Management of Aging of Reactor Internal Components

B. D. Shumaker, H. M. Hashemian, C. J. Kiger, A. H. Hashemian

Analysis and Measurement Services Corporation, 9119 Cross Park Drive, Knoxville, Tennessee 37923
brent@ams-corp.com, hash@ams-corp.com, chad@ams-corp.com, alex@ams-corp.com, edwin@ams-corp.com

INTRODUCTION

The sustainability of the existing fleet of nuclear power plants depends on management of aging of components that cannot be replaced easily or economically [1]. These components include the reactor vessel and its internal components such as the core barrel. For example, the core barrel in pressurized water reactors (PWRs) is fixed on the top and free on the bottom. Therefore, the core barrel vibrates like a pendulum while the plant is operating. As plants age, it is necessary to verify that the amplitude and frequency of this vibration is not changing beyond an acceptable limit for safe operation. The accelerometers that exist in the current generation of nuclear power plants for loose parts monitoring and other purposes cannot measure this vibration with any appreciable resolution. This is because accelerometers are more suited for high frequency vibration measurements (>100 Hz) while the vibration of core internal components is typically below 30 Hz. Fortunately, the existing neutron detectors that are meant for neutron flux monitoring can also yield low frequency vibration data as needed to verify the integrity of reactor internals. The technique to bring this about is referred to as “noise analysis”. It is based on monitoring the natural fluctuations (noise) that exists at the output of neutron detectors and other sensors during normal operation. If the output of the sensors is sampled at a high rate (>1000 Hz), the noise can be extracted from the sensor output, amplified, filtered, and analyzed to yield the vibrational characteristics of the reactor vessel and its internals. The noise analysis technique has a number of applications in nuclear power plants such as those shown in Table I.

In addition to vibration monitoring, existing sensors can be used with the cross-correlation technique to monitor for flow anomalies in the reactor coolant system and identify and locate flow blockages. For example, in PWRs, the ex-core and in-core neutron detector signals can be cross-correlated with core exit thermocouples to yield fluid flow data that may be tracked to identify changes in flow rate or flow path and determine if flow anomalies or flow blockages are developing within the core.

BACKGROUND

As nuclear power plants age, embrittlement and fatigue of metallic components and reactor internal support structures threaten the safety of the plant. Recent incidents involving baffle bolt failures at the Indian Point and Salem nuclear stations in the United States and similar events in plants outside the United States are vivid examples of why increased monitoring of reactor internals is critical to safety and sustainability of the aging nuclear fleet [2].

TABLE I. Typical Applications of Noise Analysis Technique in Nuclear Power Plants

Application	Description	Signals*
Measurement of dynamic performance of I&C systems	Transfer functions between pairs of signals are generated from which system time constants are deduced.	F, N, P, T
Core internal motion measurement	Ex-core neutron flux detectors are sensitive to the changing water gap between core barrel and reactor vessel. This results in neutron flux fluctuations.	N
Fuel motion measurement	Relative transverse or vertical motion of fuel and detectors is sensed by neutron detectors.	N
Thimble tube vibration monitoring	The in-core neutron flux detectors move in a flux gradient registering vibration of thimble tubes.	N
Individual fuel rod vibration measurement	Loose rods can generate anomalous reactivity and temperature noise which can be seen at the output of neutron detectors and core exit thermocouples.	N, T
Loose parts detection	Sounds from contacting metals of all sizes are measured by accelerometers.	S
Detection of control rod anomalies	Random rod movements affect reactivity and result in neutron flux and temperature fluctuations.	N, T
Identification of flow blockages	Changes in signal amplitudes or dynamic response of existing sensors can reveal flow anomalies and flow blockages.	N, T, P

* F = flow; N = neutron flux; P = pressure; S = sound; and T = temperature

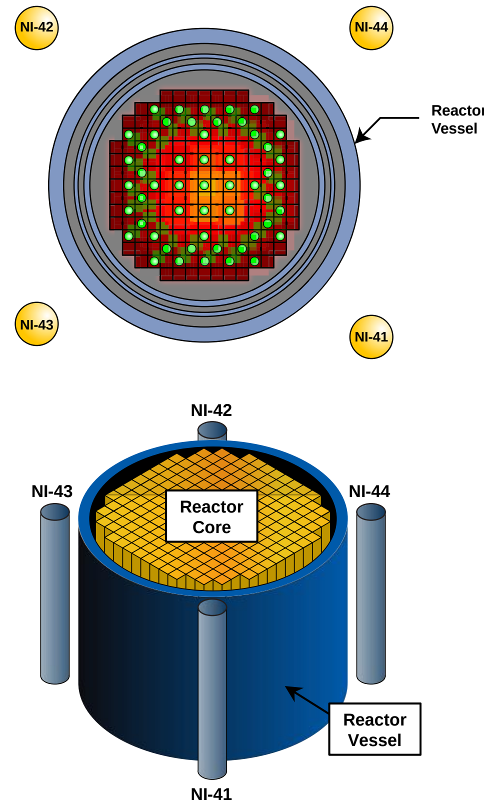
Table II shows four examples of primary system failures due to aging. These examples have also revealed that the current practice of visual inspection with underwater cameras, ultra-sonic testing, and eddy current measurements are not by themselves sufficient to detect the onset of component failures within the reactor vessel. Adding vibration monitoring using existing neutron detectors would be a passive and very cost effective measure to supplement the existing practice and thereby improve the capability to detect incipient failure of reactor internals. Plants in the U.S. and other countries have seen core barrel, thermal shield, and other major components within the reactor vessel become loose and in a few cases, fall off their support causing major disruptions to plant operation not to mention the very high repair and replacement costs [3]. Furthermore, broken metal parts have been found to block the flow of coolant near fuel rods causing partial meltdown of fuel elements [4]. These problems can easily be avoided by acquisition and analysis of existing sensor signals to provide early warning of structural failures, flow anomalies, and other problems as nuclear plants age.

