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BSI British Standards

Nuclear power plants — Instrumentation important to safety — Acoustic monitoring systems for detection of loose parts: Characteristics, design criteria and operational procedures

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British Standards

National foreword

This British Standard is the UK implementation of IEC 60988:2009.

The UK participation in its preparation was entrusted to Technical Committee NCE/8, Reactor instrumentation.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Nuclear power plants – Instrumentation important to safety – Acoustic monitoring systems for detection of loose parts: characteristics, design criteria and operational procedures

Centrales nucléaires de puissance – Instrumentation importante pour la sûreté – Systèmes de surveillance acoustique pour la détection des corps errants: caractéristiques, critères de conception et procédures d'exploitation

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CONTENTS

INTRODUCTION

a) Technical background, main issues and organisation of this Standard

This International Standard addresses the issues specific to acoustic monitoring systems for loose parts detection. It describes the principles, the characteristics and the test methods for those systems.

It is intended that this Standard be used by operators of NPPs (utilities), systems evaluators and by licensors.

b) Situation of the current Standard in the structure of the IEC SC 45A standard series

IEC 60988 is the third level SC 45A document related to acoustic monitoring systems for loose parts detection used in power reactors.

For more details on the structure of the IEC SC 45A standard series, see item d) of this introduction.

c) Recommendations and limitations regarding the application of this Standard

It is important to note that this Standard establishes no additional functional requirements for safety systems.

d) Description of the structure of the IEC SC 45A standard series and relationships with other IEC documents and other bodies documents (IAEA, ISO)

The top-level document of the IEC SC 45A standard series is IEC 61513. It provides general requirements for I&C systems and equipment that are used to perform functions important to safety in NPPs. IEC 61513 structures the IEC SC 45A standard series.

IEC 61513 refers directly to other IEC SC 45A standards for general topics related to categorization of functions and classification of systems, qualification, separation of systems, defence against common cause failure, software aspects of computer-based systems, hardware aspects of computer-based systems, and control room design. The standards referenced directly at this second level should be considered together with IEC 61513 as a consistent document set.

At a third level, IEC SC 45A standards not directly referenced by IEC 61513 are standards related to specific equipment, technical methods, or specific activities. Usually these documents, which make reference to second-level documents for general topics, can be used on their own.

A fourth level extending the IEC SC 45A standard series, corresponds to the Technical Reports which are not normative.

IEC 61513 has adopted a presentation format similar to the basic safety publication IEC 61508 with an overall safety life-cycle framework and a system life-cycle framework and provides an interpretation of the general requirements of IEC 61508-1, IEC 61508-2 and IEC 61508-4, for the nuclear application sector. Compliance with IEC 61513 will facilitate consistency with the requirements of IEC 61508 as they have been interpreted for the nuclear industry. In this framework IEC 60880 and IEC 62138 correspond to IEC 61508-3 for the nuclear application sector.

IEC 61513 refers to ISO as well as to IAEA 50-C-QA (now replaced by IAEA GS-R-3) for topics related to quality assurance (QA).

The IEC SC 45A standards series consistently implements and details the principles and basic safety aspects provided in the IAEA code on the safety of NPPs and in the IAEA safety series, in particular the Requirements NS-R-1, establishing safety requirements related to the design of Nuclear Power Plants, and the Safety Guide NS-G-1.3 dealing with instrumentation and control systems important to safety in Nuclear Power Plants. The terminology and definitions used by SC 45A standards are consistent with those used by the IAEA.

NUCLEAR POWER PLANTS – INSTRUMENTATION IMPORTANT TO SAFETY – ACOUSTIC MONITORING SYSTEMS FOR DETECTION OF LOOSE PARTS: CHARACTERISTICS, DESIGN CRITERIA AND OPERATIONAL PROCEDURES

1 Scope

This International Standard is applicable to on-site systems used for continuous monitoring of structure-borne sound measured at the reactor coolant pressure boundary of light water reactors for the purpose of detecting loose parts.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61226, *Nuclear power plants – Instrumentation and control systems important to safety – Classification of instrumentation and control functions*

IEC 61513, *Nuclear power plants – Instrumentation and control for systems important to safety – General requirements for systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
adaptive resonant frequency
natural frequency of the mechanical attachment (e.g. bolts, magnets), including sound sensors

3.2
alarm level monitor
a device which compares the value of a variable with a fixed or variable threshold. If the threshold is exceeded, the output signal changes its state

3.3
background noise
structure-borne sound which is generated during operation of the reactor plant, even in the absence of loose parts. It is composed of stationary background noise and operation-related single sound events

3.4
burst amplitude distribution
frequency distribution of the maximum observed amplitudes of the bursts in the signal of a sound sensor

3.5
burst interval distribution
frequency distribution of the time intervals observed between the individual bursts in the signal of a sound sensor

3.6
delay difference
time difference between the occurrences of the bursts generated by a single sound event in the signals of different sound sensors

3.7
detached part
part which has become detached from the component in the pressure-retaining boundary of the reactor coolant, and which therefore can be carried along with the reactor coolant

3.8
known event
an event for which comparable events occurred repeatedly, were recorded, evaluated and assessed and the criteria for the comparability of these events have been identified and defined (e. g. signal form, delay)

NOTE A known event can be a single burst or a set of bursts. A known event can be classified as an event being alarm-relevant or not being alarm-relevant.

3.9
loose part
both a detached or loosened part as well as a foreign part

3.10
loosened part
part which becomes loose, yet still remains connected to the component to which it was originally firmly attached

3.11
monitored signal
signal from a band-pass filter applied to the sound sensor signal

3.12
resonance factor
ratio of the signal amplitude at the natural frequency of response to the amplitude in the flat region of response of the sensor system with any attachments

3.13
single channel alarm inhibit
a function that inhibits an alarm if only one channel has been triggered by a single sound event. An alarm is set if at least a second channel has been triggered by the same single sound event

3.14
single sound event
structure-borne sound generated by a single event which is superimposed on the stationary background noise (e.g. impact of a loose part, control rod drive noise or a sudden reduction of stresses)

3.15
sound burst
signal component generated in the sound sensor as a result of a single event causing a sound which is superimposed on the signal of the stationary background noise

NOTE In this standard the term burst is used as an equivalent.

3.16
sound sensor
mechanical/electrical energy converters receiving structure-borne sound which is detectable at the surface of a solid body as displacement, velocity or acceleration

3.17
stationary background noise
consists of stochastic components (e.g. coolant flow noise, fluid resonances) and deterministic components (e.g. speed-dependent pump noise)

3.18
structure-borne sound
sound which propagates in solid bodies. The structure-borne sound in this standard is taken to mean the sound within the audible frequency range

4 Purpose and description of loose parts detection

4.1 General

The presence of a loose part in the primary coolant system can be indicative of degraded reactor safety resulting from a failed or weakened component or from a part inadvertently left in the primary system during construction, refuelling, or maintenance. A loose part can contribute to component damage and material wear by frequent impacting with other parts in the system. A loose part can pose a serious threat of partial flow blockage with attendant departure from nucleate boiling which in turn could result in failure of fuel cladding.

Early detection of a loose part can provide the time required to avoid or mitigate safety-related damage to, or malfunction of, primary system components. The primary purpose of a loose parts detection system is the early detection of loose, loosened or detached metallic parts with their potential to cause damage to:

a) the reactor core,
b) other internals structures of the primary circuit, or
c) the primary circuit pressure boundary.

Suitable systems shall be installed for this purpose.

Loose parts detection systems have been used successfully in water reactors for many years, and have detected bolts and tools dropped in construction or refuelling, which otherwise could have caused significant damage. They normally have a low safety significance, but due to the potential for damage that a loose part could cause, regulators will expect installation of suitable systems.

4.2 System definition

Depending on the national safety regulation,

– The system focuses mainly on the loose parts detection on the primary coolant system. The system may additionally monitor the vibrational state of the primary circuit. This option (which is outside the scope of this standard) may have consequences on the number and the location of the sensors.
– The expertise to make a diagnosis may be present either:

  locally in each plant site. This implies that the analysis tools are available on-site and the on-site operators have to be trained for a signal evaluation; or

  on a remote site at a national level. This implies that the transfer of all of the necessary data to the experts is always fully efficient.

– The triggering of an alarm sent to the control room may be based on signals exceeding a threshold by either:

  the burst amplitude of a single sound event. This makes it possible to record and analyse the signals event by event, or

  the rate at which transients are detected. This implies continuously recording the signals. The diagnosis is then made from an analysis including many single sound events.

– The monitoring of the state of the sensors may be done by

  a calibration test equipment for the measurement lines with impact hammer units on the primary circuit, or by

  in-depth monitoring and signal processing of the background noise.

When designing a new system a choice from the above-mentioned items should be made as a first step. According to the national regulation the system definition needs to be specified.

4.3 System outline

Loose parts detection systems typically consist of a set of accelerometers mounted on the reactor vessel, steam generators and coolant pump casings, with processing electronics to filter the sound signals from the sensors and monitor them for alarms. Recording facilities are provided, and operators generally listen to the sensor noise at regular intervals, and specifically after refuelling, due to the sensitivity and processing power of the human ear. A fuller description with typical sound traces is provided in Annex A.

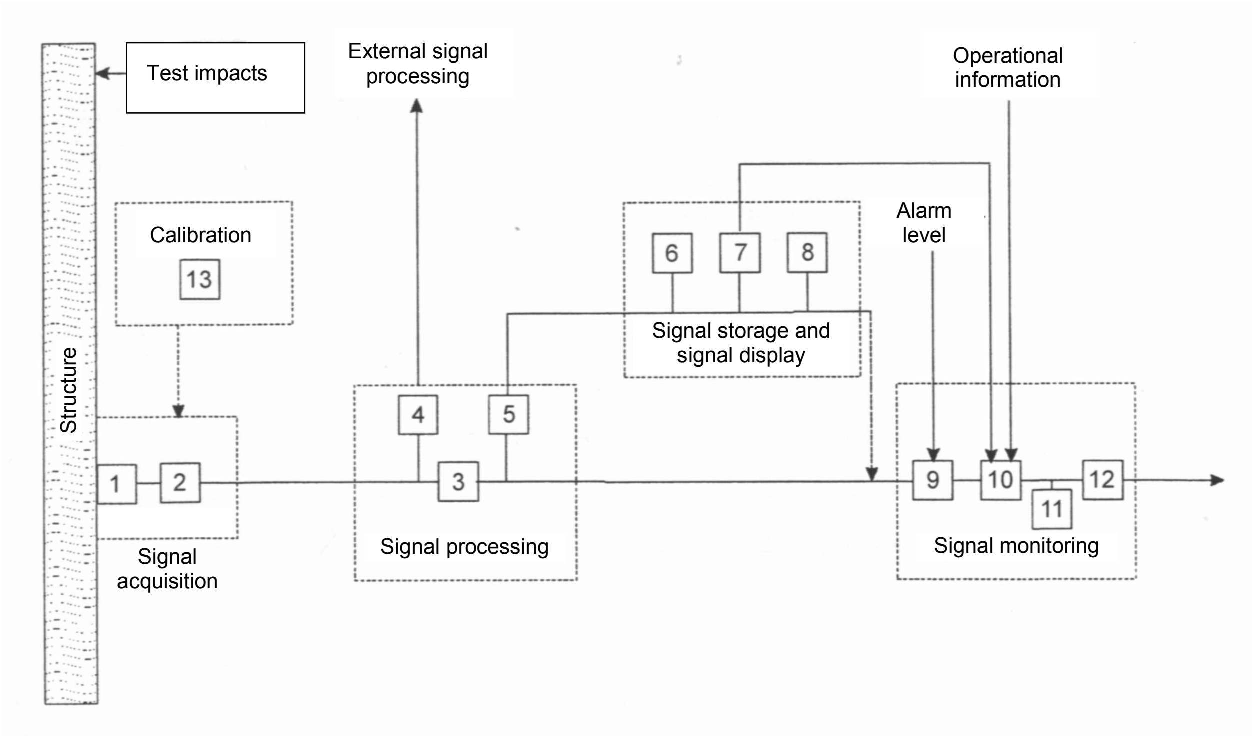
5 System requirements

5.1 Basic structure and design criteria

Generally the system has the following basic functions (see Figure 1).

