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THE CASE FOR PERIODIC MONITORING OF NUCLEAR PLANT NOISE SIGNALS: SAFETY AND OPERATIONAL SIGNIFICANCE*

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December 1991

BACKGROUND

The extraction of useful information from the "noise" component of nuclear plant signals (such as neutron flux, vessel pressure, coolant flow and temperature, accelerometers and seismometers, etc.) is a well developed science whose utility as a diagnostic tool for commercial power reactors has been firmly established by both theoretical justification and practical application over the past twenty or more years. Indeed, entire books have been devoted to the subject of "noise analysis," six international OECD/IAEA-sponsored symposia have been held to date on the subject, and many nuclear plants throughout the world acquire and analyze noise data on a regular and continuing basis as an integral part of their overall operational strategy for assuring continued plant safety and as the basis for condition-based maintenance activities[1] (see Appendix A, Session 1).

As a result of a recent review of NRC:NRR programs at ORNL, NRC management has instructed the staff to develop guidance for ORNL's noise-related work; in particular, to put ORNL-proposed development of noise-based data collection/processing/retrieval capabilities into perspective from a regulatory viewpoint and thus help assess the range of future licensing actions that might be facilitated by the construction and continuing maintenance of a reactor noise signature library and associated data handling tools at ORNL. Our answers to the following five questions (which were posed by NRC staff) are offered as an aid to development of the aforementioned regulatory perspective.

QUESTIONS AND ANSWERS

> *Question 1: What are the specific characteristics of noise analysis (particularly,* ***neutron*** *noise analysis) that permit the determination of plant operating safety margins?*

The special characteristic of neutron noise analysis that makes it valuable in the determination of plant operating safety margins is that its use permits the monitoring of safety-significant phenomena that would be difficult or impossible to monitor by means of conventional instruments and more direct means. As examples, one can cite (1) the presence of excessive fuel element vibrations within the core, (2) changes in the temperature coefficient of reactivity, (3) progressive structural degradation of the core barrel and thermal shield in a PWR, (4) estimation of coolant void fraction, and (5) inference of stability margin in a BWR. A partial list of ways in which noise analysis has been used to diagnose various phenomena occurring during operation of nuclear power plants is given in Table 1, along with the plant signal(s) required. Two special advantages enjoyed by noise analysis

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Table 1. Applications of noise analysis methods to the diagnosis of various phenomena in operating nuclear reactors (adapted from ref. 2)

Phenomenon	Signals*	Description
Boiling instability	N	A tendency toward reactor oscillation is indicated by changes of a resonance in the spectrum
Dynamic modeling	F,N,P,T	Transfer functions between pairs of signals are obtained, and system time constants are deduced
Steam velocity and void fraction measurement	N	The transit time between in-core detectors is determined; a void fraction can be deduced if volumetric flow is known
Core barrel motion	N	Ex-vessel chambers are sensitive to the changing water gap between the barrel and reactor vessel
PWR fuel motion	N	Relative transverse or vertical motion of fuel and detectors is sensed
Thimble vibration	N	An in-core chamber moves in a flux gradient
Individual fuel rod vibration	N,T	Several loose rods generate anomalous reactivity and temperature noise
Pellet oscillation	N,T	Loose pellets shifting within the cladding cause local flux and temperature changes
Vibration of vessel internals	D	Flow excitation preoperational tests use specially installed motion transducers
Loose parts	S	Sounds emanate from contacting metals
Boiling detection	N,P,S,T	Random noise is created by local disturbances of changing vapor bubbles
Control rod anomalies	N	Subtle details of rod movements affect reactivity
PWR temperature coefficient changes	N	The temperature coefficient relates temperature noise to measured reactivity noise
Flow blockage	T	Changing characteristics of enhanced exit temperature noise are used to detect blockage
Downcomer steam voids	N	Bubbles between the core and ex-vessel chambers vary the latters' signals

*D, displacement, velocity, or acceleration; F, flow; N, neutron flux; P, pressure; S, sound; ST, strain; and T, temperature.

are that (1) existing instrumentation can usually be used, and (2) monitoring can be accomplished without disturbing normal plant operations, since noise techniques focus on the observation of naturally occurring fluctuations that are inherent in the normal operation of the reactor and its auxiliary systems and do not require external stimuli.

Since sensors specifically dedicated to the measurement of the above safety-significant phenomena

are *not* provided in a plant's normal instrumentation complement (and, moreover, might not be able to withstand the harsh local environment for long if they were to be installed), ingenuity and sophistication in the data analysis and interpretation must be exercised to compensate for the lack of direct, location-of-interest sensing capability. Table 2 gives an example of the trade-offs that need to be considered in selecting appropriate sensors for a given task—in this case, the study of relative motion between the reactor fuel elements and their surrounding structures.[2]

Table 2. Comparison of experimental techniques used to study relative motion of fuel and its immediately surrounding structure (from ref. 2)

Technique	Advantages	Disadvantages
Inspection	Already a part of plant routines	A delayed discovery of a problem and therefore a delayed remedy
In-vessel motion transducers	Most direct	Not currently convenient or considered desirable except during preoperational testing
Ex-vessel accelerometers	Easily added instrumentation	Difficult to detect excessive motion not accompanied by fuel-structure contacting
In-core fission chambers	Existing instrumentation	Needs substantial modeling and calculational support for quantitative results

One disadvantage of noise analysis used in a regulatory context is that expert data interpretation is required to realize detection and classification of abnormal behavior. Secondly, mere *recognition* of a potential problem falls short of being satisfactory from a regulatory point of view: a *measure of problem severity* (or time to failure) is also needed, and this often requires the development of a mathematical model which attempts to relate changes in the noise signal(s) to (causative) changes in the reactor system in both a qualitative and quantitative way. Such relationships have been developed[3,4] for a variety of reactor types and for a fairly large number of operational/aging problems that have been encountered worldwide over the last twenty or more years (refer to our response to Question 4). If such modeling is thought to be impractical, however, an alternative and eminently workable approach is to use the wealth of data that can be accumulated throughout a plant's operating history (particularly in its early years, when systems were nearly new and thus presumably in prime condition) to establish the degree of variation in the characteristics (often age-related) of key plant signals that must be accepted as "normal." Data accumulated during periods in which the plant was experiencing some later-identified problem are similarly useful in defining signal characteristics that would need to be classified as "abnormal." Taken singly or together, such observations allow the construction of a set of discriminants whose collective central values and ranges of variation define "normalcy" for the plant, in much the same way as electrocardiogram features, blood and urine chemistry analyses, blood pressure and heart rate, pulmonary capacity, hearing frequency/amplitude range, etc., serve to describe the "normal" condition of a human. More

detail is provided in our answer to the next question, where the *trend* of these characteristics over relatively long periods of time is the information of interest.

> *Question 2: How can noise-based methods (neutron noise in particular) be applied to the process of plant life extension?*

The process of extending a nuclear plant's operational life beyond the 40 calendar years assumed in the original licensing documents involves demonstrating that, even though certain age-related material degradation processes take place over the years (in many instances, degradations that may be exacerbated by the presence of additional stressors such as long-term exposure to relatively high temperatures, moisture/humidity, radiation fields, vibration and shock, pressure surges, high-cycle fatigue, repeated testing, etc.), *the reactor nonetheless continues to maintain its design safety margins* and therefore can continue to be operated without undue risk to the plant workers and the general public.

As explained in our answer to Question 1, a program of noise monitoring can be useful for establishing–in support of plant life extension–the *relative constancy* of certain key safety-related plant characteristics (electro/mechanical, thermal/hydraulic, etc.) even as the plant approaches the end of its initial licensed period. Such establishment makes a strong case for the conclusion that the plant condition is "as good as new," and can be accomplished by sampling, periodically, a set of carefully chosen signals (among them, ex- and in-core neutron fluxes), then processing these signals to a form in which quantitative measures of normalcy can be extracted and any early signs of abnormality or incipient failure will be made evident. Thus, the first three steps of this performance tracking activity are periodic data acquisition, data processing/condensation, and feature recognition/parameter extraction. Clearly, a learning period (encompassing, it would be hoped, a substantial portion of the plant's early and mature life) is needed, during which the monitoring system will learn, as accurately as possible, the "normal" characteristics of the signals selected for tracking. The term "monitoring system" is used here in a broad sense: in an on-line system it consists of a combination of hardware and software, whereas in off-line monitoring, human brains comprise most of the system. The existence of "normal" process behavior during the learning period is, in fact, an hypothesis upon which the subsequent monitoring is based, as explained previously.

In many cases, it is useful to compute the signals' power spectra and closely related frequency-domain quantities such as phases and coherences. For automated monitoring it is often desirable to condense these detailed spectra into a small number of quantities that are characteristic of the full spectral distributions. Such select representative quantities can then be used as discriminants for the actual monitoring process.[5]

The establishment of these discriminants is the fourth step of the performance tracking activity. During the learning phase, the "normal" values of the discriminants are determined as accurately as possible. Then in the monitoring phase, the discriminant values are compared to the normal values, and a decision for normality or abnormality is made on the basis of alert and alarm limits, along with statistical measures of historic variability.

But how does one establish such limits? During the learning period, the behavior of the discriminants–particularly their fluctuations from sampling interval to sampling interval–is noted and used to adjust the alarm levels so as to avoid too high a frequency of spurious alarms. Typically,

noise-based monitoring systems in use today do not automatically intervene in the process (i.e., cause a power setback or scram) if an alarm level is exceeded. An exception occurs in the field of BWR stability, where the BWR Owners' Group has proposed to the NRC the addition of an automatic reactor scram upon detection of an unstable condition. This instability would be detected via noise analysis of local power range monitor (LPRM) signals. Establishing the correct setting for alert and alarm limits can be difficult in practice because the actual safe operation limits for the process parameters and variables are seldom, if ever, known (it is, of course, not feasible to determine them experimentally by means of intentional introduction of unsafe operating conditions or degraded reactor components).

Ultimately, then, the effective use of noise monitoring as a basis for plant life extension requires an extensive set of data with which to develop trends in the behavior of a plant that can be "seen" through noise analysis. In addition, good engineering judgment must be exercised, both with respect to the definition of "normal" operational characteristics and to the setting of alert and alarm limits. It should be understood, too, that in most cases noise diagnostic results would not be used alone, but rather in conjunction with other performance measures and trouble indicators to confirm continuing reactor system "health" and maintenance of required safety margins, and thereby to establish a basis for continued plant operation beyond the initial 40-year licensed period.

