NUREG/CR-5479
ORNL/TM-11398

Current Applications of Vibration Monitoring and Neutron Noise Analysis

Detection and Analysis of Structural Degradation of Reactor Vessel Internals from Operational Aging

Prepared by B. Damiano, R. C. Kryter

Oak Ridge National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

AVAILABILITY NOTICE

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 2120 L Street, NW., Lower Level, Washington, DC 20555
2. The Superintendent of Documents, U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20013-7082
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC bulletins, circulars, information notices, inspection and investigation notices; licensee event reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are regulatory guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG-series reports and technical reports prepared by other Federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions. *Federal Register* notices, Federal and State legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free, to the extent of supply, upon written request to the Office of Information Resources Management, Distribution Section, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, for use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

NUREG/CR-5479
ORNL/TM-11398
RV

Current Applications of Vibration Monitoring and Neutron Noise Analysis

Detection and Analysis of Structural Degradation of Reactor Vessel Internals from Operational Aging

Manuscript Completed: February 1990
Date Published: February 1990

Prepared by
B. Damiano, R. C. Kryter

Oak Ridge National Laboratory
Operated by Martin Marietta Energy Systems, Inc.

Oak Ridge National Laboratory
Oak Ridge, TN 37831

Prepared for
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN B0828
Under Contract No. DE-AC05-84OR21400

ABSTRACT

Monitoring programs using vibration monitoring or neutron noise analysis have demonstrated the ability to detect and, in some cases, diagnose the nature of reactor vessel internals structural degradation. Detection of compromised mechanical integrity of reactor vessel internal components in its early stages allows corrective action to be taken before major weakening or damage occurs. In addition to the economic benefits early detection and correction can provide, they can also help maintain plant safety. Information on the condition of reactor vessel internal components gained from a monitoring program supplements in-service inspection results and may be useful in justifying plant license extension.

This report, which was prepared under the Nuclear Plant Aging Research Program sponsored by the U.S. Nuclear Regulatory Commission, discusses the application of vibration monitoring and neutron noise analysis for monitoring light-water reactor vessel internals. The report begins by describing the effects of structural integrity loss on internals vibration and how measurable parameters can be used to detect and track the progress of degradation. This is followed by a description and comparison of vibration monitoring and neutron noise analysis, two methods for monitoring the mechanical integrity of reactor vessel internal components. The major section of the report describes the status of reactor vessel internals condition monitoring programs in the United States, Federal Republic of Germany, and France, three countries having substantial commitments to nuclear power. The last section presents guidelines for U.S. utilities wishing to establish reactor internals condition monitoring programs.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The detection of light-water reactor (LWR) internals structural degradation caused by operational aging may become more important to U.S. utilities as the median age of U.S. nuclear power plants increases. It has been demonstrated that monitoring programs using vibration monitoring or neutron noise analysis can effectively detect the loss of mechanical integrity of reactor internal components at an early stage before severe damage occurs. Such programs have the potential to reduce plant downtime and its associated costs, to make periodic maintenance more effective, and to maintain a high level of plant safety. Another potential use for the information gained from an internals condition monitoring program may be as an aid in justifying extension of a plant's operating license.

Monitoring of reactor internals structural integrity can be considered an application of the general concept of predictive maintenance. Predictive maintenance is widely used by industry to monitor the condition of rotating machinery, where it has proved to be cost effective.[1] It is assumed that the application of predictive maintenance techniques for monitoring the condition of reactor internals would similarly become widespread if comparable benefits could be demonstrated. Although some internals monitoring programs have shown mixed results, others have proved unquestionably beneficial and cost effective.

It has been stated that internals monitoring programs in Europe are five to ten years ahead of those in the United States.[2] If viewed as an opportunity rather than a criticism, this situation allows U.S. utilities to benefit from the considerable European experience base, where vessel internals condition monitoring has been integrated into regular plant maintenance programs in many cases. Thus, it should be possible for U.S. utilities to implement effective monitoring programs with a minimum of experimentation.

The information presented in this report was obtained from several sources. The main source is the series of Specialists' Meetings on Reactor Noise which have been held every two to three years since 1974. Other sources include papers from other meetings and conferences, information from contacts within the nuclear industry, and information gained by Oak Ridge National Laboratory (ORNL) staff involved in research on the application of neutron noise analysis for monitoring the continued mechanical integrity of reactor internal components. The authors recognize that there may be significant work of which we are unaware. However, the information on which this report is based is believed sufficiently complete to describe accurately current applications of both vibration monitoring and neutron noise analysis for monitoring the condition of reactor internals.

This report, which was prepared under the Nuclear Plant Aging Research Program sponsored by the U.S. Nuclear Regulatory Commission (USNRC), discusses the application of vibration monitoring and neutron noise analysis for monitoring LWR vessel internals. The report is organized as follows. First, the effects of internals mechanical degradation on the nature of sensible vibration signatures are reviewed. This is followed by a brief description of vibration monitoring and neutron noise analysis, which includes a comparison and evaluation of these two methods. Next, current practices are summarized, and example applications of these methods are given for both the United States and Europe. The report concludes with a summary of guidelines for establishing what the authors consider a reasonable internals monitoring program for U.S. utilities.

2. EFFECTS OF LWR INTERNALS MECHANICAL DEGRADATION ON VIBRATION SIGNATURES

Flow-induced vibration of reactor internal structures has been and continues to be a problem in commercial LWRs. A partial list of internal component abnormalities or failures attributable to excessive vibration is given in Table 1. In this report, internals degradation means structural integrity deterioration that does not necessarily prevent a structure from performing its intended function. Using this definition, examples of degradation include weld cracking or loss of bolt preload. Failure is reached when and if the degradation progresses to the point where the structure "breaks" in such a way that it can no longer perform its function.

Many cases of internals degradation are caused by excessive flow-induced vibration. As coolant is forced through the core, internal structures are subjected to strong fluctuating pressure and drag forces (see Fig. 1). These forces inevitably excite some of the natural vibratory modes of the internal structures, resulting in motion that may eventually degrade the structural integrity of the affected components. A component does not necessarily require direct hydraulic excitation to experience vibration. Many components are mechanically coupled; thus, excitation of one component may result in vibration of a significant portion of the internals.

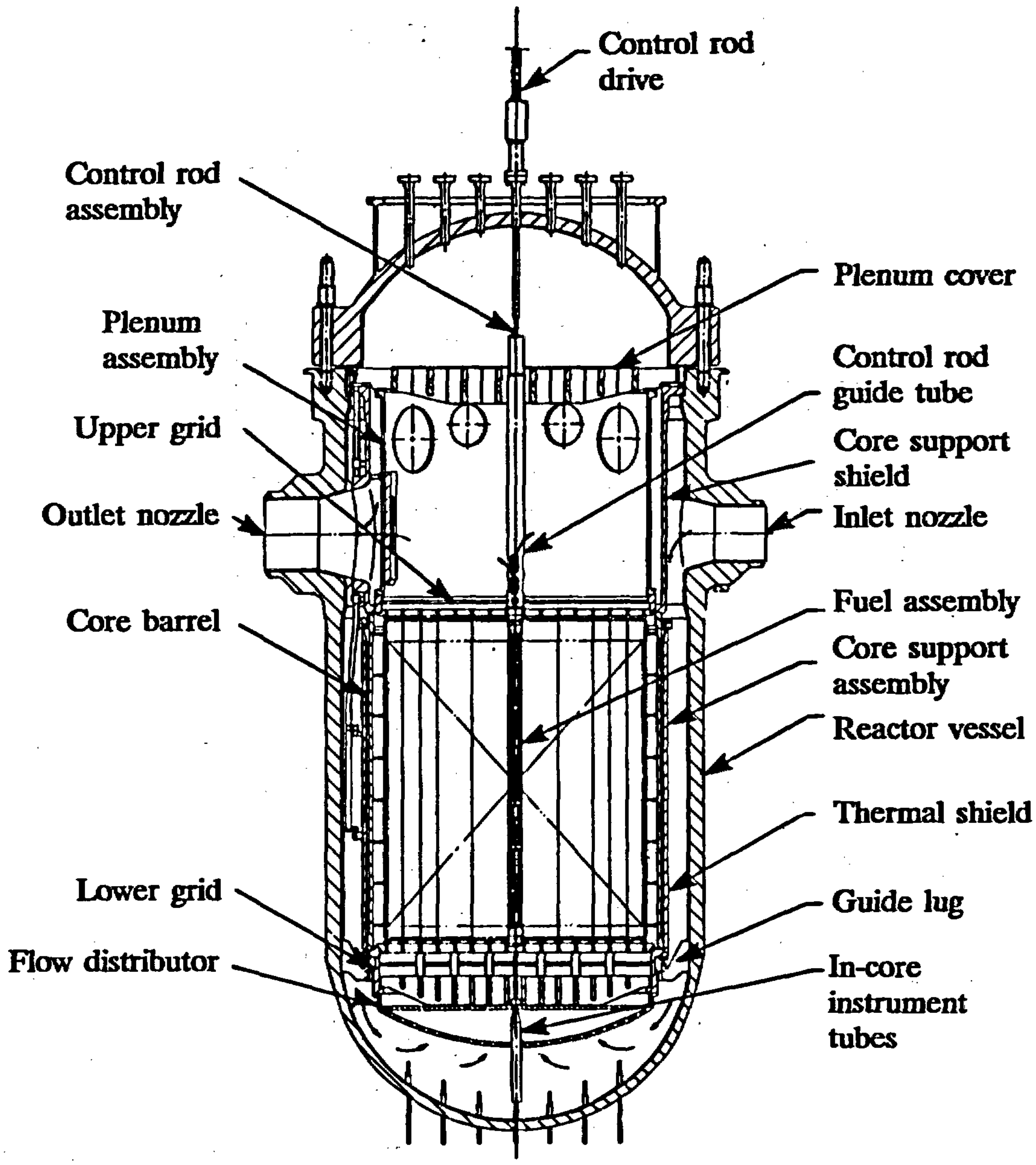
Often a mechanical degradation will affect the resonant frequencies of internal structures; thus, a resonant frequency shift may be used to detect some forms of mechanical degradation. Two forms of mechanical degradation that often result in resonant frequency shifts, loss of bolt preload, and fatigue are briefly described in the following paragraphs.