- signal acquisition,
- signal processing,
- signal storage and signal display,
- signal monitoring,
- calibration.

Requirements for each basic function are described in the following subclauses.



Key

1	Sound sensor	8	Audio unit
2	Preamplifier	9	Alarm level monitor
3	Band-pass filter	10	Logic element
4	Decoupled signal outputs	11	Internal alarm unit
5	Amplifier	12	Interface to external alarm unit
6	Indicator (display)	13	Calibration unit
7	Recording or storage		

NOTE 1 Control signals are not shown.

NOTE 2 On-line calibration equipment and test impact units need not be permanently installed.

NOTE 3 The monitoring system is an operational system whose function is not classified at a high category according to IEC 61513 and IEC 61226.

Figure 1 – Functional block diagram of a loose parts monitoring system

The detailed functions of each block are described in informative Annex B and specific requirements are given in the following subclauses.

The design and installation of the system (including its detection sensitivity) shall be in accordance with national regulations relating to system instrumentation and control for the particular reactor plant.

The system shall be designed using a frequency range consistent with detection algorithms that will ensure sufficient sensitivity of the system to detect a metallic loose part with a minimum of false alarms. Depending upon the particular detection algorithm the frequency range is typically between f_a = 0,5 Hz to 1 kHz and f_b = 10 kHz to 20 kHz, where f_a and f_b refer to the lower and upper 3 dB frequencies of the bandwidth of the pass band.

NOTE Processing up to f_b = 20 kHz is very suitable.

The differences in the transfer functions of one measuring chain from any other measuring chain, excluding the sound sensors, should not be greater than 1 dB when selecting identical cut-off frequencies of the band-pass filters.

5.2 Signal acquisition

5.2.1 Selection and installation of the sound sensors

The recommended sound sensors are piezoelectric transducers. Sound sensors shall be selected to be able to withstand the ambient conditions (e.g. simultaneous exposure to high temperature and radiation levels, splash water) prevailing at their point of installation.

The sound sensors shall be mounted on the outer surface of the pressure-retaining boundary.

All methods of attachment (e.g. screw, magnetic, clamping connections) which meet the requirements described in this standard may be used. All sound sensors should have uniform response characteristics.

The mounting locations shall be selected on the basis of the following:

- the sound sensors shall be positioned in the areas to be monitored. Monitoring areas are, e.g., the reactor pressure vessel bottom head and steam generator inlet water box,
- the sound sensors should be mounted in accessible areas where conditions for sound transmission between the internal structures and the pressure-retaining boundary are particularly favourable (e.g. in the nozzle area of the pressurised water reactor, in the area of the core supports and in the area of the dryer support ring in boiling water reactors),
- the sound sensors should be replaceable,
- the arrangement of the sound sensors shall not restrict accessibility for non-destructive examinations, and the sensor location should be selected so as to minimise dose rates to the equipment and personnel conducting maintenance on the equipment.

The number of sound sensors for each monitoring area is directly related to the function. If detection is required of a detached or loosened part only, then a single sound sensor is sufficient. To distinguish between detached and loosened parts, two sound sensors may be adequate in many cases. When it is necessary to locate detached and loosened parts two dimensionally, at least three sound sensors are required (e.g. reactor pressure vessel surveillance).

In case of defective and inaccessible sound sensors, new sound sensors may be installed in accessible areas as a replacement, taking account of the information content of the signals in comparison to the dose exposure of the personnel conducting maintenance.

NOTE It may be preferable to place at least two sensors in each monitoring area which avoids information loss in case of a defective sensor. Further sound sensors may be necessary for the diagnosis of single sound events. The associated signals may be monitored separately.

For installing the sound sensors, the mounting locations shall be prepared in accordance with the nature of the intended connection. The mounting surface for the sound sensors should be matched to the intended type of mounting. In addition, screw and clamping connections shall be protected against loosening, and magnets against slipping. Provision shall be made for the strain relief of the sensor cables.

The installation sites for sensors should be agreed with the design and site installation engineers concerned with the vessels that are monitored and those concerned with their thermal insulation. Removable sections of insulation should be used to allow access to the sensors.

5.2.2 Preamplifiers

The signals received from the sound sensors should be converted in preamplifiers (or impedance converters) in such a way that the transmission to the signal processing unit is as free from interference as possible. The design of the preamplifiers should take into account the ambient conditions which prevail at the point of installation. Electrical interference shall be minimized by suitable choice of cable type, routing and length, due consideration being given to installation and maintenance. These cables shall be designed to withstand the ambient conditions. The gain of the preamplifiers shall be adjusted to the sensitivity of each sound sensor in such a way that all channels have nominally identical sensitivities within a tolerance of ±10 %.

NOTE Identical sensitivities of the channels within a tolerance of ±10 % may also be achieved by adjustment of the gain of the processing unit.

The upper cut-off frequency shall be selected in such a way that the adaptive resonant frequency is transmitted.

5.3 Signal processing

5.3.1 General

The functions of the signal processing unit should be:

- to improve the ratio of signal strength to stationary background noise by means of band-pass filtering,
- to provide unfiltered signals for external processing,
- to process the signals so that they are suitable for signal storage,
- signal display and signal monitoring.

These requirements may be fulfilled in various ways, provided that the design criteria of 5.1 are fulfilled. The signal processing unit normally consists of the modules included below.

5.3.2 Band-pass filters

The band-pass filters shall have minimum characteristics of:

- filter steepness: 24 dB/octave,
- filter top linearity: ± 1 dB,
- pass-band: $f_a \leq f \leq f_b$.

The amplitude range which can be transmitted shall be matched to that of the preamplifiers.

NOTE The use of additional filters (stationary or temporary) or of a method for spectral subtraction for further reduction of interfering signal components of stationary background noise in the pass-band is admissible.

5.3.3 External output signal

External signal output units should be short circuit proof and isolated by transformer output circuits. Their design shall permit the full amplitude and frequency range of the preamplifiers to be transmitted. The signal output shall be compatible with data processing equipment.

5.3.4 Amplifier

If an amplifier is required for improved signal display or for an audio unit, an amplifier with variable gain is recommended. Gain should be varied in at least four steps of approximately 10 dB each.

5.4 Signal storage and signal display

5.4.1 Background noise monitoring

A method of monitoring the background noise of the sensor signals shall be provided. This can be done using either the raw signal or the signal envelope, or the RMS (root mean square) value of the signal. The RMS monitor can be used for an objective assessment of the background noise and of the signals used for the functional test. The design of the unit shall be configured such that it is possible to display the RMS values of all signals (e.g. RMS voltmeter with selector switch) or to display a background noise estimate. The RMS values shall meet at least the following requirements:

- frequency range: $0,7 \times f_a \leq f \leq 1,5 \times f_b$,
- peak factor: > 5,
- accuracy: better than 10 % full scale,
- integration time: $1 \text{ s} < t_i < 5 \text{ s}$.

Software calculation of background noise can improve on these characteristics.

5.4.2 Digitisation and storage

For evaluation and archiving of the structure-borne sound signals, the loose parts monitoring system shall be provided with a unit for digital storage of the signals.

The system should include a facility to store all channel signals. It shall enable synchronous processing of sufficient channels, such that all monitoring areas can be synchronously registered with all channels necessary for localisation.

The storage of each signal value shall meet the following:

- sampling rate per channel: ≥48 kHz,
- resolution: ≥11 bit.

The design shall have the facility for automatic signal recording on exceeding an alarm level. Transient recording or continuous recording may be used.

For transient recording the signals are stored, burst by burst. An alarm may be generated by exceeding a threshold using the burst amplitude of a single sound event.

For continuous signal recording, the background noise and the low level bursts between the detected bursts are included. An alarm may be generated from the rate at which single sound event transients are detected.

For transient signal recording the minimum requirements of signal storage are:

- recording time window: ≥40 ms,
- pre-trigger time: 0 % to 100 % of the recording time window, adjustable
- dead time: ≤200 ms,
- storage capacity: as a minimum, 300 subsequently occurring events based on a recording time window of ≤100 ms.

For continuous signal recording the recording time shall be between 10 min and 20 min for at least 4 channels. If the recorder cannot record all the channels simultaneously, there shall be a multiplex so that the signals from the monitoring area are redirected to the recorder.

The single sound events stored during surveillance (see 7.3.2) should be archived electronically for a time period of two years as a minimum.

5.4.3 Audio unit

Human listening to the signals of the acoustic sensors is a proven method of subjective online evaluation of the signals.

The audio unit shall be designed so as to enable audible monitoring of each measuring channel.

The audio unit shall provide at least:

- frequency range: $f_a \leq f \leq f_b$,
- headset output (two-channel design is acceptable),
- volume: variable.

An additional loudspeaker may be provided.

5.4.4 Information display

The display and storage of the main data of an event should include as a minimum,

a) event-related information
   1) event ID for clear identification,
   2) system code,
   3) date and time of the event,
   4) main settings of digital storage.
b) channel-related information
   1) RMS value of the background noise (this may include burst components),
   2) alarm levels at the time of event occurrence,
   3) measuring channel which has triggered,
   4) further measuring channels whose alarm levels were exceeded.

The analysis of detected events can be made on site or away from the site by experts.

If the analysis of detected events is made off-site by experts the above-mentioned main data should be provided from site. (Methods for the off-site analysis are outside the scope of this standard.) In this case the on site display information may be restricted to:

- which monitoring area has triggered the alarm (e.g. bottom steam generator, lower vessel),
- amplitudes and occurrence rate of the bursts and
- how many channels are affected.

If the analysis is made on site the display of information should provide:

– tabular display of system settings and of the data of the recorded events,
– graphical display of structure-borne sound signals designed to assist evaluation by operators.

For these display types, the use of high-resolution colour monitors is recommended. For printouts, at least a black and white graphics printer shall be used.

The tabular display of system settings should be documented at the time of the occurrence of the event such that a clear evaluation and traceability of the events will be possible at any time.

The graphical display of the structure-borne sound signals is used to visualise the time signals of an event. This type of display provides an evaluation of the structure-borne sound signals with regard to:

- identification of signatures indicating loosened, detached or foreign parts,
- localisation of the source of such signals,
- estimate of the mass of the loose part.

