1 Channel Power Discrepancies

Each fuel assembly in the reactor has a thermocouple which measures the outlet coolant gas temperature to allow the calculation of the power generated by each channel. Parallel to this, a neutronic model of the core for each fuel element also calculates the predicted power output from each channel. The discrepancy between these two values, the Channel Power Discrepancy (CPD) is typically a few percent and is normally due to errors in modelling. Definitions of CPD vary slightly between stations, with some using:

$$CPD = \frac{Power_{Thermal} - Power_{Neutronic}}{Power_{Thermal}} \tag{7.6}$$

while other stations use:

$$CPD = \frac{Power_{Neutronic} - Power_{Thermal}}{Power_{Neutronic}} \tag{7.7}$$

The specific definitions and where they are used are important for implementation, however for the general analysis discussed in this chapter, the approaches to explaining both are equivalent.

The CPDs are calculated on a weekly basis to determine Change in Channel Power Discrepancy (CCPD), defined as:

$$CCPD = CPD(t+1) - CPD(t) \tag{7.8}$$

where deviations between subsequent analyses may indicate that the fuel is not being sufficiently cooled. The existing channel power analysis consists of an engineer manually correlating abnormally large CPD or CCPD values with reactor events which may be used to explain the anomalous values.

7.3.2 Factors Affecting Channel Power Discrepancies

There are a variety of factors which can affect the CPD and CCPD, including:

- **Modelling Errors** - The models of the core are imperfect and slight deviations in the predicted neutronic power of a channel for example, can result in disagreement between thermal and neutronic power values.
- **Failed Thermocouples** - A failed thermocouple on a fuel stringer would result in an erroneous temperature value being used for the thermal power calculation.
- **Refuelling** - Refuelling of a channel will alter the flux and power of that channel and of nearby channels (up to one channel away in any direction), affecting the modelling of these channels.

A simple filter system is currently used by the engineers, whereby data that exceeds a particular range is deemed anomalous and investigated further. The collection and correlation of these data sets is a time consuming task, despite the relative simplicity of the explanation of the majority of anomalous events, however these tasks can be reduced to a spatial-temporal search problem based

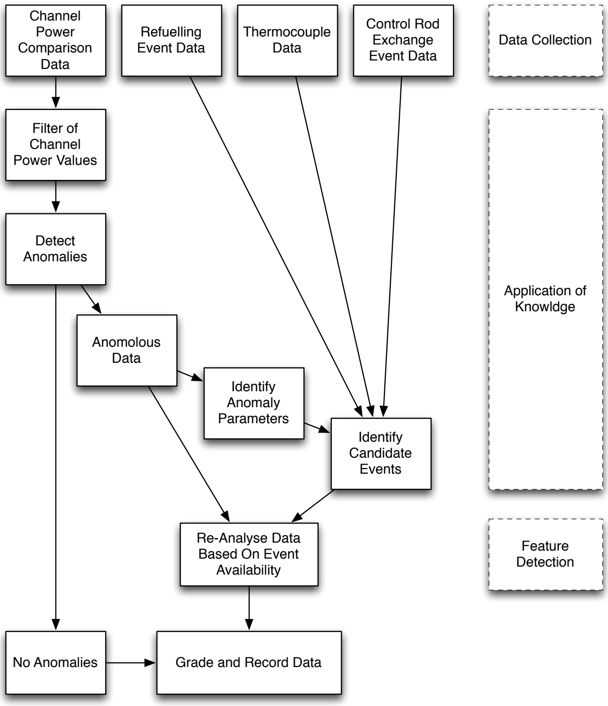


Figure 7.6: A proposed process through which reactor events can be analysed as required in order to generate explanations for anomalous CPD or CCPD values

on a set of causal rules (or explanations). That is, with the appropriate data or event information available, it is an algorithmically simple task to search for events which meet certain criteria.

7.3.3 Algorithm

It is necessary, to perform such a task algorithmically, to have the required knowledge of filters, anomalies and how they are related to reactor events encoded in such a way that they can be queried and used by an automated analysis. Figure 7.6 describes the process through which the relevant data sets can be analysed and retrieved as necessary to perform the analysis of explaining, where possible, anomalous CPD or CCPD values.

It is worth noting that the process shown in Figure 7.6 could represent either the existing analysis or an automated analysis. This highlights the fact that this analysis is a knowledge based approach, which is designed to imitate the existing

Definitions

$Grade$: The monitoring grade of the observation
lim_{low}: Lower limit for error
lim_{high}: Upper limit for error
$lim_{low-ref}$: Refuelling adjusted lower limit
$lim_{high-ref}$: Refuelling adjusted upper limit
CPD: Channel power value under analysis

```
if $CPD > lim_{low}$ and $CPD < lim_{high}$ then
  $Grade = Green$
else
  if Refuelling since last calculation then
    if Refuelling proximate to channel then
      if $CPD > lim_{low-ref}$ and $CPD < lim_{high-ref}$ then
        $Grade = Green$
      else
        $Grade = Amber$
      end if
    else
      $Grade = Amber$
    end if
  end if
end if
```

Figure 7.7: An example of the algorithm, based on the current engineer's analysis, which the channel power analysis agent performs, in this case the limit on channel power deviation is relaxed slightly due to the knowledge of a nearby refuelling.

analysis but perform it more quickly and more efficiently.

The key difference between the existing analysis and the new automated analysis, is the way in which each task is performed. In order to execute the analysis automatically, a set of rules or algorithms are required to perform each task, such as retrieving data, comparing the timestamps of particular events or any number of other functions, which are represented, with almost deceptive simplicity, as arrows in Figure 7.6.

An example of such an algorithm is shown in Figure 7.7, which describes in pseudocode a proposed algorithm for grading a CPD Value. Initially, the algorithm checks whether the CPD value is within the expected values and grades it green (or normal) if it is. Otherwise, the algorithm begins searching for refuelling events in the region near the channel and within a specific timeframe, which may explain the anomalous value. If such an event is found, and the CPD value is within an adjusted (wider) filter range of accepted values, the observation is graded green. If a refuelling event cannot be identified, the observation is given the temporary grading of amber. At this point, another algorithm might be applied which performs a similar process, checking for other types of reactor event which may be used to explain the anomalous data.

When the set of algorithms based on the knowledge of the system have been exhausted, a suggested grading is returned to the engineer along with details of the event that was used to explain the anomalous data. The engineer can then determine the final grading based on this information and any other checking of the relevant datasets that is subsequently performed.

7.4 Estimation Of Change In Channel Geometry From Friction Profile

The FGLT, described in Chapter 3, is one of the principal analyses of the MAP and provides the only source of information about the state of the graphite fuel channels between inspections, when the CBMU can be used to directly measure the channel geometry. The FGLT and CBMU provide two different descriptions, with varying characteristics compared in Figure 7.8, of the geometry of a fuel channel. Between inspections it is expected that the state of the channel will degrade, so while the CBMU data is a useful and detailed snapshot of the geometry of the channel when it is recorded, by the time the channel is inspected again, (if it ever is, noting that approximately 10% of channels are inspected every 2-3 years) the geometry will have continued to change in the meantime. Refuelling, however, occurs every 5-7 years for every channel in the core, providing a more regular source of data, albeit of lower detail, and requiring more interpretation than the CBMU.

	CBMU	**FGLT**
Noise	Low	High
Feature Detail	High	Low
Availability	Low	High
Interpretation	Direct	Indirect

Figure 7.8: A comparison of FGLT and CBMU data characteristics

7.4.1 Fusing Data Inspection And Monitoring Data

In order to form a more continuous estimate of evolving channel geometry, it is proposed [Wallace2011a] that by identifying the relationship between channel geometry and FGLT measurement and extracting specific frictional components from the FGLT, it should be possible to estimate the change in channel shape from the FGLT. When this relationship has been identified, using an initial set of CBMU data for a particular channel as a basis of the channel geometry, each subsequent refuelling event data (i.e FGLT) can be used to inform and update the model, by quantitatively estimating the change in channel shape, a procedure that is outlined in Figure 7.9.

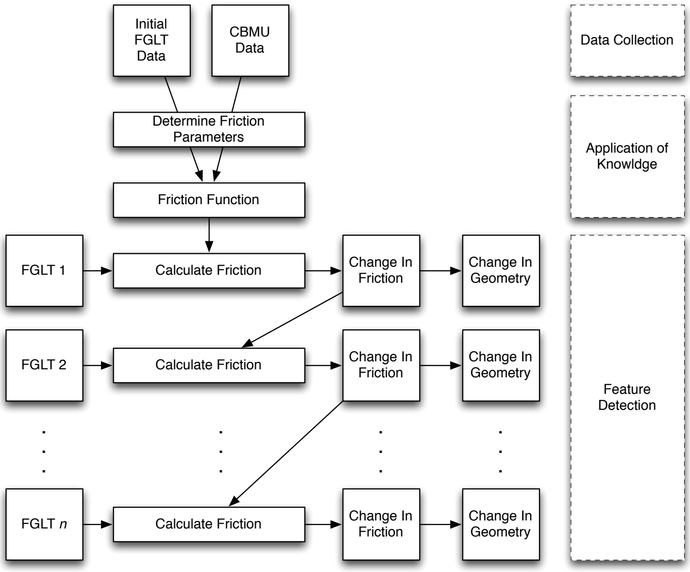


Figure 7.9: The process through which an initial set of FGLT and CBMU data can be iteratively used with new FGLT data as it becomes available to estimate changes in channel geometry

7.4.2 A Model Of Refuelling

Initially, a description of the forces involved in refuelling is required, from which the component of the FGLT that corresponds to the variation in friction due to channel size, can be identified. During the refuelling process, which for simplicity is considered to be off-load, (minimising the the aerodynamic effects of the coolant flow), for a fuel insertion (charge), the measured FGLT, F_{FGLT}, can be written as

$$F_{FGLT} = mg - F_{Fr} \tag{7.9}$$

where m is the mass of the fuel stringer and F_{Fr} is the friction of the stringer, and for fuel removal (discharge) as:

$$F_{FGLT} = mg + F_{Fr} \tag{7.10}$$

The difference between the two equations, specifically the sign of F_{Fr}, is due to the direction in which the frictional component of the FGLT acts in each situation. It has been assumed, for simplicity, that the magnitude of the frictional component of the FGLT is the same in both directions and that the mass lost due to fission is negligible and can be ignored. It is also assumed that the frictional force due to the brush being in contact with the wall is the same for different stringers, however this is unlikely to be the case as the steel brushes age and degrade while in the core. When fuel is inserted into the channel, the friction caused by the contact of the stabilising brushes with the graphite wall will act to support the weight of the stringer, essentially making the stringer appear lighter, resulting in a decrease in the measured FGLT. On removal of fuel from a channel, the friction will act against the direction of motion, increasing the measured FGLT and making the stringer appear heavier.

Figure 7.10 shows schematically the locations of the stabilising brushes on the fuel stringer, which are the sources of the friction which cause the peaks and troughs in the FGLT. The fuel stringer section which enters the active core is

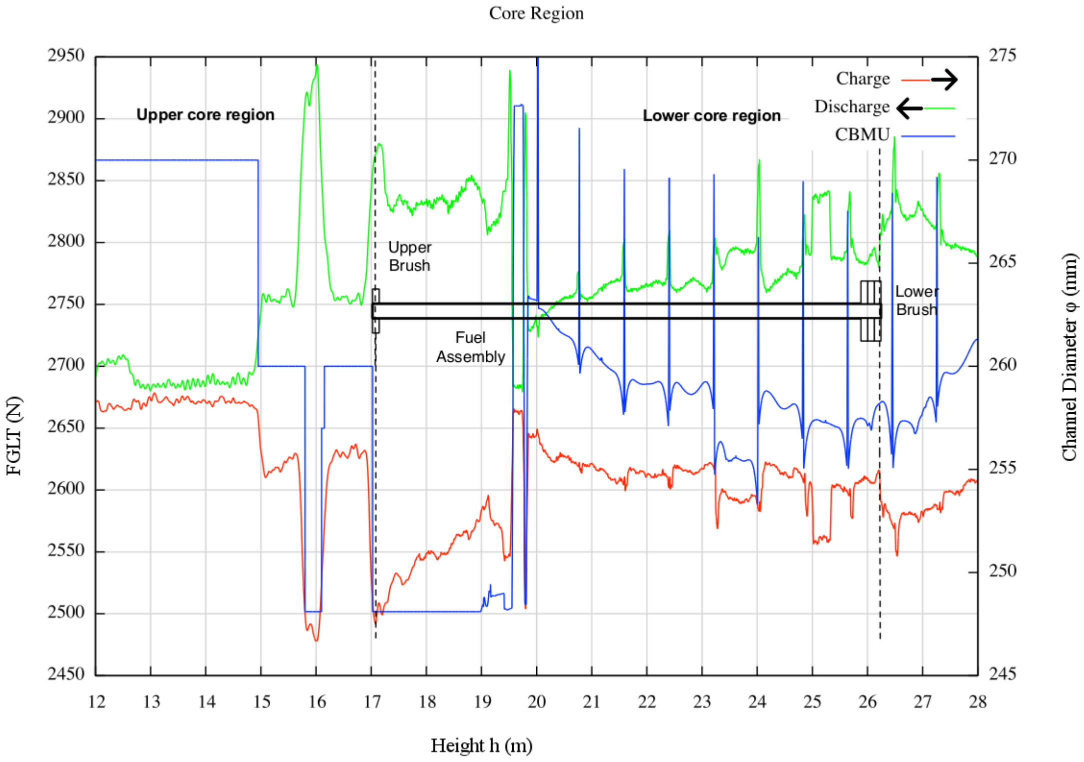


Figure 7.10: A comparison of the FGLT and the CBMU, showing that the peaks and troughs in FGLT are due to narrowing of the channel diameter at the brick layer interfaces in the channel.

approximately the same height as the active core, therefore when the lower part of the fuel assembly (where the lower brush is located) is entering the graphite brick-stack, the upper part of the fuel assembly remains in guide tubes above the active core. The structure of the FGLT can be decomposed into its component parts in different regions, using Figure 7.10 as a reference, as: at heights between approximately $20m$ and $28m$:

- The lower brush is in contact with the graphite channel of nominally constant diameter, initially at the top of the active core (or brick stack)
- The upper brush is traversing the guide tube above the core, which contains sections of varying diameter

While at heights between approximately $17m$ and $20m$:

- The lower brush is in contact with the graphite channel, near the bottom of the active core
- The upper brush enters the graphite channel at the top of the core

The channel depicted in Figure 7.10 is of nominal design diameter of $263mm$, although it is quite apparent that this value varies significantly over the height of the channel, due to distortion of the graphite as described in Chapter 3 and due to narrowing and widening of the channel, particularly at the brick layer interfaces. The diameter values at lower heights which appear as step changes, describe the geometry of the guide tube above the active core. The specific values used here are from one of the lead stations and are for illustration only, however the technique described should work in principle for any AGR.

It is also important to emphasise at this point, that while the CBMU can perform multiple measurements of fuel channel diameter under rotation, the FGLT is a one dimensional measurement of load at a particular height. For the purposes of deriving a relationship between geometry and frictional load, the CBMU must therefore also be reduced to a one dimensional value, specifically an average of all diameter data available.