Loss of bolt preload may result in abnormally large vibration amplitudes and shifted resonant frequencies and often precedes more severe structural damage. As a connection loosens, the stiffness and mechanical coupling between connected components is reduced; this often changes both the frequency and amplitude of the vibration because of changes in the stiffness and effective mass of the structure. Greater vibration amplitude results in greater stresses within the internal components, thereby accelerating the progression of damage. In structures joined by multiple connections, loss of preload in one connection increases the load carried by those remaining, possibly increasing the rate at which other connections loosen and fatigue. The accompanying frequency changes can be used to detect and ascertain the nature of these degradations.

Fatigue damage can occur when a material is subjected to alternating stresses. The rate at which fatigue damage progresses is affected primarily by the mean stress level, the frequency of stress reversal, the magnitude of the alternating stress, and the material's fatigue strength. As damage progresses, fatigue cracks grow, reducing the load-carrying portion of the structure. As in loss of preload, the remaining intact portion then carries greater mean and alternating stresses, resulting in an accelerated rate of fatigue-crack growth. As fatigue cracks grow, the connecting stiffness decreases. The progression of such fatigue damage can be detected from the resulting frequency shift.

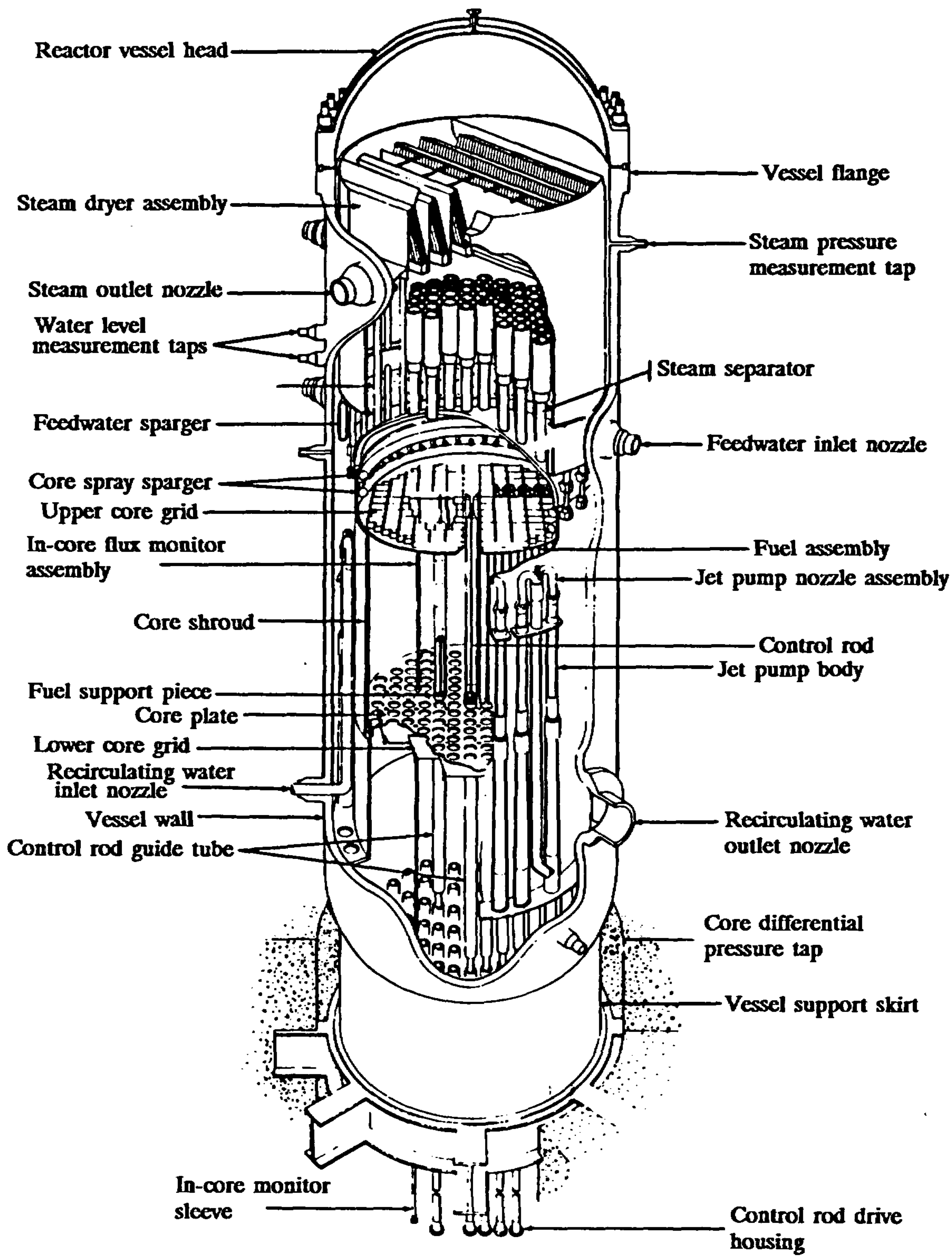
Table 1. Examples of LWR components experiencing failure or excessive flow-induced vibration during commercial operation[3]

Reactor	Component	Problem
KKS Stade	Core support	Loose bolts in structure below core barrel
Palisades	Core barrel	Flow-induced core barrel motion
Novovoronezh-1 KWO Obrigheim Oconee 1,2,3 St. Lucie Millstone Maine Yankee Trino Vercelles	Thermal shield	Loosening of thermal shield
Trojan	Fuel elements	"Baffle-jetting"–damaged fuel elements on core periphery
Crystal River	Control rod spider	Broken spider caused by flow-induced vibration of control rods
BWR-4s	Instrument tubes	Damaged fuel channel boxes caused by impacting with instrument tubes
Millstone-1	Feedwater sparger	Vibration and cracking observed
Pathfinder	Steam separators	Vibration-induced structural failure



(a) PWR internals.

Fig. 1. PWR and BWR internals. (*Source*: J. A. Thie, *Power Reactor Noise*, American Nuclear Society, La Grange Park, Ill., 1981. Reprinted by permission.)



(b) BWR internals.

Fig. 1. (continued).

3. METHODS OF SURVEILLANCE

Although the presence of structural degradation may result in both increased vibration amplitude and a shift in vibration frequency, the latter is the primary means for detecting degradation. Measurement of reactor internals vibration most often is performed using mechanical sensors mounted on the reactor vessel or other primary system components, or by analyzing the noise content of the signals generated by ex-core or in-core neutron flux detectors. Table 2 lists the major surveillance methods that have been used to detect the degradation of specific components.

3.1 SIMILARITIES BETWEEN MECHANICAL VIBRATION MONITORING AND NEUTRON NOISE ANALYSIS

The form of data collected using mechanical vibration monitoring or neutron noise analysis is similar, and data analysis techniques for both types of sensors are basically the same. Unlike in-service visual inspections, both methods are nonintrusive; monitoring requires no process perturbations or special conditions and in fact is best performed at full power during normal plant operation. Although the data may be analyzed in either the time or frequency domain, for purposes of monitoring reactor internals vibration, analysis in the frequency domain is preferable since the frequency shifts indicative of vessel internals degradation are easily detected.

Frequency domain analysis typically involves using a fast Fourier transform (FFT) algorithm to convert signals from the time to the frequency domain. The results may be displayed as an auto-power spectral density (APSD) for each signal or, if multiple signals are sampled, as cross-power spectral densities (CPSDs) and coherences for each signal pair. Examination and comparison of resonant peak amplitudes and frequencies of APSDs and CPSDs and values of CPSD coherence and phase have proved useful in detecting and diagnosing anomalies.

Since the detection process involves comparison of spectral features, a baseline or reference signature representing normal operation is an essential starting point. An effective monitoring program, therefore, entails regular data collection, comparison, and analysis to ensure that anomalies will be detected before major damage occurs. Baseline signatures may need to be updated periodically, for example, if modifications to the vessel internals are introduced.

It should be noted that baseline signatures may not remain constant over an entire fuel cycle even though the reactor is unaltered mechanically and is operating normally. For example, neutron noise signatures are often affected by fuel burnup and control rod position, both of which vary continuously during a fuel cycle. Similarly, vibration signatures may be influenced by reactor temperature, pressure, water level, and power level. Thus, the dependence of the baseline noise signatures on parameters other than the mechanical vibration characteristics of the internals must be well understood. These considerations indicate the need for a long-term monitoring program which, ideally, should continue throughout the life of the plant, beginning during construction and initial testing.

Table 2. Methods that have been used to detect failure or degradation of specific reactor internal components[3]

	Surveillance Method		
Component	Vibration monitoring*	Neutron noise analysis*	Visual inspection†
Thermal shield	X	X	X
Core support	X		X
Core barrel	X	X	X
Fuel assemblies	X	X	X
Control rods			X
Instrument thimbles		X	X

*Indicates method used for degradation or failure detection.
†Visual inspection detected failed component during refueling outage.