It should be possible to present the time signals of the individual recording channels separated for each channel with the same time axis and in graphical form. For the evaluation of the events, the graphical display of the structure-borne sound signals should at least provide the following functions: selection of the reference channel, time-stamping of burst arrivals of the residual channels and calculation of the delay differences compared to the reference channel, auto power density spectrum with, where appropriate, selectable period of time of the overall signal, calculation of the RMS value, localisation in cylindrical and spherical regions of components. The localisation may be performed linearly with the hyperbola intersection method or the Newton method, computer-based or manually (see Figures A.4b) and A.5b) of Annex A).

It is recommended that subsequent acoustic replay of recorded bursts is possible. A method should be applied which allows completion of the recorded bursts with stationary background noise and replaying it via suitable hardware.

5.5 Signal monitoring

5.5.1 General

Signal monitoring shall:

– Detect transients associated with, or due to electrical interference.
– Discriminate and eliminate those transients due to electrical interference or associated with operation related sound events (e.g. control rod movement, valve actuation).
– Trigger an alarm for each separate channel, until it is acknowledged.
– Initiate automatic recording or storing of the signals of the event.

5.5.2 Alarm level monitor

The alarm triggering is achieved by a unit which supplies a logic output signal when the monitored signal exceeds the alarm threshhold.

The monitored signal is, for instance,

- the output signal of the band pass filter, or
- a suitably formed parameter of this signal (e.g. the short-term averaged RMS value with an integration time of a few milliseconds), or
- another signal (different from the short-term averaged RMS value), which is suitable for detecting bursts. In this case the relationship between this parameter and the RMS or peak value shall be known in order to fulfil the conditions specified in 6.3.

Each channel shall be provided with its own alarm level monitor. It shall be possible to vary the alarm level and read off its setting (see 6.3). The alarm level monitor shall be able to distinguish spurious amplitude rises (e.g. such as caused by electrical pick-up) from bursts.

NOTE A signal suitable for monitoring is the RMS of the signal value integrated over about 5 ms.

For analogue monitoring

$$X(t) = \sqrt{\frac{1}{\tau} \int_{t-\tau}^{t} [x(u)]^2 \cdot du}$$

where

τ is the time constant;

t is the time;

x is the band-pass filtered signal of the sound sensor;

u is the integration variable;

X is the RMS value.

For digital monitoring

$$X(t) = \sqrt{\frac{1}{\tau} \sum_{i=0}^{n} \left\{ [x(i \cdot \Delta t)]^2 \cdot \Delta t \right\}}$$

where

τ is the time constant;

$t = i \cdot \Delta t$, time;

Δt is the sampling interval;

$n = \frac{\tau}{\Delta t} - 1$;

i is the digital variable;

X is the RMS value.

5.5.3 Logic element

A facility to suppress false alarms arising from known events shall be provided. The function of the logic element is to suppress the generation of false alarms due to known sound sources, or physically non-reasonable combinations (or shapes) of burst signals in different channels. Inputs to the alarm processing equipment should be provided from the relevant equipment (e.g. control rod controllers, valve operation switchgear). In any case, its design shall be such that if an alarm level is exceeded at the same time as single operation-related sound events, no alarm will result.

In the case of transient signal recording the logic element links the outputs of the alarm level monitors to binary signals and to internal evaluation results in such a way that:

- operation-related deterministic single sound events (e.g. control rod drive, valve actuation) and single-sound events (e.g. boiling process) related to a specific plant type do not lead to an alarm or storage,
- and known not alarm-relevant events (e.g. swing check valve) do not lead to an alarm.

The logic element can be realised by: logical linkage of the alarm level monitor output to binary signals (e.g. control rod movement), logical linkage of the trigger output to internal evaluation results, and single channel alarm inhibit (see 3.13).

In the case of continuous signal recording a coincidence is detected if bursts occur on at least 2 channels from the same monitoring area within less than – typically – 5 ms. Logic should be provided to inhibit multiple alarms that could arise from coincident alarms within more than 5 ms on several channels due to one initiating event. If in a time window the measured number of coincidences exceeds a fixed number an alarm is triggered. A typical fixed number may be 6 coincidences in 30 s.

The logic output signal of the alarm level monitor passing through the logic element shall excite the internal alarm unit and via an interface the external alarm unit and shall initiate recording or storing.

5.6 Calibration

5.6.1 General

If on-line calibration equipment is installed the equipment shall be able to:

– verify that the signal processing channel is correctly set,
– verify that the sound sensor is sensitive to impacts and is well connected to the structure as well as to the remainder of the channel,
– estimate the overall response of the channel to known simulated impacts.

The calibration device should be at least one of

– an electrical calibration unit for testing the signal processing channel from the preamplifier unit,
– an electrical calibration unit for testing the signal processing channel from the signal processing unit,
– a test impact unit for testing the overall system from simulated and reproducible impacts.

During operation of the plant, monitoring of the sensor and measurement chain may be performed by monitoring of the RMS value of the measured signal with high and low thresholds.

5.6.2 Mechanical functional test unit

Maintenance and calibration of the sensor may be done by generating impact series, using a test impact unit or a manual hammer to trigger the alarms of the loose parts monitoring system (see 7.5.4).

5.6.3 Electrical calibration unit

The electrical calibration unit shall be designed such that the signal channels can be calibrated at any time. For this purpose, a fixed unit is recommended. The calibration unit may be a sine-wave generator. The electrical calibration unit shall fulfil the following requirements:

- The frequency of the calibration signal shall be adjustable to the pass band of the band pass filter.
- The amplitude of the calibration signal shall be adjustable. Full scale shall be possible.
- Measurement tolerance of the calibration signal shall be ±5 % with $U_{\text{cal}} > 0{,}5\ \text{V}_{\text{peak}}$.
- It shall be possible to check the alarm level settings.
- If calibration is performed during plant operation, the monitoring function of the remaining channels shall continue in operation during calibration of the selected channel.

6 Initial start-up and operation

6.1 System testing before initial start-up of coolant circulating pump

The mounted acoustic sensors and all junction cables shall be visually checked as far as possible. The function of all system channels shall be checked. The amplification shall be adjusted to the sensitivity of each sound sensor in such a way that all channels have nominally identical sensitivities.

If the functions calibration and test impact are used, and the primary coolant system has been filled, mechanical pulses (test impacts of known energy) should be applied to the pressure-retaining boundary. This enables sound propagation conditions, adaptation of the sound sensors and functionality of the sensors together with the preamplifiers to be checked. The energy of the pulses shall be such that for the peak value of the burst of the sound sensor positioned next to the place of the impact, at least 50 % of the selected volume range is reached.

The signals of those sound sensors which show bursts during a test impact shall be recorded synchronously.

The following shall be documented:

- results of visual inspection of the installation,
- results of the electrical functions test,
- preamplifier settings,
- mode of generation of the mechanical pulses,
- energy of the mechanical pulses,
- position of the sound sensors,
- location of the points of impacts,
- signals of the sound sensors.

For the functional tests to be performed later during operation, additional test impacts shall be initiated at further points accessible during reactor plant outages (see 7.5.4).

6.2 Preliminary surveillance without alarm levels

Surveillance of the primary coolant system for loose parts shall be ensured from the initial start-up of the coolant circulating pumps onwards. At this time no information about the background noise of the specific plant is available and settings of the alarm levels are not necessarily known. Surveillance is performed by the operating staff specifically listening to the individual signals by means of the audio unit.

The background noises shall be recorded from selected operating states of the reactor plant e. g. different pressures, in order to permit a comparison with empirical values of other reactor plants. These operating states and the background noise recorded shall be documented in a suitable form.

6.3 Adapting the system to the plant requirements

When the operating state at which the reactor plant is monitored has been reached, the system shall be adapted to the plant requirements: the setting of the alarm level monitors and, if required, of band-rejection filters (see note in 5.3.2) are performed.

Transient recording or continuous signal recording may be adopted.

a) In the case of transient signal recording:

A pre-trigger time of 15 % to 35 % of the recording time window is recommended.

If the monitored signal exceeds five times a value deduced from the background noise, the alarm level monitor shall generate an alarm message (see 5.5.2). More sensitive settings are admissible. The setting of the alarm levels for the individual signal channels may vary. If the background noise changes during operations, it should be possible to change the alarm level settings (see 7.5 and 8). The monitored signal (e. g. RMS value $\tau = 5$ ms) and the value deduced from the background noise (e.g. RMS value $\tau = 1$ s) shall be determined by the same method.

NOTE Limiting dynamic values with follow-up or automatically adjusted gain is recommended. In this case the amplification factor and time behaviour of the signal monitoring shall be chosen so that the above criterion is fulfilled at least.

In the case of digital alarm level monitors, a minimum value may be chosen for the automatically set alarm values to suppress spurious alarms. For this minimum value, a range between 0,5 % and 5 % of the full scale is recommended. In the case of analogue alarm level monitors, the RMS value of the stationary background noise should be 5 % to 15 % of volume.

In addition to the setting of the gain, this value may also be influenced, to a limited degree, by the setting of the band-pass filters. This ensures that the alarm level can be set sufficiently low (e.g. five times the RMS value of the stationary background noise), i.e. that an adequate dynamic range is available for the recording of bursts.

The following shall be documented:

- setting of band-rejection filters,
- pre-trigger time setting,
- setting of the alarm level monitors including the set amplifications, and
- background noise after setting of the band-rejection filters.

b) In the case of continuous signal recording a reference set of recordings of background noise should be kept. Some records of single sound events and stationary background noise should be available at the plant for audible replay.

7 Surveillance programme

7.1 General

The surveillance programme distinguishes between two phases:

- preliminary surveillance (transient phase), and
- surveillance (steady state phase).

The preconditions for starting surveillance are:

a) the start-up of the loose parts monitoring system was completed,
b) the electrical system test was completed during plant outage (see 7.5.3).

7.2 Reference recordings

Several reference recordings are required to assess the actual sound signals and to interpret any changes. There are two types of recordings: Reference recording during plant shutdown (for test impacts, see 7.5.4), and reference recording during steady state plant operation (operating noise).

The reference recordings during steady state operation of the reactor plant are the basis for the interpretation of observed changes in the sound signals.

In the case of transient signal recording reference recordings should be made for:

- operation-related sound events,
- test impacts,
- background noise,
- changes of known and documented system properties.

The following shall be performed for reference recordings during steady state operation of the reactor plant: documentation of the RMS value of the signals of all active channels, recording of the signals of all channels with a dynamic range of at least 50 dB and a maximum permitted amplitude error deviation of ± 5 %, and registration of one recording each using the dedicated unit for digital storage.

In the case of continuous signal recording reference signals should be available for a diagnosis by experts, on-site or off-site. The recordings can be made at any time a sound event appears. It is useful to determine the frequency spectra and amplitude distributions of the signal recording and to perform a burst evaluation (see Annex D).

After prolonged outage periods (e.g. for refuelling), reference recordings shall be performed following the restart of the reactor plant.

NOTE In the case of boiling water reactors it is helpful to record several reference conditions at one time due to the power dependency of the background noise (pump speed).