7.4.3 Relating Friction To Geometry

Considering initially the hypothetical situation where the channel diameter ϕ is sufficiently large that the stringer brushes make no contact with the channel and hence generates no friction, then it can be argued that the existence of, or variation in, the friction must be as a result of changes in the channel diameter ϕ. This allows the friction to be written as a function μ of channel diameter

$$F_{Fr} = \mu(\phi) F_{FGLT} \tag{7.11}$$

which can be re-arranged and by substituting for equations 7.9 and 7.10, in order to solve for $\mu(\phi)$, it can be shown that for a charge:

$$\mu(\phi) = \frac{mg}{F_{FGLT}} - 1 \tag{7.12}$$

and similarly for a discharge:

$$\mu(\phi) = 1 - \frac{mg}{F_{FGLT}} \tag{7.13}$$

The stabilising brushes on the fuel stringers differ between the top and bottom brushes, with the lower nose brush consisting of three layers of brush, each of nominal diameter 263mm, while the upper brush consists of a single brush layer of diameter 254mm. Rig work [AMEC2006] has shown that for a channel diameter that is sufficiently narrow for the upper brush to make contact with the channel wall, the upper brush contributes approximately one third of the friction that the lower brush would contribute through the same diameter. Taking this approximate factor of a third (i.e. upper brush friction is equal to one third of the lower brush friction), the previous equations can be re-written as:

$$F_{Fr} = F_{FGLT} \left[\mu(\phi_{upper}) + \frac{\mu(\phi_{lower})}{3} \right] \tag{7.14}$$

where a factor of 1/3 is applied to the friction contribution from the lower brush, to reflect the smaller brush surface area and generated friction. This equation, where the same function μ is applied to both the upper and lower diameters simultaneously, provides a basis for describing the frictional component of the FGLT as a function of the channel diameter at the height of the lower brush and the upper brush.

7.4.4 Generating A Brush Friction Profile

Using a sample set of data, from a refuelling during outage, and applying equation 4 to generate a set of values for each corresponding FGLT value, the results shown in figure 6 were obtained. The channel used in this example was selected as it is an otherwise typical channel apart from the region of particularly high graphite shrinkage between 23m and 24m (brick layer 8).

The results for two brick layers are shown to illustrate the linear relationship that was discovered. Though the data from different brick layers share the same gradient, the constant in the linear equation varied for each brick layers for as yet unexplained reasons. These regions were selected since at these points, the upper brush is also passing through a narrower section of the upper channel and will contribute a more measurable part of the friction than when moving through a wider part of the channel where there is only limited contact between the wall and the brush.

As different, though very similar, linear relationships were derived for each brick layer, the equation for brick layer 11 was selected for use as it had the best correlation coefficient fit to the linear regression. The good fit of the data to the linear extrapolation suggests that the earlier assumption regarding the directional independence of the friction in the FGLT was reasonable. Using the generated equation

$$\mu(\phi) = -0.00003976\phi + 1.0645 \tag{7.15}$$

and applying it to the channel diameter data from the CBMU and structural information of the channel geometry above the active core, estimates of the friction caused by each brush were made and are shown in Figure 7.12.

The estimated friction contains all of the major features of the channel, and in particular for this data set, the region of particularly high graphite shrinkage

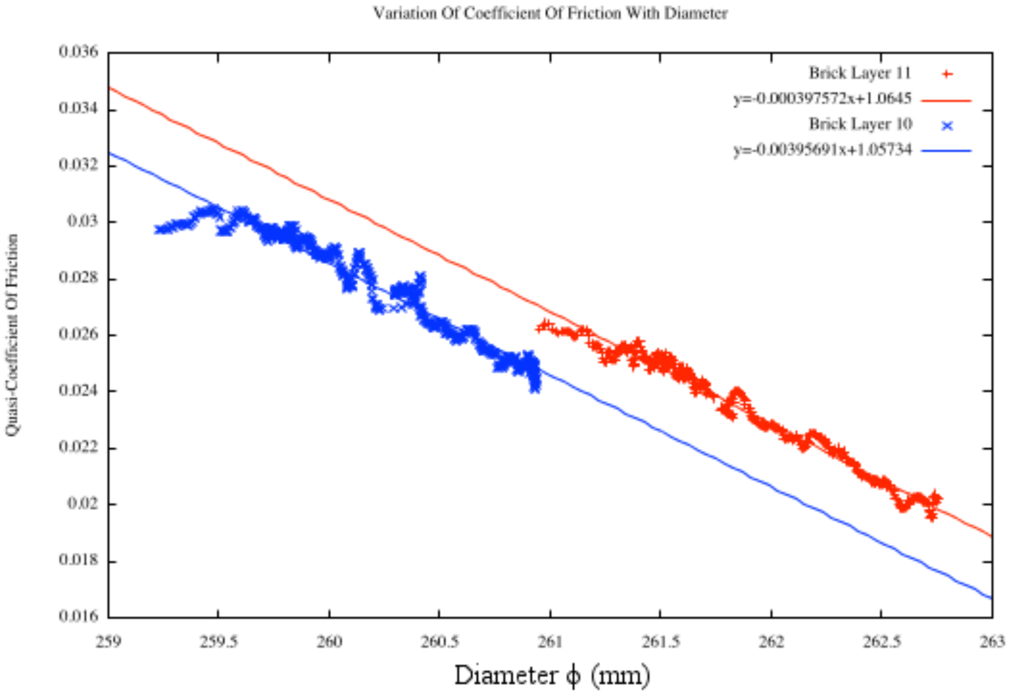


Figure 7.11: The derived linear relationship between the coefficient of friction and the channel diameter using equation 7.14.

between 23m and 24m as shown in Figure 7.13.

The brick interfaces retain their characteristic spikes from the use of the CBMU data and it can be seen that the step change in frictional load is caused by the top brush entering a narrower region of the channel, just above the core. Comparing the generated friction profile with the original FGLT, it can be seen that the friction matches, to varying degrees, the main features of the FGLT however it underestimates the friction in the upper region of the core (21–24m) and overestimates the friction in the lower region of the core (24-28m).

Superficially it may appear that there is limited value to comparing the estimated friction with the initial set of data which was used (in combination with the CBMU) to create it. Since the purpose of this procedure however was primarily to establish a relationship between channel shape and friction it is important to be able to attain the initial friction profile (the FGLT) using only half of the data (the CBMU data) used to create the model (the CBMU data and the FGLT data).

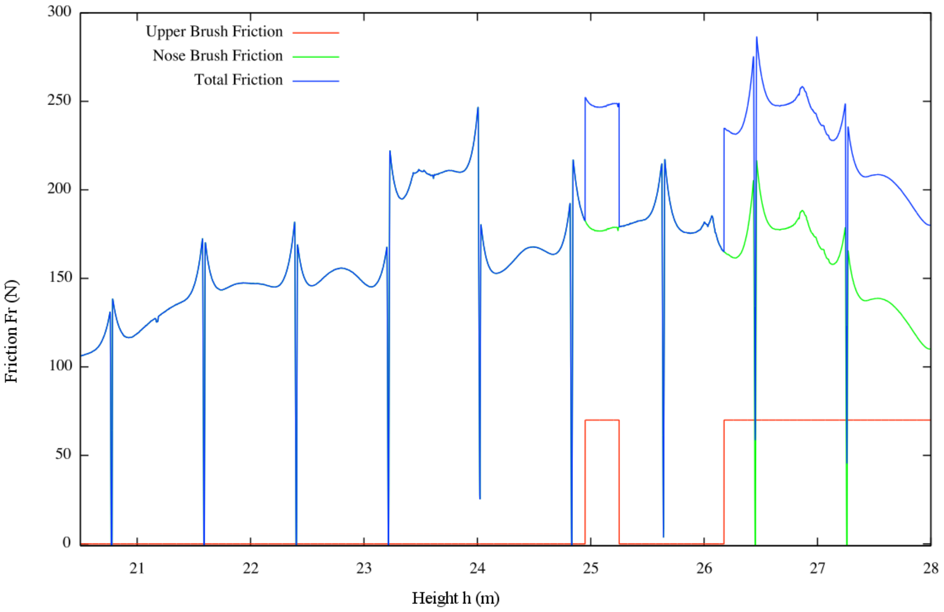


Figure 7.12: The frictional components described by the model and the channel geometry.

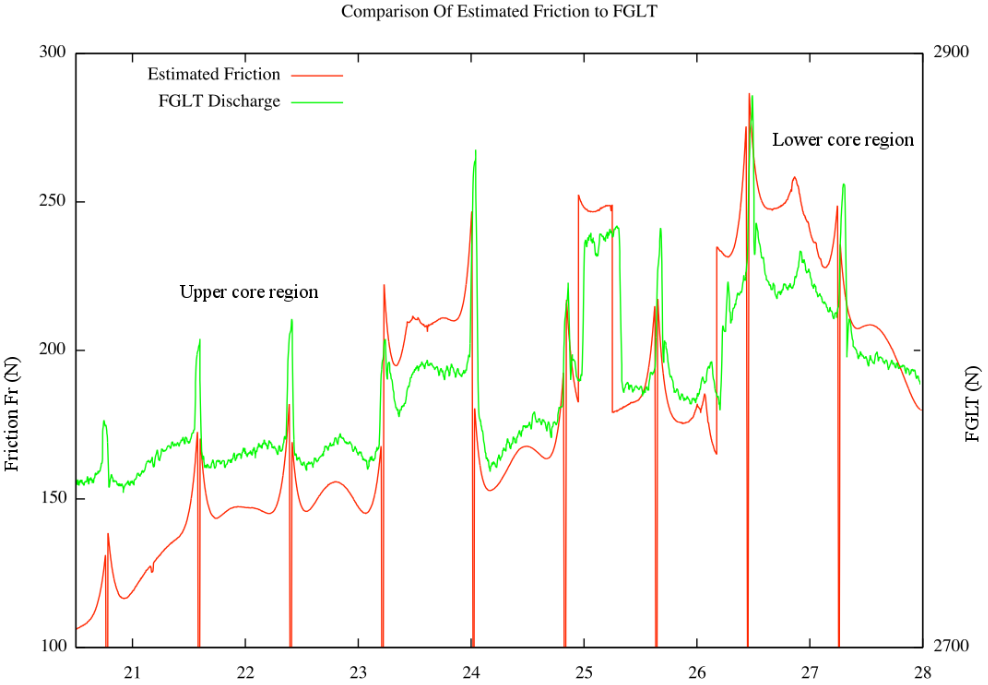


Figure 7.13: A comparison of the estimated friction profile and the actual FGLT data.

7.4.5 Limitations

This study considered only the case of an offload refuelling, during discharge. It was shown that it is possible to approximate the profile on a FGLT using only a single linear equation and the CBMU data. The estimates of total friction due to the fuel brushes are in line with values described in previous work by AMEC [AMEC2006]. Using this as a basis, it should be possible to perform the reverse operation to determine variation in channel diameter based on a known change in friction.

7.5 Discussion

This chapter has described the development of new CM analyses, using concepts of data and information fusion, such that several data or information sources can be combined to provide an estimate of an unknown parameter or a set of related events could be contextualised. The ability to re-use existing data for other purposes was shown to be very useful when suitable domain knowledge is applied to the problem and full advantage is taken of computation to calculate solution to problems which would require considerably more time if performed by an engineer. The analysis capabilities now require suitable automation and deployment, within a distributed CM framework, of the type described in the previous chapter.

Chapter 8

Implementation and Case Studies

The previous chapters have described the tasks associated with CM of nuclear reactors and a proposed architecture for a distributed nuclear CM system. This chapter describes the development and deployment of a prototype system incorporating the requirements, techniques and concepts introduced thus far. An ontology is proposed which extends the high level ontology described in the Chapter 6 for the specific problem of AGR CM and an agent based system is constructed based on this ontology, implementing the analyses developed in the last chapter. The deployment of these analyses and the software associated with them, including database interfaces and a test environment of computers is described.

8.1 Ontology

The upper ontology proposed in Figure 6.4 for general nuclear CM contains broad concepts which can be extended and used for a variety of different reactor designs, however for a functional CM system, the lower ontology must be populated with sufficiently detailed concepts that they can be used for data management and analysis. Figure 8.1 shows the population of the lower ontology for an AGR, structured using the *'is a'* predicate. The ontology implements the concepts required for the CM analyses described in the previous chapter.

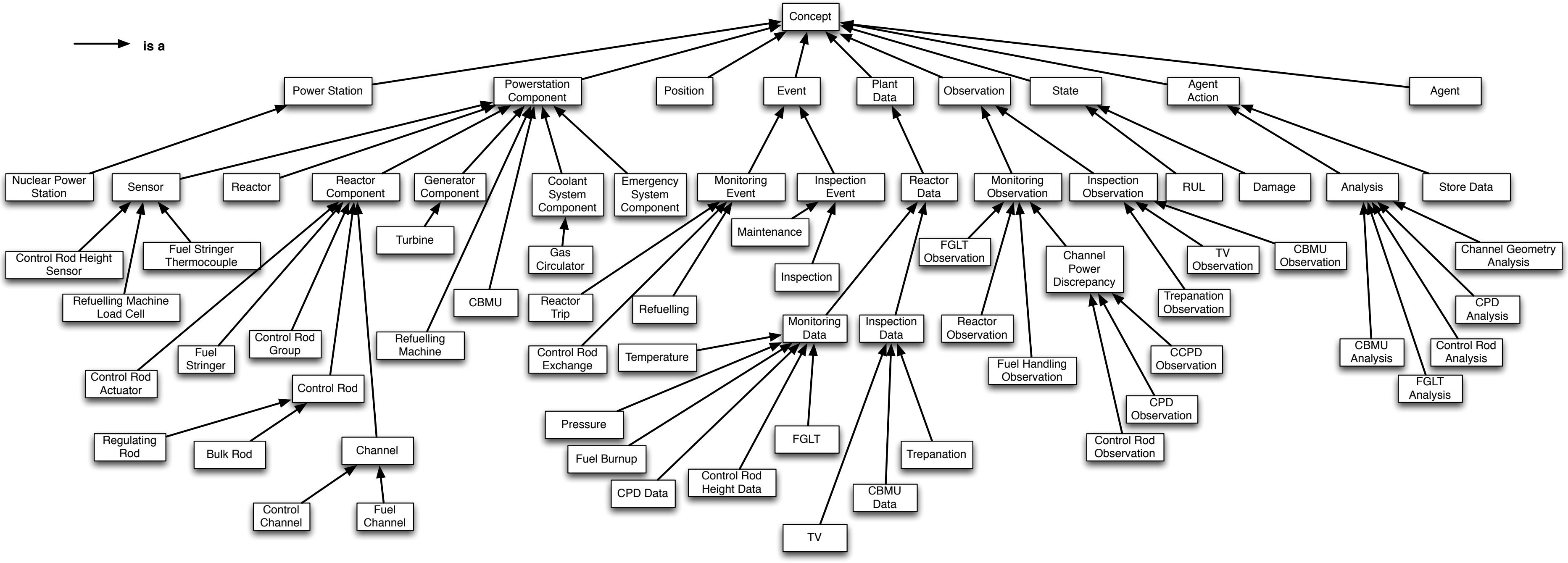


Figure 8.1: The hierarchical structure of concepts within the ontology proposed in this thesis, showing only the *'is a'* predicate.

8.1.1 Predicates

To make use of the ontology and data and concepts described by the ontology, predicates are required which describe relationships between different concepts. Predicates are logical statements which can be evaluated to Boolean values *True* or *False*. Based on the requirements of the prototype system, to perform analyses which form part of the AGR monitoring regime, the following predicates were used:

- **isA** - whether one concept is a subclass of another class.
- **atStation** - whether an object occurred at a particular station
- **deleted** - whether an object has been deleted (from storage such as a database)
- **descriptionContains** - whether a text description contains a phrase
- **hasLogLevel** - whether an object has a particular log level
- **hasPosition** - whether an object has a particular position in the core
- **inReactor** - whether an object was recorded in a particular reactor
- **loggedAfter** - whether an object was logged after a certain time
- **loggedBefore** - whether an object was logged before a certain time
- **occurredAfter** - whether an object occurred after a certain time
- **occurredBefore** - whether an object occurred before a certain time

These predicates are used to assert facts or construct queries about the concepts in Figure 8.1 which return Boolean values. The predicates can also be used to specify requests and make selections of information described by concepts. Using a predicate such as **occurredAfter** for example, allows a request (with the appropriate time also supplied) to specify the time period that the agent making the query is interested in, based on the information available in the system at the time[1].