3.2 ADVANTAGES AND DISADVANTAGES OF MECHANICAL VIBRATION MONITORING AND NEUTRON NOISE ANALYSIS

The preceding text describes similarities between the use of vibration monitoring and neutron noise analysis for monitoring the condition of reactor vessel internals. The following paragraphs describe the application and the advantages and disadvantages of each measurement technique.

Vibration monitoring uses mechanical motion sensors such as accelerometers, displacement transducers, or strain gages. The techniques for mounting the sensors and conditioning their signals are well known, since these sensor types have been used for many years in a variety of applications including rotating machinery monitoring, modal and seismic testing, and predictive maintenance programs.[1] The success of vibration monitoring depends on mechanical coupling between components to transfer vibrations from the internal structures to the exterior of the reactor vessel or primary piping where the sensors can be mounted.

Implementation of a vibration monitoring program in U.S. reactors would entail installation of a number (between 4 and 12) of new sensors, thus posing a major hurdle for establishing vibration monitoring programs in the United States because of the understandable reluctance of utilities to make modifications inside reactor containment. The main advantage of vibration monitoring is its direct nature: since vibration sensors respond to a mechanical phenomenon that is mechanically transmitted to the sensors, the measurements should be affected principally by changes in the mechanical conditions within the system.

On the other hand, neutron noise analysis extracts and processes the time-varying component of an existing neutron flux signal to gain indirect information concerning the vibration of reactor vessel internals. This method is effective in detecting structural vibration because as internal structures vibrate they induce small perturbations in the reactor's neutron field. These perturbations are detected as fluctuations around a steady-state value in the neutron flux detector signals. The signal fluctuations (noise) can be analyzed to obtain information about the nature of the perturbing vibrations.

The attractiveness of neutron noise analysis for U.S. utilities is that it uses existing plant sensors, that is, the in-core and the ex-core neutron detectors that are part of every reactor's instrumentation. Thus, implementation by U.S. utilities of vessel internals monitoring programs based on neutron noise analysis appears to be considerably easier than implementation of vibration monitoring programs. The main disadvantages of neutron noise analysis are that (1) measurements can be affected by phenomena other than vibration and (2) only information concerning the reactor vessel internals can be obtained; components of the primary system outside the reactor vessel (e.g., steam generators) cannot be monitored. These points are amplified in the following paragraphs.

Because neutron noise analysis relies on neutron flux perturbations to detect internals vibration, other phenomena that may also affect the flux must be considered when analyzing neutron noise data. For example, noise signals are known to be influenced by the fuel loading pattern, moderator boron concentration, and fuel burnup, making it necessary to understand the effects of these variables on the noise signals.[4] Thus, frequent baseline signature collection may be necessary when using neutron noise analysis for monitoring the condition of reactor internals, at least for the first several fuel cycles.

As already noted, neutron noise analysis necessarily is restricted to structures located within the reactor vessel. However, since components in the primary system are coupled both mechanically and hydraulically, additional sensors (i.e., thermocouples, pressure transducers, and accelerometers) located throughout the primary system may enable the analyst to determine the cause of internals vibrations produced by sources outside the reactor vessel. Obviously, the additional sensors provide information about a larger structural system, thus making the monitoring program more complex but more complete and potentially more useful.

In summary, both neutron noise analysis and vibration monitoring can be used for monitoring the vibration of reactor vessel internal structures. Neutron noise analysis would be easier to implement by U.S. utilities since the needed sensors are already in place, but the information gained through its application is necessarily limited to structures within the reactor vessel. Neutron noise data also are affected by phenomena other than vibration, thus complicating the analysis and subsequent interpretation. Vibration monitoring, although more difficult to implement because of the need for new sensors, provides a more direct measurement of vessel internals vibration and allows a monitoring program to be expanded, if desired, to include the entire primary coolant system. Both methods employ essentially the same signal conditioning and data analysis techniques and require the same amount of periodic data collection. Obviously, the methods are not mutually exclusive. A case can be made for the combined use of vibration monitoring and neutron noise analysis, an approach that has been widely adopted in Europe.

4. SUMMARY OF OPERATING EXPERIENCE

This section summarizes the application of vibration monitoring and neutron noise analysis for monitoring the condition of reactor vessel internal structures in both the United States and Europe. The U.S. experience is presented first, followed by reported experience in the Federal Republic of Germany (FRG) and France. Other countries such as Sweden, Japan, Belgium, Hungary, and Finland have nuclear power plants in which vibration monitoring or neutron noise analysis are used for monitoring the condition of the vessel internals. However, the experience from these countries is not included in this report simply because it is not as extensive or as widely reported as that of the German and French programs.

4.1 U.S. EXPERIENCE

Surveillance of reactor internals vibration has seen only limited application in the United States. Maintenance programs at U.S. utilities are typically composed of a combination of corrective, preventive, and predictive maintenance techniques. Utilities rely on generous design margins coupled with periodic in-service visual inspections to ensure that the structural integrity of the internals will be maintained throughout the service life of the reactor; they have not shown strong interest in real-time (but somewhat indirect) means of monitoring internals condition.

A few utilities, however, have initiated vessel internals surveillance programs based on neutron noise analysis and have demonstrated an ability to monitor vessel internals vibrations.[5-7] Of these programs, one was cut back severely, one was eliminated, and one was ineffectively implemented thereby allowing severe thermal shield damage to occur even though progressive structural degradation clearly was indicated by the changing noise signatures.[8,9] It appears that, on the whole, the managements of these utilities did not place sufficient importance on internals condition monitoring to provide the long-term support necessary for these programs to yield real benefits.

We are aware that internals monitoring programs are currently being performed by Omaha Public Power District and by Northeast Utilities. In both programs, the utility performs data collection activities and relies on the reactor supplier (in this case Combustion Engineering) for support in data analysis and interpretation. This appears to be a practical arrangement for utilities in the United States, where most of the information and expertise required to perform interpretation of noise and vibration signatures is proprietary and resides with the reactor supplier. This type of program, if properly implemented, has the potential to produce valuable information on the condition of the reactor vessel internals.

A more common application of reactor internals monitoring in the United States involves relying on noise analysis to monitor, as a condition for continued plant operation, the status of a degraded condition already known to exist. A recent proposal by Southern California Edison to USNRC requesting continued operation of the San Onofre Nuclear Generating Station 1 (SONGS 1) is an example of this type of internals monitoring.[10] SONGS 1 has experienced degradation of thermal shield supports, so as a condition of continued operation Southern California Edison proposed to monitor the thermal shield vibration periodically using noise analysis of signals from the ex-core neutron detectors to ensure that further degradation is not occurring.

An earlier but similar example involved instrument tube vibration in boiling-water reactors (BWRs).[11] In this case, neutron noise analysis was used to detect impacting of instrument tubes on surrounding fuel channel boxes. By reducing the coolant flow rate and reactor power, damaging impacts were eliminated, and the affected reactors could be operated until a more satisfactory solution could be implemented. Noise monitoring was used during this interim period to ensure that no further impacting occurred and also was used after the permanent "fix" was installed to confirm that impacting indeed had been eliminated.

U.S. research efforts in the application of noise and vibration analysis techniques to commercial reactors have declined markedly in recent years. In the late 1970s and early 1980s, researchers at ORNL studied and developed various aspects of noise analysis including: BWR stability monitoring; automated noise data acquisition, screening, and storage systems; core barrel and thermal shield vibration monitoring; and the establishment of a baseline noise data signature library for all types of reactors using data collected at a variety of U.S. power plants. This work represented state-of-the-art reactor noise analysis at that time, and the results of this research were quickly incorporated in vessel internals surveillance programs conducted abroad. In contrast to these previous, extensive research efforts, almost no reactor-oriented noise analysis work (with the exception of BWR stability monitoring) is being performed at ORNL today, and the same can be said of other organizations that once were centers of U.S. activity and expertise in this area. As support for this work continues to decline, research capabilities are being lost through disuse, transfer of trained personnel, and rapidly growing obsolescence and unreliability of data acquisition and analysis equipment.

4.2 GERMAN EXPERIENCE

In the FRG, neutron noise analysis and vibration monitoring of reactor internals are a regular part of plant maintenance operations. German utilities monitor both internals vibration and reactor coolant pump (RCP) shaft vibration on a continuing basis. The sensor types and locations for a typical four-loop pressurized water reactor (PWR) are shown in Fig. 2. The sensors consist of:

- 4 inductive absolute displacement sensors on the reactor vessel head flange (A-signals);
- 16 relative displacement sensors, 2 below each RCP, measuring in 2 directions and 2 near each steam generator, measuring horizontal and vertical displacement (R-signals);
- 8 ex-core neutron detectors (X-signals);
- 5 piezoelectric pressure sensors at the inlet and outlet pipes (P-signals); and
- 8 proximity (absolute displacement) probes, 2 on each RCP, measuring pump shaft displacement (W-signals).[12]