7.3 Measurements during operation

7.3.1 Preliminary surveillance

Preliminary surveillance is considered in this standard as the time from start of the main coolant pump until reaching steady state power operation.

The start of the main coolant pumps shall be monitored by listening.

The operating staff shall listen to all monitored channels at regular intervals determined for the particular plant (e.g. once per shift up to 3 times a week). If significant changes in the noise pattern are detected, the subjective findings shall be recorded and a recording shall be made, evaluated and assessed for the signals of all channels.

The preliminary surveillance after the end of the heating phase should be performed with preliminary alarm levels. It is permissible to use the alarm level settings from power operation of the last cycle. If this setting leads to too many alarm messages, the alarm levels may be adjusted after clarification of the cause (e.g. change of the background noises). This shall also apply to the duration of operational measures if an increased number of alarms would be expected.

If possible, these operations can be done in automatic mode.

7.3.2 Surveillance

Surveillance is performed from reaching steady state power operation until the end of power operation.

During surveillance, any exceeding of alarm levels shall be indicated automatically. For this purpose, setting of the alarm levels is to be performed according to 6.3. Surveillance shall be supplemented by regular listening to the individual signals.

The operating staff shall listen to the signals of all monitored channels at regular intervals determined for the particular plant (e.g. once per shift up to 3 times a week). The results shall be archived. In the case of transient signal recording records of the signals shall be made at regular intervals (e.g. once every three months).

The assessment is performed by objective and subjective comparison of the actual signals of the sound sensors or their parameters with the signals or their parameters which have been stored as reference data. If significant changes in the noise pattern are detected, the subjective findings shall be recorded and a recording shall be made, evaluated and assessed for the signals of all channels. A decision is required on whether a reference recording should be performed.

7.4 Actions following an alarm

For an immediate assessment, the following information shall be available as a minimum:

- alarm identification sent to the control room,
- the number of the channels where an alarm value was exceeded,
- time and frequency of the alarm values being exceeded, and
- system status as on-line or failed or off-line.

After an alarm, the following shall be performed:

- listen to the signals of all channels,
- determine whether and where new alarms have been actuated,
- log the channels for which the internal alarm unit has been triggered,
- acknowledge the alarm,
- record selected time-correlated operating parameters and the associated reactor operating mode (e. g. operation of a major control valve),
- record the signal of all channels if an alarm is present again or significant changes in the noise pattern occur during listening. The subjective findings shall be archived,
- evaluate the recordings (see Annex D) and assess the results. Here, a parameter query for further operational parameters may be helpful.

NOTE In the case of preliminary surveillance, check of alarm level according to 7.3.1. An automatic recording and storage of selected operating parameters together with event data is recommended.

These actions shall be organised so that the assessment of whether an alarm was caused by a loose part can be performed in due time before damage could result.

Further actions should be performed depending on the assessment and in accordance with the particular plant.

7.5 Periodic testing of the system

7.5.1 General

Tests shall be performed at regular intervals. There are three types: functional tests, electrical system tests, test impacts.

7.5.2 Functional tests

The functional tests take the form of a qualitative check to demonstrate the operability of the surveillance system by recording and evaluation of the background noises. Monitoring of sensor and measurement chain may be performed by monitoring with low and high thresholds of the RMS value of the measured signal.

7.5.3 Electrical system test

There are separate electrical system tests for each of the two states: reactor plant outage, reactor plant operation.

During outage of the reactor plant, a test of the electrical part of the system shall be performed to prove that the system still has the specified functionally related characteristics from the input onwards. The measuring chain should be checked from the sound sensor to the preamplifier input.

During operation of the reactor plant, if the function calibration is used, a test of the electrical part of the system shall be performed to check the system from the preamplifier input onwards. A channel calibration takes place which shall be performed at regular intervals of three months with the electrical calibration unit described in 5.6.3 as follows:

- for each channel, a test signal shall be defined. A nominal value shall be specified for each channel in accordance with the amplification set for monitoring, and compared with the actual value of the indicator and recording. The deviations from the nominal value shall not exceed ± 10 %,
- for each channel, a calibration signal (stationary value for fixed alarm level and step for sliding alarm level) shall be defined so that all alarm level monitors are activated separately. The amplitude of the calibration shall be chosen so that the monitored signal (see 5.5.2) does not exceed the alarm levels by more than 20 %. The amplitudes of the calibration signal and the settings of the alarm level monitors shall be recorded.

If the deviations cannot be eliminated, the function of the channel shall be evaluated and documented accordingly.

If monitoring with low and high thresholds of the RMS value of the measured signal is performed, these functional tests may be used to prove system functionality instead of the above described electrical system tests during plant operation.

7.5.4 Test impacts

a) If the functions calibration and test impacts are used (see 5.6.1, 5.6.2), the operability of the overall system, including the sound sensors and signal lines to the preamplifiers, is demonstrated integrally with test impacts. Moreover, they provide a comparison standard for evaluating single sound events which occur during operation (see 7.2). The test impacts shall be performed prior to the initial start-up of the coolant circulating pumps (see 6.2) and prior to restart of the reactor plant following refuelling. The time should be chosen so that the reactor pressure vessel head is pressure-tight closed and the reactor cooling circuit is filled. For pressurised water reactors, the test impacts shall be performed prior to start-up of the main coolant pumps following refuelling.

The test impacts shall be applied to defined impact points. The impact points and the energy of the test impacts at adjusted setting of the alarm level monitors of the loose parts monitoring system shall be selected such that at least one alarm level monitor is activated per monitoring area. The sound signals shall be stored synchronously while the test impacts are applied.

For the impacts, the following shall be documented: the mode of generation of the mechanical impacts, data on the estimation of the impact energy (e.g. adjustable tension, mass, form of the impactor), the location of the points of impact, the signals of the sound sensors (recording with sufficient time and amplitude resolution for determining burst forms and delay difference).

The test impact data, in particular the data on the estimation of the impact energy and impact locations, shall be kept thereafter, as far as possible.

b) If the monitoring of the sensors is performed using low and high thresholds of the RMS value of the measured signal (see 5.6.1, 7.5.2), periodic maintenance and calibration of the sensor should be done during outages. To test the alarm function, a manual hammer may be used to generate an impact series.

8 Documentation

Test reports shall be produced to record all testing done, in accordance with Clause 7. In the test reports, IEC 60988 shall be referred to as the test basis.

The most important data which shall be documented are as follows:

- system description of the loose parts monitoring system (including instructions manual),
- information on the physical arrangement and technical data of the system (e.g. sound sensors, preamplifiers, cable routings, signal processing units, calibration unit, digitisation, up-to-date software versions, signal storage),
- updated system setting data (amplifiers, band-pass filters, alarm level monitors),
- information on the mounting of the sound sensors, information on hardware and software modifications performed,
- recordings, reports and data during initial start-up (see Clause 6),
- recordings, reports and data during surveillance (see Clause 7).

Annex A
(informative)

Description of loose parts detection with typical sound traces

Whenever detached or loosened parts impact on the inner surface of the pressure-retaining boundary of the reactor coolant or its internal structures, there is an energy transfer to the walls. Any metal part or mechanical component moving with the water flow can damage the inner surface of the circuit. Single sound events are generated as a result, which propagate as structure-borne sound along the solid structure of the pressure-retaining boundary of the reactor. The measurement of the structure-borne sound is focused on the detection of a loose part.

The structure-borne sound is received by sound sensors mounted on the outside of the pressure-retaining boundary of the reactor coolant. In this standard, it is assumed that accelerometers are used as sound sensors. The sound sensor converts the structure-borne sound event to a burst as the corresponding electrical signal component.

Additionally, background noise is generated by the coolant flow and the pumps as well as by other components mounted in or on the pressure-retaining boundary and which are activated during operation (e.g. valves and control rod drives). It is composed of stationary background noise (see Figure A.1a) and operation-related single sound events (see Figure A.2) of a pressurized water reactor. Figure A.1b shows signals of stationary background noise (with fluid resonances) of a boiling water reactor. The main objectives of the system are to detect the loose parts and to indicate the location area of a loose part, to be able to remove it after shutdown.

Figure A.3 shows signals with bursts resulting from the impact of a detached part. The signal amplitudes in Figure A.3 are scaled differently for better viewing. The signal pattern of a test impact and the associated localisation results are presented in Figure A.4 for a boiling water reactor and in Figure A.5 for a pressurised water reactor.

The detection is based on the acquisition of bursts generated by the impact on the wall. The detection system has to filter the bursts generated by the loose part from the noise generated by the normal operation of the circuit (large noise of pumps and water flow). For loose parts detection, operating staff listen to the signals of the sound sensors at regular intervals.

Reference recordings are used to set alarm levels for the monitored signal. As a rule, an alarm is actuated when the alarm threshold is exceeded. The cause of a single sound event can be narrowed down by comparison with reference recordings. The criterion used to distinguish between detached and loosened parts is the delay differences of bursts of a single sound event. The evaluation of several subsequent sound events shows constant delay differences for loosened parts, whereas in the case of detached parts delay differences may vary. The analysis of signal trends is not sufficient to determine the causes of bursts in general. In these cases, additional operational information has to be referred to.

The expertise for diagnosis can be on-site or off-site in an expert laboratory, depending on the national regulation. If the expertise for the diagnosis has to be on site and if alarm triggering is based upon excessive burst amplitude and burst capture by transient signal recording, the system can locate the impacts at the pressure retaining boundary and to assess the mass of the loose part on-site. The design of the system may be different if alarm triggering is based on continuous signal recording and crossing a threshold of burst rate. The system may then provide on-site data storage for an off-site diagnosis.