With the concepts and predicates of an ontology defined, the ontology must be encoded in software so that it can be used as the basis for communication within an agent based system designed to perform the required CM tasks.

8.2 Development

8.2.1 JADE

Based on previous agent based CM experience [Baker2009, Catterson2006, McArthur2007a, McArthur2007b], the Java Agent Development Framework (JADE) [Tilab2010], a Java [Oracle2013] based agent middleware was selected as the platform. JADE is a free, mature and actively developed platform, created by Telecom Italia which features utilities and tools, as shown in Figure 8.2. A key benefit of using an existing middleware is that the underlying communication architecture already exists, allowing for greater emphasis on what messages are communicated rather than how messages are communicated. The use of a high level, object oriented language like Java allows for fault tolerant and robust programming while as Java applications, instances of agents are highly portable and able to run on any environment supporting the Java Virtual Machine (JVM). As a desired goal of the distributed system is extendability and management of large volumes of data, JADE was also selected because of its capability to scale well with an increasing volume of inter-agent messaging.[Vitaglione2002]

8.2.2 Agent Structure

JADE agents are constructed as Java classes which extend a core `Agent` class from the JADE library, an example of which is shown in Figure 8.3. Agents are given capabilities by means of behaviours, which are defined by the user and extend

---

[1] It is important to note the distinction made between *logged* and *occurred*, as decisions made based on data or analyses must be justifiable even if they were subsequently proven to have been mistaken as a result of data or information added later which may have altered the interpretation of a situation.

one of several `Behaviour` classes from the JADE library. There are three types of behaviour available within JADE: *One Shot* behaviours which are executed once and then end, *Cyclic* behaviours which continue to run until the agent ceases to exist and *Scheduled* behaviours which operate at specified intervals. It is possible to have several behaviours within a single agent, of different types, running in parallel.

Some actions, such as an analysis, may be performed only once upon request and would likely be implemented as a *One Shot* behaviour, while another agent may periodically scan a location for new data, a task more suited to a *Scheduled* behaviour. As communication is a fundamental aspect of MAS, it is common to have a *Cyclic* behaviour running within an agent which manages the interpretation and routing of requests from other agents. This is shown in Figure 8.2, where the `action()` method first creates an `ACLMessage` object from the `receive()` method of the JADE `Agent` class and checks the content of the message. Only if the message is not null (that is, if there is a message at all) does this agent perform any action. This is an example of a reactive behaviour, where the agent performs in response to an external input. Equally important are autonomous behaviours, often based on *Scheduled* behaviours, which allow the agent to perform a task *without* an external input. In either case however messaging is key and the basis of all co-operation and sociability between agents as well as the flexibility achieved by having agents in distributed locations.

8.2.3 JADE Agent Messaging

Every running JADE agent registers with the Directory Facilitator (DFa) agent, which is created automatically by the JADE platform, and acts as a directory of agents which are available and the services which they offer [Bellifemine]. Each JADE instance also initiates an Agent Management System (AMS) agent which controls the platform and manages the addition or removal of agents. When using a graphical interface to interact with JADE, a Remote Management Agent (RMA) is also created, providing a means of configuring, monitoring and interacting with JADE agents, shown in Figure 8.3. Messaging between JADE agents is based

```
Public class MyAgent extends Agent
{
  Logger logger = jade.util.Logger.getMyLogger(this.getClass().
     getName());
  /**
   * Setup the BETA agent
   */
  protected void setup()
  {
    // Describe the services offered by the agent
    ServiceDescription sd  = new ServiceDescription();
      sd.setType( "test" );
      sd.setName( this.getLocalName() );

      // Create a description of the agent
      DFAgentDescription dfd = new DFAgentDescription();
      dfd.setName(getAID());

      try {
        // Search the platform to ensure a duplicate agent doesn't
            exist
        DFAgentDescription list[] = DFService.search( this, dfd );
        if ( list.length>0 )
          DFService.deregister(this);

        dfd.addServices(sd);
        // register agent
        DFService.register(this,dfd);
      }
      catch (FIPAException fe) { fe.printStackTrace(); }

    if (logger.isLoggable(Logger.INFO))
        logger.log(Logger.INFO, this.getAID().getName()+":
           Launched");
    addBehaviour(new CyclicBehaviour(this)
    {
      public void action()
      {
        ACLMessage msg = receive();

        if (msg!=null) {
          // perform action here

        }
        else block();
      }
    }
  }
```

Figure 8.2: An excerpt of a JADE agent class. The agent waits for a message (a request) and when it recieves a suitable request, it performs an action.

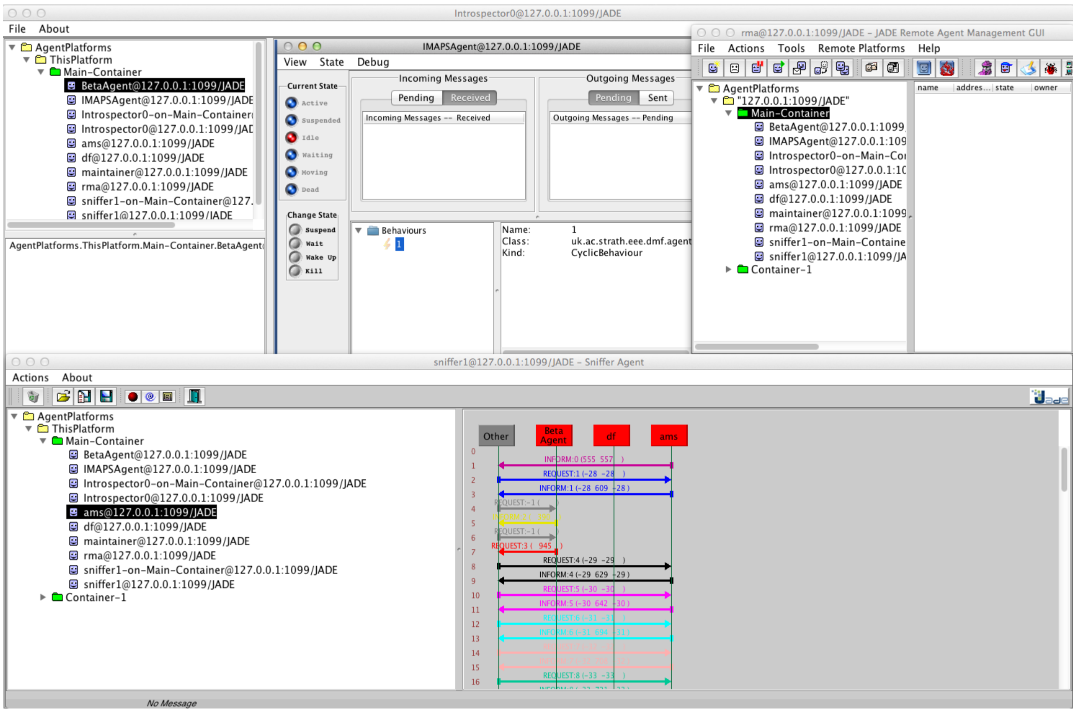


Figure 8.3: The JADE GUI, which allows the user to perform analysis tasks, connect remote platforms, browse agent behaviours and messages and interact directly with the agents through messaging.

on the FIPA compliant ACL message standard [FIPA2002a] and includes the following parameters :

- **Sender** - the agent sending the message
- **List of receivers** - a list of agents who are to receive the message
- **Performative** - a description of what the sender wishes to achieve by sending the message, such as *INFORM* or *AGREE*, discussed in more detail below
- **Content** - the actual information or data of the message
- **Content language** - name of the language or syntax used to encode the message so it can be properly parsed
- **Ontology** - name of the vocabulary of concepts and predicates dealt with in the message

- **Conversation-id** - an identifier to manage conversations
- **Reply-with** - an identifier to be read by the responding agent such that its reply can be identified in a converation
- **In-reply-to** - an identifier so that the sending agent can identify a response to the message
- **Reply-by** - a time denoting the latest time that the sending agent will accept or make use of replies

Message content can be added to messages as text, however JADE also allows the use of serialized Java objects and encoded objects based on an ontology as message content. This allows agents to send and receive instances of concepts from the ontology, such as a component or a piece of data, which can be extracted from the message and used by the receiver. For Java objects, JADE provides `setContentObject()` and `getContentObject()` methods, while for ontology objects, similar methods `fillContent()` and `extractContent()` encode and decode message as instances of ontology concepts.

8.2.3.1 Performatives

The content of a message may contain a string message, an object or a predicate or a mixture of all three, however the purpose of the message, or the *Performative* also plays an important role in message exchange. FIPA defines 22 distinct performatives [FIPA2002b]), of which the following were used in the prototype system:

- **agree** - the agents agree to the performative of a previous message
- **confirm** - the agent confirms the validity of the received content
- **failure** - the agent fails to fulfill a request
- **inform** - the agent is informing another agent of something it believes to be true

- **inform-if** - the agent is requesting a response as to whether the content of a message is true
- **not-understood** - the agent did not understand a received message
- **query-if** - the agent asks if a statement is true
- **refuse** - the agent refuses a request
- **request** - the agent requests the receiver to perform some action
- **subscribe** - the agent requests to subscribe to a particular parameter and be updated when the parameter changes

8.2.4 Predicates and Concepts as Agent Messages

Using the predicates and concepts introduced at the beginning of this chapter, within the JADE framework of ACL messaging, it is now possible to construct messages within agents that can be used to interact with other agents in a MAS. The message content of ACL messages can now be constructed from concepts and predicates from the ontology, as in Figure 8.4, and be used to make requests of other agents.

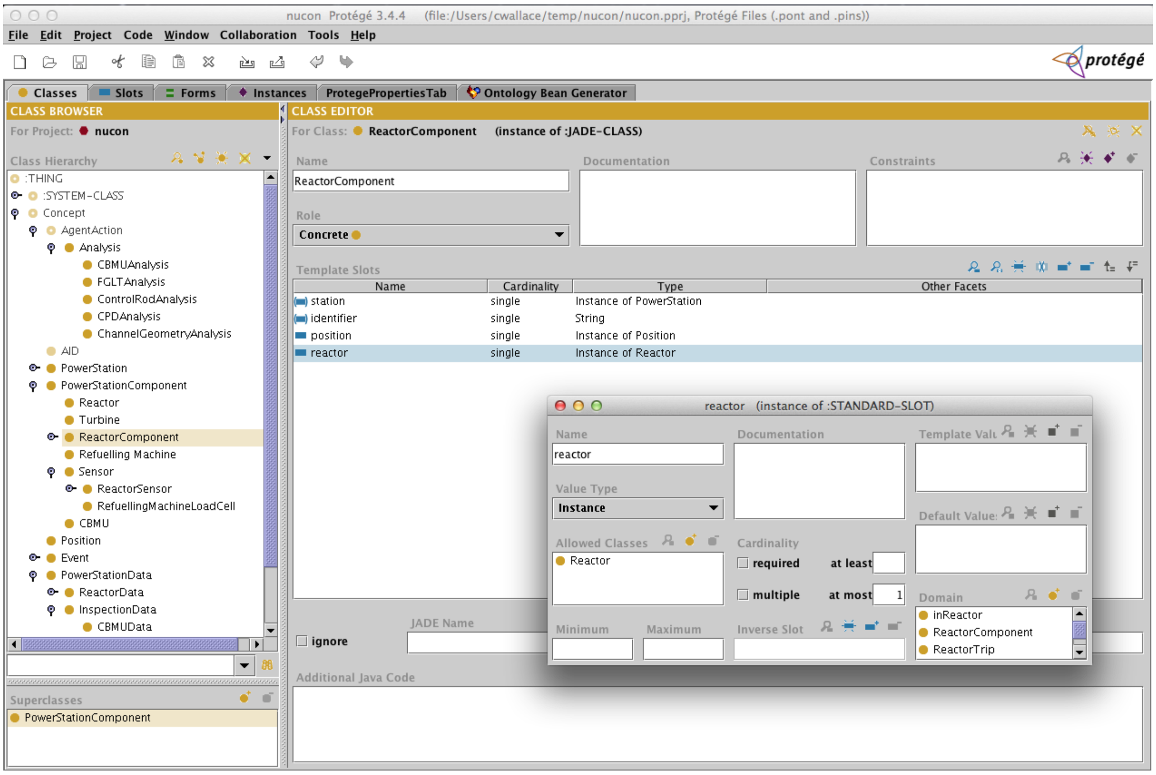
```
(all ?x (and (isA ?x MonitoringObservation)
             (inReactor HNB3)))
```

Figure 8.4: A content block which uses the *isA* and *inReactor* predicates to describe 'all monitoring observations recorded on reactor 3 at Hunterston B'. The *all* predicate is part of the FIPA content language standard [FIPA2002d].

With a defined ontology and set of predicates and a selected agent messaging infrastructure (JADE), the concepts and predicates of the ontology are required to be written in Java code, for implementation in a prototype system built on JADE.

8.2.5 Protege Ontology Development

For implementation of the ontology in Java, the Protege Ontology and Knowledgebase Framework [SCBIR2013] was used. The Protege interface, shown in Figure 8.5, allows for graphical development of an ontology and is capable of generating Java bean classes representing the ontology, for software use, examples of which are shown in Figure 8.6 and Figure 8.7. Each class variable has *getter* and *setter* methods with annotations where database table columns are required and where a variable can be joined to an existing column.



Class Hierarchy:

- :THING
- :SYSTEM-CLASS
- Concept
  - AgentAction
    - Analysis
      - CBMUAnalysis
      - FGLTAnalysis
      - ControlRodAnalysis
      - CPDAnalysis
      - ChannelGeometryAnalysis
  - AID
  - PowerStation
  - PowerStationComponent
    - Reactor
    - Turbine
    - ReactorComponent
    - Refuelling Machine
    - Sensor
      - ReactorSensor
      - RefuellingMachineLoadCell
    - CBMU
  - Position
  - Event
  - PowerStationData
    - ReactorData
    - InspectionData
      - CBMUData

Superclasses: PowerStationComponent

For Class: ReactorComponent (instance of :JADE-CLASS)

Name: ReactorComponent

Role: Concrete

Name	Cardinality	Type	Other Facets
station	single	Instance of PowerStation	
identifier	single	String	
position	single	Instance of Position	
reactor	single	Instance of Reactor	

Name: reactor

Value Type: Instance

Allowed Classes: Reactor

at most: 1

Domain: inReactor
ReactorComponent
ReactorTrip

Figure 8.5: The Protege ontology development software interface.

When the user has defined the concepts and slots and the type of data that they can contain, Protege creates Java classes with corresponding variables and standard *getter* and *setter* methods within the classes. Where one concept extends another, this corresponds to a subclass extending a superclass and normal object-oriented programming conventions are then available, such as inheritance and polymorphism. The generated Java classes, known as entity classes, are therefore a class-based representation of the ontology. Predicates are represented within the Java-based ontology in a similar manner, with variables in the predicate Java beans, as in Figure 8.7, consisting of variables of instances of concept classes which define which concepts the predicate can be used against. The predicate `occurredAfter` for example can be used with instances of `MonitoringObservation` because this concept has a time slot, however it does not make sense to use `occurredAfter` with a concept like `Reactor` which does not. Protege allows the user to specifically define the domain of predicates, such that only valid concepts are used with each predicate.

With a suitable plugin, Protege also allows the annotation of these classes such that they can be used with object relational mapping packages on commercial database platforms.