TABLE II. Examples of Failures of Reactor Internals

Failure	Nuclear Plant	Year
Core fasteners broke due to excessive core rocking motion	Palisades	1973
Thermal shield sheared and core barrel cracked	Oconee	1973
Vibration induced cracking of steam generator tube resulted in primary coolant leaks and permanent shutdown of two reactor units	San Onofre	2011
Baffle bolt degradation and failures	Indian Point	2016

TECHNOLOGY

A number of neutron detectors exist on the outside of the reactor vessel in a PWR plant. Four of these detectors (NI-41, NI-42, NI-43, and NI-44) are referred to as power range monitors and used to measure neutron flux to indicate reactor power (Fig. 1). The output of these detectors can be sampled at a high frequency (1000 Hz or greater) and analyzed to provide the vibrational signature of the reactor vessel and its internals including the core barrel, thermal shield, and fuel assemblies. Fig. 2 shows the result of analysis of noise data from a neutron detector in a PWR plant. This plot is referred to as the Power Spectral Density (PSD) of the neutron noise data which is a graph of the variance of the noise signal in a narrow frequency band plotted as a function of frequency for a wide range of frequencies. The plot is generated automatically using Fast Fourier Transform (FFT) analysis and existing software packages.



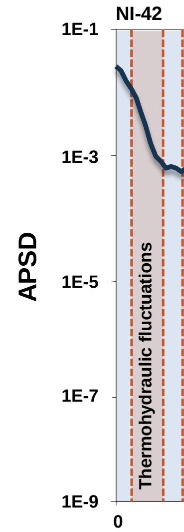


Fig. 1. Neutron detector arrangement in a PWR plant.

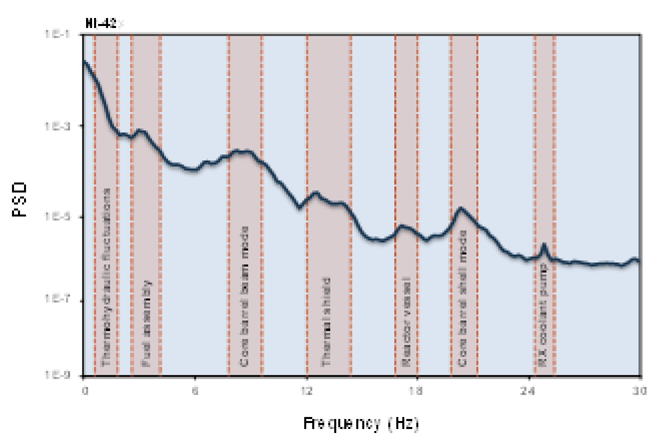


Fig. 2. The noise spectrum of a neutron detector.

The peaks in the plot of Fig. 2 show the frequency and amplitude of vibration of the reactor internal components. These components are distinguished by analysis of the phase between pairs of cross-core neutron detectors. If data from other sensors such as the existing temperature, pressure, level, and flow sensors are added to the mix, the diagnostics capabilities of the noise analysis technique will increase dramatically to the point that a “motion picture” of the movement of all components within the reactor vessel can be produced by PSD, phase, and cross-correlation analysis. This was actually done by the author for a PWR plant at the verge of forced shutdown.

CONCLUSIONS

This paper presented how signals from existing sensors may be used to extract more information about the plant equipment and processes and thereby provide a variety of diagnostics as to the condition and health of a reactor and its internal components. This type of measurement has been used anecdotally by the nuclear industry for troubleshooting but not for routine predictive maintenance, diagnostics, prognostics, or aging management. Today, with the U.S. nuclear fleet aging and license renewals allowing plants to operate 60, 80, or more years, the neutron noise analysis and cross-correlation techniques can offer substantial means for equipment and process health monitoring, management of aging of reactor internals, diagnostics and prognostics of aging effects, and structural health monitoring.

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