IAEA TECDOC SERIES

IAEA-TECDOC-1920

Condition Monitoring and Incipient Failure Detection of Rotating Equipment in Research Reactors

Results of a Coordinated Research Project

IAEA
International Atomic Energy Agency

CONDITION MONITORING AND INCIPIENT FAILURE DETECTION OF ROTATING EQUIPMENT IN RESEARCH REACTORS

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D’IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ESWATINI
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GRENADA
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE’S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORTH MACEDONIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAINT LUCIA
SAINT VINCENT AND THE GRENADINES
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

IAEA-TECDOC-1920

CONDITION MONITORING AND INCIPIENT FAILURE DETECTION OF ROTATING EQUIPMENT IN RESEARCH REACTORS

RESULTS OF A COORDINATED RESEARCH PROJECT

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2020

COPYRIGHT NOTICE

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

For further information on this publication, please contact:

Research Reactor Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

Printed by the IAEA in Austria
June 2020

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Condition monitoring and incipient failure detection of rotating equipment in research reactors / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2020. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1920 | Includes bibliographical references.
Identifiers: IAEAL 20-01336 | ISBN 978–92–0–112020–5 (paperback : alk. paper) |
ISBN 978–92–0–112120–2 (pdf)
Subjects: LCSH: Nuclear reactors — Maintenance and repair. | Nuclear reactors — Safety measures. | Turbomachines.

FOREWORD

As research reactors continue to operate, there is an increasing need for enhanced asset management programmes that involve advanced predictive maintenance technologies for monitoring the condition and controlling the degradation of equipment, and to support ageing management. Such technologies are available for the predictive maintenance of motors, pumps, compressors and fans, as well as standby generators. These technologies are generally mature and have been applied in a wide variety of maintenance processes for equipment condition monitoring, reliability assessment, ageing management, operational life extension and improved availability and safety.

There is wide acceptance that the use of such maintenance methods can keep equipment in service for longer periods of time at lower costs, while maintaining the same or achieving higher levels of safety and availability. Nevertheless, while some research reactor operators have taken advantage of these technologies, there is wide scope for their adoption across a broad spectrum of research reactors. The use of advanced maintenance practices, in a cost effective way, can be helpful in improving the operational availability of research reactors and extending their lifetime.

On-line monitoring of rotating equipment is one of these technologies. In 2016, the IAEA launched the coordinated research project (CRP) entitled Condition Monitoring and Incipient Failure Detection of Rotating Equipment at Research Reactors. The overall objective was to provide methods for and guidance on monitoring the health of key rotating components to avoid lengthy and costly shutdowns while promoting safe and reliable operation. This publication is based on the output of the CRP, which ended in 2019. Case studies on implementing on-line monitoring of rotating equipment are included as an annex and are available on-line as a separate supplementary file.

The IAEA wishes to express its appreciation to the experts who contributed to the drafting and review of this publication. The IAEA is especially grateful to A. Ikonomopoulos (Greece) for his valuable support and guidance, and for chairing the research coordination and consultancy meetings, and to D. Jinchuk (Argentina) for his editorial support. The IAEA officer responsible for this publication was R.C. Sharma of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

This publication has been prepared from the original material as submitted by the contributors and has not been edited by the editorial staff of the IAEA. The views expressed remain the responsibility of the contributors and do not necessarily represent the views of the IAEA or its Member States.

Neither the IAEA nor its Member States assume any responsibility for consequences which may arise from the use of this publication. This publication does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any person.

The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The authors are responsible for having obtained the necessary permission for the IAEA to reproduce, translate or use material from sources already protected by copyrights.

The IAEA has no responsibility for the persistence or accuracy of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

Worldwide there are approximately 224 operational research reactors (RRs), 13 on temporary shutdown and 23 planned or under construction[1]. These reactor facilities vary widely in design, fuel type, power level and location. As research reactors continue to operate past their expected lifetime through licensing extensions, there is an increasing need for asset management programs that monitor equipment performance and assess how that performance may degrade due to ageing influences. To this end, monitoring technologies are available for motors, pumps, compressors and fans as well as stand by generators that provide information on a component's operating condition or its "health." The knowledge regarding the operating condition of a component at any point in time, allows a reactor operator to early identify equipment degradation as well as its progression, thereby allowing maintenance actions to be implemented at an optimum time and cost.

From the operating experience in the application of equipment condition monitoring to guide maintenance activities, it is widely accepted that the use of such technologies for this purpose will keep equipment in service for longer periods of time while preserving the same or higher levels of safety and availability. The uses of these condition based technologies are not unique to reactors but have been applied in a wide variety of processes demonstrating high effectiveness for equipment health monitoring, maintenance optimization, ageing management, operational life extension as well as improved availability and safety.

While a few research reactor operators have taken advantage of these technologies to improve their maintenance programs, there has yet to be a systematic adoption across the broad spectrum of research reactors. The expanded use of these technologies in rotating equipment of research reactors to extend system lifetime was the focal point of the Coordinated Research Project (CRP) T34003, "Condition Monitoring and Incipient Failure Detection of Rotating Equipment in Research Reactors". (2016-2019)

All research reactors have at least one mission for operation and, more likely, multiple missions related to research, testing and training. These missions have to be completed safely and efficiently. Further, most research reactors share the common characteristic of a long operating lifetime. Current data shows that there are 87 research reactors having an operating life of less than 40 year and 151 research reactors that exceed 40 years of operation.[2] As the facilities continue to age with little indications of significant replacement capability on the immediate horizon, a key aspect of mission completion in a safe and efficient manner is the maintenance of the reactor structures, systems and components (SSCs) in a way that reflects their importance to the reactor missions.

With the advancement of digital technology, substantial improvements in the tools of SSCs maintenance have occurred, enabling an understanding of equipment performance far beyond that available only a few decades ago. Several of these tools as well as the supporting technology have been endorsed by regulatory authorities, providing further value to their

---

[1] Retrieved on 20 February 2019 at https://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx

[2] As of 20 February 2019 at https://nucleus.iaea.org/RRDB/Content/Age/AgeLow.aspx

application to increase nuclear plant reliability. To that end, IAEA has taken steps to provide awareness of these advancements to the research reactor community through the CRP T34003.

1.2 OBJECTIVE

The objective of this publication is to provide methods and guidance for monitoring the health of rotating equipment's of RRs to avoid lengthy and costly shutdowns while promoting safe and reliable operation, as this is critical for improving the operational availability of RRs and extending their lifetime.

1.3 SCOPE

The publication includes fundamentals on condition monitoring of rotating equipment, standards and guidelines, implementation strategies, current status and recent developments as well as the experience gained from a variety of projects carried out in participating Member States.

The publication will be useful to RR designers, suppliers, operators, regulators and organizations planning to construct a new research reactor installation.

1.4 STRUCTURE

This publication is divided in two parts that is, a printed document containing three chapters, one appendix and online supplementary files.

Chapter 1 of the printed part provides introductory information on the subject while Chapter 2 presents the fundamentals on condition monitoring of rotating equipment for RRs. Chapter 3 presents general aspects of maintenance activities to be considered in RR design and operation. Appendix 1 is an indicative list of Industrial standards, guidelines and regulations for condition monitoring of rotating equipment from national and international organizations.

The second part of this publication, attached as a CD ROM, contains selected contributions made by Member States in the course of this CRP regarding their experiences in condition monitoring of rotating equipment in research reactors.

2 FUNDAMENTALS ON CONDITION MONITORING OF ROTATING EQUIPMENT

Plant maintenance programs in various fields were benefited by technological advances. Condition Based Maintenance (CBM) technologies, as they are generally known, have been developed to identify various equipment degradation modes for both instantaneous and long term, trend based, decisions on maintenance regarding repair actions. CBM technologies collect equipment performance information that is characteristic to the most likely equipment degradation mechanisms, e.g. bearing failures on rotating equipment. This data may be collected by direct and continuous connection between the sensor and the data acquisition device (on line monitoring or OLM) or by temporary connection between the sensor and the data acquisition device (off line monitoring). The collection method depends upon the data analysis methods necessary to accurately assess the presence of degradation. As an example, the dominant condition performance metrics of interest for instrumentation are calibration and time response. The condition analysis techniques, used to identify calibration degradations, require the instrument reading to be recorded at a high rate (on the order of 1 to 10 seconds between recorded readings) with many consecutive readings being taken in the sample time interval (on the order of 2 to 10 minutes per interval) and with multiple intervals collected over a long period of time. This large amount of data is necessary as the techniques for calibration analysis require a high level of data statistics to have robust results. In case of time response evaluation, test signals are applied to the instrument with the immediate instrument response information recorded and trended for evaluation of acceptable performance. On line monitoring is necessary to meet these data collection demands.

For nuclear power plants, it is recognized that [1]: “On line condition monitoring of plant equipment, systems and processes includes the detection and diagnosis of abnormalities via long term surveillance of process signals while the plant is in operation. The term ‘on line condition monitoring’ of nuclear power plants refers to the following:

- The equipment or system being monitored is in service active and available (on line)
- The plant is operating, including startup, normal steady state operation and shutdown transient
- Testing are done in situ in a non intrusive, passive way”.

A significant difference between on line and off line monitoring is that the latter is vulnerable to an equipment failure[3] mode that can initiate and propagate relatively rapidly. If this failure pertains to equipment important to the reactor safety and operation, the use of routine off line data collection methods may not be sufficient to implement an adequate maintenance program for that equipment. When it comes to rotating equipment monitoring, high sampling frequencies are desirable though not required. But in most rotating equipment practical applications, both on line and off line data collection methods are equally acceptable for use in a condition monitoring program.

---

[3] The IAEA Safety Glossary [2] defines failure as: “Loss of the ability of a structure, system or component to function within acceptance criteria.

Part of the development of an effective and strategic maintenance program is to acknowledge a program is needed. If a facility always performs corrective repairs following equipment failure – in the absence of a process to define such actions as part of an overall maintenance strategy – it can be argued such an approach to maintaining equipment function is not a cost effective (and safe) maintenance program. Some benefits associated with an effective equipment maintenance program are:

- Reduced equipment cost – maintenance performed prior to a failure may need fewer component replacements at a lower cost
- Reduced labor cost – replacing less components results, generally, in lower maintenance time and hence lower labor cost
- Minimized disruption – scheduled maintenance will minimize the disruption to the production process
- Enhanced safety – reduced possibility of major equipment failures
- Enhanced equipment performance – trouble free equipment outperforms that with incipient failure[4]
- Reduced workers' radiation dose – reduced time span for maintenance
- Improved reliability and availability – reduced unplanned plant outages

2.1 PREDECESSORS TO CONDITION BASED MAINTENANCE

The earliest maintenance strategy adopted in an industrial environment was that of unplanned maintenance prompted by an equipment breakdown. This type of maintenance, operating the equipment to the limits of its operating conditions, usually to assure maximum operating time, is frequently referred to as corrective maintenance[5] [3]. However, when a fault went undetected or was considered minor in nature, the resulting failures occasionally led to unacceptable or even catastrophic consequences for safety, equipment availability and repair costs.

With advances in equipment automation, the continual attention of human operators was reduced. These circumstances left the equipment more vulnerable to undetected degradations

---

[4] Incipient failure is defined [4] as: "The failure severity incipient describes an imperfection in the state or condition of an item, component, or system such that a degraded or catastrophic failure is imminent if corrective action is not taken."

[5] Other terms commonly used in the IAEA Safety Glossary [2] are "breakdown maintenance", "unplanned maintenance" and "run to failure."

progressing to failure and led to the adoption of periodic[6] or planned[7] maintenance where a equipment maintenance action would be conducted on a periodic (or time based) schedule such that, a very small likelihood of failure would exist between maintenance actions. These maintenance practices proved to be effective in preventing unanticipated equipment failures but were also proven cost inefficient for many times the repairs and replacements were found to be unnecessary. For this maintenance strategy to be efficient, the mean time to failure for each component needs to be well understood, usually through a detailed analysis of the failure characteristics and operating history of each component. Without this basis, a sole dependence on periodic or planned maintenance activities usually results in high usage of spare parts, as well as more maintenance resources being applied than necessary to adequately maintain the equipment. Also, the wide adoption of periodic or planned maintenance results in a high rate of direct human interface or "intrusive" contact with the equipment which leads to a measurable frequency of failures caused by human errors committed during the maintenance activity.