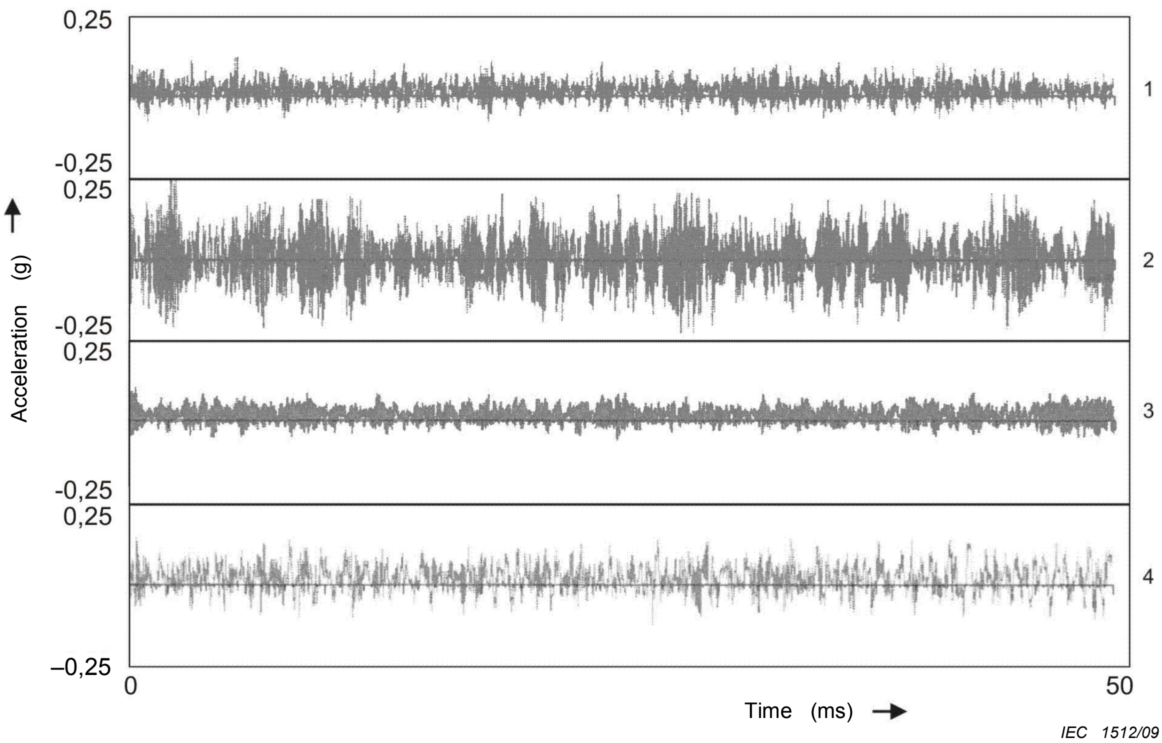


Figure A.1a – Typical signals of stationary background noise of a PWR

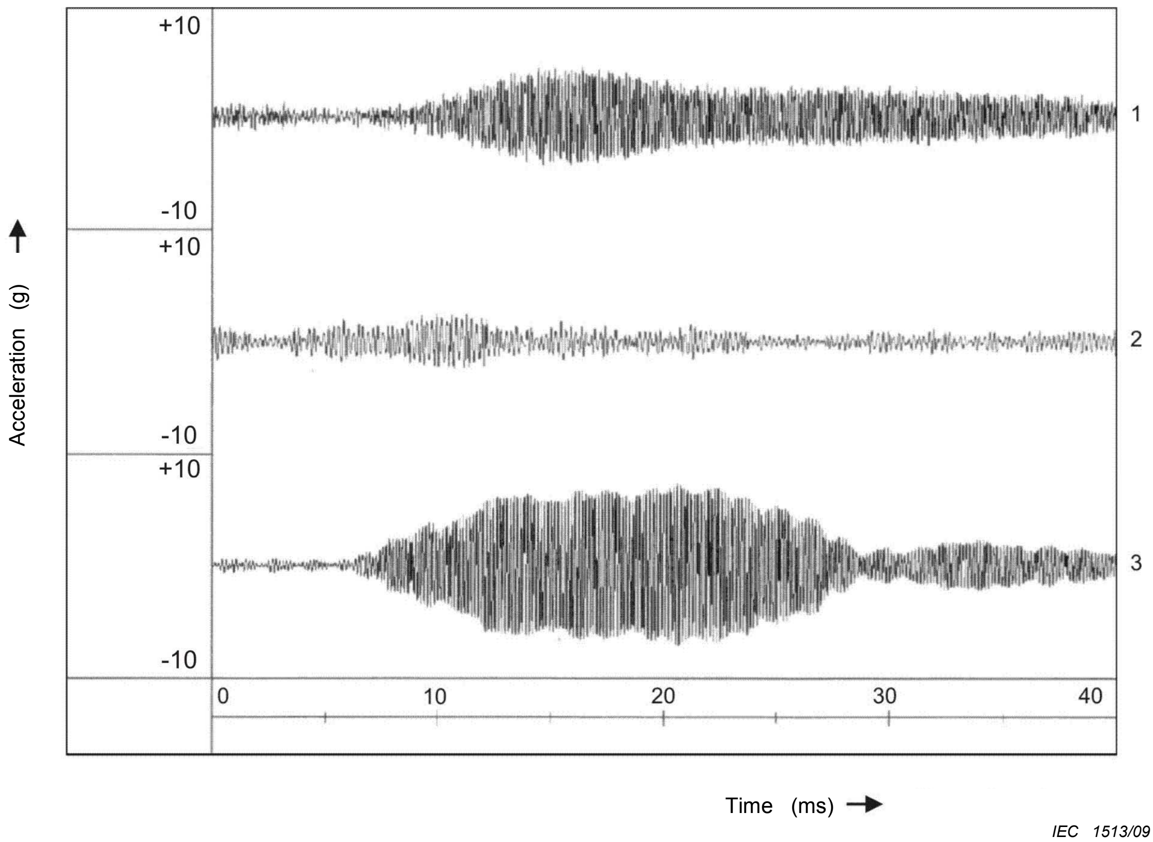


Figure A.1b – Typical signals of stationary background noise of a BWR

Figure A.1 – Typical signals

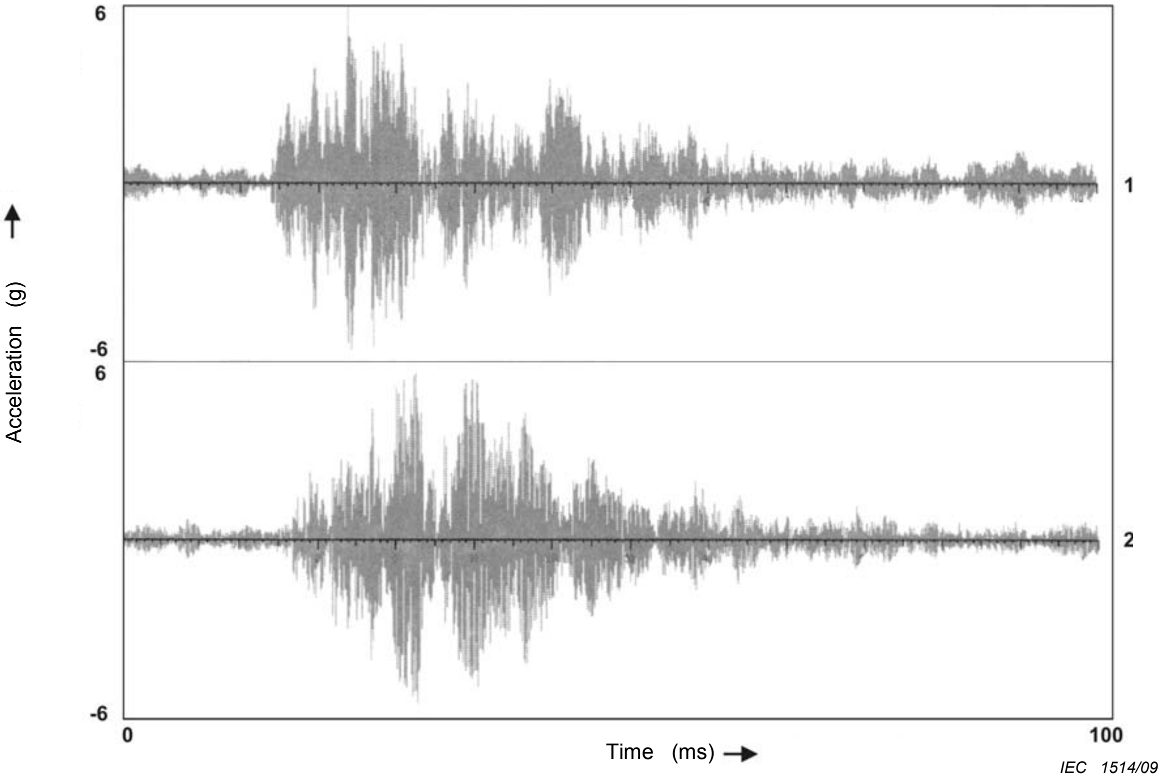


Figure A.2 – Signals with bursts caused by an operation-related single sound event (control rod drive)

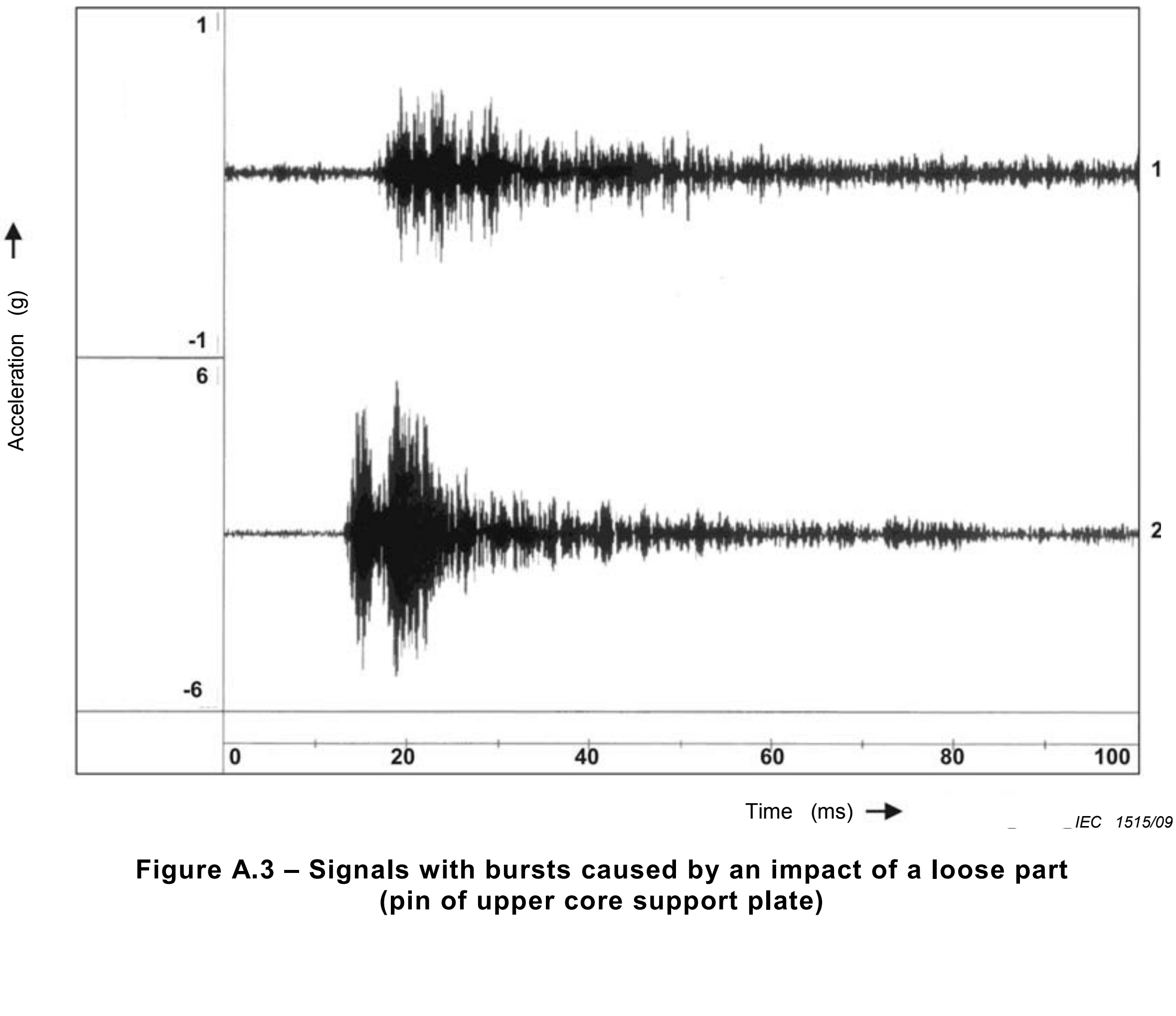


Figure A.3 – Signals with bursts caused by an impact of a loose part (pin of upper core support plate)