8.3 Storage

For storage of data and information, access to one or more databases is required in the MAS. By virtue of the federated nature of JADE agent platforms, a database connection is only required in one location, but can be made accessible to the entire system by means of an Archive agent which has the required knowledge to retrieve and store data.

8.3.1 Object Relational Mapping

For database storage, an object relational mapping library called Hibernate [JBoss2013] was selected, which maps Java classes (generated by Protege) directly onto an SQL database. Data and observations that are created by the MAS and stored in the database can then be retrieved as Java objects, which allows for simplified querying using the Hibernate Query Language which allows object oriented queries against the methods available in the objects stored. The Java bean classes generated by Protege contain annotations that indicate which variables are used as keys (typically when one class contains an instance of another) and which variables require unique columns. Each class generated by Protege which contains such annotations is listed in an XML file which is read by Hibernate, an

```
/**
* Protege name: CPD
 * @version $Id$
 */
@Entity
@DiscriminatorValue("CPD")
public class CPD extends ReactorData{

  /**
* Protege name: recordedTime
   */
   @Column
   private Date recordedTime;
   public void setRecordedTime(Date value) {
    this.recordedTime=value;
   }
   public Date getRecordedTime() {
     return this.recordedTime;
   }

  /**
* Protege name: value
   */
   @Column
   private String value;
   public void setValue(String value) {
    this.value=value;
   }
   public String getValue() {
     return this.value;
   }

  /**
* Protege name: reactorComponent
   */
   @ManyToOne(cascade = {CascadeType.ALL})
   @JoinColumn
   private FuelChannel reactorComponent;
   public void setReactorComponent(FuelChannel value) {
    this.reactorComponent=value;
   }
   public FuelChannel getReactorComponent() {
     return this.reactorComponent;
   }

}
```

Figure 8.6: A Hibernate entity class for Channel Power Data (CPD) which extends the superclass ReactorData.

```
/**
* Protege name: inReactor
 * @version $Id$
 */
public class InReactor implements Predicate {

  /**
* Protege name: reactor
   */
   private Reactor reactor;
   public void setReactor(Reactor value) {
    this.reactor=value;
   }
   public Reactor getReactor() {
     return this.reactor;
   }

}
```

Figure 8.7: An example of a Java class representation of a predicate. The class has one parameter, of the type Reactor.

object relational mapping library, which then automatically generates a database schema, shown in Figure 8.9.

8.3.2 Entities And Databases

Using an object-relational mapping approach to storage, objects are stored in the database as entities which can be persisted (stored) and retrieved and handled as any other Java object would be. These entities are managed by an `EntityManager` as shown in Figure 8.10, which provides access to objects stored in the database and the storage of new objects. A peristence query, an example of which is shown in Figure 8.11, is made through the `EntityManager`. This returns a collection of, in the example of Figure 8.11, all instances of the Reactor class stored in the database, rather than a longer SQL query which would depend on the table structure of the database.

The use of object relational mapping therefore adds portability to the system and with only slight modification, the database can be changed to any supported SQL database.

```xml
<?xml version="1.0" encoding="UTF-8"?>
<persistence version="1.0" xmlns="http://java.sun.com/xml/ns/
   persistence" xmlns:xsi="http://www.w3.org/2001/XMLSchema-
   instance" xsi:schemaLocation="http://java.sun.com/xml/ns/
   persistence http://java.sun.com/xml/ns/persistence/
   persistence_1_0.xsd">
 <persistence-unit name="nucpersist" transaction-type="
    RESOURCE_LOCAL">
   <class>uk.ac.strath.eee.nuclear.ontology.ReactorData</class>
   <class>uk.ac.strath.eee.nuclear.ontology.PowerStation</class>
   <class>uk.ac.strath.eee.nuclear.ontology.BulkRod</class>
   <class>uk.ac.strath.eee.nuclear.ontology.CBMU</class>
   <class>uk.ac.strath.eee.nuclear.ontology.State</class>
   <class>uk.ac.strath.eee.nuclear.ontology.TV</class>
   <class>uk.ac.strath.eee.nuclear.ontology.FuelBurnup</class>
   <class>uk.ac.strath.eee.nuclear.ontology.RegulatingRod</class>
   <class>uk.ac.strath.eee.nuclear.ontology.Reactor</class>
   <class>uk.ac.strath.eee.nuclear.ontology.ReactorSensor</class>
   <class>uk.ac.strath.eee.nuclear.ontology.Sensor</class>
   <class>uk.ac.strath.eee.nuclear.ontology.Refuelling</class>
   <class>uk.ac.strath.eee.nuclear.ontology.ReactorTrip</class>
   <class>uk.ac.strath.eee.nuclear.ontology.Event</class>
   <class>uk.ac.strath.eee.nuclear.ontology.FuelStringer</class>
   .
   .
   .
   .
   .
   .
 </persistence-unit>
</persistence>
```

Figure 8.8: A persistence XML mapping scheme for the ontology created for the MAS. Each concept from the ontology is defined in a class and is listed in an XML file which Hibernate uses to generate a schema for the database.

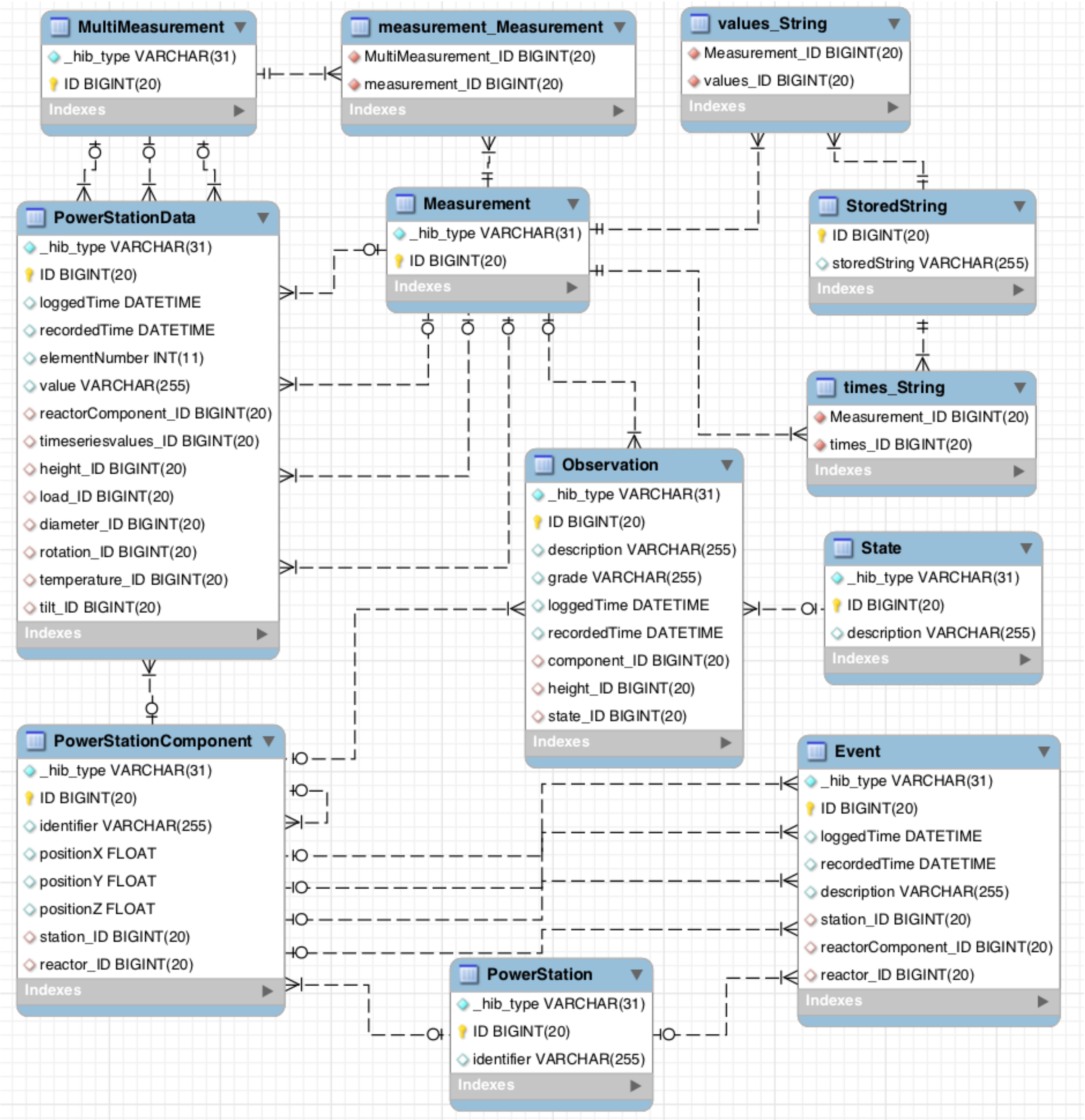


Figure 8.9: The schema, generated for this thesis, uses an object-relational mapping to relate concepts in the ontology to database tables and fields.

```
public class Test {
  static EntityManagerFactory emf = null;
  public static void main(String[] args){

  emf = Persistence.createEntityManagerFactory("nucpersist");
  EntityManager em = emf.createEntityManager();

  }
}
```

Figure 8.10: When the schema exists and is accessible, an Entity Manager Factory and an Entity Manager are created (which are aware of the object relational mapping scheme) to provide access to the database.

```
  Query query = em.createQuery("select r from Reactor r");
  List<Reactor> results=query.getResultList();
```

Figure 8.11: A query can be created an executed by referring to the class name within the ontology, rather than requiring specific knowledge of the database structure.

8.3.3 Archive Agent

The Archive Agent is essentially a small messaging and translation layer added to a standard SQL database system which can offer database services to the MAS. As the Archive agent makes use of the system ontology, on the receipt of a message containing a request for data, the evaluation of a statement or the storage of data, it can use the object relational mapping previously described to construct the appropriate database query. When data is sent to the Archive agent for storage in the database, the Archive agent need only extract the data object from the message, using the ontology, and persist the object without any further processing of the data, as described in Figure 8.12.

Service: *Store and Retrieve Data from a database*
Inputs: *Data, storage and retrieval requests*
Outputs: *Data*
Pre-Conditions: *Request or data exists*
Post-Conditions: *Data stored in database or request responded to with retrieved data*

Figure 8.12: Service model description of the Archive agent

8.4 Data Collection

A key aspect of the prototype system is the automated retrieval and management of data, prior to analysis, from any data sources relevant to the MAP analyses through the use of an Interface agent. Where data is already stored for other purposes, re-storage of the data is generally avoided to avoid duplication of effort and access is provided to these data sources on an ad-hoc basis by means of an Interface agent, to a database for example. A large quantity of MAP relevant data however is retrieved from non-networked sources periodically and stored as binary or plain-text files and it is management of this data which is typically most time consuming for the engineer.

The most important tasks associated with automated collection of such data are: scanning of files and folders, parsing of data and sending data to an Archive agent, as shown in Figure 8.13

Service: *Manage access to and collection of data*
Inputs: *Requests, data*
Outputs: *Data, Notifications*
Pre-Conditions: *Request or data exists*
Post-Conditions: *Data sent to database,*
analysis agent alerted, data sent to other agent

Figure 8.13: Service model description of an Interface Agent

Parsing libraries have been written for the available types of MAP data, including FGLT data, control rod height data, CPD data, reactor parameter data (pressures, temperatures etc) as well as CBMU data. These parsing libraries convert the known formats of these data to a form based on the ontology for storage in a database or for analysis by an Analysis agent.

8.5 Analysis Deployment

The deployment of analyses developed in the previous chapter is now described. The algorithms developed based on the MAP requirements, were written as Java code which can be executed by an agent behaviour when the agent determines

Service: *Analyse Control Rod Data*
Inputs: *Notifications, Data*
Outputs: *Analysis results*
Pre-Conditions: *Data exists*
Post-Conditions: *Analysis results sent to database,*

Figure 8.14: Service model description of a Control Rod Analysis Agent

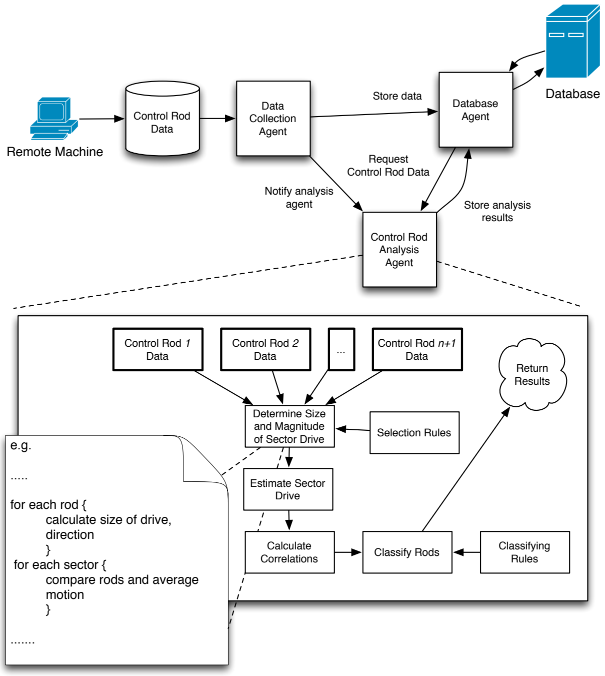
that suitable data is available for analysis. The analysis agents are normally dormant in the system until a data collection agent indicates the availability of new data or a request is made of the agent, or an internally (internal to the agent) scheduled analysis is performed.

8.5.1 Regulating Rod Analysis Agent

The regulating rod analysis is deployed within an agent which upon being alerted to new data in the system, will retrieve the data via the database agent for analysis, as shown in Figure 8.15 and as a conversation between agents in Figure 8.16. On completion of the analysis, the agent makes a request of the database agent to store the analysis results which are then available to the rest of the system as shown in Figure 8.14.

8.5.2 Thermal To Neutronic Power Ratios

The analysis of thermal and neutronic power analysis for fuel channels is written in Java code, based on the pseudocode described in Chapter 7. This processing of rules, as shown in Figure 8.18 and as an agent conversation in Figure 8.19 is applied to new CPD data as it becomes available to the system as shown in Figure 8.17. The schematic view shown in Figure 8.18 shows the analysis agent notified every time new CPD and new refuelling data enters the system, however these two types of data are unlikely to be added at the same time, therefore the agent regularly revises its analysis every time new, potentially relevant data is available, for example new refuelling data as shown in Figure 8.20.



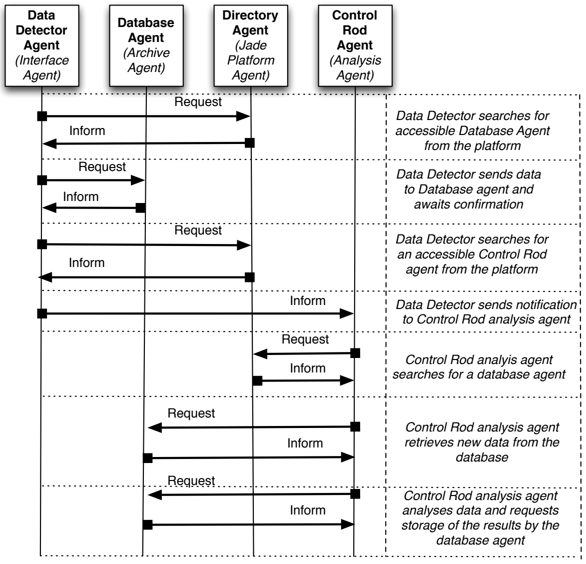
```
e.g.

.....

for each rod {
        calculate size of drive,
        direction
        }
 for each sector {
        compare rods and average
        motion
        }

.......
```

Figure 8.15: A schematic view of the control rod analysis showing the movement of data from a remote machine, to the database, before being retrieved by the analysis agent.