The recognition of the cost inefficiency associated with periodic maintenance, led to a third maintenance strategy based on the premise that if the equipment can be monitored for the inception and progression of faults and degradation, this information enables maintenance actions to be taken at a time that maximizes the service time of the equipment. This strategy is termed Condition Based Maintenance (CBM) and is an approach that has gained rapid popularity worldwide in the maintenance of various equipment types but, in particular, rotating equipment.

2.2 CONDITION BASED MAINTENANCE

It has been recognized that early detection of embryonic faults is crucial in avoiding unexpected catastrophic failures [5]. Consequently, CBM – based on collecting measurements regarding the condition of all equipment components during normal operation – has emerged as a key enhancement to an effective and efficient maintenance strategy. These measurements provide the opportunity for the prediction of a component's time to failure. This, in turn, accommodates maintenance planning for repair and re-establishing the system, structure, component (SSCs) health. Often, CBM is referred to as predictive maintenance[8] or prognostic and health management, where in [6] CBM is defined as: "a maintenance policy which does maintenance action before product failures happen, by assessing product condition including operating environments, and predicting the risk of product failures in a real time way, based on gathered product data."

Condition monitoring is the process of monitoring a component parameter (e.g., vibration, temperature) to identify a significant change indicative of a developing fault. Because this

---

[6] According to the IAEA Safety Glossary [2]: "Periodic maintenance is a form of preventive maintenance consisting of servicing, parts replacement, surveillance of testing at predetermined intervals of calendar time, operating time or number of cycles. It is also termed "time based maintenance".

[7] According to the IAEA Safety Glossary [2]: "Planned maintenance is a form of preventive maintenance consisting of refurbishment or replacement that is scheduled and performed prior to an unacceptable degradation of a structure, system or component."

[8] According to the IAEA Safety Glossary [2]: "Predictive maintenance is a form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose or trend a structure, system or component's condition indicators; results indicate current and future functional ability or the nature of and schedule of planned maintenance."

process is specifically targeted at the identification of emerging degradation, it is a major element in a comprehensive predictive maintenance strategy. The use of condition monitoring allows maintenance to be scheduled, or other actions to be taken to prevent failure and avoid its consequences. Condition monitoring has the unique benefit that conditions that would usually shorten normal lifetime can be addressed before they develop into a major failure. Condition monitoring techniques are normally used on rotating equipment such as pumps, fans, electric motors and internal combustion engines and other equipment, while periodic inspection employing non destructive testing techniques and fit for service evaluations are used for stationary plant equipment such as tanks, piping and heat exchangers. This report focuses on the application of a condition based maintenance philosophy to research reactors.

Condition monitoring tasks are accomplished using a variety of technologies that include ultrasound, vibration, lubricant, temperature and motor current signature analyses. To base maintenance on the perceived condition of operating equipment (in particular those instances where the equipment has requirements for extended operating times) necessitates that methods are available to determine their internal condition while they are in operation. In general, these technologies are manually applied to individual components using portable devices. The collected data is then analysed by staff for further actions as needed. These individual equipment test actions are accomplished using a routine schedule where the interval between tests is a function of the importance of the equipment and its condition at the time of the test. For example, a component where degradation is just beginning may prompt a higher test frequency than normal to better monitor the rate of degradation as it progresses.

Proper CBM implementation includes both diagnostics and prognostics of the condition of the equipment [7] where diagnostics concerns detection of a fault indicating a malfunction, isolation of the detected fault and identification of the nature and magnitude(size) of the fault. Prognostics provides a forecast of the remaining useful life of the equipment, its projected condition at some time in the future, or the probability of continued reliable operation [8]. In Figure 1, a schematic representation of this event sequence is presented.

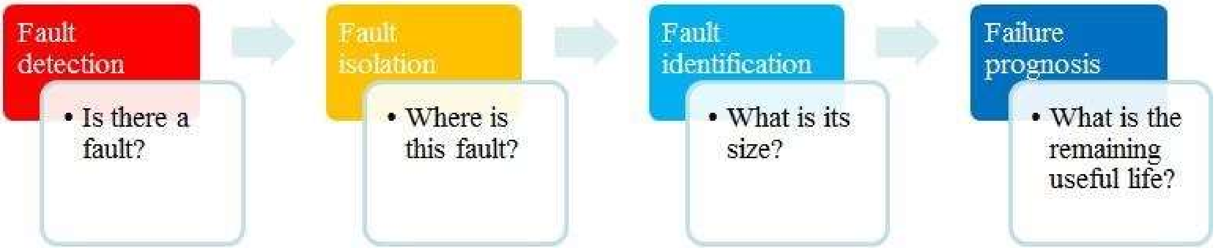


FIG 1. CBM implementation.

Condition based maintenance is implemented in three key phases [7] where:

- Data regarding system parameters is collected,
- The collected data is analyzed and

- Appropriate maintenance actions are determined

These phases are discussed in the following sections in the context of condition monitoring technologies available for application to rotating equipment in research reactors.

2.2.1 Methods of equipment performance data collection

Routine *in-situ* inspections have the advantage of the technician detecting early developing problems by direct observation before developing into faults.

Regarding the technologies for data collection they may be accomplished by a number of methods that, in general, fall under the categories of on-line and off-line monitoring.

In an on-line monitoring configuration, the sensors are attached to the equipment with direct connection to the data acquisition and analysis device supporting continuous monitoring of equipment performance during their operation.

Off-line monitoring configurations are mainly conducted manually by employing the temporary attachment of sensors to the rotating equipment with connections to hand held data acquisition units. The collection interval is of the order of minutes and upon completion of the data collection, the data is downloaded to a computer equipped with data analysis software[9]. Data collection and analysis require qualified technicians in using the equipment and interpreting the data. Off-line diagnosis is supported by a large volume of information and technical documentation originating from various industrial implementations of different types of rotating equipment. The off-line diagnosis is also supported with current standards that can be used to diagnose dormant (or hidden) failures.

Diagnosis systems may be setup as off-line or on-line. Both methods have advantages and disadvantages and their application in a particular maintenance plan depends upon the technology deployed and the surrounding environment of the monitored equipment. On-line monitoring supports failure anticipation based on the identification of detected anomalies. Apart from restrictions associated with accessing high radiation areas, off-line condition monitoring, especially of equipment in high radiation areas, may lack in detecting incipient failures resulting in unplanned outage of equipment.

Implementation of an on-line condition monitoring program supports the early detection of failures and examples of associated technologies were provided in Section 2.2. Successful equipment monitoring requires the introduction of anticipatory diagnosis methods for maintenance optimization and safety enhancement. To that end, the data collected by an on line condition monitoring system support accurate tracking of the failure progression symptoms and prediction of its evolution. [8]

2.3 COLLECTION OF EQUIPMENT PERFORMANCE DATA

The most basic equipment monitoring program utilizes information obtained during regularly scheduled inspections and walk down by plant technicians. Sound, smell and touch are useful tools in a condition monitoring program. A consistent and routine facility walk down have to

---

[9] The hand held data collection devices generally have limited means for the analysis of the collected data.

be considered a necessary component to a comprehensive equipment maintenance program and have to be regarded as a minimum requirement for any maintenance program that oversees rotating equipment. The key to an effective walk down is its consistency. A daily walk down helps the technicians to be accustomed to the sights, smells and sounds of normally functioning equipment and systems. A routine path of the walk down reinforces the expectation of normal operation that can be lost if the staff is left to determine the equipment of interest for the day.[9]

The use of a written check list of equipment to observe, the order in which they are to be observed, along with nominal acceptance criteria (e.g., satisfactory, normal, increased temperature, loud noise, etc.) to be logged for the equipment observed is highly effective in establishing the differences between normal and abnormal conditions. Targeted inspections may be implemented for specific equipment on a routine basis (monthly, quarterly, annually, etc.) to fulfil manufacturer requirements for equipment maintenance or to ensure ongoing degradation or some equipment condition of concern remains at the attention of the technicians.

The routine recording of equipment process and operating parameters such as pressures, flow rates, equipment rotation speed and run time, provide equipment condition information that can alert the technicians to abnormal conditions when trended and monitored. This collection of information may be accomplished during the facility walk down. If there is sufficient data, information and parameters to justify it, a walk down may be implemented employing electronic devices rather than paper forms.

The advantage of an “observations & measurements” process for condition monitoring is that it requires no special instrumentation for its implementation and can be accomplished by in house personnel. Its disadvantage is that for component abnormal conditions to be detected by simple observation, the degradation has likely progressed to a rather significant level. If the rotating equipment of the facility is not critical to its mission or safety, this straightforward monitoring process may be sufficient. For equipment that is considered critical, more advanced condition monitoring technologies need to be considered for identifying degradation phenomena at an earlier time in their progression.

The significant cost benefits realized by condition monitoring methods and techniques have led to the development of an extensive array of capabilities and technologies to be employed in programs monitoring equipment condition. The following discussion presents widely available condition monitoring methods in industrial sectors that include research reactor facilities. Typical rotating equipment found in RRs as well as in non nuclear installations include pumps, motors, engines and fans. Technologies commonly used for CBM of rotating equipment include vibration, ultrasound, temperature, lubricant analyses as well as motor current signature analysis (MCSA) [10]. The following brief introduction to the available technologies identifies their application to typical rotating equipment installed in research reactors.

2.3.1 Vibration analysis

As a result of varying sizes, shapes, materials and configurations, equipment and equipment components vibrate at various frequencies within a wide frequency spectrum. Vibration analysis is a widely accepted method used on rotating equipment e.g., gearboxes, motors, pumps and fans. This results from the technology advancement to the degree that a significant amount of information regarding the equipment condition, ongoing degradations and their root causes, as well as the remaining useful life can be determined with relatively high accuracy.

Implementation of a vibration monitoring process requires obtaining a baseline vibration "signature" as new or newly refurbished equipment is placed into service. Depending upon the equipment being used, this signature may include frequencies covering several decades of a frequency spectrum or consist of a single "impact" data point. Subsequent signatures are obtained at routine intervals and compared to the baseline signature to detect changes. Upon change appearance, its characteristics and development speed are characteristic of a progressing degradation type. As the degradation trend evolves, the frequency of obtaining the vibration signatures may be increased to estimate the remaining life of the equipment before its functional failure. There are different vibration data plots that serve to identify a equipment defect. For example, a typical plot used in reporting equipment problems is the trend plot of the overall vibration magnitude versus time of a motor drive end bearing (Figure 2) that shows an actual fault on the motor.

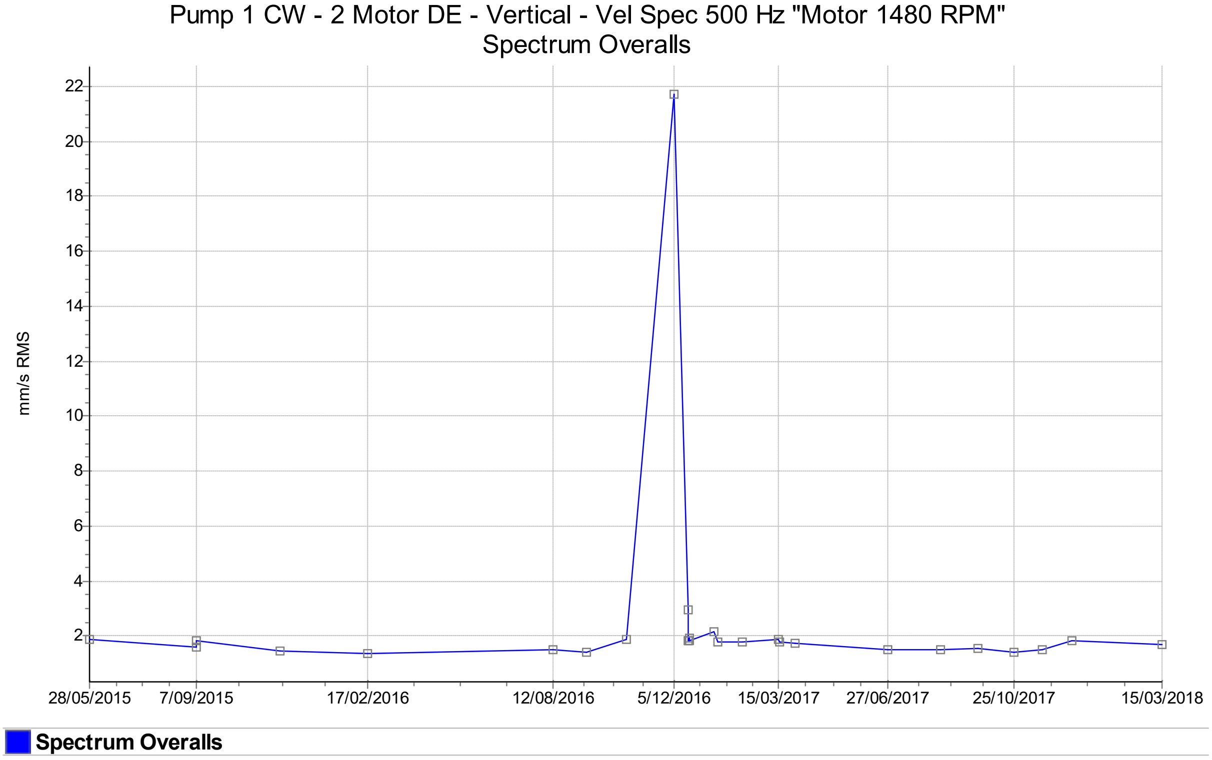


FIG 2. OPAL Chilled Water (CW) Pump Number 1 motor drive end vertical overall vibration trend

Further diagnostics may be achieved through other plot types, such as the waterfall plot (an example shown in Figure 3) that presents the history of a single position over time. Figure 3 consists of vibration spectrums collected over time that have been placed one behind the other to create a three dimensional plot showing the failure trending over time.

