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POTENTIAL OF ACOUSTIC MONITORING FOR SAFETY ASSESSMENT OF PRIMARY SYSTEM

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Abstract—**Safety assessment of the primary system and its components with respect to their mechanical integrity is increasingly supported by acoustic signature analysis during power operation of the plants. Acoustic signals of Loose Parts Monitoring System sensors are continously monitored by dedicated digital systems for signal bursts associated with metallic impacts. Several years of ISTec/GRS experience and the practical use of its digital systems MEDEA and RAMSES have shown that acoustic monitoring is very successful for detecting component failures at an early stage. Advanced powerful tools for classification and acoustic evaluation of burst signals have recently been realized. The paper presents diagnosis experiences of BWR's and PWR's safety assessment.**

1. Introduction

The classical concept to assess the integrity of components by stringent quality control measures during design, construction, and commissioning, combined with repetitive, discontinuous tests, and inspections during plant operation, is more and more supplemented by integral on-line status assessment concepts. Efforts to advance the safety of nuclear power plants (NPP) using modern computer technology have led to powerful new solutions for more automated fault diagnosis systems.

One of the main integral on-line diagnosis methods in NPPs is (besides vibration and process noise signature monitoring) acoustic monitoring by means of so-called loose part monitoring systems (LPMS). They are capable to detect component failures at an early stage /1-4/. Basic work has been sponsored by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety, which is highly acknowledged.

In the German RSK-guidelines /5/ the use of adequate measures is required in order

- to detect free and captive loose parts within the pressure retaining boundary and
- to localize loose parts as well as possible.

Piezoelectric accelerometers working in the acoustic frequency range have been found to be very effective for this task.