Data Detector searches for accessible Database Agent from the platform

Data Detector sends data to Database agent and awaits confirmation

Data Detector searches for an accessible Control Rod agent from the platform

Data Detector sends notification to Control Rod analysis agent

Control Rod analysis agent searches for a database agent

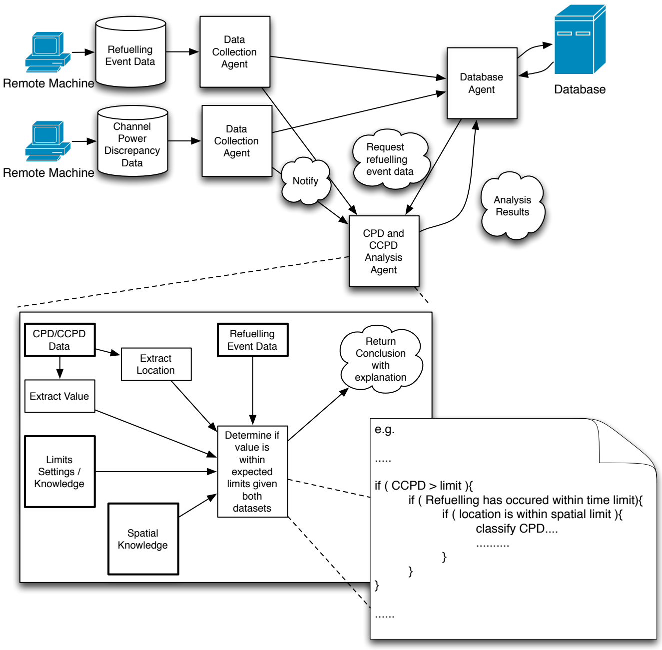
Control Rod analysis agent retrieves new data from the database

Control Rod analysis agent analyses data and requests storage of the results by the database agent

Figure 8.16: The control rod analysis procedure as an agent conversation.

Service: *Channel Power Analysis*
Inputs: *Notifications,Data*
Outputs: *Analysis Results*
Pre-Conditions: *Data exists*
Post-Conditions: *Analysis results sent to database*

Figure 8.17: Service model description of a Channel Power Analysis Agent



```
.....
if ( CCPD > limit ){
        if ( Refuelling has occured within time limit){
                if ( location is within spatial limit ){
                        classify CPD....
                        ..........
                }
        }
}
......
```

Figure 8.18: Channel Power Data Analysis schematically.

8.5.3 Estimation Of Channel Geometry From Friction Profile

The analysis of channel geometry is implemented as a behaviour in an agent which responds to new CBMU or FGLT in the MAS, as in Figure 8.21, where the data describes the same fuel channel. Figure 8.22 shows the agent messaging required to perform the analysis and store the results, while Figure 8.23 shows the flow of data through the system. The channel geometry analysis is dependent on data of both types being available for a channel therefore given the relatively small number of inspections which occur, there is a far smaller volume of CBMU data available compared to FGLT data and as a result, these analyses occur

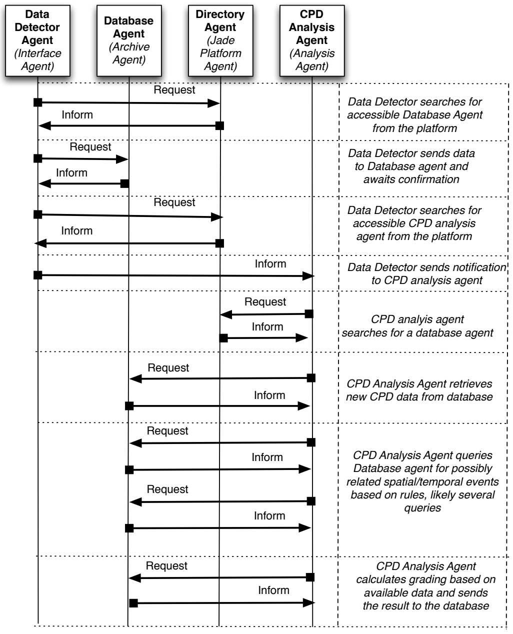


Figure 8.19: Channel Power Data Analysis on the addition of new data.

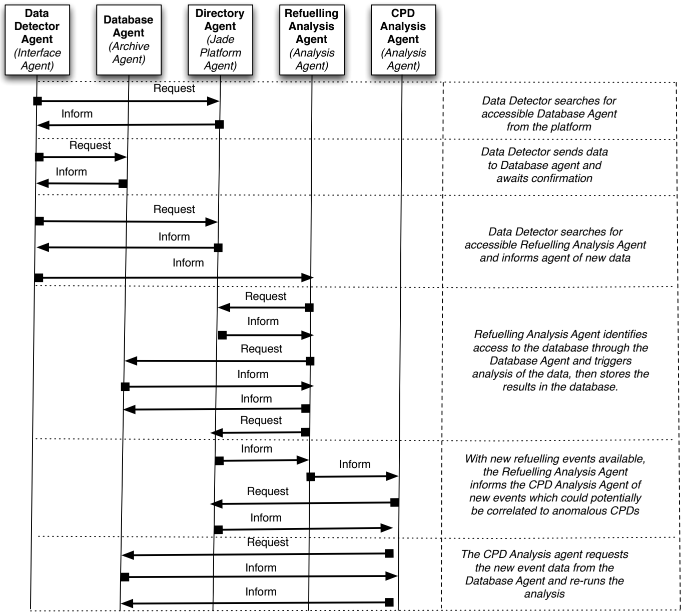


Figure 8.20: New refuelling data triggers re-analysis of previous CPD conclusions.

Service: *Estimate channel geometry based on FGLT and CBMU*
Inputs: *Notifications and CBMU and FGLT data*
Outputs: *Analysis results*
Pre-Conditions: *CBMU and FGLT Data exists*
for the a fuel channel
Post-Conditions: *Analysis results sent to database*

Figure 8.21: Service model description of the Channel Geometry Analysis agent.

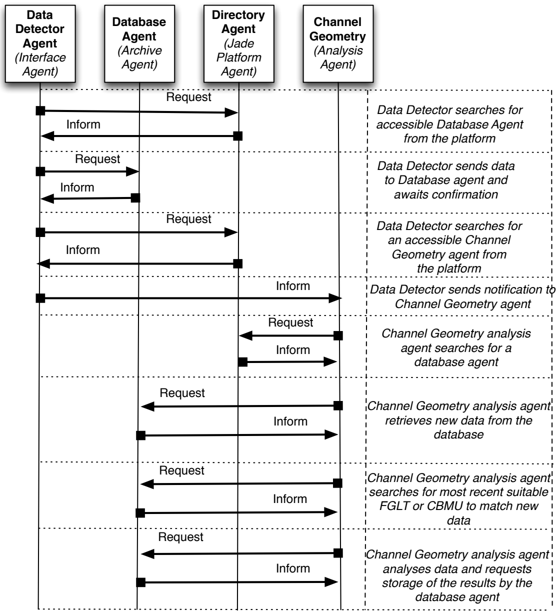


Figure 8.22: Channel geometry analysis as agent messages

infrequently. This analysis is not currently part of the MAP and will provide only supporting indication to engineers interpreting FGLT. With an increasing number of inspections occuring as the cores age however, it is expected that the applicability of this analysis will increase in future.

8.6 Generic Condition Monitoring Interface

While the autonomous, social and pro-active characteristics of intelligent agents have been shown thus far to be well suited the automated management and analysis of data, it is possible to exploit only the reactive nature of agents, along with the flexibility provided by a distributed system, in order to provide external

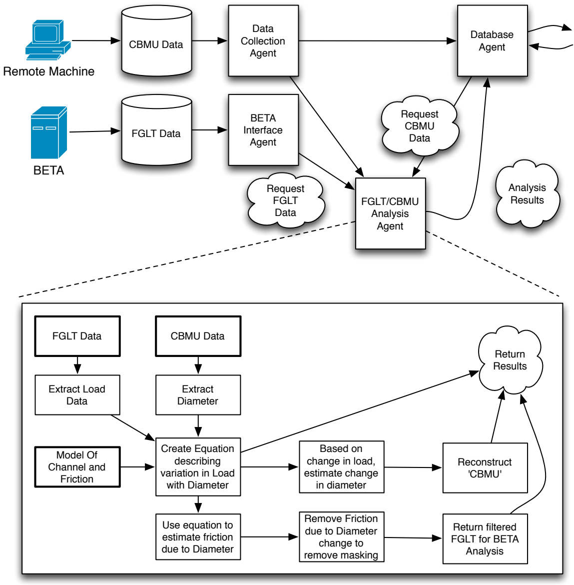
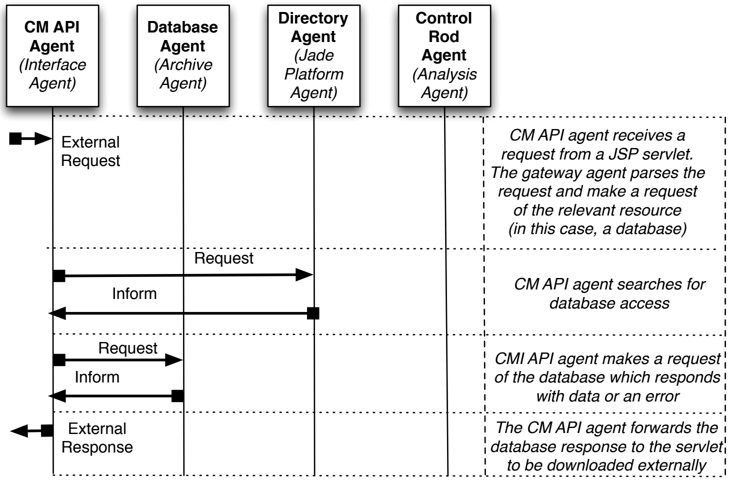


Figure 8.23: Channel geometry analysis



CM API agent receives a request from a JSP servlet. The gateway agent parses the request and make a request of the relevant resource (in this case, a database)

CM API agent searches for database access

CMI API agent makes a request of the database which responds with data or an error

The CM API agent forwards the database response to the servlet to be downloaded externally

Figure 8.24: A remote request is handled by the CM API agent which in turn makes a request of the database agent and theb forwards the results as an HTTP response.

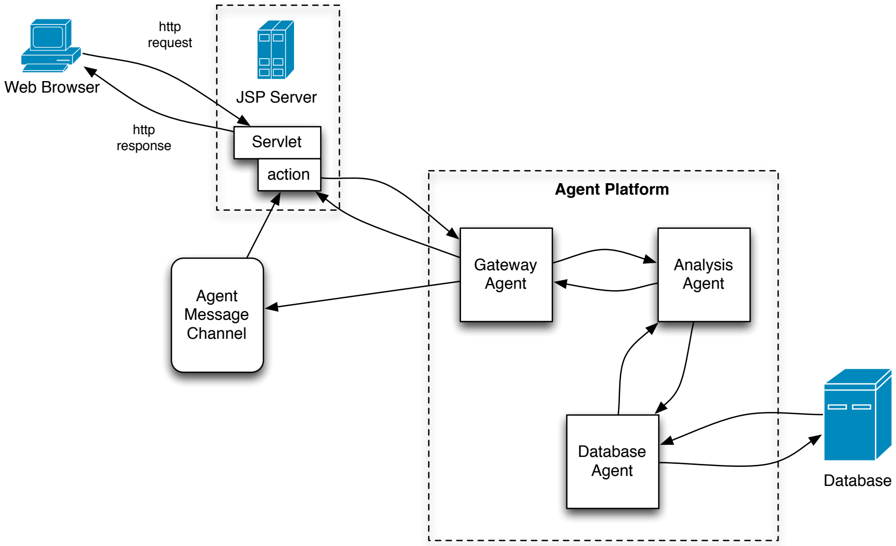


Figure 8.25: An illustration of how access to the distributed agent-based system can be provided to a user, via a web browser for example. The Java servlet parses requests and the Gateway agent routes the requests to the appropriate agents, which can then behave as they would had the request originated within the system.

access to the MAS resources. Such an agent would only respond to requests and would have no autonomy and limited sociability, in so much as it would communicate with other agents to fulfil a request, however could still provide a valuable functionality to users of the system.

Therefore, to provide access to the MAS to external users and systems, a web interface component was implemented within an Gateway Agent, which is an example of an Interface Agent (albeit one of limited capabilities,). A Java Server Pages (JSP) web service, running inside an Apache Tomcat 7 server, can pass requests directly from HTTP to the interface agent, which can then route the request to the appropriate agent, as shown in Figure 8.24 and Figure 8.25 and handle the response from the agent, forwarding the appropriate content back as an HTTP response. Apache Tomcat [Apache2013] was selected as the server software due to prior experience, particularly with IMAPS, in providing CM interfaces to the user. Different servlets running within the web service can offer pre-defined services, such as access to data or observations stored in other systems.

```
http://isap56:8080/DMF/beta/BetaView.jsp?eventid=18709&station=HNB
    &reactor=3&component=4276&date=01/10/2009&type=D&betalocation=
    http://isap56.eee.strath.ac.uk/beta/
```

Figure 8.26: A URL for accessing data from the MAS externally.

Service: *Process requests from external web access*
Inputs: *Request parameters*
Outputs: *Data, Responses*
Pre-Conditions: *Request exists*
Post-Conditions: *Response sent to web request*

Figure 8.27: Service model description of the Gateway agent

To external users, the web interface appears as a single point of access to the system and simple URLs, an example of which is shown in Figure 8.26, can be constructed to make requests of the system by proxy. Java servlets in the web service trigger an instance of a Gateway agent, which translates the request into ontology concepts and predicates and queries the MAS and then translates the systems response into content which can be returned to the user via the servlets. This approach has parallels to the concept of an Application Programming Interface (API), a common practice in software development, whereby an application provides access to content or functionality within an application through a well defined interface via a specified set of parameters.

8.6.1 Summary

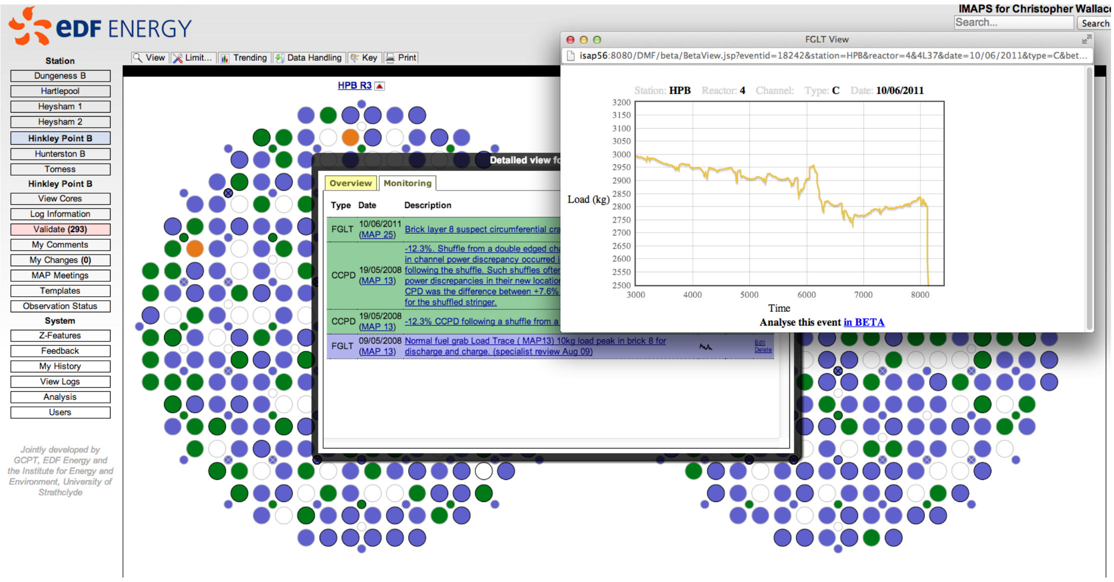
The development of the prototype system described in this chapter is the culmination of research applied to automate and increase the efficiency of the MAP analyses, in order to provide more efficient and robust CM for the operator. Evidence of this can be found in the traceability of the examples presented in this chapter, the retention and re-use of data and automation with which the analyses were performed, which resulted in shorter time to conclusion and a significantly smaller fraction of the engineer's time than the current MAP requires. Previous experience with IMAPS and BETA and the deployment of these systems to support the MAP by analysing reactor data provides an important source of knowledge about how the prototype system might be integrated into the existing CM environment. For this reason, the relationship between the prototype system and IMAPS and BETA was investigated to determine how best the prototype system can aid the engineer and compliment the existing CM applications.