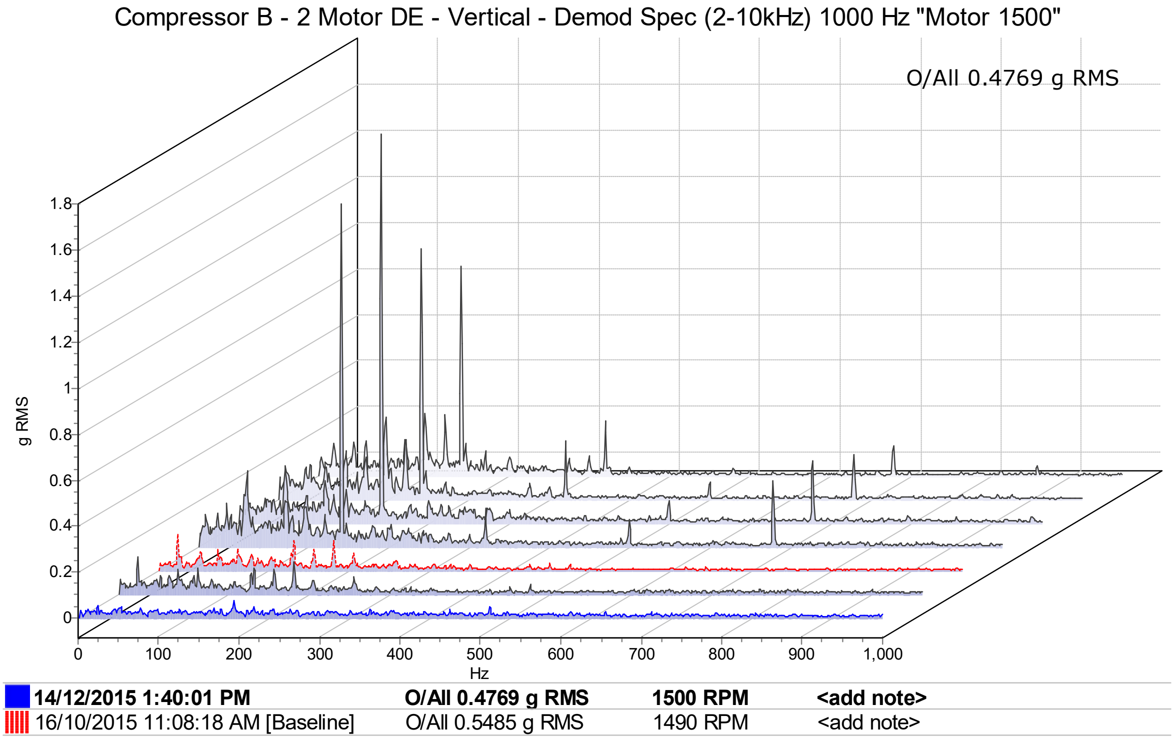


FIG 3. Vibration waterfall plot of a compressor motor drive end bearing with outer race frequency fault at OPAL .

It is important that equipment acceptance testing is performed on all new and newly rebuilt hardware. Testing have to be composed of:

- Vibration measurements on each bearing in the radial and axial directions
- Vibration measurements at hold down bolt locations
- Measurements of velocity and acceleration in rolling element bearing equipment and velocity and displacement in sleeve bearing equipment
- Measurements have to be taken with the unit under operational condition.

Vibration information may be analyzed in the time and frequency domains where in the former, vibration data consists of vibration wave amplitudes that vary in time (time waveform) and in the latter, vibration wave amplitudes are shown a series of sine and cosine waves having a specific magnitude and phase that vary with the vibration frequency. Both domains provide information for identifying issues related to equipment degradation. There are different vibration analysis techniques where the decision to use time or frequency domain methods depends upon the type of monitored equipment, monitored degradation mechanism and result accuracy. A brief introduction on these techniques in case of rotating equipment is given below.

Broadband vibration analysis – The most commonly used, frequency domain, technique for measuring the overall equipment vibration level in the 10 – 1000 Hz frequency range. It is widely accepted for diagnostic purposes and the term “vibration analysis” is usually referred to it. There are national and international standards (Appendix I) to guide establishing rotating equipment acceptance criteria for the results obtained.

Frequency analysis – It is utilized to detect non conformances from the baseline vibration frequency domain identifying abnormalities that include equipment imbalance or misalignment, mechanical looseness, wear, bearing faults, cavitation and excessive friction. Since the frequency data may span from zero to the maximum response range of the accelerometer in use, the data collection for analysis usually focuses on smaller spans depending on the type and the operating characteristics of rotating equipment being monitored, such as the equipment speed (e.g., revolutions per minute), the number of fan blades or pump impeller blades or the number of gears and gear teeth.

Amplitude demodulation – It has to be used in conjunction with time domain information to confirm genuine faults exist at roller bearing, gear and gear teeth. Amplitude demodulation may also identify friction caused by insufficient bearing lubrication when coupled with information from the high frequency acceleration at the frequency domain.

Time waveform analysis – It is frequently employed as standalone vibration analysis technique, but can also be used in conjunction with amplitude demodulation techniques to identify impacts or metal to metal contact generated by bearing, gear, or gear teeth faults where the severity of those impacts is an indicator of the severity of degradation.

Absolute Phase – Absolute phase measurements may be used for routine condition monitoring of rotating equipment and for diagnostic testing as they provide information regarding the relative motion between components. When used to identify potential motor shaft problems, a vibration sensor and a laser tachometer referencing a reflective mark on the equipment shaft measure the time interval between the mark (tachometer trigger) and the subsequent vibration waveform peak. This time interval is converted to a phase (in degrees), while the size of phase angle is indicative of equipment conditions (e.g., loose foundation, bent shaft, imbalance) that may lead to premature equipment failure.

Vibration techniques and methods have been the dominant technology for condition monitoring of rotating equipment as they are non intrusive and come with an extensive list of international standards (Appendix I) and industry guidelines that can be used to monitor a broad spectrum of equipment degradations. A typical example of a coupling fault discovered by vibration analysis appears in Figure 4, while Figure 5 shows a typical bearing fault identified applying the same technology at the OPAL research reactor in Australia The physical principles employed in this technology are not complex and are well documented in the literature. Various equipment manufacturers offer vibration sensing devices on their equipment as an installation option or design enhancement.

FIG 4. OPAL cooling pump A coupling failure as discovered by vibration analysis.

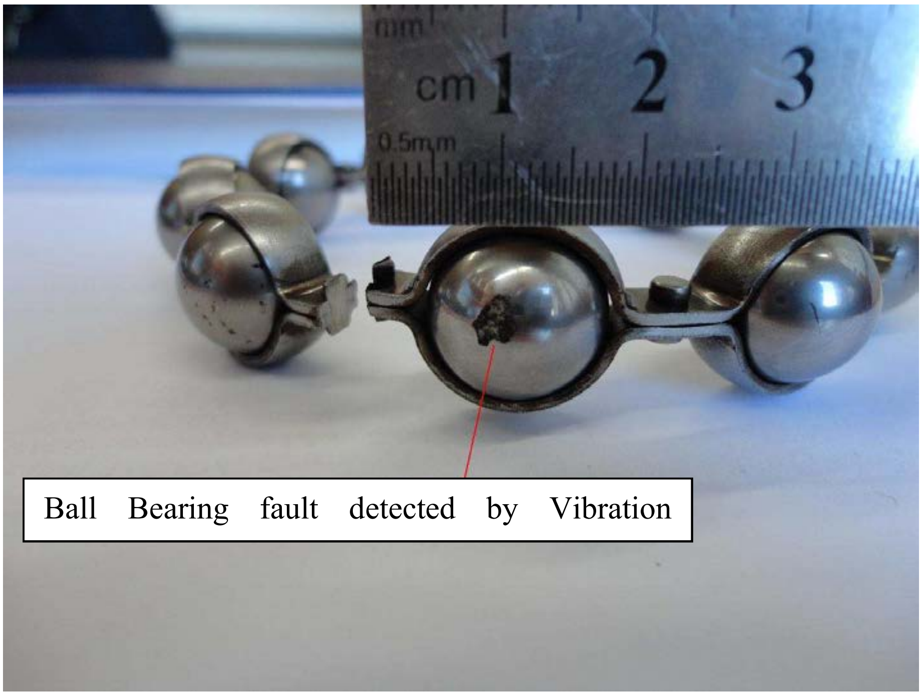


FIG 5. A typical bearing fault identified in a roller bearing at OPAL.

For nuclear facilities “Rotating equipment is monitored for vibration caused by shaft imbalance, misalignment, looseness, gear degradation, bearing faults and others. Vibration may be induced by causes that are internal or external to the equipment. The excess movement caused in the equipment components by these sources can be detected and quantified using accelerometers that are placed on the bearings, generally in three perpendicular directions. The measurements acquired from these detectors are processed in the time domain and frequency domain; the information is extracted over a period of time and, if necessary, the signatures are trended to identify incipient anomalies. Many critical rotating equipment are monitored by continuous or periodic vibration measurements." [11] ."The typical frequency band of piezoelectric accelerometers has a range of up to 20 kHz. The accelerometers have to be carefully mounted on bearing surfaces in three mutually perpendicular directions. Proximity or displacement probes are used when the bearings are of the sleeve (or journal) type, since the displacement of the shaft or the journal is of interest in this case. In some applications, it is advised to combine vibration analysis with motor electrical signatures, temperature, pressure, etc., and lubrication oil analysis, for a reliable detection and isolation of the problem. ... For completeness, the frequency band of signals must span about 50–100 times the main drive shaft rotational speed. For repeatability of measurements, barcode based data collection is recommended, to minimize the errors due to improper measurement locations and allocation of data to incorrect databases." [11]

A research reactor facility is offered many options to select an appropriate vibration monitoring program for its rotating equipment. If the selection is to implement a program using in house technicians, simple monitoring systems may be assembled using inexpensive sensors and commercially available software. Hand held devices with embedded sensors are the simplest commercial implementation that are capable of collecting vibration data and providing an overall vibration level reading after a few second of contact with the equipment. A higher expenditure will procure better data collection equipment and analysis software offering deeper insights into the component condition. On the other hand, the enhanced monitoring capability will require a commensurate increase in knowledge to ensure correct technology application and interpretation of its outcome. If resources are not available, or a large investment is not justified by the equipment criticality, contract services are available where the vibration data is collected by reactor technicians and shipped offsite for interpretation and reporting or the entire service (collection, analysis and reporting) may be contracted.