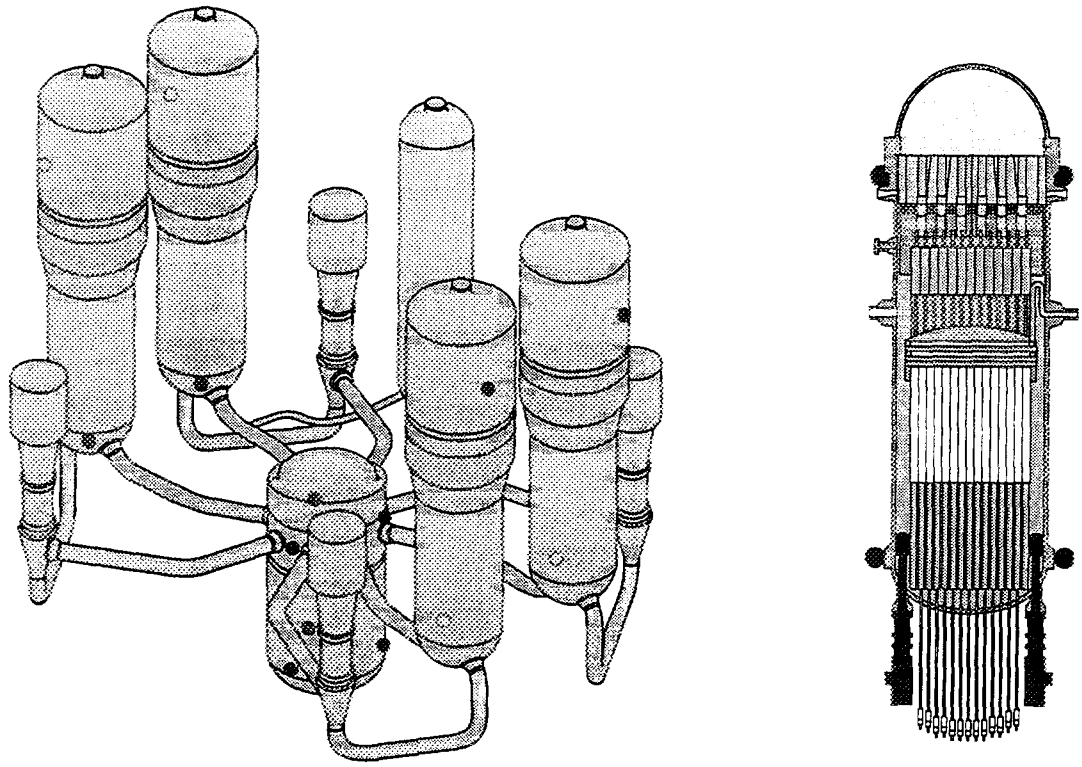

Fig. 1: Sensor positions of loose parts monitoring systems for PWR and BWR

Fig. 1 shows the sensor positions of LPMS for a 1300 MW Pressurized Water Reactor and a 1300 MWe Boiling Water Reactor. The sensors are mounted as near as possible to the surface of the monitored structure. They are positioned in different levels at the reactor pressure vessel and steam generator. ISTec/GRS has collected extensive acoustical data sets from reactor internals and primary circuit components.

2. Acoustic signal analysis systems

Loose parts monitoring systems are installed in all German NPPs. The systems work on-line and monitor the reactor coolant system for detached or loose internal or foreign parts. The technical status of the systems is different according to the different period of their construction. They have been developed now to a satisfactory status. In recent years more and more utilities have replaced old analog systems by modern digital systems. Current investigations concentrate on the improvement of on-line diagnosis methods and trending of components status. ISTec has recently developed two software modules for classification and acoustic evaluation of LPMS signatures /6,7/.

Basic requirement for monitoring of active and passive components at Light Water Reactor (LWR) primary systems is the qualified analysis and detailed burst data interpretation of acoustic signals. A fast digital off-line burst processing system (MEDEA-system) has been realized in the ISTec laboratory. Ist major components are a 16 channels transient recorder, a UNIX- workstation, fast data storage facilities, interactive analysis software and a burst data base, see fig. 2. Acoustic signatures from measurements and analyses of 13 German LWRs with more than 11000 bursts are available. In a burst pattern data base they are characterized by the event type, measurement and signal parameters.