8.7 IMAPS and BETA

The IMAPS and BETA systems described in Chapter 3 are established CM applications which are used to support daily monitoring tasks required as part of the safety case of the AGR. The increased importance placed on these systems as a result of their input into the MAP decision making process places inherent limits on the development of these systems. Specifically, any future versions of the system must be consistent with the methods, data and interpretations of previous versions. In practical terms this means that alterations to the system must be thoroughly analysed for any potential impact on the interpetation of the monitoring data and as a result it has become increasingly obvious that a modular approach to extending these systems is preferred.

There are clear benefits to sharing information between these systems, as might be expected given their overlapping scopes, therefore movement towards such integration seems logical and desirable. It is important however that there is no increased dependency of one system on another, as the standalone integrity of each system is crucial to their continued use and the reliability placed on their conclusions. That is, a failure in one system may be allowed to remove some functionality from another system (the functionality provided by the failed system), however the failure of one system should not compromise the complete functionality of another system.

For this reason, an agent-based approach to sharing information between IMAPS and BETA was investigated to provide access and contextual information. An initial application, determined by frequent user requests, was to make FGLT information and data available in IMAPS.



isap56:8080/DMF/beta/BetaView.jsp?eventid=18242&station=HPB&reactor=4&4L37&date=10/06/2011&type=C&bet...

Type	Date	Description
FGLT	10/06/2011 (MAP 25)	Brick layer 8 suspect circumferential cra
CCPD	19/05/2008 (MAP 13)	-12.3%. Shuffle from a double edged cha in channel power discrepancy occurred i following the shuffle. Such shuffles ofter power discrepancies in their new locatio CPD was the difference between +7.6% for the shuffled stringer.
CCPD	19/05/2008 (MAP 13)	-12.3% CCPD following a shuffle from a
FGLT	09/05/2008 (MAP 13)	Normal fuel grab Load Trace (MAP13) 10kg load peak in brick 8 for discharge and charge. (specialist review Aug 09)

Analyse this event in BETA

Figure 8.28: BETA interface within IMAPS

8.7.1 BETA Agent

The FGLT data contained within the BETA system, described previously, provides one of the main inputs to IMAPS however the descriptions contained in IMAPS are largely qualitative and the data used to reach conclusions is not immediately available. A BETA Agent was developed, which has direct, but read-only access to the Oracle SQL database used by BETA and is encoded with knowledge of the BETA database structure and can construct suitable SQL queries to retrieve FGLT. For each FGLT observation that exists in IMAPS, a link is now available which retrieves, via the BETA Agent, a preview of the FGLT and provides information about the event and a further link to the event in BETA. In this case, the BETA Agent, described in Figure 8.29 is performing the search of BETA which would normally be required of the user, as there is no direct key from an IMAPS observation to a FGLT event in BETA as a result of the way the systems were initially developed.

8.7.2 IMAPS Analysis

The increasing volume of CM observations stored within the IMAPS database provides a rich source of information for analysis and trending outwith the cur-

Service: *Retrieve FGLT data from BETA*
Inputs: *Request*
Outputs: *Data*
Pre-Conditions: *Request is valid, Data exists*
Post-Conditions: *Data sent to IMAPS*

Figure 8.29: The BETA agent defined using the Service model.

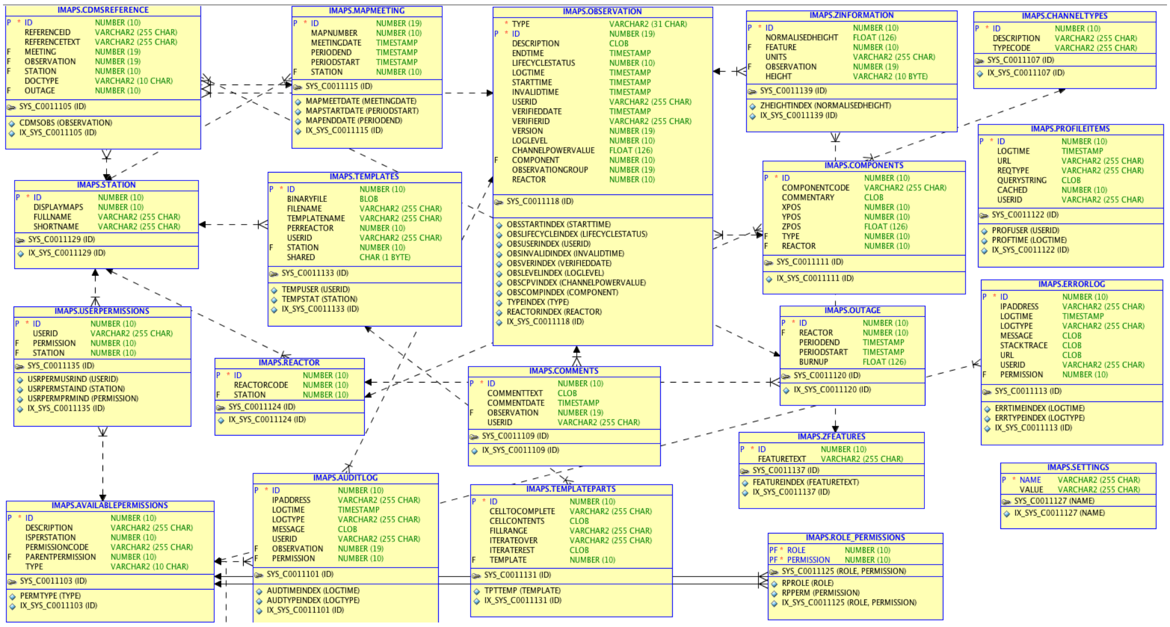


Figure 8.30: The IMAPS database schema [Jahn2007].

rently defined MAP scope. So that any additional analysis does not interfere with the availability or performance or the existing IMAPS user experience, it was determined that the required functionality could be encapsulated within an analysis agent. IMAPS users have access to the analysis results performed by the agent by means of the agent-servlet communication described earlier and presented within the IMAPS environment. The use of agents to perform additional analyses allows for the modular addition or removal of analyses without affecting the core operation of IMAPS, only the availability of particular analyses which are not themselves required parts of the MAP.

```
"select * from observation join components on observation.
    component=components.id where description like '%crack%' and
    description not like '%no crack%' and description not like '%
    egrad%' and description not like '%ew grade%' and description
    not like '%egraded%' and components.reactor='"+reactorCode+"'
    and observation.type like '%fglt%' order by componentcode";
```

Figure 8.31: An example of a query of the underlying observation data from the IMAPS database, in this case looking for observations from FGLT which may indicate cracks

Service: *Automated analysis of IMAPS data*
Inputs: *Pre-defined analyses*
Outputs: *Analysis reports*
Pre-Conditions: *Data exists*
Post-Conditions: *Analysis reports available in IMAPS*

Figure 8.32: The IMAPS data analysis agent as defined in the Service model

8.7.3 IMAPS Analysis Agent

The IMAPS Analysis Agent, described in Figure 8.32 has direct, but read-only access to the Oracle SQL database used by IMAPS for storage. Queries are encoded in the agent, an example of which is shown in Figure 8.31, which can extract arbitrary datasets from the database. In the example shown, the query extracts observations for a particular station where the description of the observation includes the word 'crack' which may then be compared with a list of known cracks to provide some estimate of where monitoring data can supplement inspection data. The ability to search for particular words or phrases in descriptions associated with observations is a particularly interesting problem, as there may be additional information recorded non-quantitatively by the engineers who submit IMAPS observations, which can then be quantitatively analysed in a statistical manner.

8.8 Testing

In order to test the prototype system a test environment was established using three different machines, described in detail in Figure 8.35. The structure of the

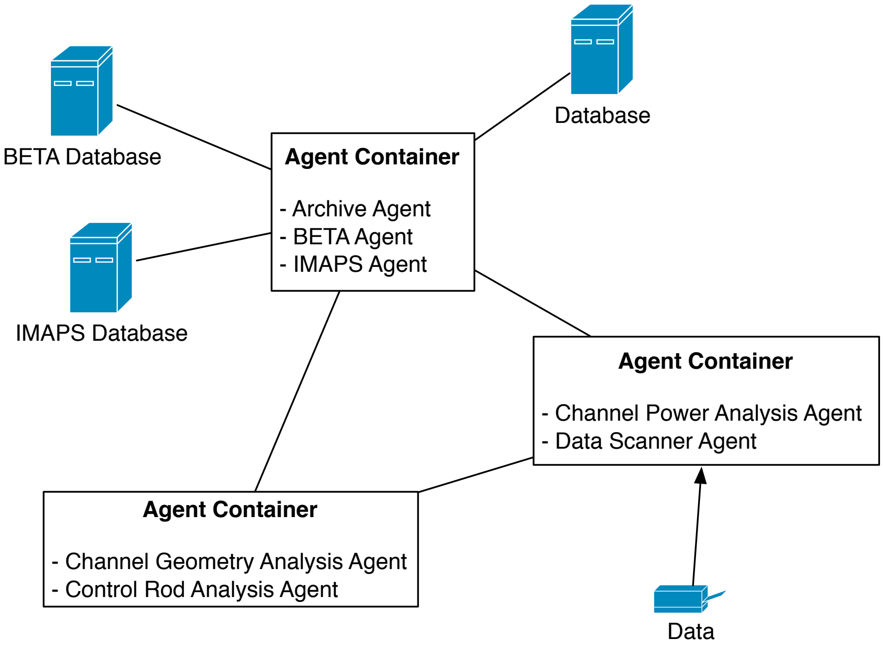
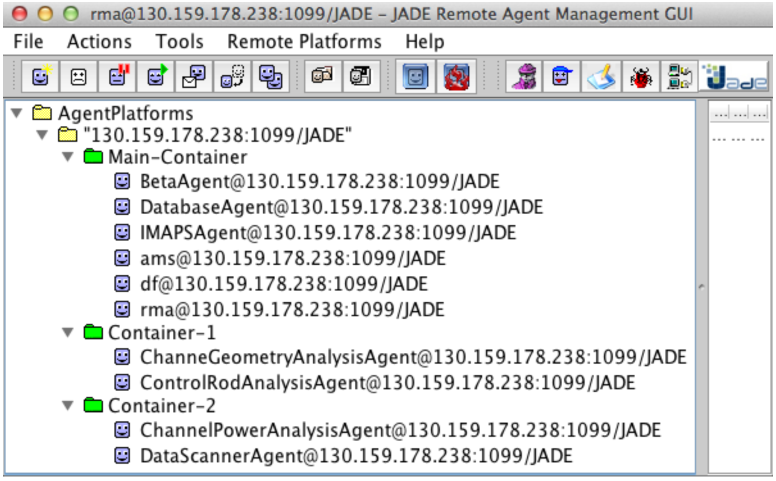


Figure 8.33: An overview of the prototype system.



AgentPlatforms
  "130.159.178.238:1099/JADE"
    Main-Container
      BetaAgent@130.159.178.238:1099/JADE
      DatabaseAgent@130.159.178.238:1099/JADE
      IMAPSAgent@130.159.178.238:1099/JADE
      ams@130.159.178.238:1099/JADE
      df@130.159.178.238:1099/JADE
      rma@130.159.178.238:1099/JADE
    Container-1
      ChanneGeometryAnalysisAgent@130.159.178.238:1099/JADE
      ControlRodAnalysisAgent@130.159.178.238:1099/JADE
    Container-2
      ChannelPowerAnalysisAgent@130.159.178.238:1099/JADE
      DataScannerAgent@130.159.178.238:1099/JADE

Figure 8.34: The agents in the prototype system running on a distributed platform over four machines.

system from a network perspective is shown in Figure 8.34 with development versions of IMAPS and BETA also running. Agent based approaches, as discussed in Chapter 5, are well established for message passing where conclusions or analysis results are transmitted between agents in a distributed system. However, in order to test the flexibility and practicality of an agent-based system as proposed for data analysis and management tasks, various configurations of agents on different containers were tested on varying hardware platforms, including a Mac desktop computer, a Linux server and a Raspberry Pi running Linux.

The latter, shown in Figure 8.36, is of particular interest given the very small footprint of the Pi and very low power consumption of around 5W under load. The purpose of an agent based approach to distributed nuclear CM is intended to be as non-invasive as possible, therefore platforms such as the Raspberry Pi are of particular interest as potential components in a distributed system.

The list of agents running in the prototype system (excluding the JADE AMS and DFa agents) included:

Platform 1

- **Beta Agent** - an Interface agent providing access to FGLT from the BETA system
- **Database Agent** - an Archive agent providing database services to the system
- **IMAPS Agent** - an Interface agent providing access to IMAPS

Platform 2

- **Channel Geometry Analysis Agent** - an analysis agent performing analysis of FGLT and CBMU data
- **Control Rod Analysis Agent** - an analysis agent performing analysis of Control Rod height data

Platform 3

- **Channel Power Analysis Agent** - an analysis agent performing analysis and grading of CPD data

	Mac Mini	**Linux Server**	**Raspberry Pi**
CPU Architecture	x86-64	x86-64	ARM6
CPU	2.26Ghz Intel C2D	1.8Ghz Intel C2D	700Mhz ARM11
Memory	8GB DDR3	4GB DDR2	512MB
Storage	320GB SATA	160GB SATA	SD Card
Optical	CD/DVD	CD/DVD	None
USB	4xUSB 2.0	4xUSB 2.0	2xUSB 2.0
Network	10/100/1000 Ethernet	10/100/1000 Ethernet	10/100 Ethernet
Wireless	802.11b/g/n	With addon	With addon
Operating System	Apple OSX 10.7.5	Debian Linux 2.6.32	Debian ARM
Display	DVI	VGA	HDMI
Power (Idle)	10W[1]	75.99W[2]	2W[3]
Power (Max Load)	85W[1]	114W[2]	3.5W[3]
Dimensions (mm)	170x170x51	92x310x304	86x54x25
Other	-	-	Based on Broadcom BCM2835

Machine specification references:

[1] http://support.apple.com/kb/HT3468

[2] http://www.dell.com/downloads/global/corporate/environ/Opti$_7$45$MT.pdf$

[3] $http://www.raspberrypi.org/$

Figure 8.35: The specifications of the machines used in the prototype system.