Typical applications of vibration analysis for rotating equipment include:

- Pumps
- Motors
- Engines
- Generators
- Turbines
- Fans
- Centrifuges
- Blowers

- Compressors
- Gearboxes

2.3.2 Ultrasound analysis

Ultrasound is similar to the dynamic pressure the human ear can hear as audible sound but ultrasound occurs at frequencies far above the audible range of humans. While most humans hear in the range from 20 Hz to 20 kHz, ultrasonic typically ranges from 20 kHz to 100 kHz. Similarly to vibration, low frequency sound energy travels long distances while high frequency ultrasound energy dissipates quite rapidly. Due to the quick dissipation of high frequency energy, the ultrasonic intensity will be the highest at the source making ultrasonic emission evaluation useful for locating the precise source of problems.

Ultrasound analysis is used in condition monitoring to identify degradation patterns very early in their progression. Properly used equipment is suitable for identifying degradation of rotating equipment bearings earlier than any of the other technologies discussed in Section 2.3. The instrumentation most frequently used is a hand held unit equipped with headphones and a display that shows the signal in decibels. The instruments may be digital or analogue, although digital instruments provide more analysis capability of the detected audio. While temperature analysis allows technicians to detect light that the eye cannot see, ultrasound allows them to detect sounds that the ear cannot hear.

In case of rotating equipment, ultrasound analysis may be used for the detection of bearing faults and friction from equipment roller bearings. An example of ultrasound analysis is shown in Figure 6 where bearing friction is identified and corrected at the OPAL Pump C. Ultrasound monitoring is also frequently used to assess when a bearing needs lubrication or when excessive lubricant has been applied.

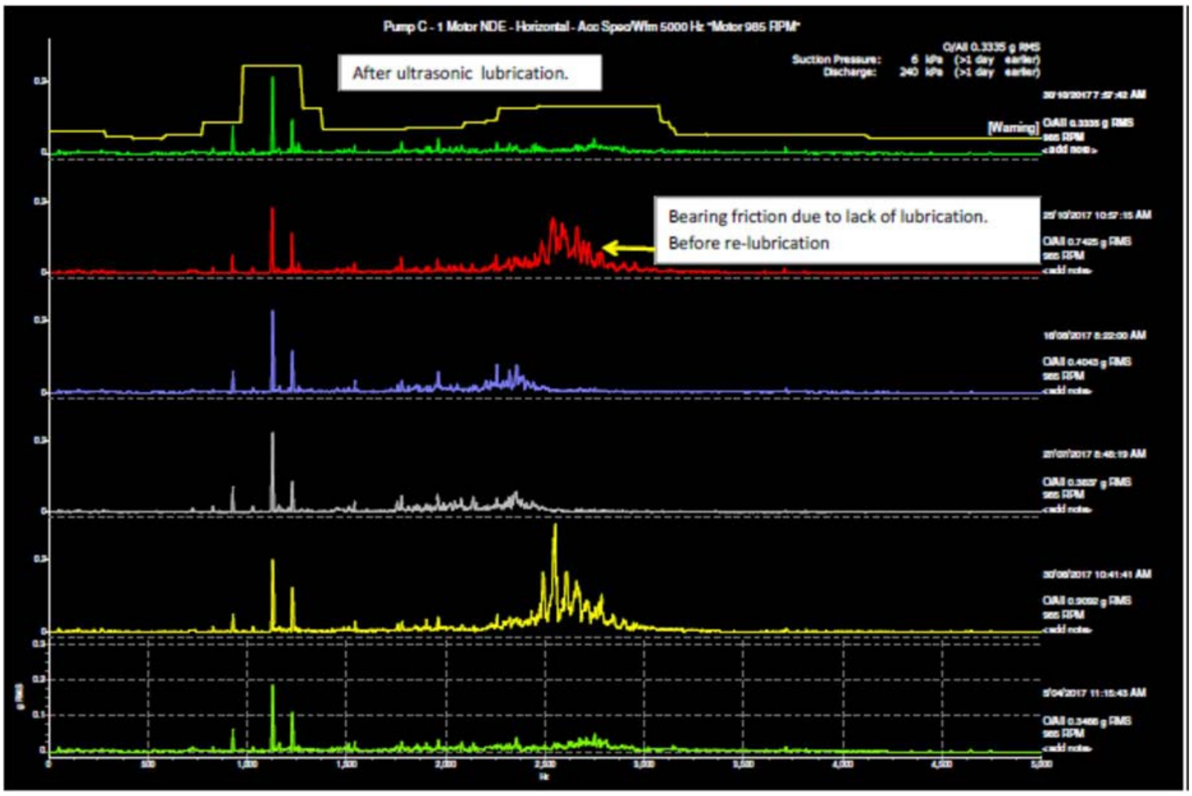


FIG 6. Routine vibration analysis over time exhibiting lack of lubrication and the outcome after bearing lubrication at OPAL Pump C.

Furthermore, in Ref. [1] it is indicated that “One particular and well developed application area for acoustic monitoring is rotating machinery. The principle of noise diagnostics is based on establishing a baseline signature for the normal condition as well as signatures for each of the different anomalous states. These signatures are collected into a library and used to classify later measurements as normal or as falling into one of the anomalous categories using some suitable expert system or algorithm... Automatic recognition is based, in most cases, on power spectra estimated using fast flux testing techniques; however, other techniques are also available, such as autoregressive analysis, wavelet decomposition, calculations of various moments estimated from the recorded noise, or a combination of these ... Acoustic monitoring based condition assessment seeks to identify changes in the acoustic response at the component’s eigenfrequencies, rotating frequency, and higher harmonic frequency. The responses at the rotating and higher harmonic frequencies usually appear in the measured spectrum as a narrow band, high amplitude peaks. Deviations of these peaks from their baseline location, shape or magnitude give a warning of changing conditions. These changes are well classified. For example, one of the classes consists of the shifting of standing wave frequencies due to temperature changes; another class for rotating machines is due to changes in the rotation speed. In the latter case, all higher harmonics will also be shifted. There is a considerable amount of experience regarding bearing failures, depending on the bearing type, lubrication, material of the axes, etc. This knowledge is built into typical expert systems ... The use of the eigenfrequencies for monitoring requires structural calculation (by finite element methods) of the vibration eigenmodes that define the mechanical behaviour of the system.” [1]

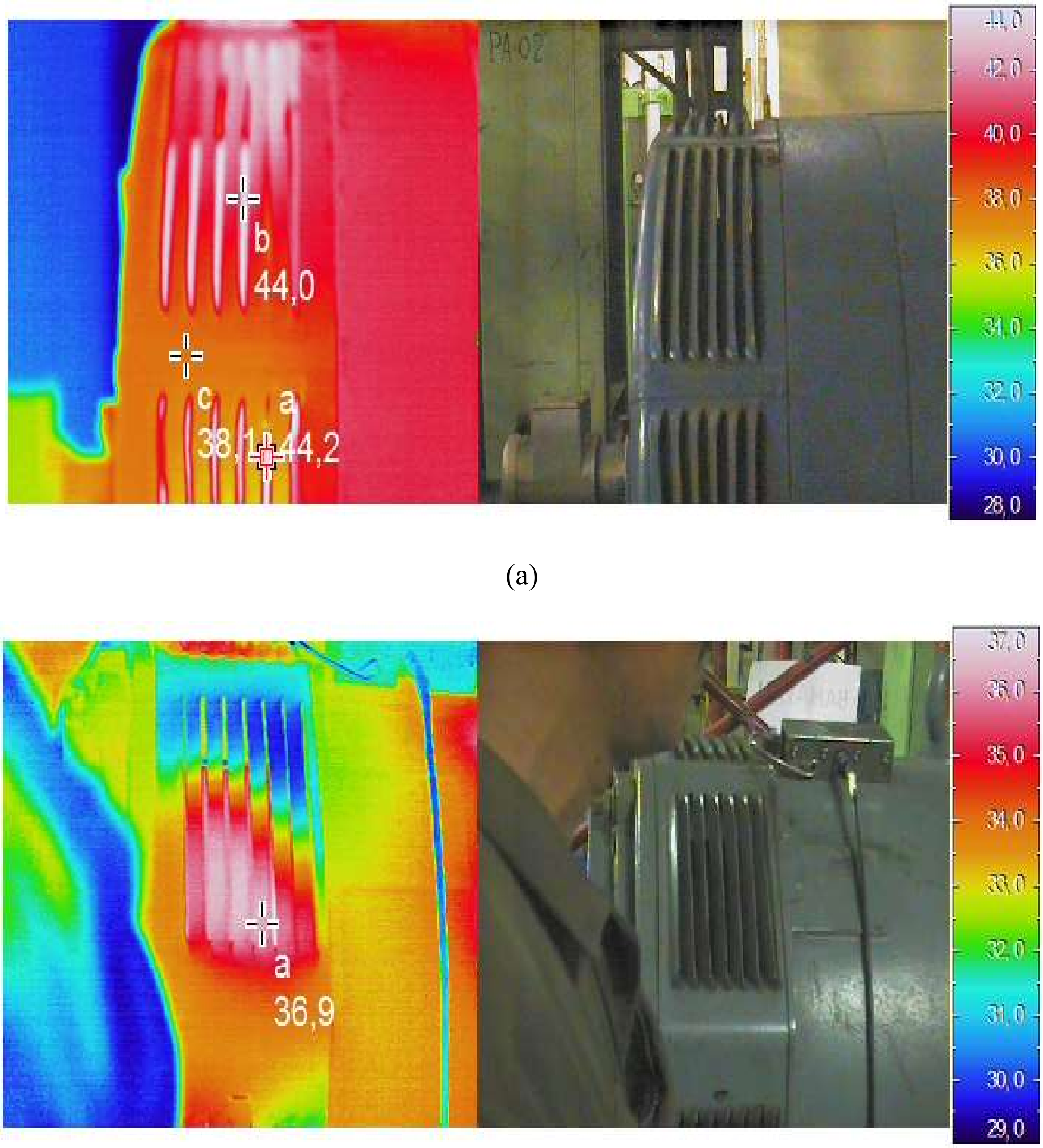
In ultrasonic analysis the sound can be detected by instrumentation at a distance not requiring direct contact with the equipment thus, minimizing physical access in hazardous areas. While the technology implementation does not require significant skills, its adoption requires a level of training and expertise that have to be considered when evaluating the need for this technology against the importance of the plant equipment.

2.3.3 Temperature analysis

Temperature analysis spans a spectrum of capability and information precision. At one end of this spectrum is a judgment of "warmer than usual" based on the touch of a technician during a routine walk down. At the other end of the spectrum is a detailed thermal assessment using infrared thermal imaging technology. The availability of inexpensive tools enables accurate temperature detection, enabling a trend of temperature increase to be detected more quickly than by touching. Commercially available instruments such as hand held contact probe thermometers enable accurate temperatures to be quickly obtained for recording and trending. For equipment where the use of a contact probe device is problematic due to access or hazardous conditions (i.e., radiation zones), hand held, "point and shoot" infrared beam thermometers are available to obtain relatively accurate temperature information from a distance. Small, inexpensive digital contact sensors are available for securing to a surface to provide a continuous readout of monitored temperature.

Temperature analysis allows to locate and monitor, in real time, both maintenance and operation problems. In cases where equipment has been identified as critical to the facility mission or safety and temperature is considered as an important degradation indicator, the use of infrared imaging may be warranted. Infrared imaging is the measurement of the invisible thermal radiation emitted from the surface of an object by a "camera" device that converts this invisible radiation to a visible image. The colours on the visible image are direct indicators of the amount of emitted infrared radiation, thereby, heat.

An advantage of this technology is its high accuracy since the image provides a temperature profile of the entire scanned view instead of the temperature at a single point as with contact or infrared beam thermometers. This allows a temperature trend "map" to be developed and compared over time rather than a series of individual data points. This technology has also proven to be highly useful for a large spectrum of equipment and applications, not just rotating equipment. The application of this technology requires personnel training for the proper use of the devices to obtain accurate results. Figures 7 (a) and (b) are thermal images from an operating cooling pump in the RSG GAS facility.



(a)

(b)

FIG 7. (a) An RSG GAS pump thermal image before repair (heat due to bearing problem effects higher than 44^o C) and (b) an image after the repair where all bearings were replaced.