> *Question 3: In what manner can NRC make use of the noise signatures acquired routinely by a number of utilities in assessing both plant-specific problems and issues that are of widespread concern throughout the industry?*

While it is true that some plant difficulties are truly one-time occurrences having relevance only to that single plant, examination of the technical literature in this area shows that many of the investigations in which noise analysis has played a role over the past 20 years (e.g., BWR-4 instrument tube vibrations, baffle jetting, PWR core barrel/thermal shield structural degradation, BWR stability margin confirmation) have, in fact, affected entire classes of reactor designs. Moreover, problems continue to occur.[6] Therefore, noise signatures—particularly those associated with the problems cited above—tend to be broadly applicable to reactors other than just those in which the problem(s) occurred, so long as the reactors are of similar physical size and construction.* These *generic* signature properties are precisely the reason that the idea of an extensive, but clearly not all-inclusive, library of plant signatures makes good technical sense.

To develop a thorough understanding of generic excitations such as flow-induced vibration, correlation equations may need to be formulated to build a bridge between structural vibrations and measurable neutron spectrum characteristics. These correlation equations are obviously dependent to some extent on plant design details. Once these relationships are established, however, the mechanical integrity of vessel internals can be ascertained with some degree of confidence using neutron noise measurements.

The practicality of a *generic* approach depends somewhat on the availability of suitable

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*Exact frequencies of resonances, for example, may differ because of differing mechanical details, but the general features of a particular problem are likely to be the same from plant to plant.

instrumentation in today's plants. In this regard, Figure 1 shows the general locations of sensors that are fairly standard in PWRs and BWRs and, in addition, are of interest to noise studies because of the information that is potentially extractable from their signals.[7] Though generally present as permanently installed (as opposed to startup/commissioning) instrumentation in the current generation of LWR plants, these sensors do not necessarily have equal potential for noise analysis. One researcher's rankings[8] of the inherent information content of various sensors (and, accordingly, their general usefulness for noise analysis) and the historical utility of various noise-based surveillance activities are given in Table 3.

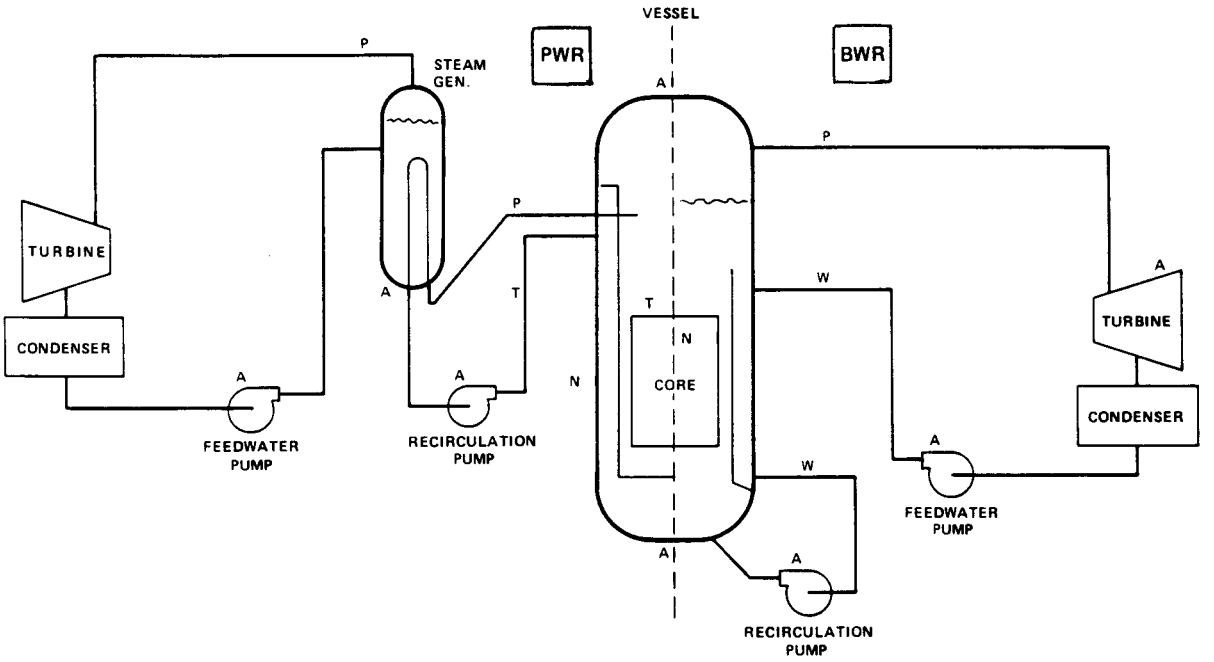

Fig. 1. Principal components of a PWR (left half of vessel and figure) and a BWR (right half of vessel and figure), and types of transducers useful for their noise information: A, accelerometer; P, pressure transducer; N, neutron detector; T, thermocouple; and W, flowmeter. This figure is excerpted from ref. 7.

Generalizing the findings from a large number of researchers reporting at conferences such as the Specialists' Meeting on Reactor Noise (SMORN) series, the following conclusions can be drawn regarding the utility of various reactor signals:

- Sensors of neutron flux and mechanical motion have seemingly yielded the largest number of practical applications for noise analysis of dynamic stability and primary coolant system component degradation.

- Information common to more than one sensor signal (obtained, for example, by computing the cross-correlation function or the cross-power spectral density function, along with the joint amplitude probability density function) is generally more useful (and more trustworthy) than information obtained from an *individual* sensor's noise. Analyzing the signals from dissimilar transducers for mutual information is an especially helpful approach.

Table 3. Rankings (approximate order of benefit to LWR safety) of sensors useful for noise analysis and of noise surveillance areas (adapted from ref. 8)

A. Sensors Sensor Type–Ranked According to Inherent Information Content	B. Areas Surveillance Area–Ranked According to Past Frequency of Usefulness	% of Incidents Cited in Table 5 of ref. 8
In-core neutron flux detector	Coolant flow anomalies	24
Ex-core neutron flux detector In-core thermocouple	Other neutronic/thermal/hydraulic performance anomalies	16
In-vessel differential pressure sensor	Excessive fuel motion	10
Primary pressure sensor	Other primary system structural motions	45
Vessel accelerometer Loop flowmeter	Improper performance of safety-grade pumps and valves Detached and loose parts	3
Loop temperature sensor	Leaks	
	Instrument integrity Zero-power physics parameters	2

Of course, it goes without saying that if use is to be made of noise signatures now acquired routinely by a number of utilities as a licensing condition, then a carefully structured and well controlled quality assurance program would need to be established in conjunction with the cooperating utilities, in order that the best possible data will be made available to the ORNL noise signature library. Attention to details at this point will be key to the establishment of believable trends and the recognition of safety-related changes in plant signatures.

> *Question 4: What are the major safety-related applications for noise analysis and what data are required to implement each of them?*

A partial list of noise-based monitoring methods applicable to problems with reactor vessel internal structures having potential safety significance has already been presented in Table 1. Table 4 provides a broader and more complete summary of noise-based surveillance techniques that are applicable to PWRs, while Table 5 does likewise for BWRs. The following paragraphs comment on these two tables.

The monitoring of *PWR* systems has reached a relatively advanced state in recent years. Many physical variables and the general state of important pressure vessel internals can be monitored by appropriate sensors, and insight into the meaning of signal characteristics has increased considerably (see Appendix A, Session 1). In addition, increased attention has been given to surveillance of the

Table 4. Summary of surveillance systems for PWRs (adapted from ref. 4)

Sensors used	Physical parameter	Physical phenomenon monitored	Type or example of anomaly	Conditions of applications
Ex-core neutron detectors	Mechanical position of internal structures	Vibrations of structures	• Loosening of hold-down spring • Thermal-shield flexure broken	Continuous or discontinuous monitoring
	Primary water temperature	Temperature fluctuations	Flow anomaly	No identified application
In-core neutron detectors	Mechanical positions of fuel assemblies	Vibrations of fuel assemblies	• Baffle jetting • Cross flows	Discontinuous monitoring
	Mechanical position of control rods	Control rod vibrations	Control rod abnormal vibrations	Discontinuous monitoring
	Void fraction in sub-channels	Boiling	Abnormal boiling (local overpower or flow reduction)	Discontinuous monitoring
	Primary water temperature	Temperature fluctuations	Flow anomaly	No identified application
Outlet thermocouples	Primary water temperature	Temperature fluctuations	Natural circulation	Complementary information for the operator in case of primary pump failure
Pressure sensors	Pressure waves	• Vibrations of internal structures • Primary pump working conditions • Velocity of sound in water	Presence of gas (steam or noncondensable gas)	Discontinuous or continuous monitoring
Vibroacoustic sensors	• Displacements or accelerations • Mechanical waves • Acoustic waves	• Vibration • Impacting • Acoustic emission due to leakages	• Abnormal vibrations • Loose parts • Leakages	On-line monitoring
Any sensors	Electric signal	Degradation of the sensor itself	Response time increase	Continuous or discontinuous monitoring for • Predictive maintenance • Verification of sensor time-constant

sensors themselves, since surveillance based on noise analysis offers the possibility to monitor relevant sensor properties without disturbing or interrupting operation. This can be important because sensor static and dynamic properties can deteriorate through changes in sensor materials (such as the gas filling of ion chambers), insulation resistances, cable capacities, connector qualities, and properties of electronic devices.