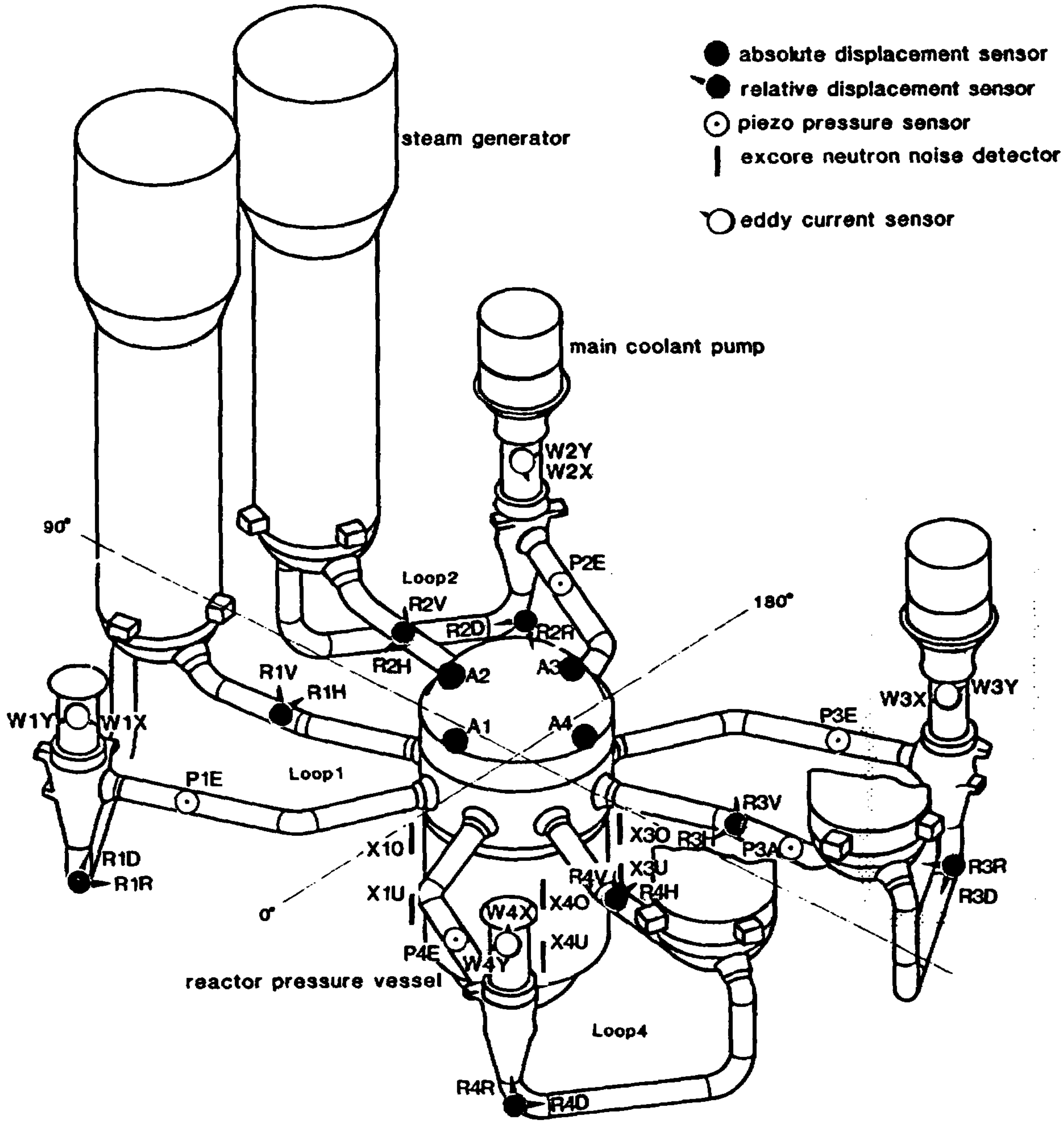


Fig. 2. Vibration and noise sensor positions of a four-loop German PWR. (*Source:* R. Sunder, Gesellschaft für Reaktorsicherheit. Reprinted by permission.)

The vibration signals are reviewed daily by plant personnel, who are thoroughly trained in noise analysis techniques. Noise experts from Gesellschaft für Reaktorsicherheit (GRS), a private research organization similar to a national laboratory in the United States, are consulted when deviations from baseline signatures or abnormal trends are detected, and they also participate in the ensuing investigations until a satisfactory conclusion is reached.

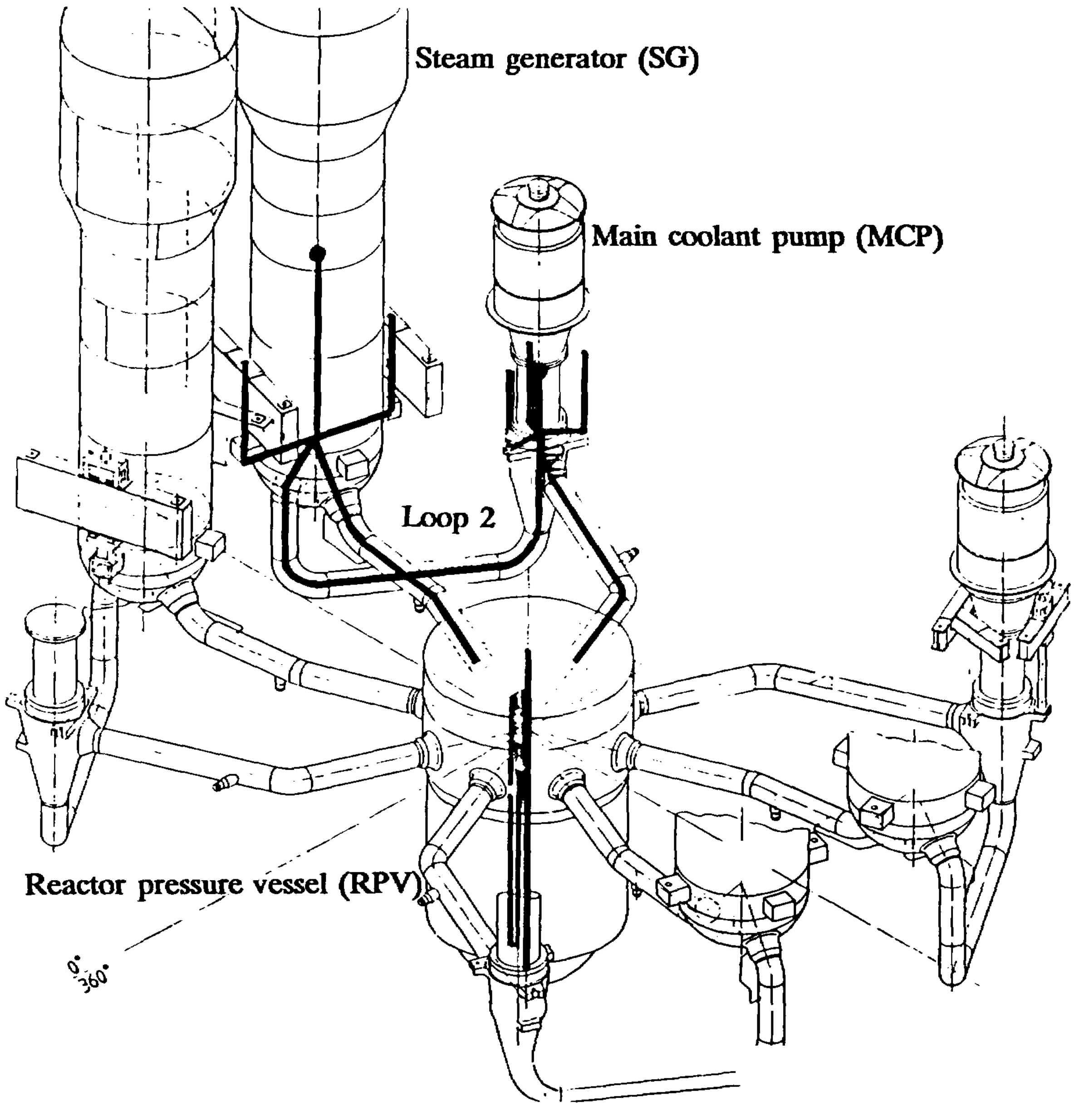
GRS has been involved in research programs aimed at improving methods for monitoring nuclear reactor components for over 15 years. These programs involve not only the reactor internals but also other parts of the primary system such as the RCPs, piping, piping supports, and steam generators. GRS also evaluates vibration measurements made periodically as part of the plant maintenance programs at German PWRs.[2]

Previous work at GRS has resulted in the solution of several vessel internals vibration problems. The most widely reported example involves using vibration monitoring to detect the relaxation of core support barrel hold-down springs.[13,14] In this case, a frequency shift in the resonance associated with the upper core barrel and core structure was observed. Results from an analytical model indicated that the most likely cause of this shift was relaxation of the core support barrel hold-down springs. New springs were ordered while the internals vibration signatures were monitored closely for signs of additional changes in structural integrity throughout the remainder of the fuel cycle. Following vessel head removal for refueling, the hold-down springs were examined, and 65 of 112 produced insufficient holding force to meet specification. The new springs were installed, and the internals vibration signatures immediately returned to normal. In this incident, a vibration monitoring program coupled with analytical model results allowed an anomaly to be detected and diagnosed and the reactor to continue operation for the remainder of the fuel cycle. Sufficient time was made available for replacement parts to be ordered, resulting in correction of the problem with minimal impact on plant operation.

More recently, GRS has been involved in monitoring for loss of preload in screws holding core former plates to their baffles. Loosening of these screws may give rise to loose parts circulating in the reactor coolant system and has caused an extended outage at one German PWR.[2] GRS researchers believe this particular degradation can also be detected by their on-line monitoring systems.