Typical applications of temperature monitoring for rotating equipment include:

- Roller and sleeve bearings
- Electric motors (bearings and windings)
- Pumps
- Fans

- Blowers
- Compressors
- Reciprocating equipment
- Gearboxes
- Turbines

2.3.4 Lubricant analysis

Lubricant analysis is a condition monitoring technology where samples of rotating equipment lubricating oil and/or grease are collected and subjected to laboratory analysis to identify any contamination that may be present. The laboratory analysis includes tests to determine the concentration of wear metal particles, properties of any contaminants and additives, the number and size distribution of contaminant particles as well as physical tests to determine degradation of the lubricant such as viscosity, water contamination and antioxidant content. A key element in lubricant analysis is the ISO 4406[10] cleanliness code [6. Appendix] that is internationally recognized.

This technology is quite mature and provides accurate information regarding equipment condition and ongoing degradation mechanisms. Because the equipment necessary to perform "in house" sample analysis is relatively expensive and mandates application in accordance with industry testing standards in a qualified testing environment, most equipment maintenance programs that utilize this technology ship their samples to a qualified laboratory for analysis. Consequently, access to qualified laboratories is readily available, making this technology available to maintenance programs at a relatively low cost. However, the value of using this technology is best achieved for rotating equipment having large volumes of oil or grease.

While not required, it is highly recommended that some minimal level of training be obtained to understand the results provided and apply them to equipment in an actionable manner. Furthermore, it is important for the facility to implement a program for the procurement of quality lubricants and their controlled storage to prevent the introduction of degradation contaminants at the time of equipment maintenance.

Typical applications of oil monitoring for rotating equipment

- Gearbox
- Oil lubricated bearings
- Compressors

---

[10] https://www.iso.org/standard/72618.html

- Blowers
- Diesel engines
- Turbines

2.3.5 Motor current signature analysis

With regard to MCSA, Ref. [1] lists that: "As the mechanical load on an induction motor varies, the current drawn by the motor changes, increasing with increasing load. Thus, a motor acts as a transducer, and the variations in the mechanical loads are reflected in the variations of motor current. Motor current can be measured non intrusively using a clamp on current probe. The technology of drawing diagnostic information from the analysis of such measurements is called motor current signature analysis (MCSA). MCSA systems can also include a signal conditioning device, which makes a sensitive and selective analysis of the current variations possible. The output of this device is processed further using standard signal processing techniques. Various anomalies can be seen as changes in the pattern of the motor current…"

MCSA complements vibration analysis quantifying the severity of electrical faults, static eccentricity and dynamic eccentricity in the motor during operating circumstances. These data are acquired using a clamp on current probe, special filters, a digital signal analyzer and (normally) an expert system to evaluate the results. Data is acquired with the unit under normal operating conditions (at least 70% load) and the resulting analysis is capable of identifying anomalies such as:

- Phase unbalance
- Bad rotor bars
- Faulty collector rings
- Dynamic eccentricity
- Static eccentricity

The rotor bar/end ring faults are easily quantified through this technique whereas vibration analysis is a more qualitative assessment of these types of problems. MCSA identifies eccentricity problems associated with non concentric rotor and stator, soft/sprung foot conditions and bowed rotor conditions. As noted earlier, MCSA uses a clamp on current probe around a primary or secondary circuit to evaluate the condition of the motor. By looking at the amperage at line frequency (60 Hz in the US, 50 Hz in Europe, Australia and others) about the amplitude at the so called slip frequency side band frequencies, MCSA can be used to determine if a problem exists in the motor rotor.

The MCSA advantages include quantifiable evidence of rotor damage in the motor, the ability to identify eccentricity problems that may or may not be evident in the vibration spectra. The group of MCSA disadvantages lists expensive hardware and software and noisy electrical signals sometimes make valid data hard to obtain.

2.4 DATA ANALYSIS

There is a wealth of data analysis techniques that are regularly employed to analyse time series recorded from various equipment. Three categories of data analysis are listed in [12]:

- Time domain analysis with tools such as the mean, peak, peak to peak interval, standard deviation, crest factor, root mean square, skewness, kurtosis and approaches such as the time synchronous average as well as the autoregressive and autoregressive moving average models;
- Frequency domain analysis by means of tools such as fast Fourier transform and the Hilbert transform;
- Time frequency analysis for non stationary signals employing popular tools such as the short time Fourier transform, the Wigner Ville distribution and the wavelet transform.

2.4.1 Diagnostics

An extended review on diagnostics appears in [12] where the fault diagnosis methods are broadly categorized, based on the process knowledge that is required a priori, in:

1. Model based methods;
2. Data driven methods.

The outlined categorization of fault diagnosis methods is listed below, while it has to be taken into account that "…There might be some overlap between the model based and data driven approaches; this is just one classification based on whether or not the knowledge about process characteristics are required." [12]

In model based methods, the model is developed based on the physical laws governing the system. The model based fault diagnosis approaches could be grouped as quantitative and qualitative model based methods. In data driven methods the models are built employing historical operating data. The data driven fault diagnosis approaches may be grouped as qualitative (e.g., expert systems, qualitative trend analysis) and quantitative artificial neural networks (ANNs), statistical approaches).

With regard to artificial neural networks and fuzzy logic techniques Ref. [11] indicates that: "Over the past decade, two significant advancements in this area have occurred. One is the introduction of artificial intelligence (AI) into the monitoring and diagnostic (M&D) system for automation of the traditional human functions … Another example is the use of the advanced techniques for data processing, including neural networks and fuzzy logic techniques." Furthermore, Ref. [1] indicates that:"…a variety of equipment and process modelling techniques have been adapted to provide a baseline for detection of equipment and process anomalies. Both empirical and physical modelling techniques are used in this endeavour. The physical modelling techniques are mostly based on first principle equations, while the empirical modelling techniques are mostly data driven and involve such tools as neural networks, pattern recognition, and fuzzy logic for data classification and pre processing."

It has to be noted that both rule based and fuzzy rule based expert systems have been applied in diagnostics though there are limitations on the number of rules that may be used [13]. A mathematical construction such as fuzzy set theory [14] is used for representing uncertain, vague or imprecise information where fuzzy sets are employed for depicting linguistic variables whose values are defined in linguistic terms. On the other hand, artificial neural networks have been proven capable to generalize from earlier paradigms [15] and have found a broad spectrum of applications in science and engineering that include implementations in the area of diagnostics. A number of algorithms have been developed under the umbrella of ANNs referring, in general, to biologically inspired computational schemes capable of adapting their behaviour responding to their environment. Moreover, there is a collection of computational tools known as evolutionary computations that have found applications in diagnostics. They are related with the notion of evolution as defined in biological processes. Genetic algorithms, evolutionary algorithms and swarm intelligence are, among others, computational paradigms that adhere to the evolution concept [16].

2.4.2 Prognostics

As defined in Ref.[11] : "Prognostics is the prediction of a remaining useful, safe or service life, based on an analysis of system or material condition, stressors, and degradation phenomena. Moving from diagnostics, based on observed data that describe the current state of material, to prediction of remaining life and technologies for structural health monitoring (SHM)/management, based on predicted future behaviour, requires development of new approaches…" and identifies various types of prognostic approaches – in a schematic form – in Figure 8.

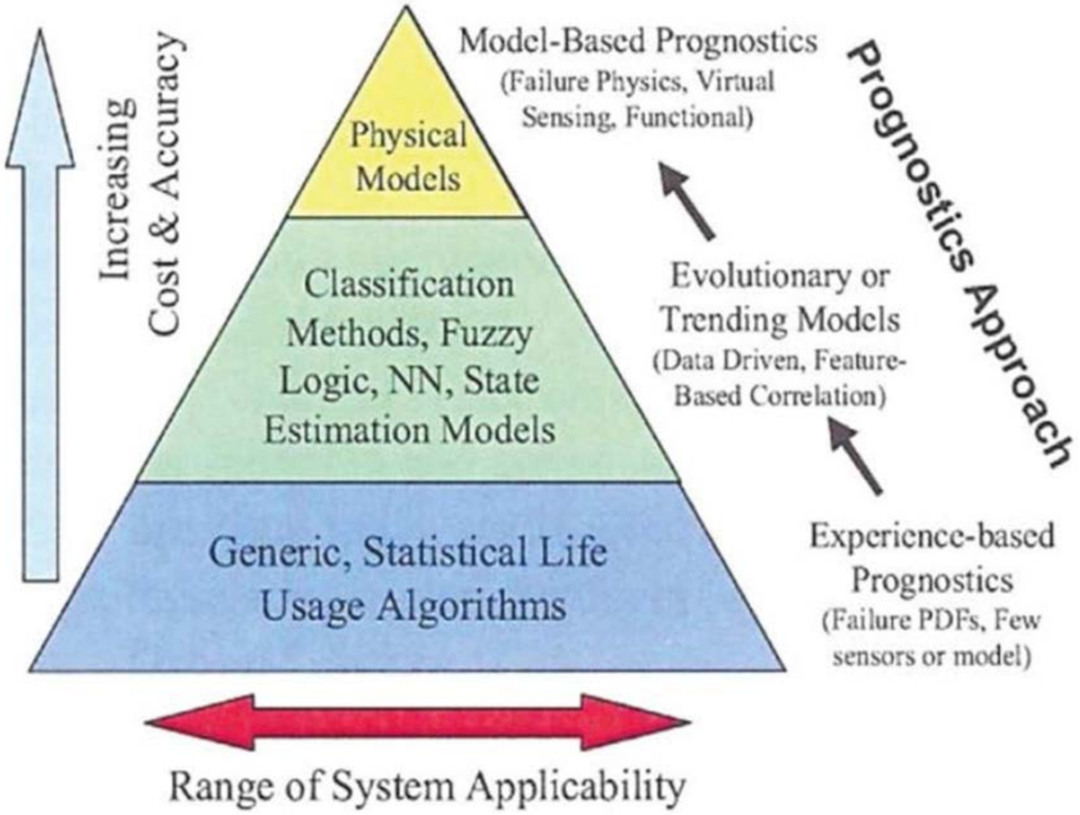


FIG 8. Prognostic approaches. [Reproduced from Ref. 11]

Two prediction types in equipment prognostics appear in the literature [7]:

1. The time until a failure occurs (or, one or more faults) taking into consideration the current equipment condition and past operation profile. This is usually called remaining useful life (or remaining service life, residual life, remnant life);
2. The probability that an equipment operates without a fault until a specific time in the future.

In accordance with a published review [8] the methods for predicting rotating equipment failures may be categorized into three major categories:

1. Traditional reliability approaches that use event data;
2. Prognostics approaches that use condition monitoring data;
3. Integrated approaches that use both event and condition monitoring data.

Traditional reliability models employ the distribution of event records of a population of identical units, while the majority of the prognostics models may be grouped into two categories:

1. Physics based prognostics models

2. Data based prognostics models

The physics based prognostic approach develops mathematical models describing the system physics and failure modes while the data based prognostic approach develops models employing condition monitoring data and provide predictions based on this data. Furthermore, there are integrated approaches that take under consideration both reliability and condition monitoring data. A comprehensive list on these methods may be found in [8].

3 GENERAL CONSIDERATION OF MAINTENANCE ACTIVITIES AT RESEARCH REACTORS

3.1 EQUIPMENT IMPORTANCE APPROACH TO MAINTENANCE

The focus of an equipment importance (EI) based maintenance process for a research reactor facility is to ensure the missions of the facility are met through the achievement of pre defined equipment outcomes that reflect an improvement in equipment performance. These improved equipment outcomes can be physical (e.g., reduction of unexpected equipment failures) or temporal (e.g., extending equipment service time) in nature, but are ultimately concentrated on improving the reliability of the equipment. Processes are implemented to monitor the performance, or condition, of the equipment to determine if these defined outcomes are being met.

EI based principles and objectives have been the initiators of equipment condition monitoring applications for many equipment types for a long time period. For example, the monitoring of engine oil pressure and water temperature has been available in automobiles for years. These signals alert the driver that conditions may exist that could result in significant damage to the engine. With the advent of the internet, cellular communication and wireless technology the opportunities for monitoring equipment conditions – in a cost effective manner – have significantly expanded. Automobile computers monitor performance characteristics (oxygen consumption, tire pressure, air bag status) and provide this information via satellite to a central station with reports provided to the owner's electronic mail on demand. The monitoring of food and beverage vending equipment inventory for data transmittal to a local handheld device or a central monitoring station allows replenishment as needed. Error codes from these same equipment may notify the owner of equipment problems, allowing repair personnel to be dispatched only as necessary; routine maintenance may not be required.