Table 5. Summary of surveillance systems for BWRs (adapted from ref. 4)

Sensors used	Physical parameter	Physical phenomenon monitored	Type of anomaly or situation to be characterized	Domain of application	Type of surveillance*	Technical application status*
In-core neutron detectors	Void fraction in (sub)channels, mechanical position of instrument tube	Channel flow velocity distribution and stability, instrument tube vibration	Anomalous flow and void distribution, channel power, bypass flow	Surveillance during operation	(Dis)continuous depending on type of in-core instrumentation	Well advanced; still some questions about interpretation
In-core gamma detectors	Void fraction in (sub)channels, enlarged field-of-view	Channel flow velocity distribution and stability	Anomalous flow and void distribution, channel power	Surveillance during operation	(Dis)continuous	Research
Ex-core detectors	Reactivity, coupled with thermal hydraulics	Reactor kinetic stability	Too small margin to instability due to overpower or low flow	Check of design parameters, surveillance during operation	Continuous	Developmental
Accelerometers	Movement of mechanical parts	Jet pump vibration	Excessive vibration	Surveillance during operation	Continuous	Well advanced
Position sensors	Position of control valve in steam line and bypass valve	Dome pressure control system	Anomalous shift of control parameters, mechanical wear	Check of design, surveillance during operation	Continuous	Developmental
	Position of control valves for feedwater	Feedwater control system	Anomalous shift of control parameters	Check of design, surveillance during operation	Continuous	Developmental
Pressure sensors	Steam dome pressure	Pressure control system	See above	Check of design, surveillance during operation	Continuous	Developmental
	Steam line pressure	Resonance behavior, steam quality	Not indicated			Research
	Water level in reactor vessel	Water balance	Anomalies in feedwater control system	Surveillance during operation	Continuous	Developmental
Flow sensors	Feedwater flow	Characteristics of controller and actuator	Anomalous shift of control parameters, valve and pump characteristics	Check of design and surveillance during operation	Continuous	Developmental
	Steam flow	Characteristics of steam dome pressure controller	Anomalous shift of control parameters and valve characteristics			

*Status "Developmental" refers to implementation in on-line surveillance system. All methods have already been applied off-line for discontinuous check of operation.

Mechanical surveillance of pressure vessel internals integrity can be performed both with accelerometers and with ex-core and in-core neutron detectors. In this way, fuel element vibrations and core barrel and thermal shield vibrations are monitored and trended (see Appendix A, Session 4). An analysis of the cross correlations among several detectors can usually distinguish the different vibration modes (beam mode and shell mode; preferred direction of vibration). To ease the interpretation, it has become usual to start vibration analysis during the construction phase of a plant. Knowledge of the influence of process conditions (e.g., temperatures, fuel burnup, and soluble boron concentration) on spectral characteristics has increased considerably. In other parts of the primary and secondary systems, vibration measurements on pumps, steam generators, and the turbine are also done routinely at many plants (particularly those abroad).

The monitoring of *BWR* systems has focused largely on some particular diagnostic items that are related to the core and to the control systems (see Appendix A, Session 2). In-core (and in some plants ex-core) neutron detectors are used for monitoring core reactivity stability. In-core detectors also provide information about channel flow stability, flow distributions, and possible instrument tube vibrations and fuel channel box damage. Core stability is a typical BWR item connected to the two-phase flow. Interest in stability monitoring has increased recently because incentives exist for operating BWRs at reduced coolant flow in a spectral shift regime, thus improving operational flexibility. Such an operational mode, however, reduces core stability and, therefore, requires operators to have a knowledge of actual stability margins, which can be obtained rather easily by measuring the resonance parameters of the power spectral density of the neutron noise or the decay ratio in the associated correlation function and interpreting the results by fitting them to a suitable mathematical model. Swedish reactors are required to have a noise-based stability monitor with display on the main control room CRT as an aid to the operators during plant start-up. At least one U.S. reactor (WNP2) has a similar device, required by Technical Specifications for plant operation at reduced flow conditions. An alternate method for assessing stability is analysis of the coupling between pressure noise and neutron noise, which is done with the aid of multivariate autoregression analysis and requires access to signals from fast-responding pressure sensors.

> *Question 5: In what way are the reactor noise signatures already a part of ORNL's database relevant to NRC needs and future licensing actions, either plant-specific or generic in nature?*

With support from both NRC and DOE, the database of reactor noise presently residing at ORNL was acquired over the past 17 years in recognition of the growing use of noise analysis by LWR manufacturers and plant operators, both for assuring continued equipment integrity in normal operating circumstances and for diagnosing the nature and severity of occasional abnormal occurrences or conditions. During this same time period, ORNL noise specialists have utilized this database on several occasions to aid NRC in their investigation of abnormalities such as loose core support barrels and damaged thermal shields in PWRs, and flow-induced instrument tube/fuel channel box impacting and reduced margin of thermal/hydraulic/neutronic stability in BWRs. There is every reason to believe that this noise database—particularly if it is augmented with noise signatures from some of the newer LWRs—will continue to serve NRC well in their assessment of any anomalous core/vessel conditions that may occur in the future.

Table 6 lists the 16 LWRs for which ORNL has obtained recordings of neutron (and, in some cases,

process) noise.[9] For the PWRs an attempt was made to obtain data at essentially normal operating conditions from plants representative of each reactor manufacturer and for typical coolant loop/circulation pump configurations. The BWR data, on the other hand, were collected in response to concerns for vibrating instrument tubes and for the study of reactor stability in nonroutine

Table 6. Plants included in the ORNL neutron noise library (adapted from ref. 9)

Plant	Type	Reactor supplier	Number of primary pumps	Number of loops	Net MWe	Date of first commercial operation
Calvert Cliffs 1	PWR	C-E	4	2	850	5/75
Calvert Cliffs 2	PWR	C-E	4	2	850	4/77
ANO 1	PWR	B&W	4	2	836	12/74
ANO 2	PWR	C-E	2	2	858	3/80
Trojan	PWR	W	4	4	1130	5/76
Sequoyah 1	PWR	W	4	4	1148	7/81
H. B. Robinson 2	PWR	W	3	3	665	3/71
Edwin I. Hatch 1	BWR 4	GE	–	–	786	12/75
Peach Bottom 2	BWR 4	GE	–	–	1065	7/74
Peach Bottom 3	BWR 4	GE	–	–	1065	12/74
Browns Ferry 1	BWR 4	GE	–	–	1067	8/74
Browns Ferry 2	BWR 4	GE	–	–	1067	3/75
Browns Ferry 3	BWR 4	GE	–	–	1067	3/77
Susquehanna 2	BWR 4	GE	–	–	1038	2/85
Grand Gulf 1	BWR 6	GE	–	–	1142	7/85
Dresden 2	BWR 4	GE	–	–	772	6/70

operating regimes, and so do not necessarily constitute diagnostic baselines for this class of plants. Table 7 provides additional detail on the numbers and identities of the signals recorded and the prevailing power and coolant flow conditions at the time the recordings were made. The PWR neutron noise recordings are mainly ex-core detector signals, although in-core signals are available in a few instances. Conversely, BWRs in the U.S. do not have ex-core ionization chambers, so neutron noise in BWRs refers to that recorded from the in-core fission detectors.

The present ORNL noise library consists primarily of raw neutron noise signals stored on FM magnetic tape, together with experimenter's logs that document the recordings. A portion of the raw data have been transformed to the frequency domain (as in Figs. 2 and 5) and/or analyzed for statistical amplitude properties (as in Fig. 4). Where available, plant descriptions and plant computer logs (documenting plant conditions at the time of the measurement) are filed with the tape logs.

Table 7. Plant conditions and signals recorded in the ORNL noise library (adapted from ref. 9)

Plant	Power level (% of full power)	Flow (% of full flow)	Dates of recording	Neutron signals recorded
Calvert Cliffs 1	100	100	1/30/79	Total signal from 6 ex-core detectors
Calvert Cliffs 2	100	100	1/30/79	Total signal from 4 ex-core detectors
ANO 1	100	100	3/27/80	Total signal from 4 ex-core detectors
ANO 2	100	100	3/27/80	Total signal from 3 ex-core detectors
Trojan	100	100	10/21/80	Total signal from 4 ex-core detectors
Sequoyah 1	0, 3, 100	100	4/81-2/83	4 lower ex-core and 1-total signal
H. B. Robinson 2	100	100	12/5-6/79	Upper and lower signals from 4 ex-core detectors
Edwin I. Hatch 1	50-80	37-80	5/75, 6/75, 11/75, 1/76	LPRM,[a] TIP[b]
Peach Bottom 2	50-100	50-100	7/75	LPRM
Peach Bottom 3	50-100	50-100	5/75, 6/75	LPRM
Browns Ferry 1	100	100	1/77	LPRM
Browns Ferry 2	0-100	33-100	8-9/74, 2/75, 1/77	LPRM, TIP
Browns Ferry 3	100	100	1/77	LPRM, APRM[c]
Browns Ferry 3	100	100	2/85	LPRM, APRM, core Δp, jet pump Δp, core flow, pressure
Susquehanna 2	~60	~45	11/86, 7/88, 12/89	APRM, core flow, pressure
Grand Gulf 1	45-100	27-100	1/87	APRM, LPRM, pressure, core Δp
Dresden 2	100	100	5/83	LPRM, APRM, core flow, pressure

[a] Local power-range monitor. [b] Traversing in-core probe. [c] Average power-range monitor.

It is important to note that most plants were visited on only one or two occasions; thus, the recordings represent but a "snapshot" of the plants' continually evolving neutron noise. However, in one plant (Sequoyah 1) neutron noise was monitored continuously over the entire first fuel cycle and

over ~2 months of the second cycle, using an on-line surveillance system. This system monitored the PSD of four lower ex-core detectors and two average signals made up of the sum of upper and lower detectors. In addition, FM magnetic tape recordings were made at periodic intervals throughout the fuel cycle to allow more detailed analysis of the noise behavior.

So what is the utility of this present database in regard to the diagnosis of possible future anomalies? The answer lies in recognizing the *generic similarities* as well as *individualized characteristics* that are to be found in the data. Figure 2, for example, illustrates the frequency-domain (spectral) characteristics of the neutron noise from six PWRs of differing construction contained in the ORNL noise library. Note that though all the curves show fundamentally similar shapes (e.g., one or more peaks in the frequency region 3 to 9 Hz, associated with motion of the core support barrel), plant-specific differences–indicative of differences in structural design, coolant flow forces, mechanical tolerances and condition of fasteners, etc.–are readily apparent.