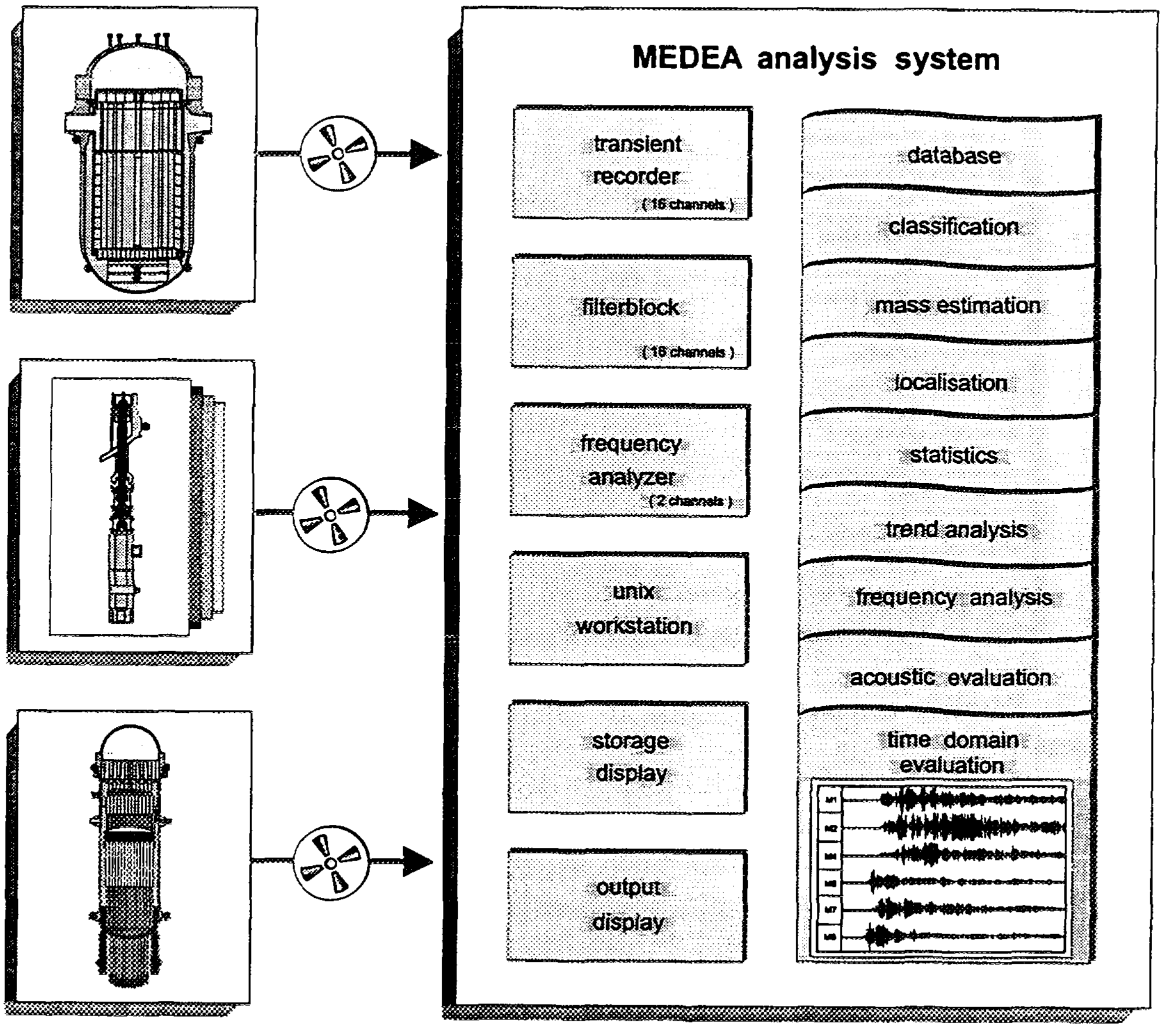

Fig. 2: MEDEA-system for off-line acoustic analysis

For on-site digital signal recording and diagnosis support to the plant a Remote Acoustic Monitoring and Signal Evaluation System (PC-RAMSES) has been developed by ISTec. It consists of six PC-based transient recorder storage modules, a graphic display and a modem. Software packages have been established for storage of the data to the on-site computer after event detection, for remote controlled settings of the transient storage modules via the telephone line and for data transfer of qualified signal patterns to the ISTec laboratory.

3. Safety Assessment by Acoustic Analysis

The common idea of safety assessment of reactor primary system by acoustic analysis is to use acoustic signatures for an integral component status assessment. Surveillance task is always a prevention of failures or a specific precaution against damage. A survey of successfully applied acoustic signal analysis methods is presented in fig. 3 as a reference taken from the practical use of the methods at the plants by ISTec/GRS. It demonstrates which status information has been gained by acoustic signal analyses, which sensor positions are especially suited for the specified surveillance task and which verified evaluation methods have been used for actual occurrences.

Surveillance Task	RPV sensor	SG sensor	SG add-on sensor	Reference
Surveillance of reactor vessel lower plenum and SG inlet plenum for free loose parts	●	●		burst analysis / strip chart record / acoustic evaluation
Surveillance of reactor vessel internals and SG internals for captive loose parts	●	●		burst analysis / localization / time interval analysis, acoustic evaluation
Surveillance of feedwater ring integrity (BWR + PWR)	●	●	●	pulse sequence analysis, tube-bundle vibration analysis
Recognition of impact events in the SG U-tube area		●	●	localization, pulse sequence analysis, acoustic evaluation
Irregularities at diffuser plate of main coolant pumps	●	●		pulse form analysis, acoustic evaluation
Loose screw connections at internal axial pump	●			pulse sequence analysis, acoustic evaluation
Core barrel monitoring for extensive screw failure	●	●		pulse sequence analysis, correlation with neutron flux
Surveillance of feedwater check valves (bearing and seat)		●	●	burst form analysis, acoustic evaluation
Recognition of impact events in heat removal system	●	●		burst analysis, correlation with operational measures
Surveillance of mechanical integrity of fuel elements during loading/unloading	●			correlation of acoustic signals with hoist force indications

Fig. 3: Possible status informations of primary system components gained by acoustic analysis

Acoustic monitoring systems contain an alarm processing unit with absolute and/or variable (floating) thresholds. Due to the high sensitivity of acoustic monitoring, the detection potential for impact occurrences is comparatively high. Low energetic and minor relevant events are indicated and could be seen as precursors of real failures. Too frequent unnecessary alarms can reduce the confidence to this monitoring technique and should be avoided by appropriate evaluation. On the other hand, they are of great value as status indicators, if they can be used for safety assessment of primary system components. In the following, experiences of status evaluation for safety assessment is presented.