These are a few examples of how technology has mainstreamed the application of monitoring equipment and its "health" to prevent or, at least, anticipate conditions having adverse consequences. This use of technology has been fully embraced worldwide within a wealth of industrial sectors that include the nuclear industry. There are several aspects that are to be considered in the implementation of an effective EI based maintenance process:

- Aspect 1: Classification of equipment leading to a determination of the type and level of maintenance necessary to keep the facility in conditions of normal operation;
- Aspect 2: Identification of important equipment metrics to be monitored for degradation conditions having adverse consequences in the operation;
- Aspect 3: Determination of the needed maintenance based on the results of the monitored metrics;
- Aspect 4: Performance of the needed maintenance actions in a timely manner;

- Aspect 5: Assessment of the effectiveness of the maintenance plan and actions by continued metrics monitoring.

Taken as a whole, it is intuitive how these aspects are integrated and how their application can provide improvements in facility availability and safety. However, regardless of the simplicity of this EI maintenance concept, there are new expenditures associated with implementing modern condition monitoring technologies at a research reactor facility. The question to be answered is if those new expenditures provide a cost effective investment return by improved facility availability and safety.

In the following sections guidance will be provided on how to determine the need for applying condition monitoring technologies at a facility (Aspect 1 above) and, if applicable, direction on the particular technologies and resources that would provide cost effective results (Aspects 2, 3, 4, and 5). A general classification of research reactor equipment important for reliability and safety can be found in Ref [4].

3.1.1 Definition of the facility missions

Every research reactor facility will have a mission or even several missions to accomplish during its operation. Depending on the facility, the mission(s) may span from research purposes, to reactor operation and training and education, to radioisotope production, to list a few. EI based approaches to maintenance begin with the identification of reactor missions and the key equipment for these missions. This, in return, provides the information leading to maintenance strategies that are effective and efficient in their costs and results. For example, where equipment failures can result in significant adverse effects on a vital reactor mission, a very aggressive program of equipment monitoring and maintenance related to that mission may be adopted. On the other hand, for equipment having little impacts on vital missions, the maintenance strategy may be to repair when found failed. An indicator of industry excellence is a maintenance strategy where all equipment (not just the important equipment) has been evaluated and a strategy assigned.

Missions are defined in a broad sense, e.g., operate reactor safely, and have to be decomposed to specific mission statements. This allows the definition of effective and efficient maintenance strategies to be much more straightforward. The use of specific performance metrics can be very effective in the specification of clear mission statements, such as:

1. *The reactor will have a 90% annual availability*: This mission statement utilizes a very specific performance metric and states the reactor will be available for use (in operation or in operational standby) 90% of the time during a given calendar year. This provides for 10% planned reactor downtime for repairs and maintenance activities.
2. *The reactor will have a startup predictability of 99%:* This mission performance metric states 99% of the time the reactor will start on the date and time scheduled. This performance metric gains importance as the commitments for reactor operating time are scheduled farther into the future.
3. *The reactor will not have equipment failures during operation:* This mission statement has an implied performance metric, i.e., “100% reliable operation,”

though this performance metric may be difficult to fully implement or may not be needed in all circumstances. More practical mission statements may be:

   a. *The reactor will have no protection reactor shutdowns during operation for training purposes*: to address the importance of equipment reliability as well as human error; or

   b. *The reactor will have no unscheduled shutdowns during capsule irradiations*: to address the importance of a delivered product to a customer.

4. *The reactor will pose no safety hazard to staff:* This mission is an absolute for any operating reactor facility. However, the system aspects of this mission can be addressed with more specifically defined statements:

   a. *The reactor will not have any unnoticed criticality episode*: is a specific statement of an unacceptable reactor condition, particularly for personnel safety considerations

   b. *Exposure to radiation, industrial, and chemical hazards needs to be prevented to the extent practical:* acknowledges there may be hazards to personnel other than just radiation that have to be identified and addressed in a reasonable manner.

A specific mission definition can be an advantage to setting maintenance in an optimized resource perspective. The mission selection for identifying key reactor functions have to address both production and safety missions. Production missions, in addition to normal or routine evolutions, may include special or infrequent operations. This additional attention is because systems and system functions may not be deemed as key, or critical, during normal operation but for a new or infrequent evolution that system or system function may gain importance. Consequently, the review of a reactor's missions have always to be future oriented and undergo continuous assessment for change.

Continuous missions – Refer to tasks a nuclear reactor facility performs continuously and the requirements to achieve them. For instance, in some reactors the main purpose could be:

- Operate under the ALARA concept (personal safety);
- Operate safely from a nuclear point of view;
- Radioisotope production with the requirement to start up on time without any trip later
- Training and education
- Scientific research (basic and applied): Neutron activation analysis, prompt gamma neutron activation analysis, boron neutron capture therapy, neutron scattering, powder diffraction, neutron radiography
- Accomplish operation time at required power.

Changing missions – Refer to a special requirement which is not part of the normal schedule. For instance:

- Special irradiations requirements;
- Different neutron flux;
- Operate at a different power.

3.1.2 Determination of mission importance using an EI approach

Upon determination of the facility missions, the next step of an EI based maintenance process is to categorize the identified missions by their importance to the overall reactor purpose. If care has been taken in the definition of a comprehensive and clear set of mission statements, this "ordering" of mission importance will be readily accomplished. This mission ordering is important as maintenance strategies will vary depending on mission importance. For example, if equipment failures result in significant adverse effects on a key reactor mission (e.g., loss of experiment data) a very aggressive maintenance program may be adopted. On the other hand, for missions having little importance the proper maintenance strategy may be to repair when found failed.

The adverse consequences of mission failure can vary greatly depending on many factors, including the reactor type, purpose, experimental capability and the owner requirements. Regardless of the type and number of missions of any specific research reactor, the consequences of mission failure can impact the following four general risk groups:

- Customers/Users (C/U);
- Installation Staff (Staff);
- Public, including reputation, or Environment;
- Regulatory/Capital costs (R/CAP).

It is worth noticing that for any reactor facility, missions related to nuclear safety always remain of paramount importance and maintenance programs addressing these missions have always to be evaluated for appropriate implementation.

Table I is a paradigm of compiling facility missions along with the necessary information needed to assign an importance ranking to each mission. Each entry represents:

- *Mission*[11]*:* A single mission description is to be provided with all needed performance metrics or deliverables of the mission.

---

[11] If more than a single mission exists for a reactor, the robustness of this process is enhanced if Table I consists of multiple, uniquely defined, mission statements rather than a single, generally inclusive, mission statement. This permits a clearer assessment of risks and importance as one component may have impacts across several missions while another only impacts a single mission.

- *Description of Mission Failure:* This is a description of how mission failure is defined and identified.
- *Affected Risk Pool for Mission Failure:* The general risk groups affected by mission failure are identified where more than one group may be identified for failure of a given mission.
- *Mission Rank Estimate:* While detailed and quantitative ranking systems can be developed for ranking individual missions, this resource expenditure is not necessary to achieve the objectives of the described process. A subjective judgment of High, Medium or Low mission importance could suffice.

TABLE I. COMPILATION OF MISSIONS AND RANKED IMPORTANCE

Mission	Description of Mission Failure	Affected Risk Pool for Mission Failure	Mission Rank Estimate
Production of medical isotopes	Unplanned shutdowns result in commitments for medical isotopes not being met	C/U	Short lived isotopes – High Long lived isotopes – Medium
Scientific research	Unplanned shutdowns result in loss of data or experiment	C/U	Loss of experiment – High Loss of data – Medium
Scientific research	Loss or failure of experiment instrumentation	C/U	High
Control of hazardous material	Hazardous material outside of design boundaries	Public	Radiological – High Non radiological – Medium
Reactor start-up as scheduled	Systems required for start-up and operation out of service at schedule start-up	C/U	High

TABLE I. COMPILATION OF MISSIONS AND RANKED IMPORTANCE

Mission	Description of Mission Failure	Affected Risk Pool for Mission Failure	Mission Rank Estimate
Control of capital funds	Unbudgeted failures of large equipment	R/CAP	High
Minimal dose to plant staff	Leakage of contaminated fluid Equipment failure in high rad areas	Staff	Spills – Medium High rad areas – High
Training	Unplanned automatic or administrative shutdown	C/U Staff R/CAP	External customer training – Medium Internal refresher training – Low Internal required training High

3.1.3 Identification of vulnerabilities to mission completion

Once the facility missions are ordered or “graded” by importance, the next task is to identify what could happen that may jeopardize those missions. It is important to view missions and associated threats with a very broad perspective. Threats may exist that require maintenance attention while threats to both personnel and equipment have to be addressed as well as threats to the public. The most obvious situation of a threat to mission loss would be the failure of a component or system whose function is necessary to that mission. However, there may be other threats present that are not reactor related but could nonetheless create an impact on the reactor, such as steam, water hammer or flooding from potable water. Less direct threats may also need consideration such as a degraded or failed component may not have a large impact on an operational mission, but its repair would challenge a personnel safety mission due to exposure to radiation or other hazardous materials at the time of failure or during repair activities.

While this threat assessment have to be applied across all plant systems and equipment for the definition of a fully comprehensive maintenance program, the process will be demonstrated in this document by a concentration on the effects associated with rotating equipment problems.[12]

---

[12] For example, arc flash of a non maintained electrical circuit breaker can cause extensive damage to adjacent equipment or injury to personnel.

The threat identification process is rather straight forward if the missions are identified in a comprehensive manner. Industry experience has demonstrated that a thorough facility walk down, using a systematic process of risk evaluation, can be highly effective in the identification of most significant threats.

Table II identifies some examples of facility mission functions with the associated rotating equipment necessary for achieving that function and the type of failure produced.

TABLE II. EXAMPLES OF MISSION FUNCTIONS AND EQUIPMENT FAILURE IMPACTS.

Mission function*	Equipment**	Type of Failure***
Shutdown due to primary system failures	Primary pump failure	RE – one of two pumps are required for system operation
Shutdown due to power system failure	Emergency power failure	SPV – Loss of power to safety system initiates scram
Experiment loss	Cooling system failure	SPV – Single cooling pump provided for removal of heat. Single flow control valve for cooling water
As Schedule start up prevented	Safety rod motor failure	SPV – two out of three rods are available, but safety requirements require all three to be available for reactor start-up
Unbudgeted capital cost	Primary pump motor failure	SPV – No spares available; rebuild can take a long time
Hazardous release outside confinement boundaries	Fan failure results in filter bypass	RE – Filter bank consists of two 100% fans

**Mission function*: Examples of mission functions failures.

***Rotating Equipment:* The rotating equipment accomplishing the functions associated with the mission is identified.

****Type of Failure:* Equipment failure is classified into one of two groups that identifies if the single failure of the equipment results in loss of the mission function (single point vulnerability (SPV) or redundancy exists (RE) for completing the mission function. This information provides an indirect indicator of equipment importance to mission function.

3.1.4 Identification of the failures that could jeopardize or fail the mission successes

Facility missions were identified in Subsection 3.1.1 and ranked by importance in Subsection 3.1.2. Equipment significant to the successful completion of each mission was also identified in Subsection 3.1.3.

In this section the degradation or failure modes for the equipment identified in Subsection 3.1.3 are indicated. Detailed failure mode identification is important to the cost efficiency of the maintenance program as it leads to the identification of specific preventive maintenance needs. For example, if the identified threat to a mission is the spillage of a hazardous material, a seal failure of a pump may be an important failure (leading to a decision to implement seal temperature condition monitoring), whereas failure of the motor to run (leading to bearing vibration condition monitoring) may not be identified as being important—a simple "pump fails" is generally not of sufficient detail to address the threat, and prospective monitoring techniques, in an efficient manner.

In a comprehensive maintenance program, this task have to be addressed from both an individual component perspective as well as from a functional group perspective to ensure identification of adverse effects for both the equipment (i.e. motor failure) as well as any essential support for the equipment (i.e. compressed air or electric power) are identified. A functional group may consist of a single component.

