Applications of prognostics for maintenance optimization of research reactors

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Abstract: The optimization of operation especially maintenance and surveillance of various components and systems of research reactors using prognostic have been emphasized in this study to save cost and time while keeping safety and reliability high. This study is focused on the research reactors due to margin of cost competitiveness and regulation. The feasibility study has been performed in order to find the potential candidates from research reactors, on which prognostic can be implemented. System and components has been classified into category I and category II, based on the nature of working during the operation of research reactor. The systems of category I are those which, either full or part of them, remain in working condition during normal operation of a research reactor. For instance, instrumentation & control components of safety, protection and monitoring systems belong to this category. Contrary to this, the systems which remain standby during normal operation and start operation on safety signals are grouped in category II. Motor operated valves, pumps of emergency system and vital power system are well suited examples. The online and offline prognostics have been proposed as a work approach for category I and category II systems respectively.

Keyword: prognostics; maintenance optimization; instrumentation & control monitoring; research reactor

1 Introduction

Research reactors are important in the research and development (R&D) of a country as many industrial applications are linked with facilities such as training, target material irradiation for materials science, transmutation studies, commercial production of radioisotopes, neutron activation analysis and the likewise. Keeping eye on its importance, Korean government has intention to upgrade and extend this industry. Presently, South Korea is operating only HANARO at Korea Atomic Energy Research Institute (KAERI) and AGN-201K at Kyung Hee University (KHU), which are not sufficient to meet the current requirements of research and education[1]. As highlighted earlier that research reactor has a key role in the development of industry in any country, therefore its demand is increasing worldwide. In order to satisfy this demand, it is necessary to perform a study focusing on the cost of its design and operation.

The motivation for selecting a research reactor in this study is based on two factors: cost and regulatory requirements. Cost competitiveness of a facility is a significant parameter, which is considered during design, commissioning and operation of facility. Since research reactors are used most of the time for research and experimental work, hence producing less revenue compared to other plants instigate the need of optimization of operation to save cost while maintaining high level of safety and reliability. Regulatory requirements should have to be kept in view while performing/suggesting a new approach. Since we are proposing prognostic for operation optimization of a research reactor which has not yet been applied in nuclear facilities, therefore it is important to verify regulatory provisions. Regulatory requirements of research reactors are comparatively less strict than those of nuclear power plants and hence providing the provision for predictive maintenance. As an evidence, the regulatory requirements for design, commissioning and operation of nuclear power plant are exclusively described in separate SSR-2/1[2] and SSR-2/2[3] whereas the requirements of design, commissioning, operation and radioactive waste handling in case of research reactors are defined in NS-R-4[4] only. Furthermore, the requirements of

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preventive and corrective maintenance can be fulfilled by predictive maintenance. Therefore a research reactor has been opted for implementation of prognostics in order to attain the objective of maintenance optimization using prognostics.

Optimization concept based on the predicted results of prognostic model has been elaborated in Figure 1. The existing maintenance and surveillance schedule is conservative such that surveillance has to be performed unconditionally whether system or component requires it or not. Intuitively, it is logical that equipment may need less frequent surveillance when it is new and this interval should be reduced with passing cycles of operation.