GRS has developed and tested a system for use by trained plant personnel and operators that continuously monitors vibration of the RCPs and the reactor internals. A prototype of the system, named COMOS (COndition MOnitoring System), was tested on the Grafenrheinfeld pressurized water reactor for nearly one full fuel cycle, and updated versions of COMOS are being installed in the newest Kraftwerk Union (KWU) "Convoy" plants.[2] Both frequency and amplitude of resonances are monitored to detect deviations from reference (baseline) spectra. Abnormal deviations are detected by comparing a quotient spectrum, which is calculated from current and reference spectra, to preset thresholds. The system produces no control-board alarms, but the plant operations staff reviews the analysis results daily. Abnormal spectra are referred to GRS personnel for analysis and interpretation based on results from analytical model studies. A 45-DOF finite-element model of the primary system (including the reactor vessel, internal structures, steam generator, and RCP) has been developed and validated against measured vibration data.[13] This model is shown in simplified form in Fig. 3.

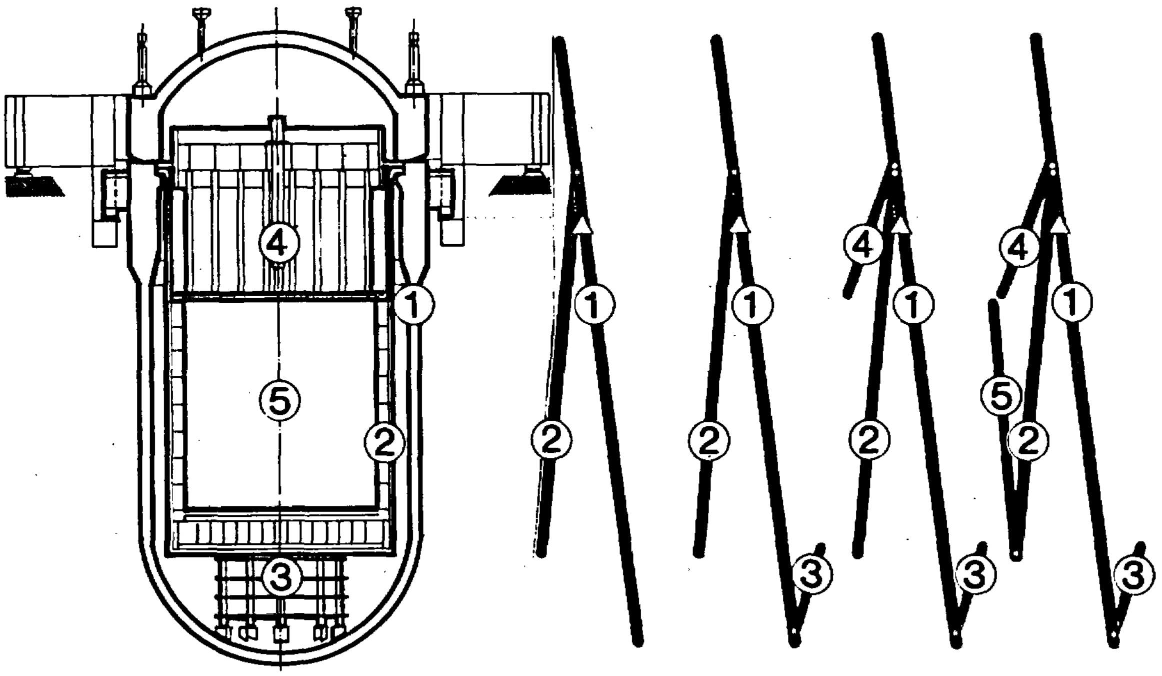
Five beams are used to represent the reactor pressure vessel (RPV) and its internals; referring to Fig. 3(b), these beams represent (1) RPV, (2) core barrel, (3) lower support structure, (4) upper plenum assembly, and (5) fuel. Figure 3(b) also shows the pinned connections joining the beam elements. Each connection has a rotational stiffness, and each beam has an associated mass distribution and flexural stiffness. The model calculates pendular, vertical, and rotational displacements of the internals.



(a) PWR primary circuit.

Fig. 3. Modeling of PWR primary circuit and reactor internals. (*Source*: V. Bauernfeind, Gesellschaft für Reaktorsicherheit. Reprinted by permission.)

The remainder of the model represents one loop of the primary system. Again, beam elements are used to model these components, allowing calculation of translation, rotation, and bending displacements. The piping and component supports are modeled using springs. In addition to natural frequency and mode calculations, the model can be used to calculate the response to applied forces, such as flow excitation. Component



(b) Rigid body model representation of RPV internals.

Fig. 3. (continued).

masses were obtained from manufacturer's data, and results from shaker tests were used to estimate the model rotational and flexural stiffness, which then were adjusted until model results closely matched measured data. After validating the model, the results can be used to study the effects of various postulated forms of mechanical degradation on internals vibration. This model was used in the previously mentioned example of relaxed core barrel hold-down springs to postulate the probable cause of the observed deviation from the baseline vibration signatures. It also has been used to determine the alarm criteria built into the COMOS system.[15] Thus, this model is a valuable tool used extensively by GRS to gain understanding of how the core internals are expected to behave when subjected to various postulated degradations. Within the limitations of the model, the understanding thus gained allows abnormal vibrations to be diagnosed and appropriate actions taken.

The German program for monitoring vibrations of primary system components, including the reactor internals, is extensive and well implemented. It has evolved to the point that vibration and neutron noise data are continuously monitored by automated systems, with daily review by plant personnel being a normal part of plant maintenance activities. The development and validation of analytical models are a keystone in this program, allowing GRS personnel to accurately interpret abnormal noise signatures so that the seriousness of any anomaly may be ascertained and appropriate actions taken.

4.3 FRENCH EXPERIENCE

A similar situation regarding noise and vibration analysis exists in France. Reactor internals condition monitoring is performed for all French plants by the Surveillance and Diagnostic Maintenance Group at Electricité de France (EDF). This group is responsible for research, development, application, and training in the areas of reactor maintenance, surveillance of reactor internals and rotating machinery, and diagnosis of abnormal vibration and loose parts. EDF operates a comprehensive monitoring program, like that in the FRG, that includes regular data collection and analysis as a part of normal plant maintenance practices.

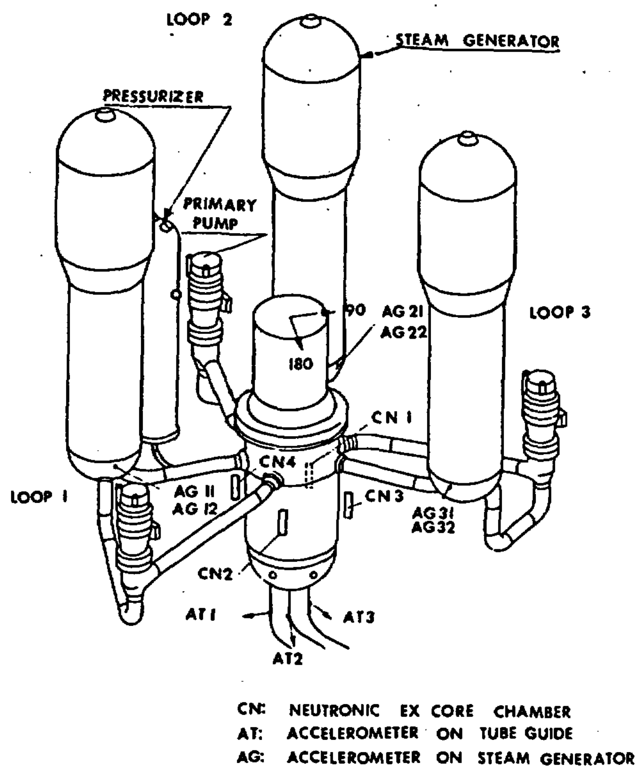
Signals used to monitor primary system components in French PWRs are obtained from accelerometers mounted on the reactor vessel, steam generators, primary system piping, and pump casings, as well as from pump shaft displacement transducers and noise signals from the in-core and ex-core neutron flux detectors.[2,16] These sensor locations as well as a block diagram of the entire monitoring system are shown in Fig. 4. The accelerometers share the dual roles of monitoring vibration and detecting loose parts. Each month, signals are collected from the ex-core detectors and from accelerometers mounted on the reactor vessel and analyzed using a spectrum analyzer and a microcomputer. The computer compares the collected signatures with baseline signatures acquired at the beginning of the fuel cycle and thus determines whether or not an anomaly is present. A more extensive analysis of all signals is performed every 3 months. The vibration data are sent to EDF, where they are transferred to a central data base. This data base includes vibration signatures obtained during hot functional and shaker tests, as well as 80 fuel cycles of operating history covering 45 reactor units (as of May 1987).[2]

In contrast to the German programs, interpretation of anomalous signatures is performed at EDF headquarters in Paris rather than at the plant sites. Interpretations are based on modeling results, results from hot functional tests, the vibration and neutron noise signatures collected periodically and stored in the data base, and experience with previously encountered anomalies.