Table III provides a listing of typical failures associated with commonly available rotating equipment.

TABLE III. TYPICAL ROTATING EQUIPMENT WITH COMMON DEGRADATIONS AND FAILURES.

Common Rotating Equipment	Typical Failure
Motors	Rotor unbalance
	Misalignment
	Seal failures
	Bent shaft
	Bearing fault
	Stator/Rotor failures
	Wire or connection problems
	Base or anchor failure
Pumps	Bearing fault
	Mechanical looseness

Common Rotating Equipment	**Typical Failure**
	Coupling fault
	Seal failures/Leaks
	Base or anchor failure
	Cavitation
	Blade rub or friction
Fans/Direct Drive	Gear fault
	Blade rub or friction
Fans/Belt Drive	Misalignment
	Belt issues
	Bent shaft
	Imbalance
	Bearing Fault
Gearboxes	Gear fault
	Bearing fault
	Misalignment
Shafts/Couplings	Resonance
	Base or anchor failure
	Misalignment

.

3.1.5 Determination of equipment importance

As the EI process continues forward, the identification of missions and associated hazards provide sufficient information to determine the equipment “importance” to the facility. This identification is necessary to develop a maintenance program that balances facility reliability improvement with costs. At one extreme, for equipment having no significant impacts on a facility mission if it fails, there is no justification for a large expenditure of limited resources to prevent its unexpected failure. On the other hand, equipment failure that has significant adverse impact on multiple facility missions have to be accorded the majority of available resources, or the addition of new resources, to the prevention of unexpected failure and its associated consequences.

Importance is established using a graded approach where the missions and the equipment associated with those missions are categorized and ranked. The definitions and criteria to perform this categorization may vary from the simple to the complex depending on the mission definitions and needs. At its most basic level, equipment importance can be determined as “essential” and “not essential.” A three tier graded approach process is expected to adequately serve most circumstances and is described further in the following paragraphs.

Critical – Plant equipment in this importance category generally are necessary to reactor operation and safety and their failure would negate these functions. Rotating equipment in this category include the primary and secondary circuit coolant pumps.

Condition monitoring improves the safety, productivity and cost effectiveness of such research reactor critical equipment. By providing early indications of potentially severe problems, significant reductions can be achieved in maintenance time and repair costs. If the critical equipment is radioactive, reduction in maintenance or repair time will result in minimal radiation exposure to the personnel. Furthermore, unexpected malfunctions of the critical equipment may be prevented thus, resulting in more consistent reactor schedules. If critical function redundancy exists, condition monitoring will be an essential tool to maintain the availability and reliability of the backup, ensuring the fast and reliable start up when it is required to go into full service. Equipment could be categorized critical if:

- Failure of the equipment impairs safe reactor operation and requires immediate shutdown
- Failure may result in potential contamination release
- Failure results in unavoidable dose to operations staff due either to the failure or repair of failure

Essential – Equipment characterized as essential is a key part of a system, but if there is a failure a reactor can still operate. Examples of rotating equipment in this category include redundant cooling tower fans and air filtration fans.

For equipment qualified as essential, the convenience of implementing a condition monitoring plan have to be evaluated from an economic point of view. Essential equipment may be designated based on any of the following:

- Loss or damage to experiment or experiment data
- Loss of redundancy in the reactor protection system
- Prevention of reactor startup
- Not meeting established availability or operating time requirements
- Administrative shutdown if not repaired in allowed time

Other – Equipment categorized as “Other” are those making up the remainder of the reactor systems and they are not of importance to the identified missions. Examples include auxiliary pumps, machines of the auxiliary pneumatic systems, etc. Advanced condition monitoring techniques would be necessary only if justification could be based on the maintenance and repair costs. Generally, this is equipment that is not classified as *Critical* or *Essential*.

The previous categorizations were segregated by individual and specific failure effects criteria defined for that category. A second categorization process can be considered that utilizes the equipment mission importance and equipment failure type (redundancy or SPV exists). Using this information, a matrix of categorizations may be prepared as shown in Table IV:

TABLE IV. EQUIPMENT IMPORTANCE CATEGORIZATION MATRIX.

	Equipment Failure Type	
Mission Importance	**SPV**	**Redundancy**
High	Critical	Essential
Medium	Essential	Essential
Low	Essential	Other

Thus, if equipment is mission ranked as High, it would be categorized as Critical if redundancy does not exist and Essential if redundancy does exist. These two methods for categorizations of equipment performance are provided only as propositions. Alternative categorization processes are at the discretion of the maintenance program user as necessary to respond to specific reactor needs. It is useful summarizing the importance categorization in a table format to allow for easier comparison, for example as shown in Table V

TABLE V. COMPILATION OF EQUIPMENT IMPORTANCE INFORMATION.

Component	Mission and Importance	Category
Pump A	Reactor operation, no redundancy - High	Critical
Pump B	Decay heat removal, backup system exists – Medium	Essential

3.2 DECISIONS ON IMPLEMENTING CONDITION BASED MONITORING METHODS

3.2.1 Determination of maintenance cost/benefit – corrective, preventive or predictive

It has been suggested earlier that, before starting an investment of research reactor resources in the application of a condition monitoring processes for rotating equipment, the first step is to determine if the need for such an investment is present and, if the need does exist, to determine the investment appropriate for an effective program. The determination of such need could start with a systematic process that (a) identifies plant equipment necessary to the purposes of the reactor and (b) categorizes this equipment as to its importance in achieving those purposes (cf. Subsection 3.1.5). Application of this process results in an equipment list of concern having a general ranking by the equipment importance to the research reactor missions and purposes. Upon list preparation, a relative and qualitative assessment of the potential benefits achievable with the expenditure of fixed maintenance program assets becomes more evident.

Research reactors may deploy maintenance strategies considering the safety and reliability of its facilities according to their own needs and budget provided. Consequently, reactor staff may consider not only initial deployment costs of a condition monitoring program, but also the systematic benefits of an efficient maintenance program when implementing effective maintenance strategies.

While the use of a maintenance philosophy through condition monitoring methods is highly emphasized, there may be circumstances of mission and equipment importance where any of the identified maintenance philosophies may be appropriate for a particular application considering their varying cost. For example, the Electric Power Research Institute conducted an industry study evaluating the cost of maintenance strategies for the annual maintenance cost for a pump in US dollars per horsepower (HP) for different maintenance practices and the results are summarized in Table VI [17].

TABLE VI. COST OF MAINTENANCE STRATEGIES [17].

	Corrective Maintenance	**Preventive Maintenance**	**Predictive Maintenance**
USD / HP	17 – 18	11 – 13	7 – 9

While several technologies are available for condition monitoring of research reactor rotating equipment, these technologies have varying capabilities and their effectiveness is dependent on the degradation or fault to be identified. The technologies also have varying degrees of effectiveness in detecting early or incipient equipment faults. The OPAL research reactor facility has adopted a condition monitoring technology selection method [18] where Table VII provides a comprehensive list of rotating equipment common faults along with an estimate of the suitability of various technologies for identifying the listed common faults.

TABLE VII. OPAL REACTOR CONDITION MONITORING TECHNOLOGIES SELECTION METHOD. [18]

Equipment Common Faults	Vibration Analysis	Oil[13] Analysis	Thermal Imaging[14]	Temperature Measurements	Electrical Condition Monitoring	Process Condition Monitoring	Visual Inspection
Unbalance	S	●	●	●	●	●	●
Misalignment	S	●	●	●	●	●	S
Bearing fault	S	S	●	●	●	●	●
Mechanical looseness	S	S	●	●	●	●	●
Coupling fault	S	●	●	●	●	●	S
Gear fault	S	S	●	●	●	●	●
Rotor rub	S	S	O	O	●	●	●
Cavitation	S	●	●	●	●	S	●
Flow turbulence	S	●	●	●	●	S	●
Vane and blade pass	S	●	●	●	●	S	●
Friction	S	S	O	O	●	●	●
Bent shaft	S	●	●	●	●	●	S
Stator eccentricity	S	●	O	●	S	●	●
Eccentric rotor	S	●	●	●	S	●	●
Rotor bars	S	●	O	O	S	●	●
Belt drives	S	●	●	●	●	●	S
Resonance	S	●	●	●	●	●	●
Soft foot	S	●	●	●	●	●	●

LEGEND: *S: Suitable O: Optional ● Not Suitable*

According to Table VII vibration analysis is most commonly used for the listed faults. Indeed, the presence of a good vibration analysis program can, by itself, provide significant

---

[13] Lubricant

[14] Thermal Imaging and Temperature Measurements are in the category of Temperature Analysis

improvement to the overall reliability of rotating equipment. However, this single technology impact is predominately due to the large number of rotating equipment degradation mechanisms that manifest themselves by excessive vibration; this is also the reason for the bias towards vibration based technologies in Table VII.

Other types of equipment, such as electrical or instrumentation and controls would benefit from other types of condition monitoring techniques more aptly suited to failure degradations of that equipment type. Corona, arcing and tracking that may not show up in temperature analysis are revealed by ultrasound analysis. The monitored sound may be captured by direct contact of ultrasonic sensors to the equipment (structure born) or by general scanning of the environment (airborne). Applications of airborne ultrasonic analysis include:

- Pressurized gas
- Air leaks
- Vacuum leaks
- Boiler tube
- Heat exchanger leaks
- Valve seat leaks
- Bearing lubrication timing
- Bearing faults
- Compressor valve leakage

3.2.2 Guidance on costs of condition monitoring technologies for rotating equipment

Similar to the technology implementations, the costs associated with their application in a research reactor environment also vary widely and may be dependent on the particular technology application.

When it comes to low cost CBM applications lubricant, vibration and temperature analyses are applicable technologies. The senses of sight and smell of used bearing oil and grease can provide the inspector an indication of damage by observation of lubricant colour, viscosity, odour, or metal impurities. The senses of touch, smell and hearing can provide the inspector abnormal temperature and vibration conditions contingent upon adopting the practice of laying hands on equipment or plant walk down on a frequency sufficient to establish a "normal" baseline for equipment operation. While these inspection practices have the advantage of, essentially, no additional costs to the maintenance budget, significant damage to the equipment is likely to have occurred before symptoms of degradation would be detectable by human senses.

For a modest expenditure of maintenance funds, technology can be made available for most of the condition monitoring methods discussed. Vibration and temperature analyses may be performed with hand held instrumentation available from a wide variety of suppliers that can detect degrading equipment conditions significantly earlier than human senses. These handheld devices are widely utilized and their application is extensively documented by their suppliers and the available literature. For lubricant, ultrasound and motor signature analysis technologies, the equipment cost and necessary training for their adequate utilization would be beyond what is considered a modest expenditure. However, there are numerous companies that can provide equipment condition monitoring as a service for a modest fee without the need for the capital investment. Adoption of equipment condition monitoring as a service, especially for very important equipment, has the advantage for a research reactor facility to have highly qualified technology experts collecting and interpreting the equipment condition data and providing written documentation of the results along with recommendations for maintenance actions.

All condition monitoring technologies discussed, that is vibration, lubricant, ultrasound, motor current signature and temperature analyses come with test instrumentation that may be purchased from industry suppliers if funding is available and the equipment importance is sufficient to justify the cost of the test instrumentation and the personnel training to adequately utilize it. Technologies such as vibration, temperature and lubrication analyses have advanced to the point that continuous, on line, monitoring is feasible with an additional cost for the necessary hardware, software and training. Again, the costs or consequences of equipment failure have to be judged against the additional costs of adopting the technology capability completely in house.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, On line monitoring for improving performance of nuclear power plants. Part 2, Process and component condition monitoring and diagnostics, IAEA Nuclear Energy Series No. NP-T-1.2, IAEA Vienna (2008)

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety glossary: Terminology used in nuclear safety and radiation protection, , IAEA, Vienna (2018).

[3] MARTIN, K.F. "A review by discussion of condition monitoring and fault diagnosis in equipment tools," Int. J. Mach. Tools and Manufacture, Vol. 34, No. 4, , (1994)

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Manual on reliability data collection for research reactor PSAs, IAEA – TECDOC No 636, IAEA Vienna (1992)

[5] RAI, A. , UPADHYAYA,S.H. "A review on signal processing techniques utilized in the fault diagnosis of rolling element bearings," Tribology International, Vol. 96, (2016).