4. Experiences of Status Evaluation for Safety Assessment

Emphasis of current activities on acoustic monitoring at the primary system of BWR's and PWR's is put on the enhancement of the knowledge base for the interpretation of acoustic signatures. The detailed evaluation of acoustic events requires extensive know-how and analysis efforts; interpreted case studies and well known reference patterns are the basis for the evaluation of extraordinary acoustic signatures. Plant independent registration and analysis of operational experiences, which have been gained on site, provide status information for components assessment.

ISTec/GRS has been involved with a large number of occurrences for analysis and for clarification of the problem by acoustic analysis. The advantage of its use has become obvious in numerous cases. Their bandwidth reaches from

- status assessment of the primary system and its components over
- support and optimization of repair measures with reduction of radiation dosage to personal up to
- flanking and accompanying measures for worst case considerations for plant operation

In the following some representative cases of the number of occurrences will be presented.

Status Assessment of Internal Axial Pumps after Replacement of Hydrostatic by Hydrodynamic Bearings.

In recent years consecutively in the three German BWR plants of construction series 69 with 800 MWe respectively 900 MWe electric power the hydrostatic bearings of internal axial pumps (8 respectively 9) have been replaced by hydrodynamic bearings; the pump shafts have been modified and exchanged. The task for the acoustic analysis was to perform a very sensitive surveillance of the pump area for low energy impact or contact occurrences as an additional, time-limited measure. In all three plants the RAMSES system of ISTec has been set up in parallel to the installed LPMS systems during the startup-phase for a period of typically six weeks with relatively low alert levels for an integral status assessment of the internal axial pumps. By a modem connection from the plant to the ISTec laboratory it was possible to follow the trend of the acoustic occurrences and to transfer registrated burst signals to the ISTec laboratory for analysis.

For a 800 Mwe plant, the results of the measurement campaign are shown in fig. 4. The measure was part of the start-up program after the shaft replacement, accepted by the authoritiy. Measurement phases A, B and C with additional FM tape recording are marked in the pump speed diagram. Measurement phase B contains test impact recordings for upper and lower signal evaluation region. Measurement phases A and C show recordings of cold testing and hot testing of the pumps. The analyses were supplemented by the recently developed acoustic module and classification module of ISTec /6,7/. The registered signatures delivered no specific occurences of mechanical impact or contact type. The experience with the new shafts and bearings of the internal axial pumps is positive.