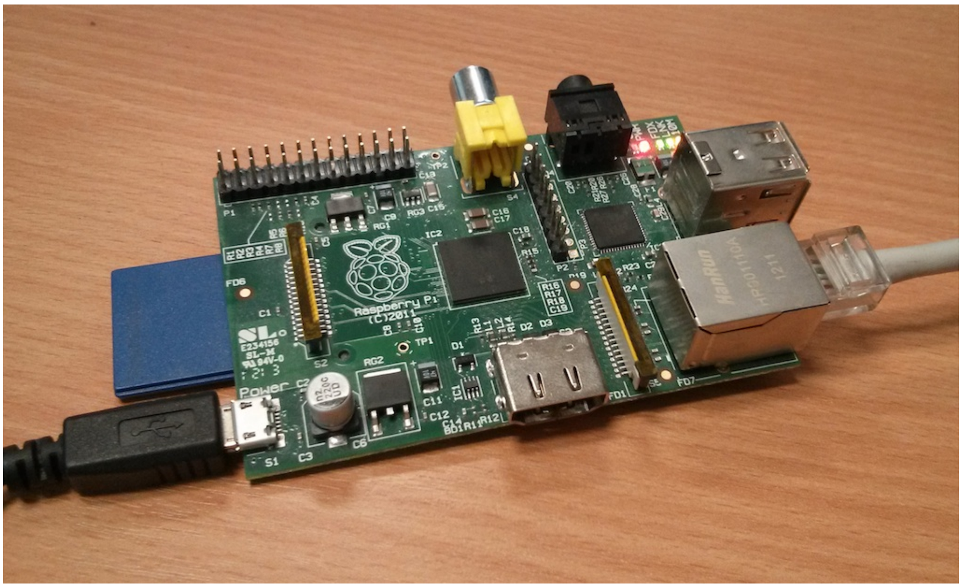


Figure 8.36: A Raspberry Pi computer. For testing, a JADE platform is created on the device running in a Linux based OS which boots straight from an SD card.

8.8.1 Testing 1: Parsing And Trasmitting Files

An initial set of testing was conducted to provide a context for the relative computational powers of the test machines, using real station data. As particular resources may or may not be suited to particular tasks, this set of testing allows the comparison of the same set of tasks using different permutations of machines and inputs. Three different CBMU data files were created using the same base data, of sizes 500kB, 1500kB and 2750kB[2] and a distributed platform created between the three machines in different configurations. Each machine was tested as a database host and as a remote machine retrieving and parsing the file. The test procedure each time was:

- Main container started with core Jade agents and an Archive agent and are registered to the JADE DFa agent
- Two Remote containers are started with a Data Collection (DC) agent which are registered with the JADE DFa agent

---

[2] A typical CBMU file is about 500kB and most monitoring data files are less than 1MB, with the exception of reactor parameter data, which is only available infrequently and is normally segmented into files of 1-3MB

- The DC agent detects the test file and parses the content to an ontology object
- The DC agent then queries the DFa for an agent offering the 'database' service
- Upon receiving the agent address of an Archive agent on the main container, the DC agent transmits a request to store the CBMU object
- The Archive agent, receives the request, confirms receipt of the data object
- The Archive agent then persists the CBMU data in the database

Two instances of each test were running at any one time, with a single database host in a main container, queuing requests from the remote containers. The key parameters which indicate the practicality of the prototype system are the times required for *parsing of the file*, *transmission of the data object* and *storage of the data*. These values were measured several times for each configuration with the results shown in Figure 8.37.

The results of the testing clearly show that the Raspberry Pi is significantly slower than the other systems used. These results can largely be explained as a result of the Pi's slower, single core processor and smaller amount of memory. The Java implementation for ARM processor based platforms is relatively new and likely contains many inefficiencies compared to more established Java implementations on X86 and X86-64 processors, also contributing to the lower measured performance of the Pi.

8.8.2 Interpretation Of Testing 1

For database use, the Pi is clearly unusable in its current state as database access (both storage and retrieval) is likely to be a bottleneck in any monitoring system where data throughput is high. In both other tests (parsing and trasmitting) the Pi was slower than the other systems, however only by a factor of two to five and for tasks which typically take only a few seconds to complete. This suggests

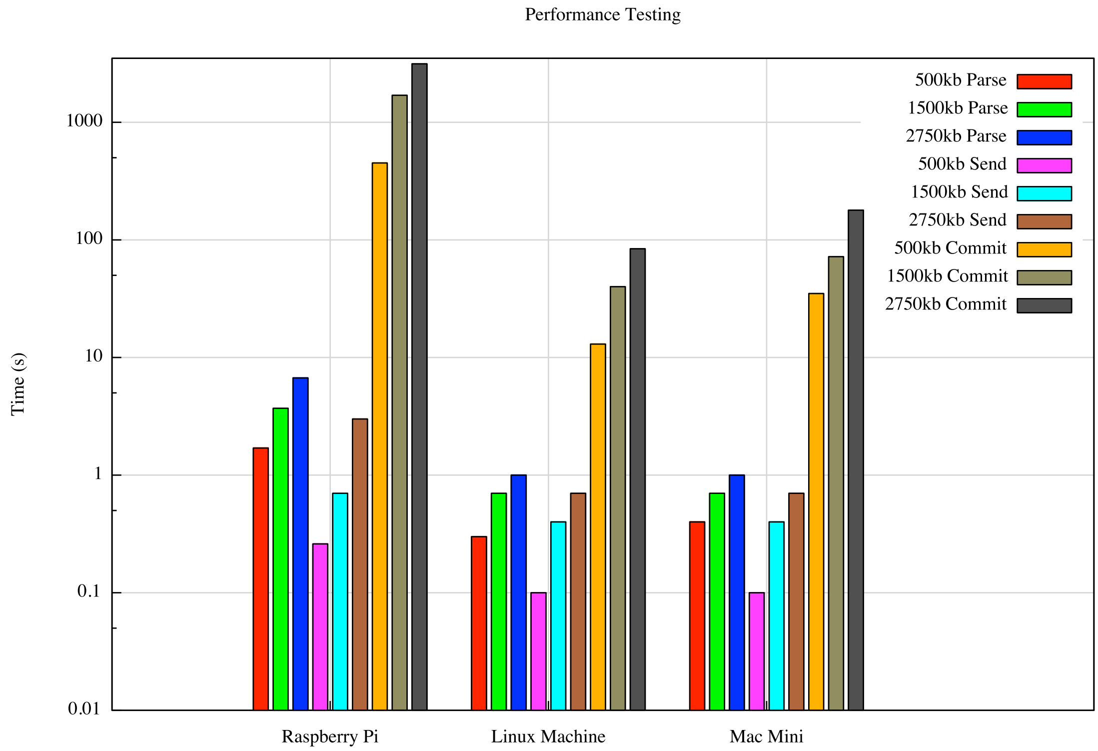


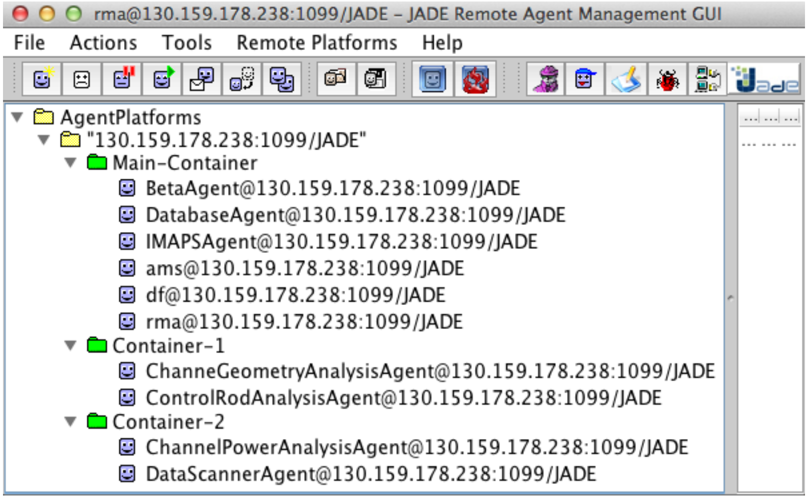
Figure 8.37: Parsing, sending and committing times for the test configurations – note the log scale on the y axis. Note that all parsing and sending operations for the Mac Mini and Linux machine are perfomed under one second and all under ten seconds including the Raspberry Pi. The database commit times are at least an order of magnitude greater on every platform.

there may yet be use for such comparitively low power platforms, where they can be used unobtrusively and although they function slower than a larger machine, do not introduce any excessive lag to the system as a whole.

8.8.3 Testing 2: Multiple Parallel Tasks

In order to establish the practicality of a distributed system of multiple analyses and data sources active at any one time, simultaneous analyses and data processing tasks were triggered, in a test scenario using the agents described previously, designed as follows:

- On platform 1 (Mac Mini): The database contains an existing CBMU dataset, 300 ungraded CPD observations and 20 refuelling events, half of



- AgentPlatforms
  - "130.159.178.238:1099/JADE"
    - Main-Container
      - BetaAgent@130.159.178.238:1099/JADE
      - DatabaseAgent@130.159.178.238:1099/JADE
      - IMAPSAgent@130.159.178.238:1099/JADE
      - ams@130.159.178.238:1099/JADE
      - df@130.159.178.238:1099/JADE
      - rma@130.159.178.238:1099/JADE
    - Container-1
      - ChanneGeometryAnalysisAgent@130.159.178.238:1099/JADE
      - ControlRodAnalysisAgent@130.159.178.238:1099/JADE
    - Container-2
      - ChannelPowerAnalysisAgent@130.159.178.238:1099/JADE
      - DataScannerAgent@130.159.178.238:1099/JADE

Figure 8.38: The distributed system with three connected JADE platforms.

which occurred on channels in the ungraded CPD dataset. The Database Agent responds to requests from agents on the other platforms.

- On platform 2 (Linux Server): The Channel Geometry Analysis agent begins analysis of the available CBMU and requests a corresponding FGLT from the BETA interface agent (data for which is available)
- On Platform 2 (Linux Server): A Control Rod Height dataset for a single channel is detected by the Data Collection Agent, parsed and sent to the database
- On Platform 3 (Raspberry Pi): The Channel Power Analysis agent begins analysis of the ungraded CPD observations in the database

The time taken for each of these tasks to complete is shown in Figure 8.39, including the time required by the main sub-parts of each task.

8.8.4 Interpretation Of Testing 2

As with Testing 1, it can be seen from the results in Figure 8.37 that tasks such as parsing and transmitting require relatively short times, compared to database storage and tasks which require large numbers of messages. The Channel Geometry analysis results showed the effect of the added latency of interfacing with an

	Task Time (s)	**Total Time (s)**
Channel Geometry Analysis		
Retrieval of CBMU Data	0.5	
Request Availability of FGLT	0.8	
Retrieval of FGLT Data	1.7	
Analysis	2.1	
Transmit and store analysis	5.2	
		10.3
Control Rod Data Parsing and Storage		
Parse Control Rod Data	0.7	
Transmit and store Data	7.1	
		7.8
Channel Power Analysis		
Retrieval of Ungraded CPD Observations	0.8	
Analysis of CPD Data*	18.1	
Transmit and Store Observations	2.1	
		20.2

Figure 8.39: Times for parallel analysis and data management tasks. Note that all tasks started at the same time and that the completion time indicates the point at which the agent had its last interaction with respect to that task, for example — awaiting confirmation from the Database Agent contributes to the total time, even if the agent is otherwise idle while it awaits that message.

external system, with slightly larger database retrieval and query times that the database service offered within the MAS, however at a level of only 1–2 seconds it is unlikely that this would be noticeable to the user. The control rod parsing task, an example of the results of which are shown in Figure 8.40, was performed at a similar speed to the CBMU parsing in Testing 1, with the database storage once again the largest delay. The Channel Power Analysis task, the output of which is shown in Figure 8.41, contained the largest overhead of messaging, as a key aspect of the analysis is to request from the database any events which may be used to explain anomalous data values. In this case, the number of such explicable values was relatively low, however the analysis is still required to make a request of the database and process the null response, even if no events are available, hence the analysis of the CPD data was by far the longest running task in this test scenario.

8.8.5 Summary of Testing

It can be seen by reviewing the results of the testing that the analysis algorithms performed the necessary calculations, messaging and classifications far faster than a human could perform the same tasks. The principal limitation observed in

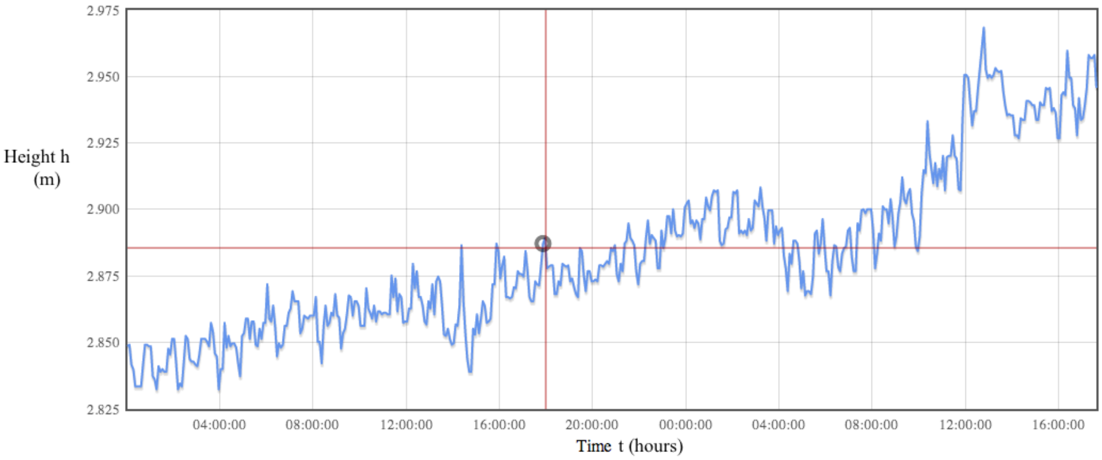
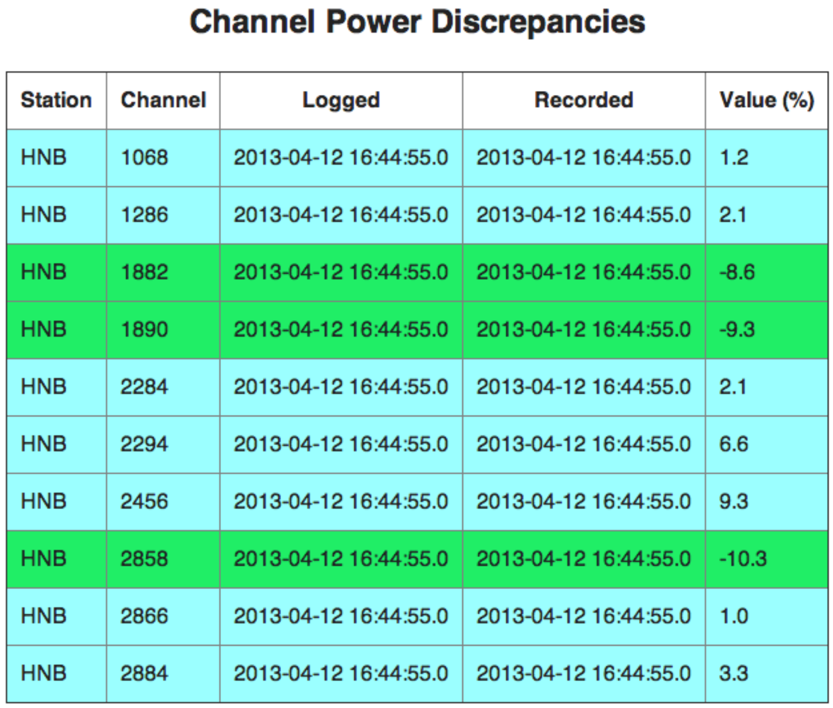


Figure 8.40: Control rod data is parsed, stored in the database and available for trending and analysis, allowing detailed inspection through the a prototype interface.

testing was the storage of large datasets to the database, access to which, in the testing, was provided by a single Archive Agent. The management of data and observations from the database which are added, altered, removed and persisted is a computationally expensive task. It is likely therefore that a deployed version of such a system would require multiple Archive agents, however this in itself introduces further practical problems relating to the synchronicity of database objects, tracking of database alterations and data integration where duplicate data exists. With these caveats, compared to the existing monitoring regime and the limited storage and re-use of data, the delays introduced by database overhead are likely to be negligible to the user where sufficient explanation is provided as to the time taken to perform certain database intensive tasks. The majority of the analyses of the MAP are based on the correlation of events, tasks which place a greater emphasis on messaging rather than data management, which were shown to perform comparatively quickly, even on the lower powered Raspberry Pi.