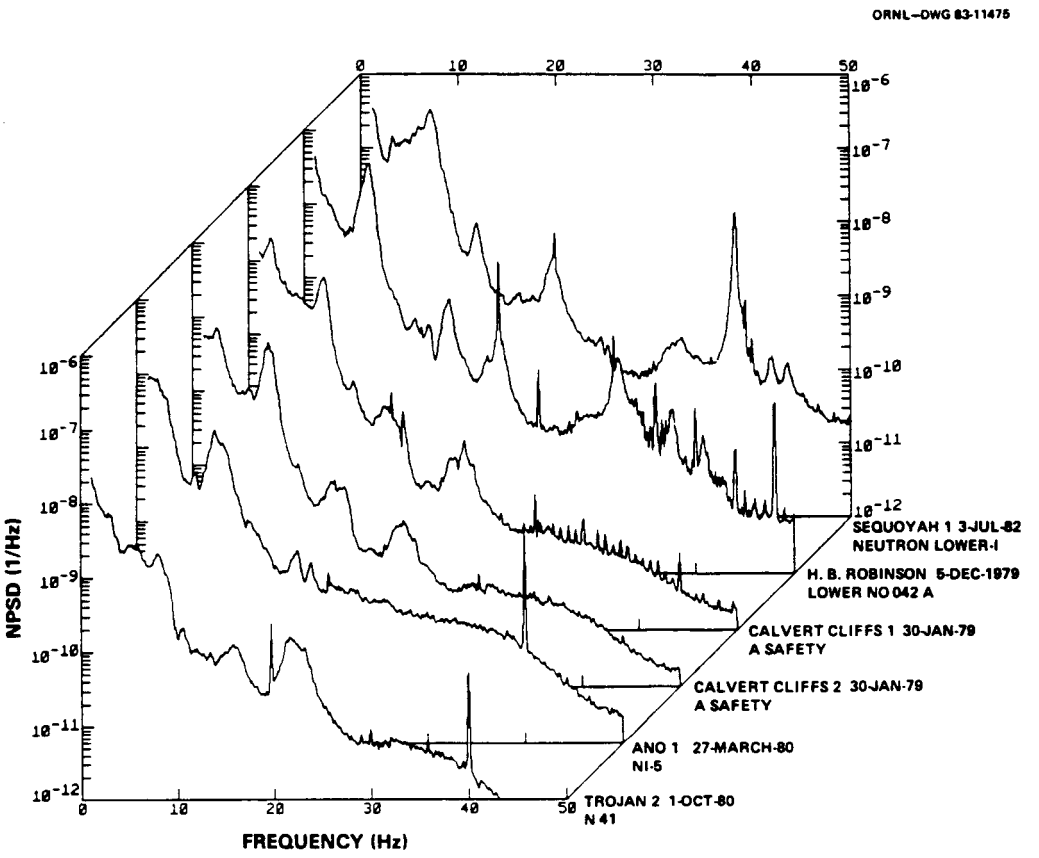

Fig. 2. Typical ex-core neutron noise signatures from six U.S. PWRs (from ref. 9).

In a similar vein, Figs. 3, 4, and 5 illustrate the remarkable differences between neutron noise data typical of PWRs and BWRs. Figure 3 compares neutron noise from the two reactor types as it would appear on an oscilloscope (i.e., in the time domain), where marked differences in both amplitude and signal character (frequency content) are apparent.

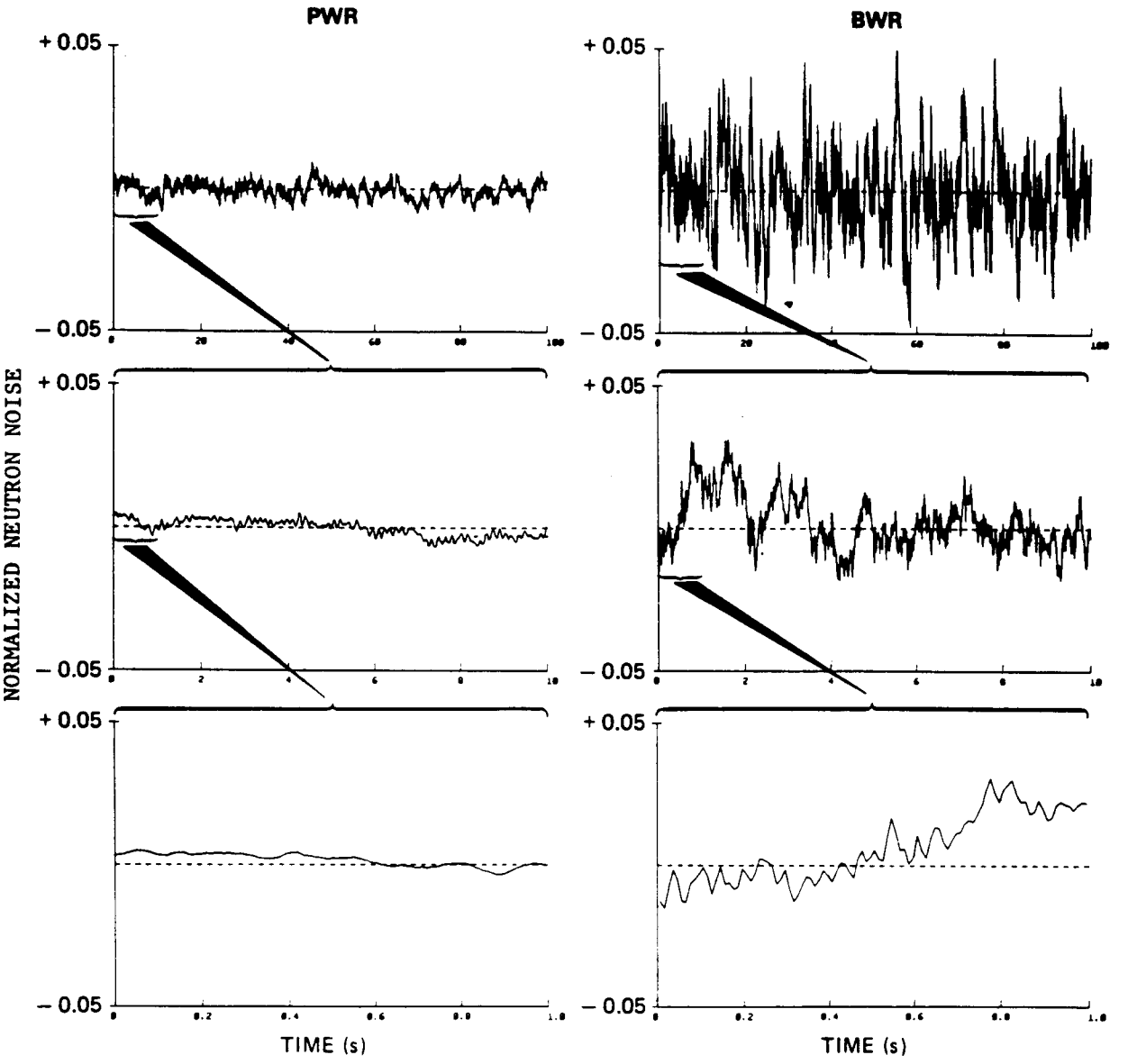

Fig. 3. Comparison of BWR and PWR neutron noise signals when normalized to the dc signal level (signals bandpassed 0.01 to 40 Hz and sampled at 100/s). Excerpted from ref. 9.

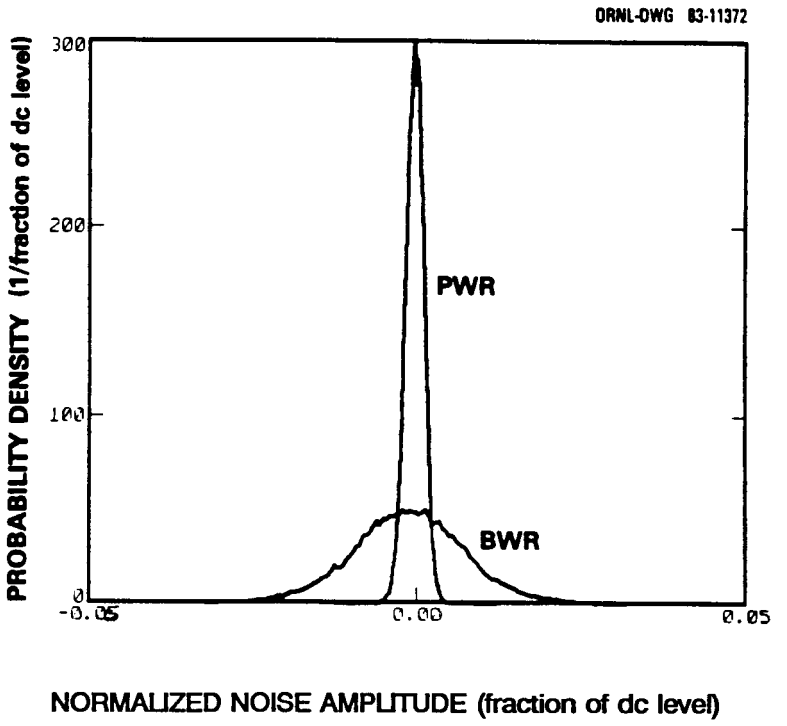

Fig. 4. Comparison of BWR and PWR neutron noise amplitude probability densities (APDs) when normalized to the dc signal level and the total number of samples (signals bandpassed 0.01 to 40 Hz and sampled at 100/s for 2048 s). Excerpted from ref. 9.

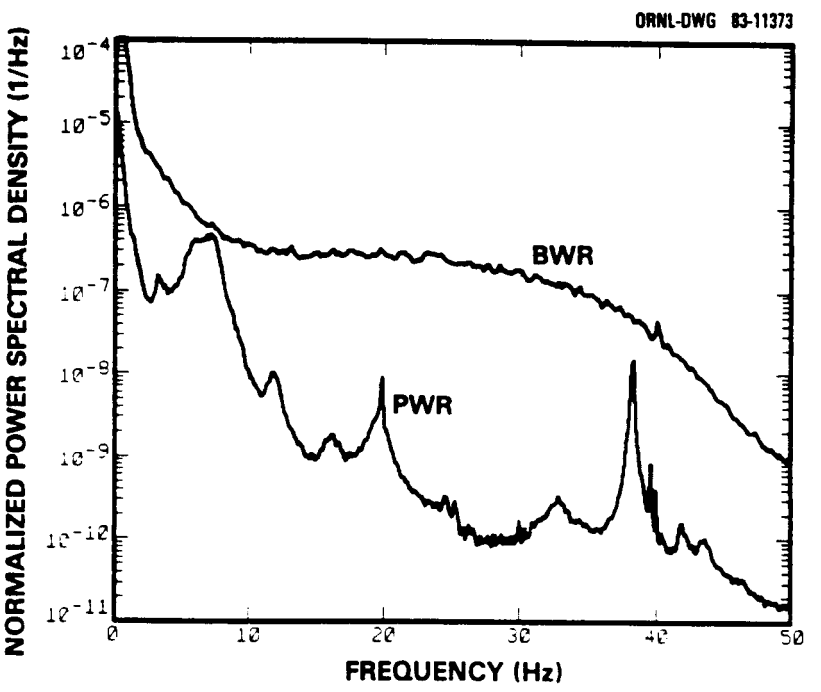

Fig. 5. Comparison of BWR and PWR neutron noise spectra when normalized to the square of the dc signal level (from ref. 9).