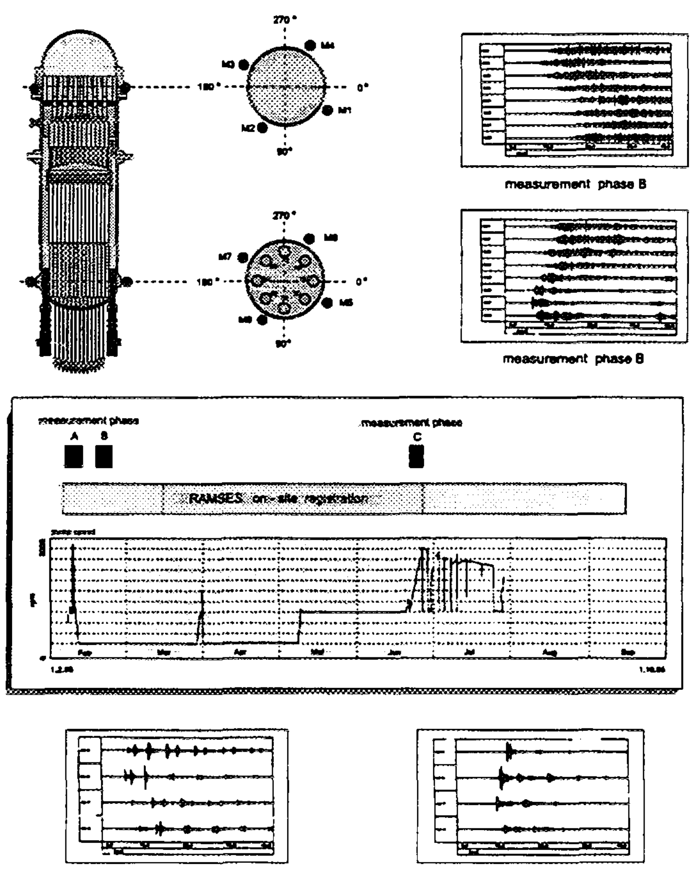

Fig. 4: Status assessment of internal axial pumps after replacement of bearings

Support and Optimization of Repair Measures at Steam Generators

In the Swedish plant Ringhals 2 (a Westinghouse type PWR) as a repair measure the steam generators have been replaced by new steam generators of Siemens/KWU. Unexplained acoustic indications occurred in a steam generator at high power levels. Clarification was required by the authorities before granting licence for full power. The acoustic signals, stored on magnetic tape were analyzed in ISTec laboratory. Fig. 5 shows the sensor positions and a measured burst pattern. The signatures could be interpreted as being caused by fluid induced, position invariant impacts of a loose metallic part with a mass between 100 g and 250 g within the feedwater ring at a specified angular position of 260 and 280 degrees. The localization graphs drawn on the development of the steam generator are shown in fig. 5.
A steam generator measurement phase with different water levels and constant feed water flow showed differently frequent impact signals in accordance with the results, see fig. 5. The following surveillance program, which had been accepted by the Swedish authority, was then established to monitor the steam generator until the regular end of the fuel cycle. A later inspection of the feedwater ring confirmed the ISTec diagnosis. A metal disc for inert gas provision during pipe welding, fixed by a wire, was found exactly in the specified region of the feedwater ring of the steam generator.