[6] SHIN,J H. , JUN, H B. , "On condition based maintenance policy," Journal of Computational Design and Engineering, Vol. 2, , (2015).

[7] JARDINE, A.K.S.,LIN, D. ,BANJEVIC, D. "A review on machinery diagnostics and prognostics implementing condition based maintenance" Mechanical Systems and Signal Processing, Vol.20, (2006).

[8] HENG, A., ZHANG, S. , TAN, A.C., MATHEW, J., "Rotating machinery prognostics: State of the art, challenges and opportunities" Mechanical Systems and Signal Processing, vol 23, , (2009)

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Maintenance Optimization Programme for Nuclear Power Plants, IAEA Nuclear Energy Series No. NP-T-3.8, IAEA,Vienna (2018).

[10] MITCHELL, J.S. , "From Vibration Measurements to Condition Based Maintenance Seventy Years of Continuous Progress," Sound and Vibration Magazine, (2007).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Advanced surveillance, diagnostic and prognostic techniques in monitoring structures, systems and components in nuclear power plants, IAEA Nuclear Energy Series No. NP T 3.14, IAEA, Vienna (2013).

[12] YANG, Q., "Model Based and Data Driven Fault Diagnosis Methods with Applications to Process Monitoring," Case Western Reserve University, Cleveland, Ohio (2004),

[13] COBLE, J. ,RAMUHALLI, P. ,et al, "A review of prognostics and health management applications in nuclear power plants," International Journal of Prognostics and Health Management, vol. 6 (2015)

[14] ZIMMERMMANN, H. J. , Fuzzy Set Theory and Its Applications, Second Edition, Kluwer Academic Publishers, Boston, MA, (1991)

[15] BISHOP, C.M. , Pattern Recognition and Machine Learning, Springer Science+Business Media, LLC, New York, NY, (2006)

[16] PALIT, A.K. ,POPOVIC, D. , Computational Intelligence in Time Series Forecasting: Theory and Engineering Applications, Springer–Verlag, London, (2005)

[17] ELECTRIC POWER RESEARCH INSTITUTE, "Online Monitoring Guide for Equipment Diagnostics and Reliability Nuclear Generation", EPRI, 3002010577, USA (2017).

[18] AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION, OPAL Reactor Condition Monitoring Framework, ANSTO, Australia, (2018).

TERMS AND DEFINITIONS

Degradation

Deterioration in the physical condition of a system, structure, or component, that is due to mechanisms that occurs over time while in service and could impair its ability to perform its design functions.

Condition monitoring

Continuous or periodic tests, inspections, measurement or trending of the performance or physical characteristics of structures, systems, and components to indicate current or future performance and the potential for failure. Condition monitoring is usually conducted on a non intrusive basis. Also termed condition based monitoring. [2]

Diagnostics

The detection and isolation of faults or failures through the analysis of the outputs from periodic or continuous monitoring. A part of condition based monitoring.

Maintenance

The organized activity, both administrative and technical, of keeping structures, systems and components in good operating condition, including both preventive and corrective (or repair) aspects. [2]

Corrective maintenance

Actions that restore, by repair, overhaul or replacement, the capability of a failed structure, system or component to function within acceptance criteria. Contrasted with preventive maintenance. [2] Also termed breakdown maintenance, unplanned, or run to failure.

Preventive maintenance

Actions that detect, preclude or mitigate degradation of a functional structure, system or component to sustain or extend its useful life by controlling degradation and failures to an acceptable level. Contrasted with corrective maintenance. [2]

Periodic maintenance

Form of preventive maintenance consisting of servicing, parts replacement, surveillance, or testing at predetermined intervals of calendar time, operating time or number of cycles. Also termed time based maintenance. [2]

Planned maintenance

Form of preventive maintenance consisting of refurbishment or replacement that is scheduled and performed prior to unacceptable degradation of a structure, system or component. [2]

Predictive maintenance

Form of preventive maintenance performed continuously or at intervals governed by observed condition to monitor, diagnose or trend a structure, system or component's condition indicators; results indicate present and future functional ability or the nature of and schedule for planned maintenance.

Also termed condition based maintenance. [2]

On line monitoring

On line monitoring (OLM) is an automated method of monitoring instrument output signals and assessing instrument calibration while the plant is operating, without disturbing the monitored channels. [1]

Prognostics

The prediction of a remaining useful, safe or service life, based on an analysis of system or material.

LIST OF ABREVIATIONS

AI:	Artificial Intelligence
ANN:	Artificial Neural Network
BPFO:	Ball Pass Frequency Outer
CBM:	Condition Based Maintenance
CVMS:	Continuous Vibration Monitoring System
CNS:	Cold Neutron Source
CW:	Continuous Wave
DSP	Digital Signal Processing
EI:	Equipment importance
EPV:	Extended Park's Vector
FPS:	Frames Per Second
HP:	Horse Power
ISO:	International Standards Organization
MCSA:	Motor Current Signature Analysis
M&D:	Monitoring and diagnostic
OEM:	Original Equipment Manufacturer
OLM:	On Line Monitoring
RE:	Redundancy exists
RMS:	Root Mean Square
RPM:	Revolutions Per Minute
SHM:	Structural Health Monitoring
SOM:	Self Organizing Map
SPV:	Single Point Vulnerability
SSC:	System Structure Component

CONTRIBUTORS TO DRAFTING AND REVIEW

TOUATI, Said	Commissariat à l'énergie atomique (COMENA), Algeria
GARCÍA PEYRANO, Oscar	Comision Nacional de Energia Atomica, Argentina.
ICO, Reynaldo	Australian Nuclear Science and Technology Organization (ANSTO), Australia
ELLIOT, Darren	Australian Nuclear Science and Technology Organization (ANSTO), Australia
RODRIGUES DE CARVALHO,	Comissão Nacional de Energia Nuclear, Brazil
MANRIQUEZ, Luis	Chilean Nuclear Energy Commission, Chile
HAGGAG, Said	Egyptian Atomic Energy Authority (EAEA), Egypt
IKONOMOPOULOS, Andreas	National Centre of Scientific Research (NCSR) 'DEMOKRITOS', Greece
SUBEKTI, Muhammad	National Nuclear Energy Agency (BATAN), Indonesia
MASHIAH, Hilel	Nuclear Research Center Negev (NRCN) Israel
MAGROTTI, Giovanni	University of Pavia (LENA), Italy
BAE, Sanghoon	Korea Atomic Energy Research Institute (KAERI), Korea
IM, Yun-Taek	Korea Atomic Energy Research Institute (KAERI), Korea
QADIR, Javed	Pakistan Institute of Nuclear Science and Technology (PINSTECH), Pakistan Atomic Energy Commission (PAEC), Pakistan
KUZCAYA, Caner	Artesis Tecnologi AS, Turkey
LINN, Mark A.	Oak Ridge National Laboratory (ORNL), USA
SAHIN, Dagistan	National Institute of Standards and Technology (NIST) Center for Neutron Research, USA
COBLE, Jamie	University of Tennessee, USA
EGGERS, Shannon	University of Florida, USA
KELLY, Jordan	University of Florida, USA
EMMER, Joshua	Sandia National Laboratory, USA

EILER, Janos	International Atomic Energy Agency
SHARMA, Ram Charan	International Atomic Energy Agency
CHO, Yeog Garp	International Atomic Energy Agency
JINCHUK, Dario	International Atomic Energy Agency
VORONOV, Maxim	International Atomic Energy Agency
MORRIS, Charles	International Atomic Energy Agency

APPENDIX

STANDARDS, GUIDELINES AND REGULATIONS FOR CONDITION MONITORING OF ROTATING EQUIPMENT

A selected list of documentation that applies to condition monitoring appears below:

1. API Standard 670, Machinery Protection Systems, Fifth Edition, November 2014, Product No. C67005
2. ISO 10816-1:2016, Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts – Part 1: General guidelines
3. ISO 10816-1:1995, Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts – Part 1: General guidelines
4. ISO 10816-3:2009, Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts – Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15000 r/min when measured in situ
5. ISO 1940-1:1986, Mechanical Vibration – Balance quality requirements of rigid rotors – Part 1: Determination of permissible residual unbalance
6. ISO 4406:1987, Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles
7. ISO 4406:2017, Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles
8. ISO 13372 Condition monitoring and diagnostics of machines – Vocabulary
9. ISO 13373–1 Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 1: General procedures
10. ISO 13373–2 Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 2: Processing, analysis and presentation of vibration data
11. WD 13373–3 Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 3: Diagnostic techniques
12. ISO 13374–1 Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 1: General guidelines
13. ISO 13374–2 Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 2: Data processing
14. ISO/DIS 13374–3 Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 3: Communication
15. ISO 13379–1 Condition monitoring and diagnostics of machines – Data interpretation and diagnostic techniques – Part 1: General guidelines
16. ISO 13380 Condition monitoring and diagnostics of machines – General guidelines on using performance parameters
17. ISO 13381–1 Condition monitoring and diagnostics of machines – Prognostics – Part 1: General guidelines
18. ISO/PWI 14830–1 Condition monitoring and diagnostics of machines – Tribology based monitoring and diagnostics – General guidelines
19. ISO 15243:2004 Rolling bearings – Damage and failures – Terms, characteristics and causes

20. ISO 16587 Mechanical vibration and shock – Performance parameters for condition monitoring of structures
21. ISO 17359 Condition monitoring and diagnostics of machines – General guidelines
22. ISO 18434–1 Condition monitoring and diagnostics of machines – Thermography – Part 1: General procedures
23. ISO 18436–1 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 1: Requirements for certifying bodies and the certification process
24. ISO 18436–2 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 2: Vibration condition monitoring and diagnostics
25. ISO 18436–3 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 3: Requirements for training bodies and the training process
26. ISO 18436–4 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 4: Field lubricant analysis
27. ISO/DIS 18436–5 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 5: Lubricant laboratory technician/analyst
28. ISO 18436–6 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 6: Acoustic emission
29. ISO 18436–7 Condition monitoring and diagnostics of machines – Requirements for qualification and assessment of personnel – Part 7: Thermography
30. ISO 19860 Gas turbines – Data acquisition and trend monitoring system requirements for gas turbine installations
31. ISO 22096 Condition monitoring and diagnostics of machines – Acoustic emission
32. ISO 29821–1 Condition monitoring and diagnostics of machines – Ultrasound – Part 1: General guidelines
33. ISO 29821:2018, Condition monitoring and diagnostics of machines – Ultrasound – General guidelines, procedures and validation
34. ISO 4406:2017 Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles

ANNEX

CASE STUDIES ON IMPLEMENTING ONLINE MONITORING OF ROTATING EQUIPMENT (ONLINE SUPPLEMENTARY FILES)

An overview of the current practices on condition monitoring and incipient failure detection of rotating equipment in the research reactor facilities participating in CRP T34003 appears in the online supplementary files. The outline is accompanied by the lessons learnt from practice adoption within the infrastructure operation while it provides evidence of their benefits. The use cases discussed have been studied in vitro and in vivo in order to examine their applicability.

The supplementary files for this publication can be found on the publication’s individual web page at www.iaea.org/publications.

ORDERING LOCALLY

IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

NORTH AMERICA

Bernan / Rowman & Littlefield

15250 NBN Way, Blue Ridge Summit, PA 17214, USA
Telephone: +1 800 462 6420 • Fax: +1 800 338 4550
Email: orders@rowman.com • Web site: www.rowman.com/bernan

REST OF WORLD

Please contact your preferred local supplier, or our lead distributor:

Eurospan Group

Gray’s Inn House
127 Clerkenwell Road
London EC1R 5DB
United Kingdom

Trade orders and enquiries:

Telephone: +44 (0)176 760 4972 • Fax: +44 (0)176 760 1640
Email: eurospan@turpin-distribution.com

Individual orders:

www.eurospanbookstore.com/iaea

For further information:

Telephone: +44 (0)207 240 0856 • Fax: +44 (0)207 379 0609
Email: info@eurospangroup.com • Web site: www.eurospangroup.com

Orders for both priced and unpriced publications may be addressed directly to:

Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 26007 22529
Email: sales.publications@iaea.org • Web site: www.iaea.org/publications

International Atomic Energy Agency
Vienna
ISSN 1011–4289