Likewise, Figs. 4 and 5 show alternative, more quantified ways of expressing these same differences: Fig. 4 treats signal amplitude distribution characteristics and Fig. 5 the frequency and overall amplitude characteristics.

Of course, these differences in the character of neutron noise in PWRs and BWRs are well understood, and can be traced to the basic design of the core internals and the principle of operation of the two systems, as well as the way in which neutron flux is measured in the two types of plant. In PWRs the core is supported in a core barrel that is suspended from the vessel head in a cantilevered fashion (creating a vibratory system), whereas BWR cores are supported from the vessel bottom. PWR cores consist of open lattices of fuel rods, thus permitting a crossflow of coolant. Also, flow in a PWR is greater than in a BWR, thus providing stronger hydraulic forces to stimulate mechanical vibrations. In contrast, BWR fuel rods are contained in channel boxes which confine the coolant flow within a given bundle of fuel rods.

However, the overwhelming difference relative to neutron noise is that steam is produced in a BWR core, whereas PWRs have a negligible amount of boiling coolant in the core. Fluctuations and movement of steam voids are a major source of neutron flux perturbations, and thus of neutron noise, in BWRs. For this reason, BWR neutron noise is generally of greater amplitude than PWR noise. Figure 3 illustrates this difference; note that the peak-to-peak noise (normalized to the dc level) is ~10% in a BWR, in contrast to only 2% in a PWR. This difference is not due to the fact that BWR noise is measured with in-core detectors whereas PWR noise is generally measured with ex-core detectors (some PWRs don't have fixed in-core neutron detectors with a response time fast enough to measure neutron noise) but is in fact due to steam void formation, transport, and collapse in the BWR. A great deal more information on the interpretation of neutron noise from LWRs may be found in ref. 9, to which the interested reader is referred.

The material above is intended to give some idea of the wealth of information—both generic and plant-specific—contained in the current ORNL noise data library. However, as acknowledged earlier, we feel the database is presently deficient in two main areas: (1) latest-generation plants (e.g., plants in which thermal shields have been structurally redesigned or removed entirely) and (2) BWRs (particularly, the BWR-6, for which we have data from only one plant) operating under normal (baseline) conditions. Correction of these deficiencies is not thought to be a difficult task, however, because (1) a number of utilities already collect neutron noise on a periodic basis for their own use and might be willing to contribute to an updated ORNL noise database, and (2) an excellent step-by-step "how to do it" document,[10] published by EPRI, exists to aid those utilities who have not already done so to develop well founded noise analysis programs whose output would meet the quality level desired for inclusion in the ORNL noise database.

CONCLUSION

The discussions and representative data supplied in answering the foregoing five questions confirm the usefulness, relevance, and regulatory/safety significance of ORNL's noise data library to NRC in their investigation of a broad range of reactor problems that may occur in the future. The present library contains a wealth of information that merits preservation, expansion, and the addition of data handling "tools" with which to increase its accessibility and realize its full potential as an aid to regulation, including the review of future applications for operating license extensions. The usefulness of the noise library could be enhanced further by the addition of data from some of the

newer plant designs (e.g., BWR-6s), PWRs modified by the removal of their thermal shields, and BWRs operating at normal power and flow conditions. Such additional data could be acquired by ORNL or may be available from utilities already pursuing noise analysis programs.

RECOMMENDATION

It seems appropriate that NRC:NRR fund ORNL to carry out a program to preserve and upgrade the existing ORNL noise signature library, so that this valuable resource—acquired at considerable expense to NRC over the last 17 years—will not be lost, but rather be put in a condition that will make its contents maximally useful to NRC staff in their resolution of future plant problems.

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2. J. A. Thie, "Core Motion Monitoring," *Amer. Nucl. Soc. Crit. Rev. No. 7,* reprinted from *Nucl. Technol.* 45 (1), mid-August 1979.

3. F. J. Sweeney and J-P. A. Renier, *Sensitivity of Detecting In-Core Vibrations and Boiling in Pressurized Water Reactors Using Ex-Core Neutron Detectors,* NUREG/CR-2996 (ORNL/TM-8549), Oak Ridge National Laboratory report, July 1984.

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8. J. A. Thie, "Justification of a Noise Analysis Signature Program From a Safety Standpoint and Programmatic Recommendations," special report prepared under contract to Oak Ridge National Laboratory, December 1979.

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10. F. J. Sweeney, *Utility Guidelines for Reactor Noise Analysis,* EPRI NP-4970 (final report, Research Project 2640-1), Electric Power Research Institute report, February 1987.

APPENDIX A: CHAIRMEN'S SUMMARIES OF SELECTED SMORN VI SESSIONS

The following summaries from three sessions of the Sixth Symposium on Reactor Noise (SMORN VI), held May 19-24, 1991 in Gatlinburg, are especially relevant to the topics discussed in this letter report. The summaries are excerpted from ref. 1.

Summary of Session 1: Operational Experience with Surveillance and Diagnostic Systems

J. A. Thie
Consultant
Knoxville, Tennessee, U.S.A.

In a session entitled operational experience, understandably a considerable variety of experiences were presented. It is possible to see from these the directions in which surveillance and diagnostics (S&D) are going.

Many fundamental methods and analysis approaches have been in existence for some time. Their potential had been envisioned in previous years. But now these are being used on larger scales and given opportunities to prove their potential. The following examples of S&D power are selected as representative from the papers of this session.

- Primary system vibration and anomaly monitoring by signal analyses—extending over many reactor fuel cycles and sites (*Türkcan, Sunder, Por*).
- On-line monitoring with varieties of algorithms at work stations remote from the plant (*Türkcan*).
- Exceptionally thorough understandings of the intricacies of measured PWR spectra in terms of underlying physical phenomena (*Sunder*).
- Low thresholds of detection capabilities, for purposes of giving warnings well in advance of traditional operator monitoring methods (*Mullens, Kanemoto, Sunder, Por*)
- Special algorithms providing immediate alerts of changed conditions for whatever reason (*Mullens, Kanemoto, Por*).
- On-line comparisons of detailed fundamental principles models with plant behaviors—to give alarms and then even diagnostic information (*Poujol, Kanemoto*).
- Signal validation and sensor checking by a variety of methods (Mullens, Por).
- Sensor response time measurement (*Türkcan, Por*).
- Database management system for retrievability of staggering amounts and varieties of S&D signal analysis data (*Kanemoto, Türkcan*).

- Human-factored and ingenious colorful displays for both operations and diagnostic specialists (*Mullens, Kanemoto, Sunder, Por*).

- Practical utilization of tools of artificial intelligence, including pattern recognition and expert systems assistance in diagnostics (*Poujol, Kanemoto, Türkcan*).

Sophisticated signal-processing usages are making substantial inroads into commercial power plants. It can be expected that over a period of time specific, concrete safety and economic advantages of S&D methods of this conference will accrue. The authors in this session made no attempt at compiling all the particular advantages arising within their own experiences. But a few payoff examples they give may be taken to be representative:

- A main coolant pump shaft crack detected in on-line spectra several months before detection by conventional broad-band amplitude surveillance (*Sunder*).

- Detailed spectral trending accepted as a substitute for a planned inspection of a secondary core support structure (*Sunder*).

- Reduction in minimum noise levels from a neutron detector fault while shut down (*Mullens*).

Beyond these there are implicit safety and economic benefits realized in many items on the longer applications list cited above.

Finally, an observation might be made on the outlook for S&D methods of this conference. There seems to be an underlying force, usually taken for granted, in helping to make possible the advances in research and applications reported: the ever-growing computer hardware and software advances at one's disposal. It might be projected, due to intensive use of such tools in signal analyses and interpretations, that continued computer technological expansion will be a synergistic effect with growing plant S&D needs–leading to a paralleled expansion somewhat in S&D signal analysis applications.

Summary of Session 2: BWR Stability Monitoring: Theory and Practice

J. E. Hoogenboom
Delft University of Technology, The Netherlands

Stability problems of BWRs are as old as BWRs themselves. It was recognized from the beginning that a BWR could become unstable when operating at low pressure. This effect is due to the coupling of reactor kinetics and thermal hydraulics via the reactivity feedback of the void production. The stability problem ceased with increase of the vessel pressure. Nonetheless, a renewed interest in BWR stability arose a few years ago after some incidents and further research at several BWRs in which large power oscillations occurred (known as limit cycles) when the circulation flow through the core was reduced. As a result, a certain region of the power-flow map, which is determined

experimentally in some power plants, has to be avoided or the stability of the reactor has to be monitored when operating in this region. During instability the amplitude of the power oscillation grows but is finally limited by the strongly nonlinear behavior of the reactor system. The occurrence of such oscillations is, of course, of direct importance to reactor safety. The growing interest in this subject was also reflected in the Workshop on BWR Stability held in Holtsville, N.Y., in October 1990. An accurate description of this phenomenon, especially the exact circumstances leading to such an unstable situation and the role of reactor noise as a driving force, turns out to be very complicated. A so-called reduced-order model proposed by *March-Leuba* and consisting of five partially nonlinear differential equations is capable of describing the phenomenon of limit cycle oscillations and is used by several authors for further investigation. However, it cannot describe the noise features of the signals.

Blázquez used this model to connect the parameters from an ARMA model of the appropriate order of the measured APRM signal to physical parameters, which can be monitored to detect changes in the stability of the reactor. The parameters are obtained using the Dynamic Data System technique, which calculates the poles of the reactivity-to-power transfer function. From these also the decay ratio (DR) of the impulse response is calculated, which is a widely accepted parameter for stability monitoring. Using the prompt jump approximation, the author introduces further reduction of the theoretical model and, accordingly, the ARMA model order.