8.9 Discussion

This chapter has described the development of a prototype system based on the model described in the Chapter 6. The creation of a more detailed, AGR-specific



Channel Power Discrepancies

Station	Channel	Logged	Recorded	Value (%)
HNB	1068	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	1.2
HNB	1286	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	2.1
HNB	1882	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	-8.6
HNB	1890	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	-9.3
HNB	2284	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	2.1
HNB	2294	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	6.6
HNB	2456	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	9.3
HNB	2858	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	-10.3
HNB	2866	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	1.0
HNB	2884	2013-04-12 16:44:55.0	2013-04-12 16:44:55.0	3.3

Figure 8.41: Example of Graded CPD data after analysis by the CPD Data Analysis agent in the prototype system. The data shown was from real station data with simulated anomalies (highlighted as green).

ontology was used as the basis for a MAS developed in JADE. Description of the main functionalities of a JADE based MAS, along with examples of ontology concepts and predicates written in Java showed how the system can communicate to share knowledge and data and reason to perform analyses. An object relational mapping, based on Java classes representing the ontology was introduced to store information and data through the use of an Archive agent for managing access to a database. The CM analyses developed in the previous chapter were deployed as agent behaviours, each capable of responding to new data, requests from other agents or of autonomously conducting periodic analyses. The use of a well defined ontology allows for the addition of further analyses, as new trends and relevant analyses are identified in the data. A method of exposing the distributed monitoring system to external users and systems was implemented and the use of agents as interfaces to other CM systems described to enhance the functionality of other systems and provide access to their data. The prototype system was tested using different hardware platforms, with results indicating that low power computing devices such as the Raspberry Pi may be suited to some tasks within a distributed monitoring system where they do not introduce undesirable time constraints, and that database provision is a key issue which must be considered for further development. The system as developed in this chapter is a prototype system designed to demonstrate the feasibility of the approach and is therefore not currently deployed though real station data has been used on the prototype system. Some aspects of the system however, particularly the provision of access between BETA and IMAPS described in Section 8.7 is currently undergoing testing on the live monitoring system for use with new versions of BETA and IMAPS.

Chapter 9

Conclusions

9.1 Introduction

The application of intelligent systems techniques to CM of nuclear power stations is a relatively new development in the context of stations which are in some cases up to 60 years old. The continued development of such systems however has allowed engineers to make greater use of existing data to derive more knowledge of the state of plant equipment. This in turn has had an impact on safety and the justification for continued operation, maintenance and fault detection and potentially, through the use of prognostics, some estimate of the RUL of key components which determine the operating life of the plant.

9.2 Summary And Conclusions

This thesis has introduced the essential functions of nuclear fission reactors, including a discussion of the importance placed on safety in the nuclear domain, both in design and operation in Chapter 2. The specific issues associated with CM of the AGR were reviewed in Chapter 3, describing the multi-faceted approach to safety, including independent monitoring and inspection aspects of the safety case required to justify continued operation of the reactors. It was identified that the problem of CM of AGR cores is a data intensive and highly distributed problem, which is dependent on the correlation of anaomlies with various reactor parameters and operational states. It was proposed that with the application of modern CM techniques, more detailed supplemental information about the state of the cores could be provided between inspections.

A critical review of previous work in intelligent systems approaches to support nuclear CM in Chapter 4 highlighted common approaches for data and model driven monitoring for both online and offline applications. Limitations to previous work were identified, including isolated applications of nuclear CM across a single plant and issues of data and information management, which in particular for the AGR, emphasised the need for a distributed method of managing analyses and data.

The application of intelligent agent approaches to similar CM problems was introduced, describing the flexibility and autonomous intelligence which MAS can introduce. It was argued therefore that an agent based system could provide the distributed framework required for nuclear CM. On closer examination of many of the analyses performed for nuclear CM and in the AGR monitoring regime in particular, the use of DF techniques to combine multiple sources of data, to estimate coarsely measured or unknown parameters, or information to correlate events and anomalies was proposed in Chapter 6.

A generalised model was introduced in Chapter 6 for an agent-based system which could implement such analyses, taking advantage of the requirement for an agent ontology (for communication) to provide a common structure for DF analyses and data management. This model was described in a manner that allows it to be applicable to many NPS designs, not only the AGR, the monitoring requirements of which this work was prompted by. A generalised ontology was proposed which could be extended with more detail for particular applications, and a generalised classification of agents was suggested as a means of structuring a framework to perform distributed CM of a nuclear reactor.

Analyses were developed in Chapter 7 for the CM regime of the AGR for the analysis of control rods, thermal and neutronic power ratios and channel geometries based on formal algorithms, which in each case were designed to improve upon existing manual, subjective analyses performed visually by engineers. The application of DF techniques within these analyses was shown to provide more detailed results and correlate and contextualise anomalous data. These analyses were deployed in a prototype system, described in Chapter 8, based on the general model of distributed nuclear CM introduced previously, with detailed discussion of the development, deployment and testing of the prototype system.

Testing of the prototype system in Chapter 8 with real station data showed the practicability of an agent-based approach to nuclear CM to provide decision support and complement and enhance other monitoring systems. The analyses were performed more rapidly than a human engineer could achieve and the use of a CM framework, retained the data for further use. It was shown that low power, small footprint devices such as the Raspberry Pi were quite suitable for the execution of such CM analyses, however were not suited to intensive data management tasks (i.e. database use). These results suggest therefore that as CM seeks to be less invasive but provide flexible, distributed computational power, such devices may have a role in a distributed system of the type described in this thesis.

9.3 Deployed Components

The prototype system developed in this thesis remains largely a proof of concept system, however some components, including the agent-based links between IMAPS and BETA, and IMAPS analysis agent, are currently in use on the live AGR monitoring system. The outputs from the control rod monitoring analyses, described in Chapter 7 have been used on multiple occasions to supplement the analyses of the MAP engineers.

9.4 Further Work

There remain important questions associated with a more comprehensive deployment of such a system which, when addressed, may provide greater justification of the adoption of this approach, by providing more comprehensive support and

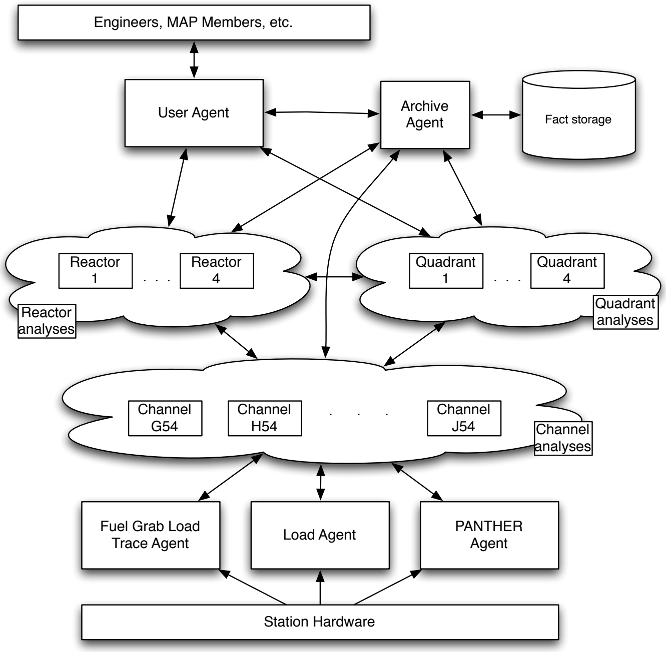


Figure 9.1: A proposed structure of different communities of agents, each monitoring and analysing different components, where Fuel Grab Load Trace, Load and PANTHER [AMEC2013] (a reactor modelling package) are examples of data inputs that these components may base their analyses on.

analysis capabilities to the engineer.

9.4.1 Component Agents

The possibility of creating agents for major components in the core (fuel channels, control channels, coolant pumps etc) that can be delegated the responsibility of managing their own data and analyses has been investigated [Wallace2011b]. Though this would involve the creation of around 300-400 agents per reactor core as in Figure 9.1, it has been shown [Vitaglione2002] that the JADE platform scales quite well to systems of several hundred agents. It is likely in the interests of performance however that multiple agent containers would be used to make use of distributed computational resources and incorporate redundancy into the system by allowing some containers to fail, should an agent within that container crash, while the rest of the distributed system continues to run.

These agents would be able to request appropriate analyses as data becomes available to them, potentially keeping snapshots of the most recent states of the component and tracking the evolution of various parameters. They might also have the ability to share this data with other components, and in certain circumstances, such as in the event of an anomalous result in an analysis, suggest to other component agents particular analyses that they might wish to perform. This rolling model of CM would allow for greater depth of analysis of parameters for which there are often secondary causes and effects and the availability of data is not synchronized.

9.4.2 Component Health Monitoring

Individual component health monitoring will become more important as the core ages and a more detailed view of the state of groups of components or the whole core is required. It is envisaged that this may present itself as an agent hierarchy with different agent societies' responsibility depending on the component grouping which might manifest itself as a layered architecture as shown in Figure 9.1.

This method of performing analyses at different levels of component grouping should also allow for competing theories regarding localized and global hypotheses for each reactor. These analyses could then be presented and assessed by the reactor agents to present a consolidated case, with a risk profile, enabling the engineer to make an informed judgment based on the outputs of the MAS.

9.4.3 BETA Analyses As Agents

Given that the content of a JADE agent behaviour is essentially a Java program, it is possible that any existing analysis, such as the BETA analysis could be wrapped in an agent, with only a small amount of work. The existence of the essential FGLT concepts in the ontology provides the framework for this and the BETA database structure has already been encoded in an agent which provides access to FGLT from IMAPS. Such an automated analyses could be designed to constantly generate and refine new benchmark datasets (against which FGLT data is compared) whenever new data is added to the system, without requiring the user to manage this task.

9.4.4 Inspection Data Management

Though CBMU data was discussed earlier in this thesis and indeed used as test data in Chapter 8, inspection data is currently not analysed as part of the MAP and only qualitative information from inspections is contained within IMAPS. Recent work on the channel geometry analysis and the detection of distortion in the graphite fuel channels has suggested that closer integration of the CBMU data with other data sets could provide potentially useful information to the engineers. An important caveat however is the required independence of the AGR safety case, which considers inspection and monitoring to be two distinct sources of safety related information. It should be possible however to ensure that inspection data is not used to bias any monitoring analysis before it is completed and is only available for comparison after an independent monitoring analysis has been completed.

9.4.5 Whole Core Monitoring

Many nuclear power stations feature a number of different CM systems for monitoring a variety of different reactor and non-reactor systems. Recent work [Wallace2013] has proposed that there may be utility in integrating the inputs and outputs of systems which monitor physically connected systems, potentially to derive prognostic information. An important aspect of any such work will be the consideration of how information which may be considered either factual or probabilistic is managed where conflicts arise or where there is two way communication between systems and feedback loops may emerge.

The investigation of how different conclusions, perhaps models of component state, are considered by an intelligent system, potentially in a similar manner to previous work on power transformers[Catterson2006], may help provide a broader perspective for decision support to engineers. Recent work has emphasised the importance of careful interpretation of such analyses, particularly in the case of conflicting conclusions [Osang2012].

9.4.6 User Trending

The increasing user-base of IMAPS creates the possibility that further development of CM tools for AGR core monitoring may be guided by current user behaviour. Identification of user behaviour or patterns of behaviour may allow for greater automation of the MAP process, minimising the time that the user is required to perform administrative tasks.

9.4.7 Bayesian Network Analysis Of Parameters

With an increasing volume of information within IMAPS, it may become possible to estimate, based on historical data, the likelihood of a particular anomaly occuring based on reactor operations or behaviour. Channel power discrepancies for example are known to be affected by recent refuellings and the use of a technique such as Bayesian Networks to incorporate historical data to attempt to predict the likely discrepancy may generate more robust bounding values than the currently defined refuelling limits, which are the same for every channel.

9.4.8 Semantic Analysis Of Documents

A substantial volume of qualitative information exists in a variety of documents associated with reactor operations. The operator's desk log, written in a templated document every day, for example contains information about the operating state of the reactor, issues and anomalies and on-going maintenance. An automated analysis of a large volume of these documents to detect key words and phrases may be able to extract information which is not otherwise recorded in plant data or in official documentation which is often written days, weeks or even months later.

9.4.9 Prognostics

Recent interest in prognostics for nuclear components to forecast remaining useful life and failure modes [Zio2010, Coble2009] is of particular interest from both a safety and economic perspective. The introduction in this thesis of more rigorous, numerical outputs from CM analyses may be of benefit to introducing prognostics techniques to AGRs. The evolution of graphite distortion is the most obvious example where prognostics might be applied, though the trending of control rod characteristics (including the correlations introduced in this thesis) for example, may also allow for the introduction of more efficient maintenance regimes if some predictability of failures or performance is possible.

9.5 Challenges

The particular importance of safety in a Nuclear Power Station means that deployed technologies are required to be well-proven and their impact well understood. This results in a relatively slow adoption of new technologies, so while a MAS may be in principle capable of performing some of the tasks of an engineer, it is likely that any initial deployment of an agent-based CM system will be in a supporting role and will only be used for verification of the existing engineer's analysis. It will also likely be held separately from the main IT infrastructure with several well defined data interfaces for the purposes of verifying data integrity and security.

9.5.1 Access And Data

The need to protect the operational plant and associated sensor and control systems from any interference by unauthorised parties has historically been met by complete segregation of operational and corporate networks. Whilst this ensures malware and control signals cannot pass from, for example, Internet e-mail to the plant, these systems generally reduce interoperability within the plant and result in increased difficulties when deploying new, network based technologies.

As mentioned earlier, the usefulness of a CM system is a function of the data available to it and though there is increasing buy-in from utilities to use intelligent systems approaches to support engineers, access to data, for a variety of safety and security reasons, remains an important aspect of any future nuclear CM research. Among several possible solutions to this is the creation of *information security zones* within the plant, using data diodes. Such technologies are not faultless [Pietre-Cambacedes2009] due to the inability of the receiver to provide feedback, such as acknowledgements, to the sender and this could result in missing data.

9.5.2 Database Constraints

A key issue encountered in the testing of the prototype system was the potential for delays introduced to the system when a single database agent is providing database service. Further research into the provision of database access by multiple agents may improve the performance and overall flexibility of MAS for CM.

9.5.3 Ontologies

While Chapter 6 introduced a general ontology for nuclear reactor condition monitoring and Chapter 8 expanded on this for the particular case of the AGR, the problem of a common upper ontology and the interaction between different ontologies is a large obstacle to wider used of agent-based technologies and to some extent, many other intelligent autonomous systems. FIPA currently has an experimental standard for ontology translation (as a service which an agent can offer), however managing the mapping between ontologies is extremely complex [Shvaiko2013]. Some attempts at a common upper ontology, such as SUMO [Niles2001] have been proposed, however there is not yet a generally accepted approach to how such an upper ontology should be constructed and what it should contain.

The power industry is comparatively advanced in this respect, which increasing use of the Common Information Model (CIM) in power system applications [Britton2005]. The problem of where a nuclear ontology sits in relation to other ontologies and how it interacts with them remains an important research problem, however the potential benefits, in terms of interoperability and re-use of analyses or other tools when such an ontology is established, merit continued work in this area.

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