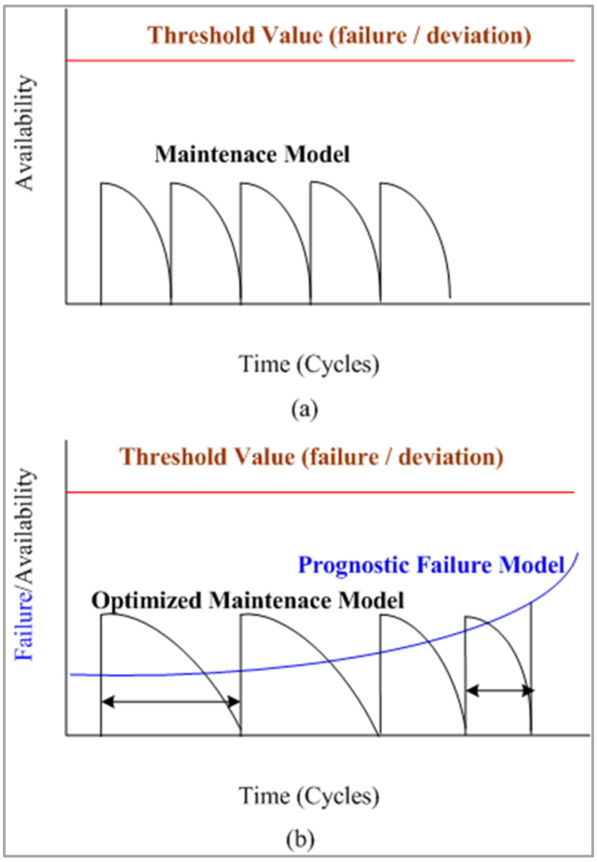

Fig. 1 Optimization concept for maintenance (a) existing maintenance and surveillance model (b) modified maintenance model based on prognosis.

The benefit of study can be realized in this way that there are 500-600 sensors and detectors in a typical research reactor and maintenance work is intensive and frequent such as every 30-60 days, hence making 6-12 Refueling Outages (RFO) per year. Though refueling outage varies from plant to plant depending on size and type of facility, yet we can consider an average duration of one and half weeks (10 days). The loss due to downtime during surveillance of sensor can be estimated using equation (1). This can be endorsed by research performed by Horenbeek and Pintlelon, in which they found out that cost and down time can be reduced by 16% and 39% while considering prognostics instead of corrective maintenance[5]. Therefore, it is proposed to implement prognostic for maintenance optimization purpose.

$$
\begin{aligned}
C_{ss} &= W \times \sum_{i=1}^{N_s} (\Delta t_i) \\
&= N_s \times W \times (\overline{\Delta t})
\end{aligned}
\qquad (1)
$$

where

C_{ss} - cost factor (loss) due to surveillance of sensors

N_s - number of sensors and detectors

W - loss due to down time per day

$\overline{\Delta t}$ - average time required for caliberation and maintenance

The article has been organized into four chapters such that the need, motivation and significance of study have been described in chapter 1 (Introduction) while classification of systems and components for prognostic applications has been discussed in chapter 2 (Prognosis Applications). Similarly chapter 3 has been dedicated to work approach followed by chapter 4 which highlights outcome of study and recommendations for future work.

2 Prognosis applications

In order to find prognostic applications in research reactors, inspection, testing and surveillance activities, the systems and components of a research reactor have been divided into two broad categories category I and category II. It is important to highlight that this classification is different from safety classification of components in research reactor. The study has been conducted to identify the potential candidates on which prognostics can be implemented.

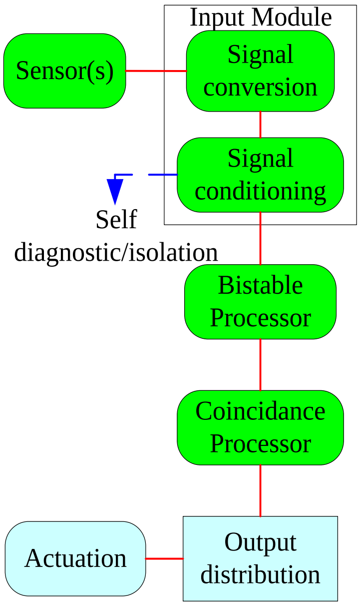

Fig. 2 Working components of RPS instrument channel during normal operation.

Basis for the categorization of systems and components is the nature and mode of working during normal operation of a research reactors. Those systems and components are classified as category I, which remain in working condition during normal operation of research reactors. The systems, which do not perform their intended function fully rather a part of them work only, are also considered in this category. We are bringing an example from the research reactor system in order to validate this statement. More than 70% components of Reactor Protection System (RPS) remain in working condition and they keep performing assessment of parameters till they exceed the set point. As highlighted in Fig. 2, starting from measurement of parameter to coincidence logic verification, the components (highlighted in green in Fig. 2) keep performing their intended function while Engineering Safe Feature Actuation System (ESFAS) initiation, circuit breakers remain idle/standby to operate.