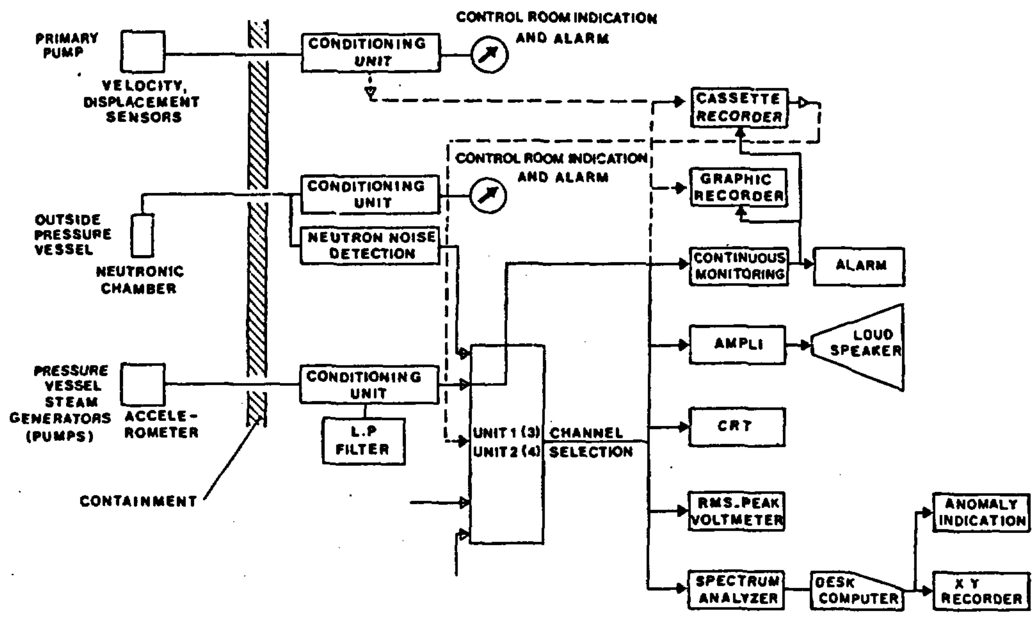
An additional unique tool available to EDF for model verification and anomaly diagnosis is the SAFRAN test loop located in Saclay.[17] SAFRAN (Fig. 5) is a 1/8th scale mock-up of the primary system of a 900 MW(e) French PWR. SAFRAN includes a detailed representation of the reactor vessel complete with internals; pressurizer; and the piping, pumps, and steam generators present in each loop. The mock-up is instrumented with 80 sensors, including pressure transducers, displacement probes to measure core barrel and thermal shield movement, and accelerometers. SAFRAN has been used to estimate damping rates for use in analytical models, to validate the model results, and to investigate directly the effect of various degradations on vibration signatures. The heavily instrumented internals allow modeshapes to be verified experimentally, a capability unavailable to other researchers.

Like the Germans, the French have been able to detect and diagnose abnormal internals vibration using surveillance and monitoring techniques. Two examples are described subsequently: the first involves detection of baffle jetting in 1981–82, and the second is a more recent occurrence involving excessive instrument tube vibration.

Baffle jetting is a phenomenon that can occur because of the gaps between the baffle plates that separate flow in the coolant downcomer from upward core flow. A pressure difference exists between the coolant on each side of the baffle; thus, the



(a) Vibration and noise sensor positions.



(b) Block diagram of monitoring system.

Fig. 4. Monitoring system in French PWRs equipped with partial thermal shield. (*Source:* C. Puyal, Electricité de France. Reprinted by permission.)

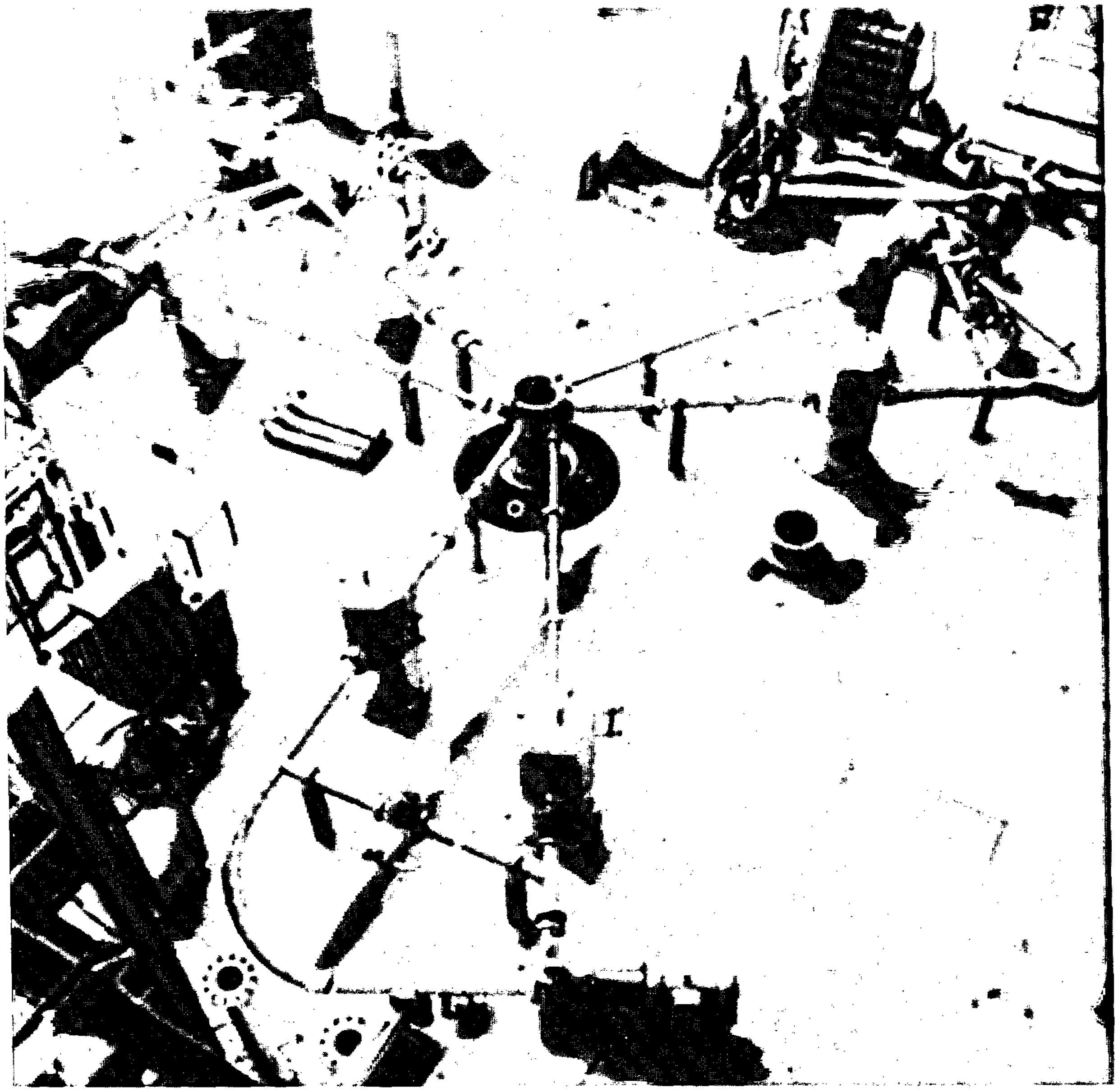


Fig. 5. SAFRAN test loop. (*Source*: J. C. Carre, Commissariat a L'Énergie Atomique. Reprinted by permission.)

presence of an unintentional gap causes a horizontal coolant "jet" to impinge against an adjacent outer fuel assembly. Baffle-jetting damage was first encountered in France in 1981 on the Bugey 2 reactor during its second fuel cycle.[16] A sudden increase in primary water activity was observed, which was traced to a cladding breach in a peripheral assembly. Two damaged fuel assemblies were found at the end of the cycle.

In response to this finding, a monitoring program based on in-core neutron noise signals was initiated by EDF in Bugey and Fessenheim (another French PWR of similar design). The measurements showed a clear anomaly, namely excessive spectral energy between 20 and 30 Hz.[16] The source of this anomaly appeared to be an assembly near the baffle jet in Bugey Unit 2. Results of the monitoring program allowed several conclusions to be drawn. First, baffle jetting may not always be detectable, even in assemblies directly in the jet's path, if the outermost fuel pins on which the jet impinges do not transmit their vibration to the remainder of the fuel assembly. Second, baffle jetting may sometimes cause a fuel assembly adjacent to the one actually being impinged upon to vibrate, thereby generating excessive neutron noise. Finally, in any event the vibration signature anomaly is detectable only by sensors positioned close to the jet location. Thus, noise signatures from in-core detectors are probably necessary to detect the presence of baffle jetting and thereby allow appropriate maintenance to be scheduled during the next refueling.

A more recent problem experienced in many 1300 MW(e) French plants is excessive instrument tube vibration caused by flow turbulence below the core support plate.[2,18] These vibrations eventually lead to perforation of the tube at or above the core support plate, allowing cold water to impinge on adjacent fuel rods and thereby cause cladding failure. Several methods of stiffening the connection between the instrument thimble and the core support plate have been used to reduce the vibrations. The effectiveness of stiffening the instrument-tube/core-support-plate connection was verified by analyzing vibration data from accelerometers mounted on the tubes. The experience gained from this investigation allowed a new approach to this problem. Accelerometers are now mounted on all instrument tubes and their vibration is monitored daily. When incipient failure of a tube is predicted, the tube is replaced as soon as possible.

The French, like the Germans, have implemented a comprehensive and effective program for monitoring the components in the PWR primary coolant systems. Vibration and neutron noise data are monitored as a normal part of plant maintenance, enabling component degradation to be detected and providing additional information that can be used to identify the degraded component.

4.4 COST EFFECTIVENESS

It is evident from these examples and others reported in the literature that internals condition monitoring and analysis research programs can provide valuable information to utilities and licensing authorities on nuclear plant operability and condition. Reliable estimates of benefit-to-cost ratios are not so easily found, however. EDF has recently estimated the benefit-to-cost ratio of their monitoring and noise research programs to be ~2:1.[19] This figure is based on actual costs and the estimated value of savings accumulated between 1976 and 1986 attributable to the reactor noise and vibration monitoring programs. Since these EDF programs include vibration, neutron noise, and loose parts monitoring, the cited 2:1 benefit-to-cost ratio reflects the combination of these three activities, for which a separation has not been provided. The cumulative cost is the total spent on design and development, equipment, personnel training, and routine data collection and analysis. Benefits were calculated using estimates of the damage that would have occurred had the monitoring system not been present. Damage, repair, and outage estimates were based on similar incidents that had occurred at other EDF facilities, and the financial benefits include the estimated repair and outage costs.