Konno took a more fundamental theoretical starting point to describe the processes in a BWR by considering a nonlinear stochastic theory for reactor dynamics. Features like self-excitation and multiple-mode oscillations are demonstrated for a mathematical model of two coupled, nonlinear oscillators with slightly different resonance frequencies. Space-dependence is introduced by considering a one-dimensional time-dependent diffusion equation with nonlinear feedback and assuming a stochastic reactivity noise source. With this model the noise suppression noted in Japanese BWRs can be illustrated. A further extension of the theoretical model to 2-D diffusion theory with point temperature feedback results in spatial modes that can be related to observations in different BWRs. Finally, a model based on the nonlinear Van der Pol oscillator is suggested to derive parameters like the decay ratio, which can also be used in case of limit cycle oscillations.

From Eurosim, Sweden, two papers were presented. *Åkerhielm* discussed the analysis of measurements on different Swedish BWRs. Univariate and multivariate AR analyses are applied to APRM and LPRM signals. Limit cycle oscillations were observed at the Forsmark-1 NPP, showing a resonance peak at 0.5 Hz and a growing peak at double frequency during the growth of the oscillation amplitude. Decomposition techniques were applied, leading to the conclusion that the poor stability is a core resonance phenomenon. However, from a general model such as AR no basic physical causes can be identified. From different measurements it was noted that the fuel type (8x8 or 9x9) as well as burnup and the axial power distribution all influence stability. Furthermore, clear space-dependent effects were noticed, showing phase changes with position. The use of LPRMs instead of APRMs is therefore to be recommended for better monitoring of the core stability, since the oscillations in the APRM signal will be partially damped due to phase differences among the various LPRMs.

Lorenzen showed results obtained with a PC-based on-line stability monitor system called SIMON. This system calculates the value of the decay ratio as a function of time. It is intended for routine use in NPPs, and therefore much effort was spent to improve the accuracy of the estimated DR and its robustness against different reactor operating conditions and power transients. These features

were demonstrated for benchmark tests with simulated signals, which include step changes in the signal characteristics determining the DR. Its response time to step changes in DR is well below 1 min. Moreover, it has prognostic capabilities for limit cycle behavior 20 to 30 s before onset. Operational experience is now being gathered at the Oskarshamn NPP.

The last presentation in this session, by *Kitamura*, had a wider scope and described a methodology for signal analysis that improves diagnostic and prognostic capabilities. For system identification the MAR method is used with a special form of signal path transmission (SPT) analysis. To separate disturbances from the stationary part of the signals, a nonlinear filter is introduced which calculates the median value over a number of samples. This filter responds faster to sudden changes. The difference signal satisfies the stationarity requirement for the STP analysis of the noise. A next improvement is in the causal identification of the system, using *a priori* knowledge of the system dynamics and considering different plausible causal structures by systematically including and excluding signals in a multivariate analysis. By combined use of the model and the trend diagram of the noise signatures, predictive information can be obtained (power spectra, coherences, etc.). The method was demonstrated with simulated signals, focusing on monitoring the performance of the feedwater control system. It was remarked that such frequency-domain STP analysis should be accompanied by time-domain analysis, since certain anomalies are more effectively detected though time-domain analysis.

Putting the papers of this session into perspective, there appears to be a wide gap between theory and practice. Progress has been made on both sides. Practitioners can very well determine important parameters (like the decay ratio) for stability monitoring from general signal modeling techniques, sometimes supported by a simple physical model. Such methods can be made robust for routine application in power plants and can alert the operator if reactor operation is evolving to a less stable situation. However, limits to parameters that are monitored must be set in advance on a rather arbitrary basis. No generally accepted rules are available for determining those limits for a specific reactor. Nor can it be predicted under which precise circumstances instability will occur. Operational experience will ultimately show whether such systems will really be accepted in the control room as an aid to achieving safe operation of a reactor. From the theoretical side there is progress in exploring models with which to explain basic phenomena observed in BWRs. However, dealing with such models becomes mathematically more and more complex. In this respect, I may also refer to the Workshop on Noise and Nonlinear Phenomena in Nuclear Systems, held in Valencia, Spain, in 1988. Further work on nonlinear stochastics—including space dependence—will be necessary to arrive eventually at an applicable description of the essential processes describing stability-related phenomena in a BWR. Much work in this field is originating in Japan. However, it will probably be a long road before details like axial power distribution, fuel burnup, and fuel type can be adequately incorporated. Nonetheless, the gap between theory and practice must be bridged. On the one hand, we can include more physics in the signal analysis methods, of which several authors in this session already showed examples. On the other hand, we can make more fundamental but very complex theoretical models better understandable for practitioners.

Summary of Session 4:
Modeling and Monitoring the Motion of PWR and BWR Structures

D. Wach
GRS, Garching, Germany

This session and the conference as a whole have clearly demonstrated that vibration monitoring of mechanical structures in nuclear power plants based on vibration, neutron noise, and dynamic pressure signals has reached a well developed state with respect to understanding the physical phenomena used for feature monitoring as well as signal analysis methods and monitoring systems installed in the plants. Vibration monitoring of reactor internals and primary circuit components has become—next to loose parts and acoustic monitoring—the most widely applied method for early fault/degradation monitoring in PWRs.

In Session 4, seven outstanding papers from Argentina, Czechoslovakia, U.S.A., Hungary, and France have been presented (and at least seven additional papers in other sessions), in which modeling and monitoring of structural motions were described for quite different nuclear power plant types such as: PHWR-320 MW, WWER-440 (and 1000) MW, Westinghouse 1200-MW PWR, Framatome 900- and 1300-MW 3- and 4-loop PWRs with and without thermal shields, and (outside this session) 2-loop PWR Borsselle, Siemens/KWU 900- and 1300-MW PWRs, Koeberg 900-MW PWRs and Chinese PWRs.

The variety of plants proves that vibration monitoring is a generally applicable surveillance technique and is well established in PWRs. It is surprising that for BWRs no vibration monitoring programs have been realized: there was just one poster presentation reporting on flow-induced vibration of in-core instrumentation tubes in a German BWR similar to earlier findings in the U.S. BWRs in the seventies.

Rather than going through the particular papers and repeating the various abstracts, I should like to summarize the main points of the session in a more generalized form. However, before doing that, I want to remind you of the particular speakers by mentioning the highlights of their presentations.

Laggiard (Argentina) reported on a neutron noise monitoring program at the PHWR Atucha I, established as required by the plant management and the licensing authority when a fuel assembly rupture led to strong neutron flux fluctuations.

Vavrin (Czechoslovakia) discussed the results of a single-degree-of-freedom structural model for core barrel impact oscillations in a WWER-440 as a basis for coolant pressure and steam generator vibration spectra interpretation.

Presnell (U.S.A.) reported on an ex-core neutron noise analysis program at the two units of the McGuire NPP. Classical as well as "unusual" coherence and phase behavior have been detected during different fuel cycles. The influence of a higher mode of fuel assembly vibration is supposed to be an essential signal source with changing intensity.

Wood (U.S.A.) presented a model and analysis results for PWR ex-core neutron noise signals: a thermal-hydraulic model for the lower frequencies (below 1 Hz), and a mechanical motion model for

the higher frequencies. Discriminant monitoring was applied to available stored data.

Kozlosky (U.S.A.) presented a new vibration monitoring system for reactor internals designed to address the standards and guidelines provided by EPRI and ASME/ANSI.

Hollo (Hungary) reported on a model development for the loop component vibrations at the PAKS NPP and described an advanced vibration monitoring system.

Trenty (France) described the system SINBAD used in France as a data base for handling and interpreting neutron noise and vibration spectra in 54 plants. Detailed interpretation of spectral components and several long-term feature trends were discussed.

In all of the papers, interpretation of the different peaks in the frequency spectra played an important role. Peak identification has been performed by means of more or less comprehensive model developments and investigations (at least by means of the results of pre-operational in-core vibration analyses). A reliable spectral interpretation is seen as an important prerequisite for the establishment of a vibration monitoring program and practice-oriented fault diagnoses.

Although there are many different plant-specific signatures found in the various plants, in principle, however, very often quite similar phenomena could be identified—such as core barrel beam mode motion, fuel assembly eigenfrequencies (first and higher modes) with clamped or flexible support conditions, core barrel shell mode vibrations, and reactor vessel vertical vibrations.

Many plants show characteristic time-variant signatures over the fuel cycle or in the long term. Very often, relaxation of spacer grids in the fuel assemblies has been found as the cause for the changes; however, the signature changes are not fully understood in all cases. Feature trending (for instance, peak trending of relevant features) seems to be a useful tool for monitoring and cause identification. Though not a new observation, it became evident during this symposium that there is a strong desire to introduce more and more computerized systems on site to facilitate data handling, feature monitoring, and automated signal analysis. Advanced systems from France, Hungary, and the U.S.A. have been reported in this session, and in other sessions, systems from Germany, South Africa, and the Netherlands.

Vibration monitoring programs are in some cases required by the licensing authorities, especially if mechanical problems of internals or fuel assemblies have been detected. An example was given in the paper of Argentina. Other examples could be baffle jetting due to gaps in the core liner caused by bolt cracks, shaft cracks in the main reactor coolant pumps, and thermal shield degradation.

In most cases, however, it is the intention of the utilities to use vibration/neutron noise monitoring on their own accord as a predictive maintenance tool. Collection of data to detect aging phenomena and to provide a data base for structural integrity assessment is another important aspect of the overall motivation for applying vibration monitoring systems to NPPs.

During the conference we were informed that in the U.S.A. standards and guidelines are either available or are in preparation. I can add that this also holds for Germany.

In this context I should also like to address one aspect that I believe is very important for future development: vibration monitoring is a useful tool for integrity assessment, but we should never forget

that it provides an *early warning* of developing faults. The users of such systems (namely, the plant operators) should never be forced to treat the detection of the beginning of an abnormal behavior as if it were a safety issue (i.e., be forced to give an immediate report to the licensing authorities). Such a requirement would inevitably lead to a negative attitude on the part of the utilities and would hinder further and broader application of vibration monitoring. As long as the information provided by vibration monitoring systems can be used for the optimization of plant operation, it serves in the best way also to enhance the safety of the plant. Early fault diagnostic methods will be used more generally also for other monitoring tasks in equipment or components, and in this way will contribute materially to further improvement of the operational safety of nuclear power plants.