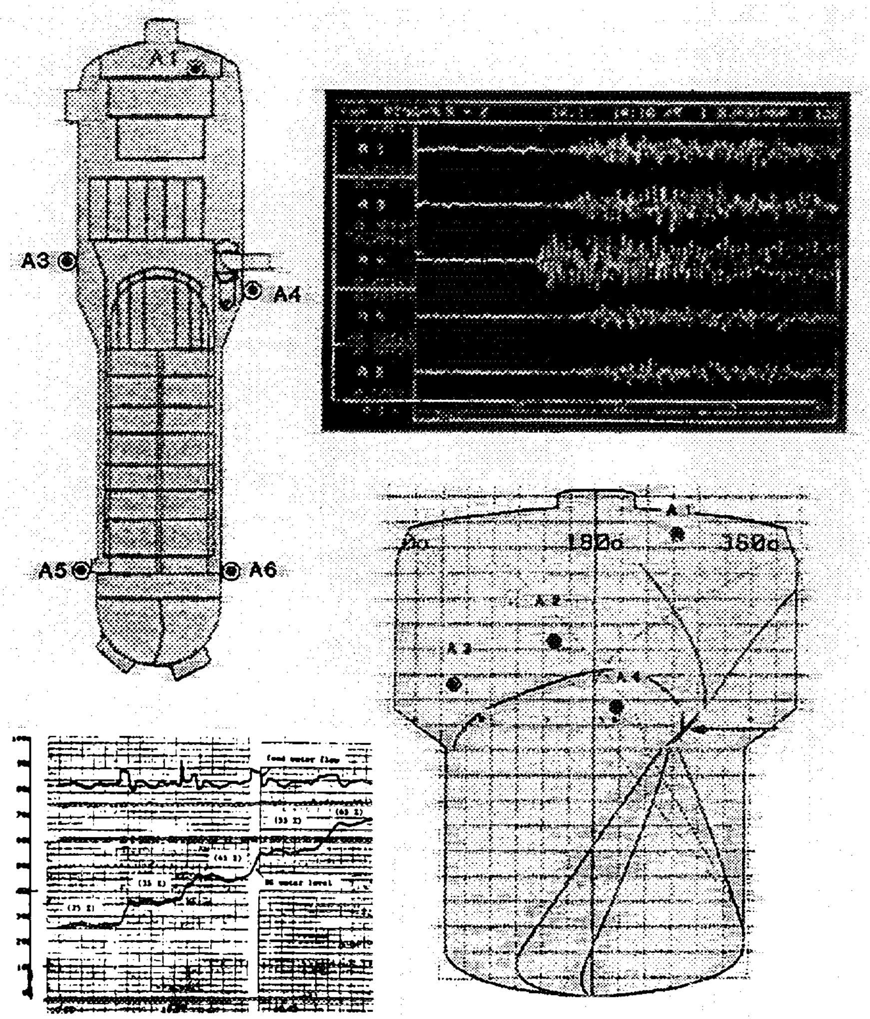

Fig. 5: Support of a repair measure at a steam generator

In a 1300 MWe PWR as a repair measure the steam generator tube bundles in the four steam generators have been fixed in the U-tube area with a comb-like construction by movable metallic swords. A combined instrumentation and monitoring program has been established in acceptance of the authority and TUEV. In the height of the U-bend area at each steam generator two accelerometers, shifted by 180 degrees, have been installed. The signals of each first sensor have automatically been monitored by alert levels, the second sensor was used as a passive measurement channel. Test impacts with an extended accelerometer instrumentation within the steam generator have been performed and recorded as reference signatures. Fig. 6 (left part) shows the observed signal pattern of a test impact to the comb construction with an aluminium rod. Vibrational measurements have been carried out under full power operation, too. Fig. 6 (right part) shows the APSD of a tube bundle sensor. Frequency peaks can be attributed to eigenfrequencies of the tube bundles and pendular vibrations of the steam generator.