Category I enlists the system and components related to Instrumentation and Control (I&C) systems of safety, protection, monitoring and likewise. Online monitoring & prediction has been recommended for this category. On the same lines, those system & components which remain standby during normal operation of facility and are only required to perform during abnormal/accident conditions, are placed in category II. Category II encompasses mechanical equipments such as pumps, valves (pneumatic/motor operated) and vital power supply source, for which prognostic can perform well. Sub-sections 2.1 and 2.2 have been dedicated to provide more details on subject items.

2.1 Prognostics of category I

This section explains the issues related to I&C components of protection and safety systems and highlights the need of online monitoring and failure prediction of I&C channels. Many instruments are integrated in a sequence to form a channel to perform protection, control, monitoring or other desire function. Each instrument in these channels has comprising components which may undergo problems due to environment, working fluid, severe conditions, radiation dose and other similar issues. The sensors amongst all other components, such as pressure, temperature, and neutron flux sensors are of critical importance because of their impact on plant productivity and safety. The major effects of degradations are changes in the sensor response time and calibration drift which indirectly changes the sensor accuracy[6]. The degradation, ageing issues and need for prognostic for each type of sensors are described one by one.

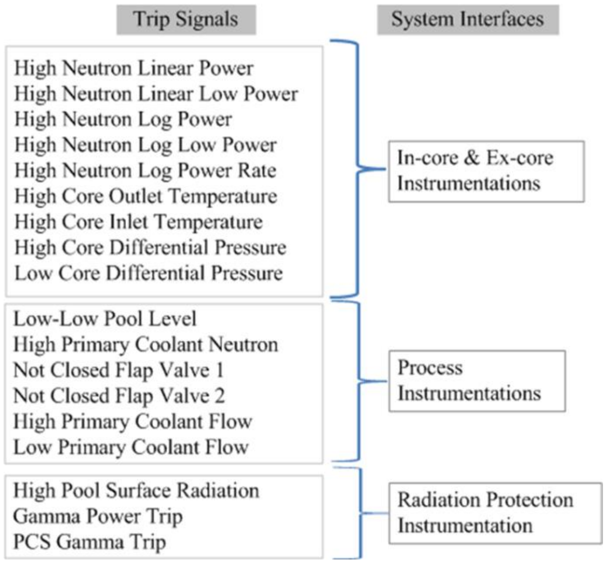

Fig. 4 Trip parameters and interfacing systems.

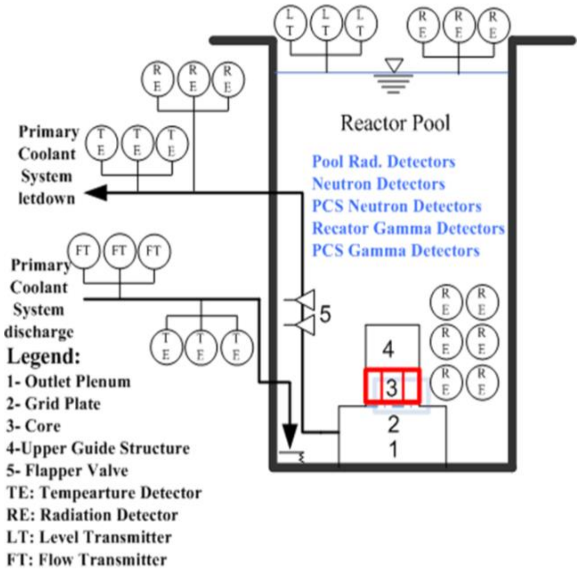

Fig. 3 Selected instrumentations for safety and protection systems.