APPENDIX B: PAPERS PRESENTED AT SMORN VI, GATLINBURG, 1991

Monday Morning

Session 1 **Operational Experience with Surveillance & Diagnostic Systems**
Chairman: J. Thie (Consultant, Knoxville, USA)

1.1 *Advanced Techniques for Nuclear Plants Malfunctions Detection, Diagnosis, and Mitigation*
A. Poujol, B. Papin, P. Bernard (CEA Cadarache, France), J. M. Evrard, J. B. Thomas (CEA Saclay, France)

1.2 *Plant Monitoring and Signal Validation at HFIR*
J. A. Mullens (Oak Ridge National Lab., USA)

1.3 *Operational Experiences on the Borssele Nuclear Power Plant Using Computer-Based Surveillance and Diagnostic System On-Line*
E. Türkcan, W. H. J. Quaadvliet, T. T. J. M. Peeters, J. P. Verhoef (Netherlands Energy Research Foundation, The Netherlands)

1.4 *Experience with On-Line BWR Plant Diagnosis System and its Technical Support System Development*
S. Kanemoto, Y. Sonoda, M. Enomoto, T. Kondo, N. Komai, S. Ebata (Toshiba Corporation, Japan)

1.5 *Experiences and Results with COMOS - An On-Line Vibration Analysis and Monitoring System*
R. Sunder, M. Baleanu, K. Kieninger, A. Kolbasseff, W. Kuhn, H. Rösler (Gesellschaft für Reaktorsicherheit, Germany)

1.6 *Development and Utilization of an Automated Reactor Noise Measuring and Processing System*
G. Pór, S. Bende-Farkas, O. Glöckler, S. Kiss, K. Krinizs, S. Lipcsei (Central Research Inst. for Physics, Hungary)

Monday Afternoon

Session 2 **BWR Stability Monitoring: Theory and Practice**
Chairman: W. Bastl (Gesellschaft für Reaktorsicherheit, Garching, Germany)

2.1 *Parameters of Reduced Order Model BWR Dynamics from Neutron Noise Analysis*
J. Blázquez, F. Barrio, J. Ballestrin (CIEMAT, Spain)

2.2 *Space-Dependent Nonlinear Nuclear Stochastic Theory*
H. Konno (University of Tsukuba, Japan)

2.3 *Core Stability Investigations in Swedish Boiling Water Reactors*
F. Akerhielm, B.-G. Bergdahl, R. Oguma, J. Lorenzen (EuroSim AB, Sweden)

2.4 *Development and Verification of an On-Line BWR Stability Monitor*
J. Lorenzen, R. Oguma, B.-G. Bergdahl, F. Akerhielm (EuroSim AB, Sweden),
S. Jonsson, P. Lundin (Oskarshamn Nuclear Power Station, Sweden)

2.5 *Combined Use of Model-Based and Symptom-Based Techniques for Diagnosis and Prognosis of BWR Dynamic Characteristics*
M. Kitamura, J. Kobayashi, M. Takahashi, K. Sugiyama (Tohoku University, Japan)

Session 3 **Leak and Boiling Detection in Fast Reactors**
Chairman: R. Martinelli (C.R.E. Casaccia, Rome, Italy)

3.1 *Joint R & D Programme on Acoustic Leak Detection for Steam Generators of the European Fast Reactor EFR*
J. Voss (Interatom, Germany), J. P. Girard (CEA Cadarache, France),
P. J. Thomas (UKAEA, Great Britain)

3.2 *Acoustic Surveillance of Fast Reactor Primary Circuits - Experience with the Dounreay PFR Monitor*
P. J. Thomas, J. A. McKnight, R. Rowley, C. G. Taylor (UKAEA, Great Britain)

3.3 *New Statistical Features and Multivariate Pattern Recognition Analysis for Boiling Noise Detection in Fast Reactors*
O. P. Singh, G. S. Srinivasan, R. K. Vyjayanthi, R. Prabhakar (Indira Gandhi Centre for Atomic Research, India)

Tuesday Morning

Session 4 **Modeling and Monitoring the Motion of PWR & BWR Structures**
Chairman: D. Wach (Gesellschaft für Reaktorsicherheit, Garching, Germany)

4.1 *Monitoring of the Internals in the PHWR Atucha I by Means of Neutron Noise Analysis*
J. Piñeyro, H. Lescano, E. Laggiard, L. Wentzeis, A. Pereyra (CNEA, Argentina), J. Sidelnik, R. Perez (Atucha I Nuclear Plant, Argentina)

4.2 *Noise Analysis of Reactor Core Barrel Impact Oscillations*
J. Vavrin (Nuclear Research Institute, Czechoslovakia)

4.3 *Duke Power's Investigation of Changing Neutron Noise Signatures at McGuire Nuclear Unit 1 During Recent Cycles of Operation*
G. M. Presnell (Duke Power Co., USA)

4.4 *Modeling and Analysis of Neutron Noise from an Ex-Core Detector at a Pressurized Water Reactor*
R. T. Wood (Oak Ridge National Lab.), R. B. Perez (University of Tennessee)

4.5 *Reactor Internals and Core Support Monitoring System*
T. Bogard, T. Kozlosky, S. Lowenfeld, N. Singleton (Westinghouse Electric Corp., USA)

4.6 *On-Line Diagnostic Method for Vibrational Surveillance of PAKS NPP Primary Circuit Equipments*
E. Holló, P. Siklossy (Institute for Electric Power Research, Hungary), L. Turi, S. Ratkai (PAKS Nuclear Power Plant, Hungary)

4.7 *SINBAD, a Data Base for PWR Internals Vibratory Monitoring*
A. Trenty, C. Puyal, H. Klajnmic (Electricité de France)

Tuesday Evening

Session 5A **Surveillance and Diagnostic Issues/Viewpoints**
Chairman: R. Uhrig (Univ. of Tenn., Knoxville/ORNL, Oak Ridge, Tennessee, USA)

5.1 *IAEA Activities on Nuclear Reactor Diagnostics*
P. Dastidar, A. Kossilov, V. Arkhipov, L. Ianko (IAEA, Austria)

5.2 *ASME Reactor Standards Using Noise Techniques*
G. Zigler (Science and Engineering Associates, USA)

5.3 *Effectiveness of Neutron Noise and Loose Parts Monitoring Methods in Aging*

Management for Reactor Relicensing
G. Zigler, R. Knudson, F. Sciacca, R. Walsh (Science and Engineering Associates, USA)

5.4 *PSAD, an Integrated Tool for the Global Vibratory and Acoustic Surveillance of EDF Nuclear Plants in the Near Future*
J. M. Mazalerat, J. Morel, C. Puyal, J. L. Morel, B. Monnier, A. Fernandes, P. Legaud (Electricité de France)

Session 5B **Open Forum**
Chairman: R. Uhrig (Univ. of Tenn., Knoxville/ORNL, Oak Ridge, Tennessee, USA)

Wednesday Morning

Session 6 **Advances in Signal Processing Methods**
Chairman: M. Kitamura (Tohoku University, Sendai-shi, Japan)

6.1 *Innovation Model and Reactor Noise Analysis*
K. Kishida (Gifu University, Japan)

6.2 *Study of a Modeling Method for Nonlinear Reactor Noise*
K. Hayashi, Y. Shinohara (JAERI, Japan), H. Konno (University of Tsukuba, Japan)

6.3 *Some Considerations on Chaotic Reactor Noise Signals*
Y. Kuroda, H. Miyamoto (Tokai University, Japan)

6.4 *Search for Chaotic Character of the Time Series of Reactor Signals*
T. Suzudo, K. Hayashi (JAERI, Japan)

6.5 *Failure Detection by Adaptive Lattice Modeling Using Kalman Filtering Methodology: Application to NPP*
Ö. Ciftcioglu (Technical University of Istanbul, Turkey), E. Türkcan (Netherlands Energy Research Foundation, The Netherlands)

6.6 *Uncertainty Treatment in Knowledge-Based Early Failure Diagnosis by Fuzzy Logic Application*
Y. Ding (Technische Universität München, Germany), D. Wach (Gesellschaft für Reaktorsicherheit, Germany)

6.7 *The Artificial Noise Benchmark Test on AR Modeling and Anomaly Detection*
J. E. Hoogenboom (Delft University of Technology, The Netherlands), J. Pohlus (Zentral Institut für Kernforschung, Dresden)

6.8 *Synthetic Noise Benchmark Data Analysis for Anomaly by Pattern Recognition*

Methodology
Ö. Ciftcioglu (Technical University of Istanbul, Turkey)

Wednesday Afternoon

Session 7 **Parameter Estimation Techniques**
Chairman: K. Behringer (P. Scherrer Institute, Würenlingen, Switzerland)

7.1 *PWR Moderator Coefficient via Noise Analysis: Time Series Methods*
J. R. Thomas, A. W. Clem (Virginia Polytechnic Institute and State University, USA)

7.2 *Estimation of PWR Moderator Temperature Coefficient as a Function of Neutron Noise Amplitude*
Lj. Kostic (Boris Kidric Institute of Nuclear Sciences, Yugoslavia), A. Husemann, J. Runkel, D. Stegemann (Universität Hannover, Germany), P. Kahlstatt (Nuclear Power Plant Gröhnde, Germany)

7.3 *Reactivity Temperature Coefficient Monitoring in a PWR of WWER Type Based on Low-Frequency Temperature/Neutron Noise*
O. Aguilar, M. Montesino, J. Santos (Advanced Institute for Nuclear Sciences & Technology, Cuba)

7.4 *The Downcomer Flow in a Natural-Circulation-Cooled BWR*
A. J. C. Stekelenburg, T. H. J. J. van der Hagen (Delft University of Technology, The Netherlands), W. H. M. Nissen (Dodewaard, The Netherlands)

7.5 *Interpretation of Velocities Measured by Neutron Noise in BWRs*
R. Kozma (Delft University of Technology, The Netherlands)

7.6 *Decay Ratio Estimation in Pressurized Water Reactors*
G. Pór (Central Research Inst. for Physics, Hungary), J. Runkel, D. Stegemann (Universität Hannover, Germany)