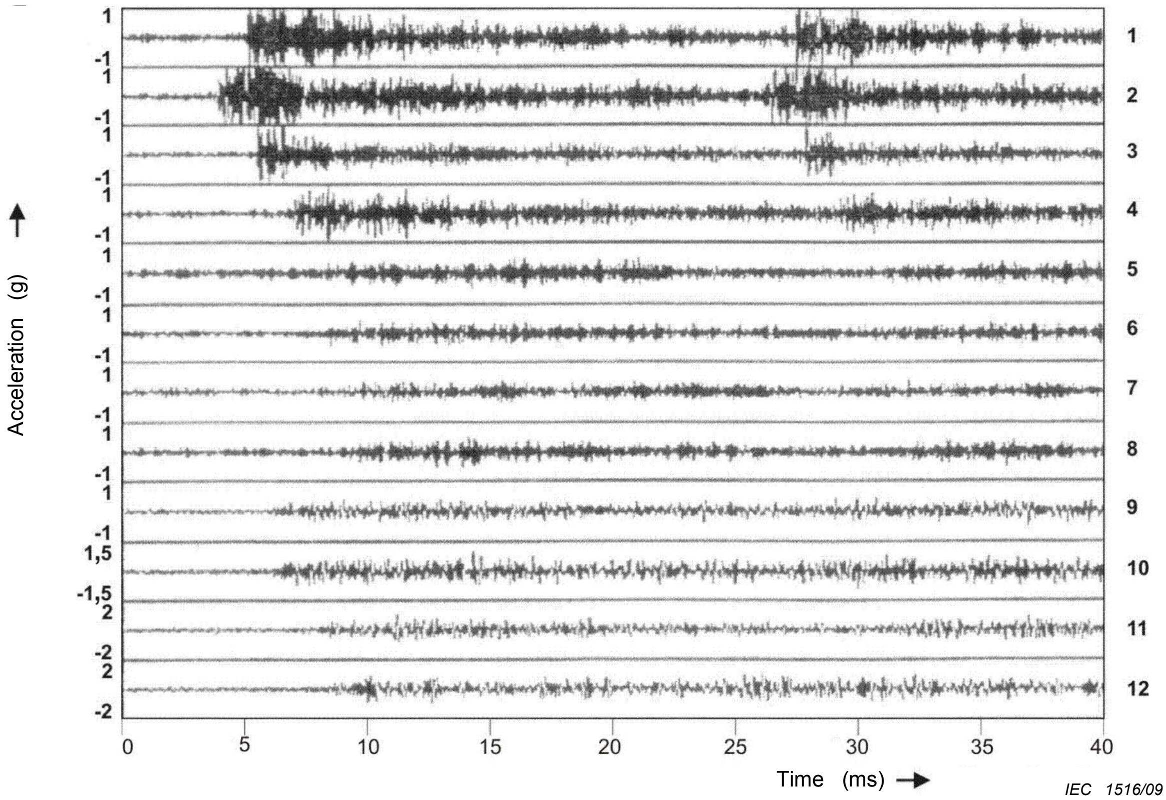


Figure A.4a – Signals with bursts, caused by a test impact at a BWR

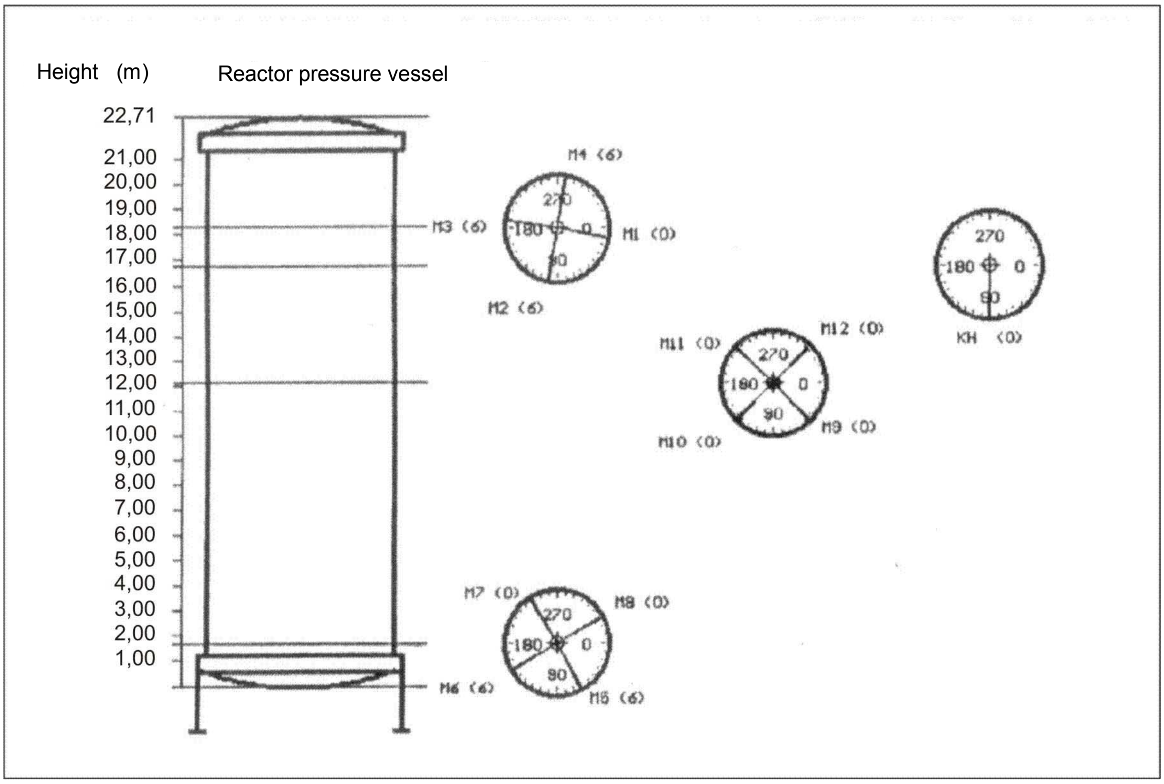


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Figure A.4b – Localisation at a BWR

Figure A.4 – BWR

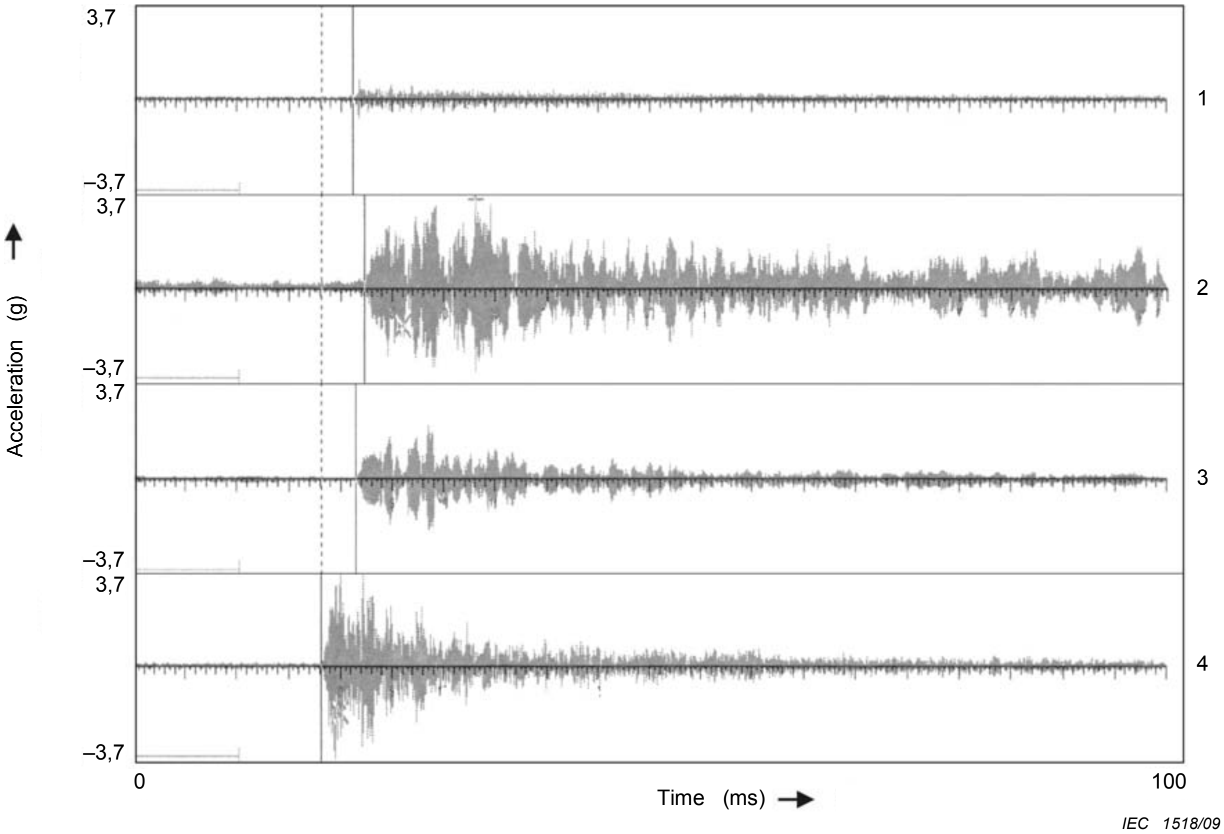

Figure A.5a – Signals with burst, caused by a test impact at a PWR

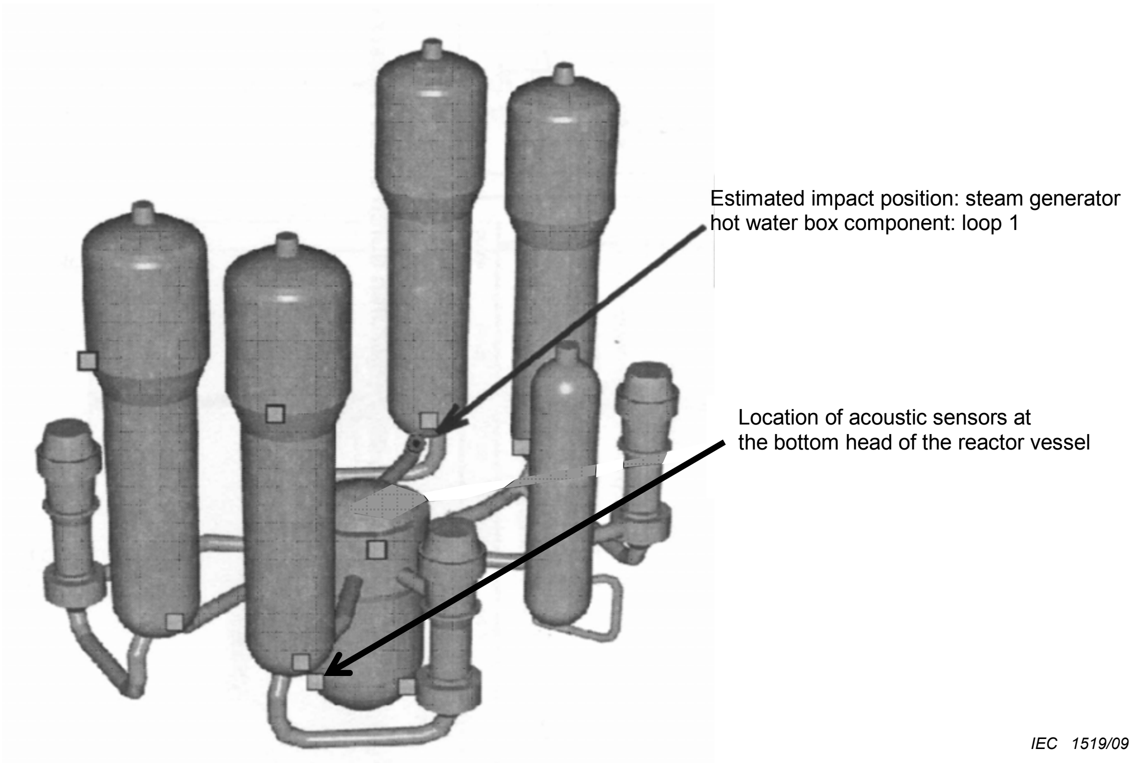

Figure A.5b – Localisation at a PWR

Figure A.5 – PWR

Annex B
(informative)