Because of the similarity in plant and equipment design between European and U.S. plants, it seems reasonable to expect that reactor vessel internals condition monitoring programs applied in the United States would yield benefits comparable to those experienced abroad. Based on European experience and an emerging consensus among U.S. noise analysts, guidelines have been developed to assist U.S. utilities in initiating and executing an internals monitoring program.[20] These guidelines are reviewed in Sect. 5.

5. UTILITY GUIDELINES FOR THE IMPLEMENTATION OF INTERNALS MONITORING PROGRAMS

This section describes some aspects of the implementation of an internals condition monitoring/neutron noise analysis program by U.S. utilities. It is recognized that although a well-designed and well-implemented internals monitoring program can be an asset to plant operation and safety, a poorly organized or poorly implemented program can actually be detrimental to plant operation, producing low-quality data that may lead to false alarms under normal conditions or lack of alarms under abnormal conditions. Some important considerations of noise monitoring program implementation are: (a) program organization, (b) integration of the program into plant or utility operations, (c) formulation of data acquisition and analysis procedures, and (d) personnel training in noise and vibration analysis techniques.[20] This section (5) closely follows Sect. 3 of ref. 20.

Reactor internals condition monitoring/neutron noise analysis programs are typically organized at the utility engineering level or plant operations level, or they are dependent on expertise supplied by outside consultants. Table 3 lists some of the advantages and disadvantages inherent in each type of organization.

Organization at the utility engineering level is most advantageous for utilities having multiple reactor units or when personnel or equipment is limited. This level of organization reduces duplication of equipment and personnel positions, but communication between plant personnel and the noise/vibration analyst may be compromised. If permanent access to plant signals is not provided, data acquisition and quality assurance (QA) activities may become costly and inefficient.

If a utility has only one plant or can afford to support programs at each plant site, then organization at the plant level may be advantageous. Data acquisition, QA, and integration of the program into plant operations are thereby simplified. However, communication between noise/vibration analysts at different plants and between the plant programs and design or analysis groups at the utility engineering level must be ensured. This is especially important if a utility operates several units of similar design.

Specialist consultants are useful when plant personnel are unable (or untrained) to solve a particular noise analysis problem. It is nonetheless desirable for the utility to maintain its own in-house expertise to evaluate the results and understand the interpretations and recommendations of the consultants. The utility must also take steps to ensure that adequate information is provided to the consultant so that he or she gains a proper appreciation of relevant plant history as well as the current problem.

It should be pointed out that the levels of organization just described may be applied to different aspects of the same program. The German and French programs provide examples of this. In both the FRG and France, data collection, screening, and integration with plant activities are performed at the plant level. With EDF, central data storage, analysis, and research are all performed at the utility level, whereas in the FRG, GRS provides the analysis and research capability. The monitoring programs in place at Northeast Utilities and Omaha Public Power District both carry out plant noise analysis programs, and both have service arrangements with Combustion Engineering, which provides diagnostic and analysis services.

Table 3. Advantages and disadvantages of reactor noise program organization[20]

Organization level	Possible advantages	Possible disadvantages
Utility	Fewer personnel Less equipment duplication Communication with design groups Pooling of analysis results	Manpower shortages Lack of: plant access signal access communication with plant
Plant	Knowledge of plant activities Knowledge of plant instrumentation Signal access Personnel availability	More training required More personnel required Equipment duplication Lack of: communication among plants communication with utility communication with design and analysis groups
Consultant	May be called when needed May supply own equipment Fast problem solution Knowledge and experience Low short-term costs	Limited problem solution Knowledge leaves with consultant Lack of: results verification plant access knowledge of plant activities communication with plant or utility

The effectiveness of a vessel internals condition monitoring/neutron noise analysis program depends to a large extent on how well the program is integrated into overall plant operations. Communication between noise/vibration analysts and the plant is vital if the analyst is to know about operational changes or problems that may have an effect on noise signatures. Likewise, the plant staff must be aware of abnormal noise signatures and their interpretations if corrective action is to be taken. Good communication usually requires that the noise/vibration analyst and plant personnel jointly review results at least quarterly (preferably monthly).

Procedures must be developed to ensure that noise data acquisition and analysis are carried out properly and are effectively integrated with plant activities. Procedure formats are usually dictated by utility guidelines. Well-formulated procedures for data acquisition and analysis will include the purpose of the procedure, execution time and personnel requirements, precautions, limitations and actions, prerequisite plant conditions, required equipment, data to be collected, acceptance criteria, and any special instructions.

Highly trained noise/vibration analysts with extensive analysis experience are essential to the success of an internals condition monitoring/neutron noise analysis program. Based on experience at ORNL, the subjects the noise/vibration analyst should be familiar with are listed in Table 4. Although the analyst should assume responsibility for all aspects of the internals condition monitoring program, it is possible to have certain aspects of the program such as data collection and reduction performed by personnel not trained specifically in noise or vibration analysis.

Table 4. Desired knowledge for reactor noise analysts[20]

Random processes
Random signal analysis
Fourier transforms
Statistics
Nuclear plant instrumentation
Digital signal processing
Fast Fourier transform (FFT) algorithms
Use of spectrum analyzers
Use of tape recorders
Fluid flow
Heat transfer
Reactor dynamics
Structural analysis
Electronics
State-of-the-art noise analysis

6. CONCLUSIONS

Vibration monitoring/neutron noise analysis has progressed over the past 20 years from a research topic to a practical tool that can be (and is) used to obtain information on the condition of a nuclear plant's reactor vessel internals and other primary coolant system components. Monitoring programs implemented in both France and the FRG have demonstrated the benefits of these methods, and these programs can be used by U.S. utilities as models for constructing their own reactor vessel internals condition monitoring programs. The success of such programs in the United States would depend on the priority utilities give them. If the guidelines outlined above and discussed in greater detail in ref. 20 are followed during the creation and operation of a reactor vessel internals condition monitoring program, one can expect that economic and safety benefits similar to those obtained by the French and German programs will be realized. This would give U.S. utilities a tool with which to improve daily plant operation, monitor this one aspect of plant structural aging, perform more effective maintenance, and provide a portion of the technical basis necessary for evaluating the feasibility of extended plant operation without replacement of reactor vessel internal structures.

ACKNOWLEDGMENT

The authors would like to thank the Electric Power Research Institute and individuals representing U.S. reactor manufacturers and nuclear utilities for their valuable constructive criticism of a draft version of this report.

REFERENCES

1. J. S. Mitchell, *An Introduction to Machinery Analysis and Monitoring*, Pennwell Publishing Co., Tulsa, Okla., 1981.

2. F. J. Sweeney, *Oak Ridge National Laboratory Foreign Trip Report*, ORNL/FTR-2537, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, April 1987.

3. B. Damiano, *Reactor Internals Surveillance for Plant Life Extension*, U.S. Nuclear Regulatory Commission informal letter report ORNL/NRC/LTR-86/11, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, April 1986.

4. F. J. Sweeney and J. A. Renier, *Sensitivity of Detecting In-Core Vibrations and Boiling in Pressurized Water Reactors using Ex-Core Neutron Detectors*, U.S. Nuclear Regulatory Commission report NUREG/CR-2996, Oak Ridge National Laboratory, 1984.

5. G. P. Horne, "Recent Experience with Noise Analysis at Oconee Nuclear Station," *Prog. Nucl. Energy 15,* 395–402 (1984).

6. R. S. Johnson, *Neutron Noise Analysis Program for Surveillance of Reactor Internals Vibration*, TR-NF-1022, Duke Power Company, Charlotte, N.C., 1985.

7. J. W. Quinn, J. A. Stevens, and C. J. Sterba, "The Use of Ex-Core Neutron Noise at Near-Zero Reactor Power to Monitor Thermal Shield Support System Integrity," *Prog. Nucl. Energy 21,* 127–33 (1987).

8. F. J. Sweeney and D. N. Fry, "Thermal Shield Support Degradation in Pressurized Water Reactors," *Flow-Induced Vibration - 1986*, PVP-Vol. 104, American Society of Mechanical Engineers, New York, 1986.

9. B. T. Lubin, R. Longo, and T. Hammel, "Analysis of Internals Vibration Monitoring and Loose Part Monitoring System Data Related to the St. Lucie 1 Thermal Shield Failure," *Prog. Nucl. Energy 21*, 117–26 (1987).

10. F. R. Nandy, "Concerns Regarding Thermal Shield at SONGS 1," letter from Southern California Edison Co. to USNRC, Mar. 21, 1989, Enclosure 1.

11. D. N. Fry, R. C. Kryter, and M. V. Mathis, *Summary of ORNL Investigations of In-Core Vibrations in BWR-4s*, ORNL/NUREG/TM-101, Oak Ridge National Laboratory, 1977.

12. R. Sunder, "On-Line Monitoring of Neutron Noise and Vibration Signatures; Operating Experience with COMOS in German PWRs," 1988 Informal Meeting on Reactor Diagnostics, Orlando, Fla., June 8–10.

13. R. Sunder and D. Wach, "Reactor Diagnosis using Vibration and Noise Analysis in PWRs," in *Operational Safety of Nuclear Power Plants* I, International Atomic Energy Agency, Vienna (1984).