(a) Pressure , flow and level transmitters

The largest number of sensors on nuclear facility are pressure transmitters which can vary from 500 to 600 in numbers and are used for pressure, level and flow measurements[7]. Fig. 4 demonstrates the selected sensors providing measurements for safety and protection trip signals highlighted in Fig. 3.

The blockage of sensing line for these transmitters is a major concern which can make these sensors specially pressure measuring one essentially useless or even dangerous. In such blocked lines, operating pressure may get locked in the transmitter but its indication would be normal, which is dangerous. The transmitter will not respond due to locked-in pressure and will continue to show normal indication, hence confuses the reactor operators leading towards potential risk to the safety of the plant. In case this blocked pressure transmitter happens to be a part of a redundant safety channel, it can be dangerous in dual way either tripping the plant during a transient or avoid tripping by providing normal signal. Triggering of trip would be due to the mismatch between the redundant channels and blocked one. In mid 1980s, partial blockages in flow transmitters happened in two French PWRs and it initiated reactors trip during load following[8].

(b) Temperature sensors

Temperature is also one of the most important parameter which has to be monitored. For this purpose, nuclear grade Resistance Temperature Detectors (RTDs) and thermocouples are used to measure pool water, coolant system and core exit temperatures in research reactors. The salient ageing concerns of these sensors are platinum wire thinning, cracking of thermo well and reverse connection of thermocouple wires[9]. Platinum wire is used as sensing elements in nuclear-grade RTDs due to its superior features such as linear response and wide range of temperature. It has been experienced that corrosive thinning of this element is caused by the chemicals that were used to clean the elements when they or the RTD were manufactured. The corrosion causes the cross section area of the sensing wire to decrease and its resistance to increase, hence providing inaccurate signal. Another issue is a development of crack in thermo-well due to fluid force, which causes the assembly to bend. This may lead towards the initiation of shearing off assembly or loss of coolant. Reverse connection in thermocouple wires is also a highlighted issue in thermocouple. Researchers have shown that when positive and negative wires get crossed, thermocouple shows negative reading at high temperatures.

(c) Neutron and radiation detectors

Ageing mechanism for neutron flux and radiation detectors is different for each detector belonging to this category due to diversity of detection technology. Yet these too have some common problems like others such as ageing of cables and connectors due to harsh environment. Ionic attack on the central wire of ion chambers of boron trifluoride (BF_3) detector and degradation of insulation resistance in fission chambers affect the sensitivity of detector and instigate the need of frequent replacement.

Keeping the highlighted issues in view, monitoring and failure prediction in prior manner is essential. In order to achieve this, online monitoring accompanied with prognosis is being recommended for the aforementioned sensors and I&C components. The relevant work performed by various researchers in this area recommending the use of prognostics in nuclear facilities, has been briefly described in the following paragraph.

International Atomic Energy Agency (IAEA) issued guidelines for online monitoring of I&C channels in 2008[10] and application of prognostics has been recommended for monitoring of Structures, Systems and Components (SSCs) in 2013[11]. Hashemian emphasized on the need of automated measurements, condition monitoring and diagnostics for maintenance optimization as built-in design feature in next generation nuclear facilities[12]. Heo also highlighted the need of condition monitoring in nuclear industry to avoid time-consuming, expensive, and unnecessary maintenance[13].

2.2 Prognostic of category II

Since the components enlisted under this category are mechanical in nature and they are required to operate during abnormal or accidental conditions, so online monitoring will pose additional cost. The motor operated valves of emergency water supply systems have been enlightened to demonstrate components of category II in Fig. 5. It is proposed that prognostic, which will take the form of prognostic maintenance for this category, can be recommended for this category of components. The data generated from the periodic tests would be utilized in prognostics of category II, which makes it different from that of category I in terms of data collection.