7.7 *Reactor Parameter Estimation and Anomaly Detection Work at Centre for Multipurpose Reactor, Indonesia*
U. Jujuratisbela, B. Arbie, A. Siswiyanto, S. Pinem (PRSG, Indonesia), O. P. Singh (Indira Gandhi Centre for Atomic Research, India)

7.8 *Study of the Fluctuating Mechanism of Rate of Increase in CV Sump Water Level*
M. Morita, K. Tokura (Kansai Electric Power Co., Japan), T. Tokunaga, T. Tamura (Sumisho Electronic Co., Japan)

Session 8 **Poster Presentations**
Chairman: O. Glöckler (CRIP, Budapest, Hungary)

8.1 *A Simple Way of Fitting ARMA Model to Stationary Noise*
J. Blázquez, F. Barrio (CIEMAT, Spain)

8.2 *Research on Incipient Failure Diagnosis for PWR Using Noise Analysis Technique*
J. Y. Du, W. F. Zhou, A. R. Shi, Z. Ziao, S. J. Zhao (Nuclear Power Institute of China, P.R. China)

8.3 *Neutron Noise Surveillance in the INET Test Heating Reactor*
Z. Zuoyi, L. Jincai, Z. Shutang (Institute of Nuclear Energy Technology, P.R. China)

8.4 *Improvements in Signal Processing for Primary Coolant Flow Measurements in Power Reactors using N-16 Gamma Noise*
K. K. Arora, R. V. Koparde (Bhabha Atomic Research Centre, India)

8.5 *Kalman Filtering of Self-Powered Detectors for Neutron Noise Analysis*
M. L. Kantrowitz (ABB Combustion Engineering, USA)

8.6 *The Standardization of Nuclear Reactor Surveillance and Diagnostics Techniques for Safe and Optimal Plant Operation*
L. G. Kemeny (University of New South Wales, Australia)

8.7 *A Unified Noise Sources Catalogue for NPP with WWER Reactors as a Data Base for a Noise Diagnostic Expert System*
O. Aguilar, V. Badia, J. Santos (Advanced Institute for Nuclear Sciences and Technology, Cuba)

8.8 *Electrical System Condition Monitoring and Troubleshooting at San Onofre Nuclear Generating Station Using the ECAD Test System*
L. Pentecost (Southern California Edison Co., USA), T. Weir (ECAD Division of Pentek Inc., USA)

8.9 *Diagnostics of Fire Dangerous Situations in Nuclear Power Plant*
S. I. Azarov, V. V. Tokarevsky, A. M. Ellansky (Academy of Sciences of the Ukranian SSR, USSR)

8.10 *BWR Vibration Measurements by In-Core Neutron Noise Analysis*
A. Husemann (Universität Hannover, Germany), E. Laggiard (CNEA, Argentina), H.P. Mies, R. Oed (KRB, Germany), J. Runkel, D. Stegemann (Universität Hannover, Germany)

8.11 *Check Valve Monitoring Using Loose Parts Monitoring Techniques*
G. A. Morris, B. Rogers, R. L. Springer (Tennessee Valley Authority), G. L. Zigler (Science and Engineering Associates, USA)

8.12 *On-Line Acoustic Monitoring of EDF Nuclear Plants In Operation and Loose-Part Diagnostics*
J. L. Morel, C. Puyal (Electricité de France)

8.13 *On-Line Vibration Monitoring at the Koeberg Nuclear Power Plant*
F. van Niekerk, K. J. Page, M. Trumpelmann, J. J. van Dongen (Atomic Energy Corp., Republic of S. Africa), A. C. van Schalkwyk (Koeburg Nuclear Power Station, Republic of S. Africa)

Thursday Morning

Session 9 **Application of Neural Networks and Pattern Recognition**
Chairman: J.-P. Girard (CEN Cadarache, France)

9.1 *Applications of Neural Networks to the Operation of Nuclear Power Plants*
R. E. Uhrig (University of Tennessee/Oak Ridge National Lab., USA)

9.2 *Approach to Identification and Advanced Control of PWRs Using Neural Networks*
J. C. Carre, J. M. Martinez (CEA Saclay, France)

9.3 *An Evaluation of Neural Networks for Identification of System Parameters in Reactor Noise Signals*
L. F. Miller (University of Tennessee)

9.4 *Estimation of Feedback Parameters in Pressurized Water Reactors Using Neural Networks*
B. R. Upadhyaya (University of Tennessee, USA), O. Glöckler (Central Research Inst. for Physics, Hungary)

9.5 *Vibration Monitoring with Artificial Neural Networks*
I. E. Alguindigue (University of Tennessee), R. E. Uhrig (University of Tennessee/Oak Ridge National Lab., USA)

9.6 *Investigation of Neural Network Paradigms for the Development of Automatic Noise Diagnostic/Reactor Surveillance Systems*
K. Korsah (Oak Ridge National Lab.), R. E. Uhrig (University of Tennessee/Oak Ridge National Lab., USA)

9.7 *Pattern Recognition System for Nuclear Reactor Noise Image Analysis and Diagnostics*
Yu. N. Pepyolyshev (Joint Institute for Nuclear Research, USSR),
W. Dzwinel (Institute of Computer Science, Poland)

9.8 *Knowledge Representation and Inference in Noise Diagnostic Expert Systems*
I. Nagy (PAKS Nuclear Power Plant, Hungary), A. Soumelidis, J. Bokor (Computer and Automation Inst., Hungarian Academy of Science, Hungary)

Thursday Afternoon

Session 10 **Sensor Monitoring & Signal Validation Methods**
Chairman: F. Akerhielm (EuroSim AB, Nyköping, Sweden)

10.1 *The Use of Noise Analysis to Detect Bubbles' Appearance into the Pressure Transmitter Sensing Line*
J. Barbero, J. Blázquez (CIEMAT, Spain)

10.2 *Conceptions and Applications of Different Methods for the On-Line Identification of Sensor and Process Faults in Real Time*
J. Prock (Gesellschaft für Reaktorsicherheit, Germany)

10.3 *An Innovations-Based Method for DC Signal Failure Detection: Application to NPP*
T. T. J. M. Peeters (Netherlands Energy Research Foundation, The Netherlands), Ö. Ciftcioglu (Technical University of Istanbul, Turkey), E. Türkcan (Netherlands Energy Research Foundation, The Netherlands)

10.4 *The Use of Radiation Detection Noise for Signal Validation and Sensor Degradation Monitoring*
S. A. Arndt (U.S. Nuclear Regulatory Commission), D. W. Miller (Ohio State University, USA)

10.5 *Sensor Health Monitoring of the Entire Sensing Loop in the Safety Systems of Nuclear Power Stations*
R. C. Colley, J. Weiss (Electric Power Research Institute), M. Widmeyer (The Supply System), H. R. Wiegle (Philadelphia Electric Co., USA)

10.6 *On-Line Measurement of Response Time of Pressure Transmitters Using Noise Analysis*
H. M. Hashemian, K. M. Petersen (Analysis & Measurement Services Corp.)

10.7 *EPRI Program to Justify Response Time Testing Requirements for Pressure Sensors*
J. Weiss (Electric Power Research Institute), C. Mayo (North Carolina State University), V. Swisher (Performance Associates, USA)

10.8 *Fault Detection via Sequential Probability Ratio Test of Multivariate Autoregressive Modeling-Based Residual Time Series*
O. Glöckler (Central Research Inst. for Physics, Hungary)

Friday Morning

Session 11 **Advances in Machinery Diagnostics & Loose-Part Monitoring**

Chairman: E. Türkcan (Netherlands Energy Research Foundation, Petten, The Netherlands)

11.1 *PCI Transient Recorder Monitoring Machine Vibrations on Nuclear Powered Ice Breakers*
A. L. Lattka (Siemens AG, Germany)

11.2 *A Diagnostic System for Transient Monitoring and On-Line Fatigue Usage Factors Evaluation of Primary Circuit Components at the 1000-MW Nuclear Unit in Temelin*
O. Matal, L. Vorel, J. Soukup (Institute for Research and Application of Specialized Techniques, Czechoslovakia)

11.3 *Automated System for Motor-Operated Valve Diagnostics*
J. Eklund (Imatran Voima Oy, Finland), B. R. Upadhyaya (University of Tennessee, USA)

11.4 *Acoustic Monitoring of U-Tube Steam Generators*
B. J. Olma (Gesellschaft für Reaktorsicherheit, Germany)

11.5 *Discovery and Characterization of Loose Part Activity at Maine Yankee Atomic Power Station*
J. C. Robinson, J. W. Allen (Technology for Energy Corp.), J. Quinn (ABB Combustion Engineering), L. Oesterling, W. Johnson (Maine Yankee Atomic Power Station, USA)

11.6 *Design Considerations of Digital-Based Loose Parts Monitoring Systems*
G. L. Zigler (Science and Engineering Associates, USA), B. Bechtold (Siemens AG, Germany)

Friday Afternoon

Session 12A **Summaries Prepared by Session Chairmen**
Chairmen: R. C. Kryter (Oak Ridge National Laboratory, USA)
B. R. Upadhyaya (University of Tennessee, USA)

12.1 *Summary of Session 1*
J. Thie (Consultant, Knoxville, Tennessee)

12.2 *Summary of Session 2*
W. Bastl (GRS, Garching, Germany)

12.3 *Summary of Session 3*
R. Martinelli (C.R.E. Casaccia, Rome, Italy)

12.4 *Summary of Session 4*
D. Wach (GRS, Garching, Germany)

12.5 *Summary of Session 5*
R. Uhrig (Univ. of Tennessee, Knoxville/ORNL, Oak Ridge, Tennessee, USA)

12.6 *Summary of Session 6*
M. Kitamura (Tohoku University, Sendai-shi, Japan)

12.7 *Summary of Session 7*
K. Behringer (P. Scherrer Institute, Würenlingen, Switzerland)

12.8 *Summary of Session 8*
Ö. Glockler (CRIP, Budapest, Hungary)

12.9 *Summary of Session 9*
J.-P. Girard (CEN Cadarache, France)

12.10 *Summary of Session 10*
F. Akerhielm (EuroSim AB, Nyköping, Sweden)

12.11 *Summary of Session 11*
E. Türkcan (ECN, Petten, The Netherlands)

Session 12B **Symposium Conclusions**
B. Upadhyaya (The University of Tennessee, Knoxville)
R. Kryter (Oak Ridge National Laboratory, Oak Ridge)

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