14. W. Bastl, R. Sunder, and D. Wach, "The Influence of Noise Diagnostic Techniques on the Safety and Availability of Nuclear Power Plants," *Prog. Nucl. Energy 15,* 513–24 (1984).

15. V. Bauernfeind, "Vibration Monitoring of a Four-Loop PWR: Model Investigations of the Sensitivity of the Monitored Signals on Mechanical Failures," *Prog. Nucl. Energy 21,* 247–54 (1987).

16. C. Puyal, A. Fernandes, and C. Vincent, "Primary System Surveillance and Diagnostics of PWR Power Plants in France," 5th Power Plant Dynamics, Control, and Testing Symposium, Knoxville, Tenn., Mar. 21–23, 1983.

17. J. C. Carre et al., "PWR Internals Vibrational Mode Shapes Calculation and Tests," *Prog. Nucl. Energy 1,* 353–62 (1977).

18. C. Puyal et al., "Solution to Thimble Vibrations of French and Belgian Reactors using Accelerometers and Neutron Noise," 19th Informal Meeting on Reactor Noise, Rome, June 4–6 1986.

19. B. Michel and C. Puyal, "Operational and Economical Experience with Vibration and Loose Parts Monitoring Systems on Primary Circuits in PWRs," *Prog. Nucl. Energy 21,* 469–74 (1987).

20. F. J. Sweeney, *Utility Guidelines for Reactor Noise Analysis*, EPRI NP-4970, Electric Power Research Institute, Palo Alto, Calif., 1987.

NUREG/CR-5479
ORNL/TM-11398
NRC Dist. Category RV

INTERNAL DISTRIBUTION

1. H. R. Brashear
2. D. A. Casada
3. N. E. Clapp
4-8. B. Damiano
9. B. G. Eads
10. D. M. Eissenberg
11. E. C. Fox
12. D. N. Fry
13. W. L. Greenstreet
14. W. R. Hamel
15. H. D. Haynes
16. C. M. Horak
17-21. R. C. Kryter
22. J. March-Leuba
23. D. W. McDonald
24. D. R. Miller
25. J. C. Moyers
26. J. A. Mullens
27. L. C. Oakes
28. C. E. Pugh
29. C. M. Smith
30. F. J. Sweeney
31. R. E. Uhrig
32. R. T. Wood
33. A. Zucker
34. J. B. Ball, Advisor
35. P. F. McCrea, Advisor
36. T. B. Sheridan, Advisor
37-38. Laboratory Records Department
39. Laboratory Records ORNL-RC
40-41. Central Research Library
42. Y-12 Technical Reference Sect.
43. ORNL Patent Section
44. I&C Division Publications Office

EXTERNAL DISTRIBUTION

45. V. Bauernfeind, Gesellschaft für Reaktorsicherheit mbH, Forschungsgelände, 8046 Garching, Federal Republic of Germany.
46. Dennis Berry, Sandia National Laboratory, Division 6419, 1515 Euband SE, Albuquerque, NM 87123.
47. J. C. Carre, Commissariat A L'Énergie Atomique DEDR/DEMT - C.E.N. Saclay 91191 GIF-sur-YVETTE Cedex, France.
48. James Chardous, GPU Nuclear Corporation, 1 Upper Pond Rd., Parsippany, NJ 07054.
49. C. Child, Yankee Atomic Electric Company, 590 Main Street, Bolton, MA 01740.
50. Robert C. Colley, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303.
51-55. W. S. Farmer, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Electrical and Mechanical Engineering Branch, 5650 Nicholson Lane, Rockville, MD 20852.
56. Joseph Gilman, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303.

57. Tim Griesbach, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303.
58. Dennis L. Harrison, U.S. Department of Energy, NE-42, Washington, DC 20545.
59. Marcos L. Herrera, General Electric Nuclear Operations, 175 Curtner Ave., San Jose, CA 95125.
60. John Hosler, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303.
61. A. B. Johnson, Battelle-PNL, MS P8-10, P.O. Box 999, Richland, WA 99352.
62. Robert C. Jones, NRR/SRXB, White Flint 8E23, U.S. Nuclear Regulatory Commission, Washington, DC 20555.
63. Lambros Lois, NRR/SRXB, White Flint 8E23, U.S. Nuclear Regulatory Commission, Washington, DC 20555.
64. Alexander Marion, Nuclear Management & Resources Council, 1776 NW Eye St., Suite 300, Washington, DC 20006-2496.
65. C. W. Mayo, Science Applications International Corp., 2550 Murrell Rd. Unit B, Suite 4, P.O. Box 2557, Lynchburg, VA 24501.
66. C. Michelson, Advisory Committee on Reactor Safeguards, 20 Argonne Plaza, Suite 365, Oak Ridge, TN 37830.
67. L. F. Miller, The University of Tennessee, Department of Nuclear Engineering, 315 Pasqua Building, Knoxville, TN 37996.
68. Victor Miselis, Westinghouse Electric Corporation, P.O. Box 355, Pittsburgh, PA 15230.
69. G. Allen Morris, Tennessee Valley Authority, CST 1C 132A, 1101 Market St., Chattanooga, TN 37402-2801.
70. Joseph V. Persio, Northeast Utilities Service Company, MS RH B4F3, P.O. Box 270, Hartford, CT 06141.
71. Lawrence E. Phillips, NRR/SRXB, White Flint 8E23, U.S. Nuclear Regulatory Commission, Washington, DC 20555.
72. C. Puyal, Electricité de France, Direction des Etudes et Recherches, Départment Surveillance Diagnostic Maintenance, 6, quai Watier - B.P. 49, 78401 Chatou, France.
73. James E. Richardson, NRR/DET, White Flint 8H3, U.S. Nuclear Regulatory Commission, Washington, DC 20555.
74. Norman R. Singleton, Westinghouse Electric Corp., P.O. Box 2728, Pittsburgh, PA 15230-2728.
75. George Sliter, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303.
76. R. Sunder, Gesellschaft für Reaktorsicherheit mbH, Forschungsgelände, 8046 Garching, Federal Republic of Germany.
77. J. H. Taylor, Brookhaven National Laboratory, Bldg. 130, Upton, NY 11973.
78. H. J. Thailer, Pacific Gas and Electric Co., 333 Market St., Room A1205, San Francisco, CA 94106.
79. J. A. Thie, Consultant, 12334 Bluff Shore Dr., Knoxville, TN 37922.
80. J. W. Tills, Institute for Nuclear Power Operations, 1100 Circle 75 Parkway, Atlanta, GA 30339-3064.
81. B. R. Upadhyaya, The University of Tennessee, Department of Nuclear Engineering, 315 Pasqua Building, Knoxville, TN 37996.

82. M. Vagins, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Chief, Electrical and Mechanical Engineering Branch, Division of Engineering, 5650 Nicholson Lane, Rockville, MD 20852.
83. J. P. Vora, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Electrical and Mechanical Engineering Branch, 5650 Nicholson Lane, Rockville, MD 20852.
84. Dieter Wach, Gesellschaft für Reaktorsicherheit mbH, Forschungsgelände, 8046 Garching, Federal Republic of Germany.
85. G. H. Weidenhamer, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Electrical and Mechanical Engineering Branch, 5650 Nicholson Lane, Rockville, MD 20852.
86. Joseph Weiss, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303.
87. J. S. G. Williams, Tennessee Valley Authority, P.O. Box 2000, Decatur, AL 35602.
88. Raymond P. Wood, Duke Power Company, P.O. Box 33189, Charlotte, NC 28242.
89. G. L. Zigler, Science & Engineering Associates, Inc., P.O. Box 3722, Albuquerque, NM 87190.
90. Gilles Zwingelstein, Electricité de France, Direction des Etudes et Recherches, Départment Surveillance Diagnostic Maintenance, 6, quai Watier - B.P. 49, 78401 Chatou, France.
91. Office of Assistant Manager for Energy Research and Development, Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN 37831.

92-93. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831.

94. Given distribution as shown in NRC category RV (10 - NTIS).

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/CR-5479
ORNL/TM-11398

2. TITLE AND SUBTITLE
Current Applications of Vibration Monitoring and Neutron Noise Analysis:

Detection and Analysis of Structural Degradation of Reactor Vessel Internals from Operational Aging

3. DATE REPORT PUBLISHED

MONTH	YEAR
February	1990

4. FIN OR GRANT NUMBER
B0828

5. AUTHOR(S)
B. Damiano, R.C. Kryter

6. TYPE OF REPORT

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Oak Ridge National Laboratory
Oak Ridge, TN 37831

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

This report, which was prepared under the Nuclear Plant Aging Research Program sponsored by the United States Nuclear Regulatory Commission, discusses the application of vibration monitoring and neutron noise analysis for monitoring light water reactor (LWR) vessel internals. The report begins by describing the effects of loss of structural integrity on internals vibration and how sensible parameters can be used to detect and track the progress of degradation. This is followed by a description and comparison of vibration monitoring and neutron noise analysis, two methods for monitoring the mechanical integrity of reactor vessel internal components. The major section of the report describes the status of reactor vessel internals condition monitoring programs in the United States, Federal Republic of Germany, and France, three countries having substantial commitments to nuclear power. The last section presents guidelines for U.S. utilities wishing to establish reactor internals condition monitoring programs.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

reactor vessel internals
vibration
neutron noise analysis
structural degradation

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
(This Page)
unolassified
(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

SPECIAL FOURTH-CLASS RATE
POSTAGE & FEES PAID
USNRC

PERMIT No. G-67

NUREG/CR-5479