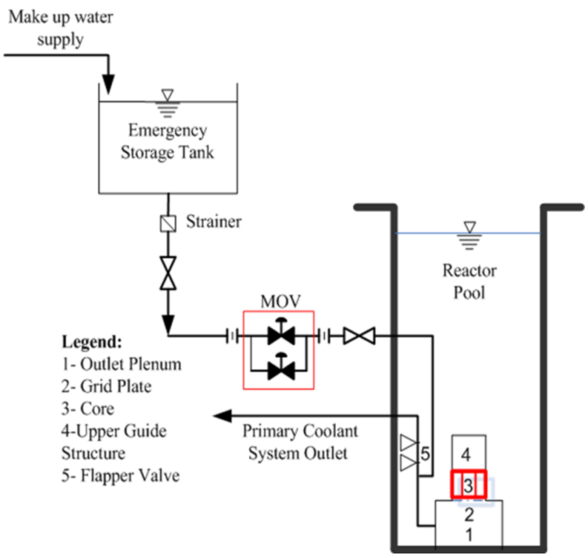

Fig. 5 Stand by components of Emergency and safety systems.

IAEA technical report NP-T-3.14[11] explains that there are many Surveillance, diagnostics and Prognostics (SDP) techniques which can be applied to monitor ageing for active components such as pumps, valves, motors *etc.* Prognostic maintenance is one among these techniques which can be applied for the following category II systems & components:

- Vital power system
- Valve (pneumatic/motor operated)
- Pumps
- Diesel Generators

3 Work approach

The technique prognostic has been elaborated by many researches in different ways depending upon the field in which it is applied. Traditionally starting from the fracture mechanics and fatigue, where it was applied as a tool for the prediction of systems life time, it had been adapted for determining probability measure: a way to quantify the chance that a machine operates without a fault or failure up to some future time[14]. Similarly Buttler[15] and Hess *et al.*[16] highlighted that prognostic can yield information, which can be processed to perform fault detection / isolation, remaining useful life, time-to-failure and advance diagnostics. Prognostics with condition monitoring, made great technical progress in the aviation and electronic area and has been recommended as a solution for the above problems in a previous research[17].

For application purpose in this study, the work approaches for prognostics of category I & II systems are based on the (i) deviation (drift) monitoring of sensor measurements in I&C channels and (ii) prognostic maintenance respectively. Deviation in the measurement parameter keeps on increasing with the passage of time due to issues aforementioned in section 2.1.

A. Data acquisition and pre-processing

The main objective of data acquisition and pre-processing is to detect out-of-normal situations and find the trend of measured signals. The deviations or residuals of each individual sensor are then checked for abnormal values by various fault detection methods. Once the parameter estimate is calculated using an averaging technique, the deviations of each individual sensor in the redundant group from this estimate are computed.

B. Model definition and selection

Model selection is an important task in this method depending upon the type of problem such as pump/valve prognostics or I&C channel monitoring. In all cases, the selected models have to fulfill the requirements of reliable prediction and accuracy. There are two criteria, both of which or either one of them can be adopted for the selection of model. These criteria are (a) best subset regression criteria and (b) prognostic metrics.

A best subset regression criterion returns the most suitable model that fits the data. A multiple variable regression model can be considered and best model is obtained based on either of the following metrics[18]:

- Value of R^2 achieved by the least squares fit
- Value of s^2, residual mean square
- C_p statistics

Second criterion is based on the performance described in prognostic metrics. According to this criterion, the model, which shows good performance in terms of following metrics till the end of life of unit under test[19], can be considered as most suitable model for prognostics.

- Mean Absolute Percentage Error (MAPE)
- Mean Absolute Deviation (MAD)
- Prognostic Horizon (PH)
- Prognostic Precision (PP)

It is important to note there are two more parameters which are not being considered while finding the suitable model using best subset regression criteria. These are end of life of the unit under test (UUT) and prediction of parameter (time dependence) for future, which are important in prognostics algorithm. Hence more focus should be given to prognostic metrics while finding the suitable model.