Description of detailed functions of each block of the functional block diagram

Figure 1 (in the main text) shows a typical system. The signals of the sound sensors (1) pass through wideband preamplifiers (2) to outputs (4) for further processing; these outputs are reserved for connecting external devices. For further internal processing of the signals, interference signal components (e.g. pump noise, electrical pick-up) are reduced with the aid of a band-pass filter (3) and the signals are amplified (5). Signal monitoring is implemented by an alarm level monitor (9), a logic element (10), an internal alarm unit (11) and an interface to the external alarm unit (12). The signals are displayed by means of an indicator (6), a multi-channel recorder or memory (7) and an audio unit (8). The signal channels can be tested and calibrated with the aid of a calibration unit (13). The loose part monitoring system can be tested by a test impact. The module (13) is not necessarily permanently installed. The components in the system are arranged, insofar as technically possible and feasible, in accessible locations.

The system design is influenced by the sensitivity of the sensors, the gain of the amplifier and the details of sensor mounting. The performance of the mounting is difficult to predict. Typically, the sensor and amplifier design are such that an acceleration of 30 g of the structure at the sensor position coincides within the operational range with the maximum linear amplifier output at minimum gain setting. The effect of the mounting can be neglected provided that resonances would not generate a multiplication that would affect the operational range unacceptably (e.g. by a factor greater than 15).

For higher resonance multiplication factors, the sensitivity of the measuring chain requires to be adjusted accordingly.

If the resonant frequency of the mounted sound sensor is within the monitored frequency range, the use of units of measurement relative to full scale deflection is recommended.

The block schematic diagrams of typical digital loose parts monitoring systems with transient signal recording and continuous signal recording are exemplified in Annex C with indication of the functional units (see also legend of Figure 1). Clause C.1 of Annex C shows a loose parts monitoring system with transient signal recording, Clause C.2 of Annex C shows a loose parts monitoring system with continuous signal recording.

Annex C
(informative)

Examples of digital loose parts monitoring systems

C.1 Example of a digital loose parts monitoring system with transient signal recording (see Figure C.1)

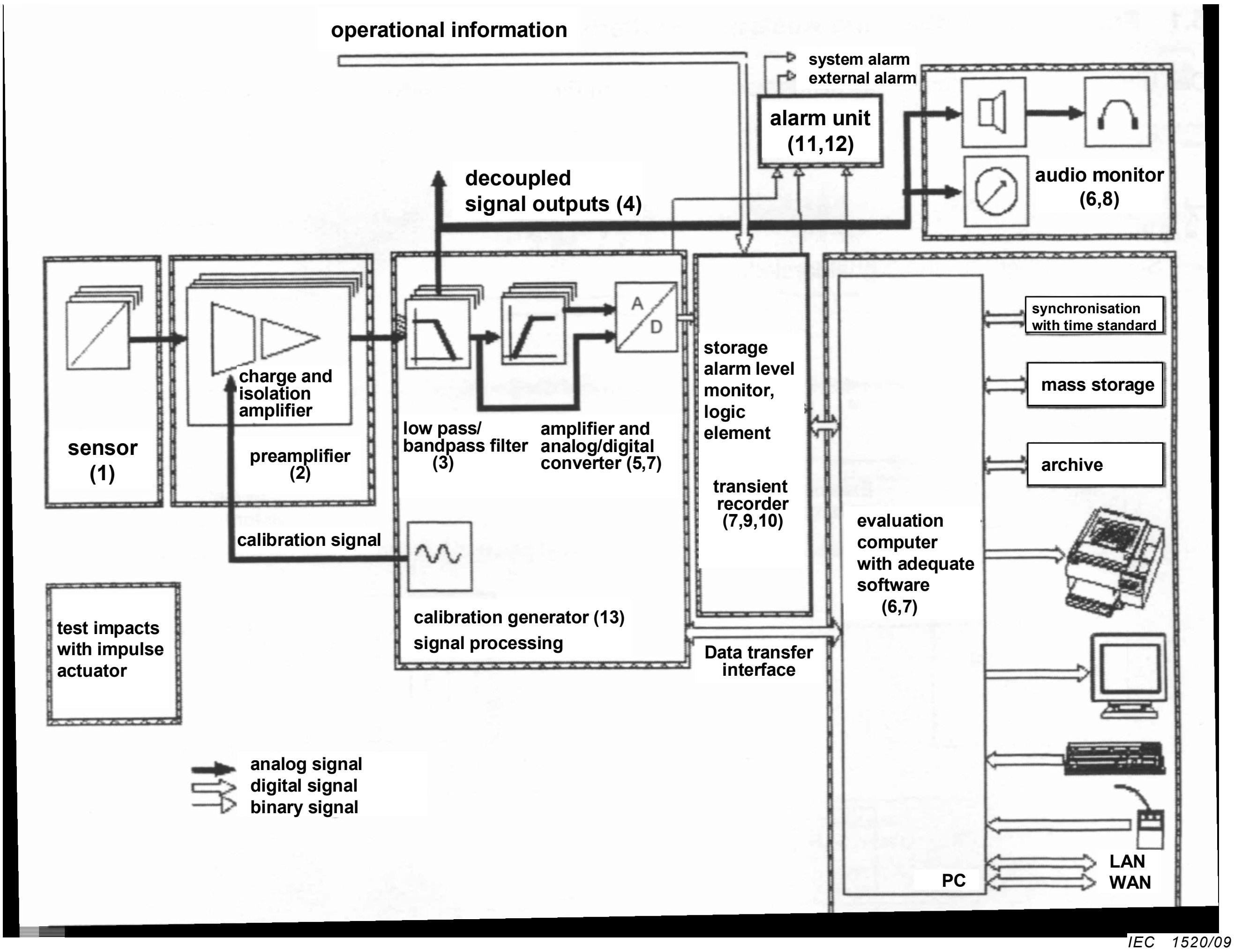

Figure C.1 – Block schematic diagram of a digital loose parts monitoring system

The signals of the sound sensors (1) pass through preamplifiers (2) to the inputs of the signal processing. The wideband, decoupled signal outputs (4) of the signal processing serve to connect external recording and signal processing devices (e.g. for reference recordings) as well as to feed the indicator (6) and the audio unit (8). For further internal processing of the signals, interference signal components are first reduced with the aid of a band-pass filter (3).

The filtered signals are amplified (5), where necessary, and digitised with an analogue/digital converter (7 - digitisation).

The digitised signals are acquired and stored (7 - storage). Internal alarm level monitors (9) and a logic element (10) is used to trigger the transient recorder. The trigger signal is led to the internal alarm unit (11) and to the interface to the external alarm (12). The trigger signal of (9) and (10) starts the storage function of the transient recorder and the data transfer from the transient recorder to the evaluation unit. The final storage (7) (archiving) of the signals is realised in the evaluation unit. Operational information is used for the reduction of the operation-related alarms via the logic element (10) of the transient recorder.

The system should be designed so as to allow for triggering of the functions calibration (13) and the test impacts with impulse actuators per operating commands via the peripheral devices of the evaluation unit. There is the possibility of internal and external data transfer of signal pattern via remote data transmission and network connection.

C.2 Example of a digital loose parts monitoring system with continuous signal recording (see Figure C.2)

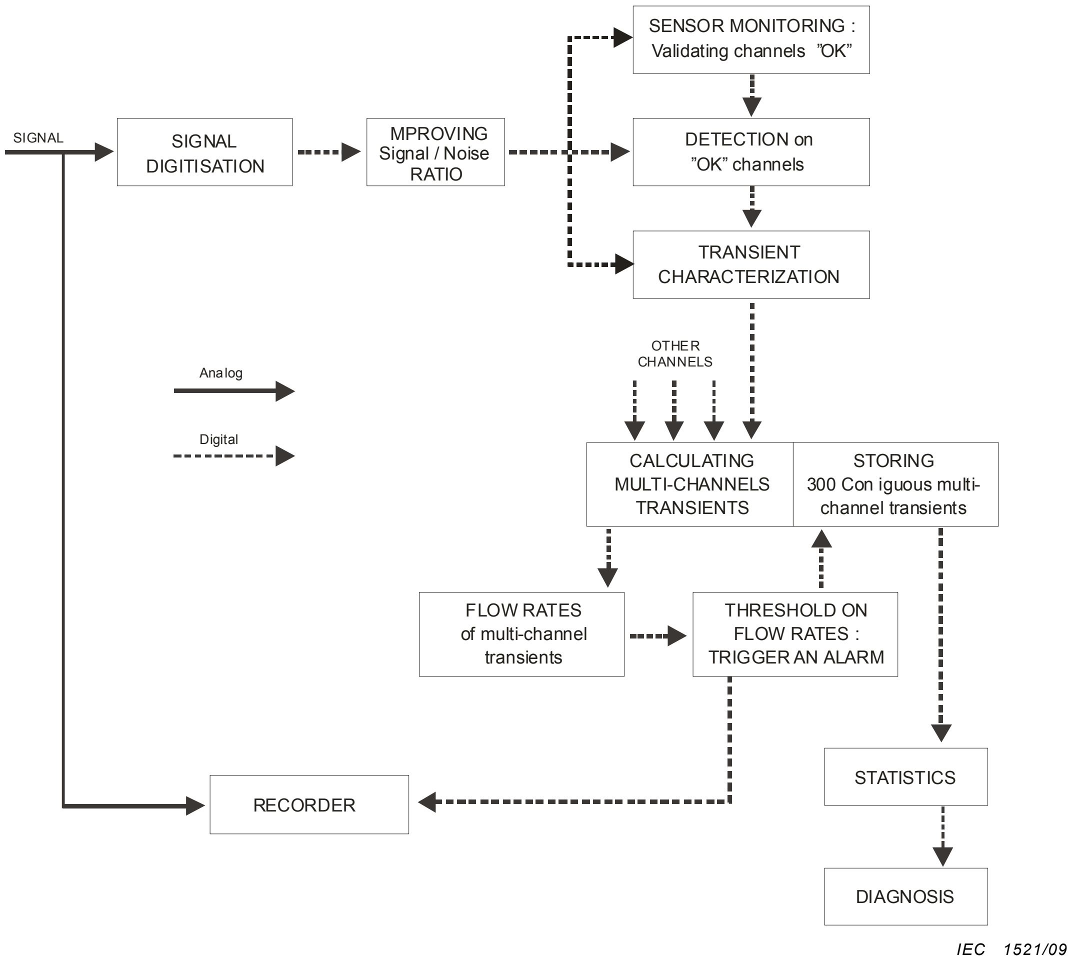

Figure C.2 – Block schematic diagram of a digital loose parts monitoring system

After digitisation, the signal / noise ratio is improved (for instance through a high-pass filter or using the spectral subtraction method). The resulting signal is used to monitor the sensors, checking that each of them is OK. On the "OK" channels, the transients are detected and characterized: for instance, their rising time is very precisely measured (precision better than 0,1 ms), as well as their amplitude and duration. Each characterized transient is then assembled in a "multi-channel transient" with other transients, detected on other channels and coming from the same impact of a loose part. A flow rate of the multi-channel transients is calculated, and a threshold is set on this flow-rate: when the threshold is overcome, an alarm is triggered and sent to the control room.