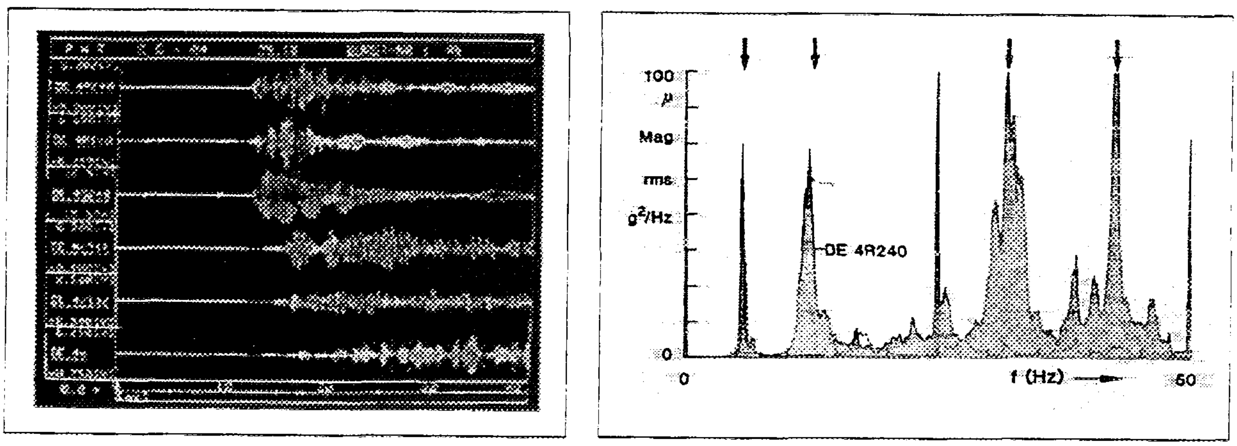

Fig. 6: Test impact pattern and APSD of steam generator instrumentation

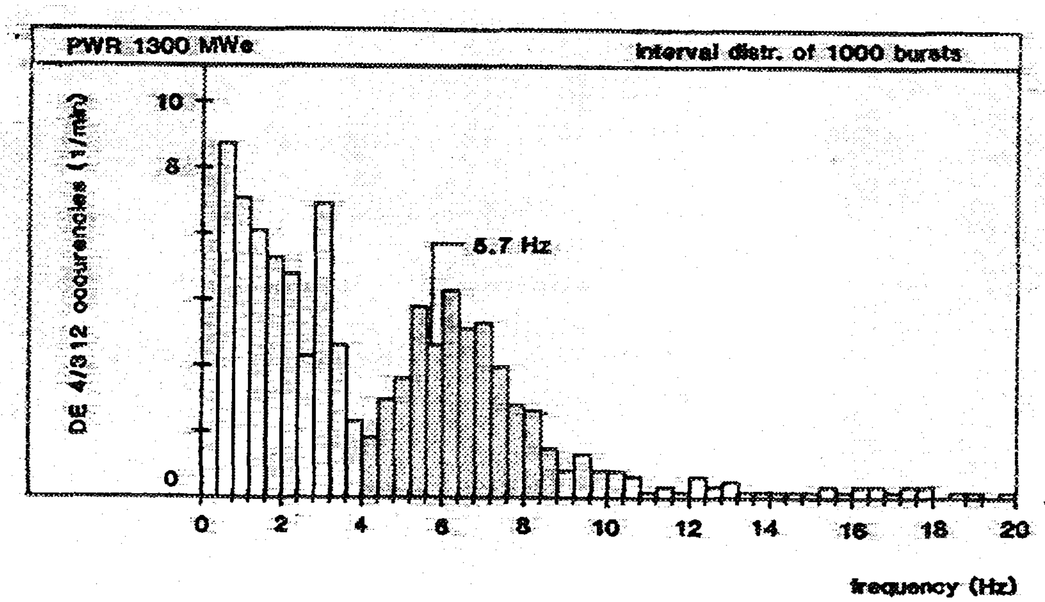

Fig. 7: Distribution of burst time intervals of tube bundle impact signals

During normal power operation of the plant characteristic burst signals from one sensor with a high sequence rate could be observed, yielding metallic impacts originating from one fixed position. Interval time analysis of fig. 7 showed a distribution with a characteristic shape and a dominant peak, which could be correlated to measured vibrations of steam generator tube bundles. This finding was supported by the fact that the impacts were subjected to operating conditions of secondary side (feedwater flow, asymmetric fluid load). Impacts of this kind could be avoided during subsequent operation by appropriate operating measures. Trending of the measured signals showed the success of the measures taken; the experience with the repair measures are positive.

Flanking and Accompanying Measures Needed for Plant Operation

An example for a flanking measure of acoustic analyses will be given below. Inspection of the core barrel of a 1200 MWe PWR showed indications for defective austenite core barrel screws, which should be replaced by ferritic screws then in the next plant revision. If screw failure should happen to a major extent, then by a worst case consideration it should be assessed that it could be recognized at an early stage by an appropriate measuring program.
A theoretical estimate of the acoustic evaluation showed that expected reactor vessel acoustic accelerometer amplitudes of a possible loose and impacting form sheet would reach signal noise ratios of more than 3:1 for the reactor vessel sensor and should therefore be detectable.
A combined acoustic and vibration monitoring program was performed till the end of the fuel cycle. The RAMSES system was installed on the site, the signals of four acoustic sensors of the reactor vessel have been used as monitor channels and were measured with relatively low alert levels. In the left part of fig. 8 the sensor positions are shown, in the right part the number of alarms per day in a 20-days period for the four sensors is presented. Digital signals of registered occurrences were transferred by telefone to the ISTec/GRS laboratory. The signal patterns could be evaluated as being not specific of the core barrel. No indications of ongoing screw failure of core barrel could be observed for this fuel cycle. This finding was confirmed later by inspection.