C. Estimation algorithm

There are many predictor algorithms which are used in prognostics depending upon nature of problem such as Kalman filter, Unscented Kalman filter, particle filter and Monte Carlo techniques. In this study, we are proposing particle filter as a prognosis tool, as it is suitable for nonlinear parameters as well as for systems lacking characteristic parameters. The work approach in integrated form has been demonstrated in Fig. 6.

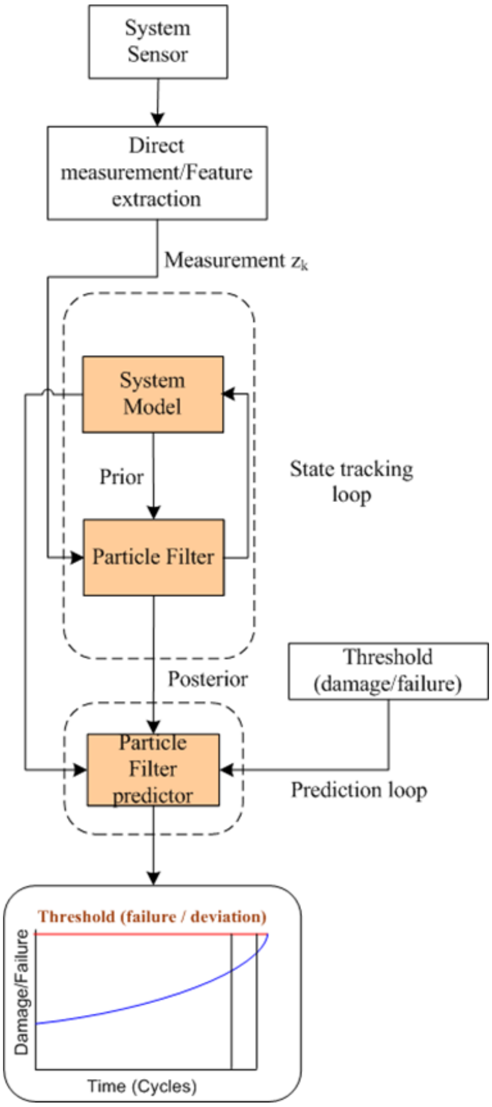

Fig. 6 Prognostic work approach

Particle filter is a special case of density propagation algorithm, in which prior and posterior densities are estimated based on Bayes estimation[20]. Posterior density is a filtering or update step while prior density is a predictive step. In this algorithm, n samples are drawn from prior information of initial density and these samples are propagated forward (in time) using system dynamic model, as shown in state tracking loop of Fig. 6. The outcome from system model now becomes prior density for the current time step. The importance weights, which correct the state vector and predict next state, are calculated using importance density, prior density and likelihood function. Future damage state or desire parameter (deviation/failure) can be predicted by performing post processing of obtained information and threshold deviation or failure values.

4 Summary and conclusions

Feasibility study for implementation of prognostics in nuclear industry specifically research reactors has been performed in this article and prognostic has been proposed to obtain the objective of optimization of maintenance and surveillance of various components and systems of a research reactors. It has been realized that prognostics has ability to save cost and time of maintenance as well as it will enhance safety and reliability of facility. The systems and components of research reactor have been classified into two categories category I & II, based on their mode of operation during normal operation of research reactor. The online prognostic has been recommended for systems and components of category I, the representative potential candidates for this category are I&C channels of protection and safety and monitoring systems. Similarly, prognostic maintenance has been recommended for category II components such as valves, pumps, vital power system, which has to perform in emergency conditions.

Based on literature survey, it has been found that prognostics maintenance, which has been applied in non-nuclear industries, can reduce cost and down time. It is concluded that implementation of prognostics to systems, components of research reactor, highlighted under category I & II, would be very beneficial to (a) reduce cost and down time (b) enhance reliability by reducing downtime, (c) satisfy regulatory requirement of maintenance for research reactor, in which preventive and corrective maintenance will be replaced by predictive, optimized preventive and corrective maintenance.

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