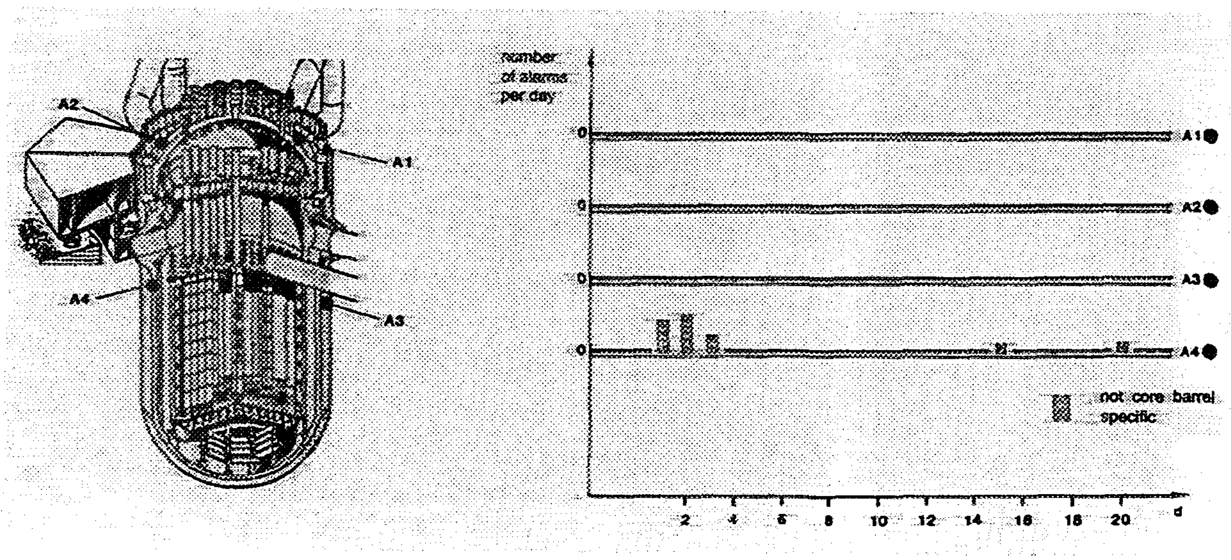

Fig. 8: Acoustic monitoring of possible screw failure of form sheet of core barrel as a flanking measure

5. Conclusions

Experiences during recent years proved that - more than the mere detection of loose parts - acoustic signal analysis has high potential for safety assessment of the primary system and its components with respect to their mechanical integrity. Basic requirement for a reliable diagnosis is the availability of a knowledge basis for the interpretation and evaluation of acoustic signatures. Successful applications of acoustical analyses have been described and illustrate the comprehensive potential of an active on-line monitoring and alarm processing of acoustic signals in nuclear power plants. The high cost of unplanned shut-down of the plant can be reduced and the safety of the nuclear power stations can be improved by applying such methods. Safety assessment of primary system and ist components with respect to their mechanical integrity can be performed now during operation of the plant.

6. References

[1] B. J. Olma, "Acoustic Monitoring of U-tube Steam Generators", proceedings of SMORN VI Symposium, Gatlinburg, USA,19.-24.5.1991, Vol. 2, pp. 74.01 - 74.13

[2] B. J. Olma, Y. Ding, R. Enders, "Operational Experiences with Automated Acoustic Burst Classification by Neural Networks", proceedings of the 7th Symposium On Nuclear Reactor Surveillance And Diagnostics (SMORN VII), Avignon, France, June 1995

[3] B. J. Olma, D. Wach, "Acoustic, Noise and Vibration Monitoring - Useful Methods in Condition Monitoring and On-line Degradation Diagnosis", IAEA Technical Committee Meeting on "Utilization of Condition Monitoring and Degradation Systems to Improve Nuclear Safety", Wien, Austria, 7.-9.10.1991

[4] B. J. Olma, "Source location and mass estimation in loose parts monitoring of LWR's", SMORN IV, Prog. of Nuclear Energy, Vol. 15, pp. 583-594, 1985

[5] RSK-Guidelines for Pressurized Water Reactors, 3.Edition, October 1981

[6] B. J. Olma, "Audio replay of acoustic burst signals for digital loose parts monitoring systems", Kerntechnik, November 1995, Vol. 60/5-6

[7] Y. Ding, "Advanced Software Tools for Digital Loose Part Monitoring Systems", IAEA Technical Committee Meeting on "Monitoring and Diagnosis Systems to Improve Nuclear Power Plant Reliability and Safety", Gloucester, U.K., May 1996