When an alarm is triggered:

- A continuous signal recording is launched.
- The storing of 300 contiguous multi-channel transients is launched: statistics are calculated, and a diagnosis is deducted from the statistics: "there is a loose part", or "there is no loose part".

Annex D
(informative)

Comments on evaluation

The evaluation measures to be performed in an actual case depend on whether there are any variations in the stationary background noises or any single sound events are observed in the monitoring channels.

For an evaluation of variations in the stationary background noises it is useful to determine frequency spectra and to compare these with the corresponding previous ones. Changes in frequency components (peaks):

- may give indications on changes of the sensor adaptation and changes of the electrical measuring chain,
- but may also be caused by a change of the operating mode of the monitored unit.

Moreover, the amplitude distribution density may support the determination of necessary parameters and e.g. give indications on interference within the electrical measuring chain (see Figure D.1).

If bursts occur, the evaluation measures to be performed are directed towards determination of location and cause of sound generation.

For the evaluation, a number of questions have to be answered:

- Is it a single sound event or a multitude of events?
- What is the time distribution of the events? (see Figure D.3)
- Are there groups of bursts of the same type? (see Figure D.2)
- Is the part detached or loosened?

The determination of the following burst parameters is recommended:

- delay differences (see Figure D.4),
- channel-selective burst maximum amplitudes and their time behaviour (trend) (see Figure D.3),
- burst amplitude distribution,
- number of bursts per time unit, burst interval distribution, and
- burst forms (rising edge, burst duration, falling edge, microstructure, burst spectrum (see Figure D.2), trend of RMS).

Delay differences serve to locate the loose part. The distribution of the delay differences allows one to clarify whether the part is loosened or is detached (foreign part).

The maximum burst amplitudes provide qualitative information on the impact energy, the burst amplitude distribution is useful for the evaluation of the event.

The identified burst forms allow one to draw conclusions on the length of the sound path and the primary single sound event. Steep rising edges indicate short sound paths, smooth rising edges may indicate longer sound paths. The burst duration depends on the type of single sound event (e.g. loose part, temperature relaxation, flow noise). The burst interval distribution is important for determining the type of excitation (e.g. flow-induced).

Burst patterns can be assessed with the aid of a high-time resolution of the bursts (including their immediate previous history), the parallel representation of several signal channels and an optimised form of representation for the amplitude resolution of the individual bursts. This last requirement generally means selecting a different scaling for each signal channel.

In addition, further analyses may be required (e.g. digital signal filtering, determination and evaluation of frequency spectra, acoustic evaluation of bursts, classification of burst signals, RMS value for selected frequencies).

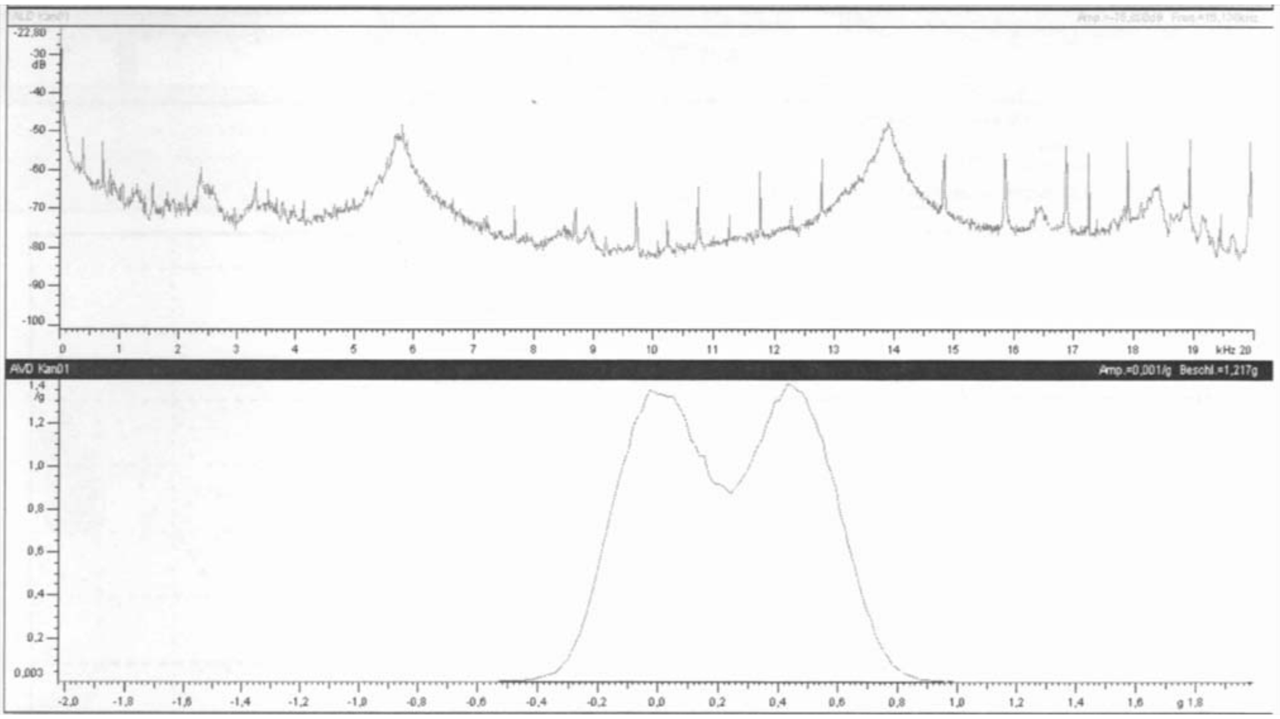

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Figure D.1 – Auto power spectral density and amplitude distribution of a measurement signal with electrical interference

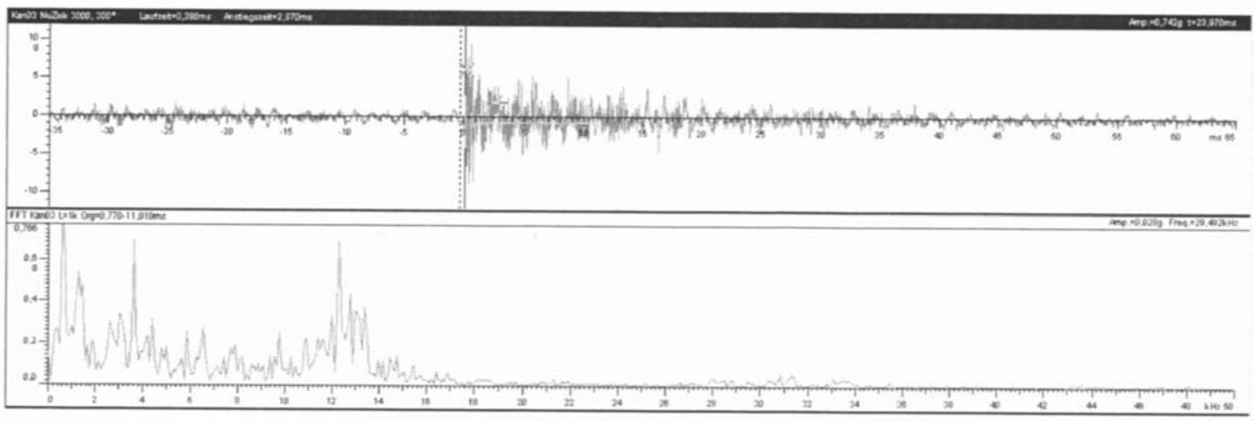

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Figure D.2 – Burst with corresponding frequency spectrum

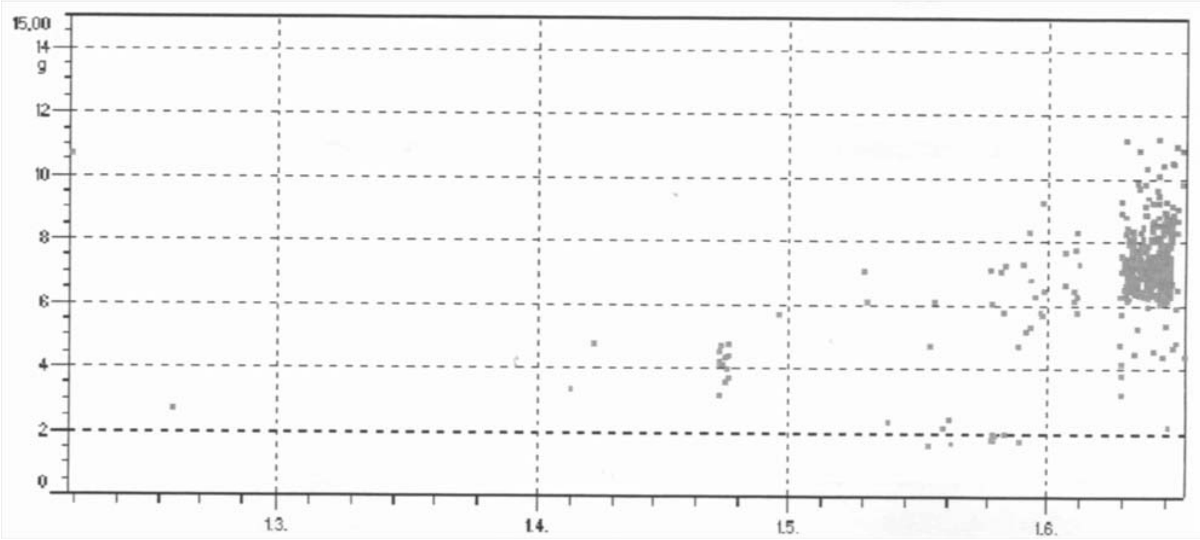

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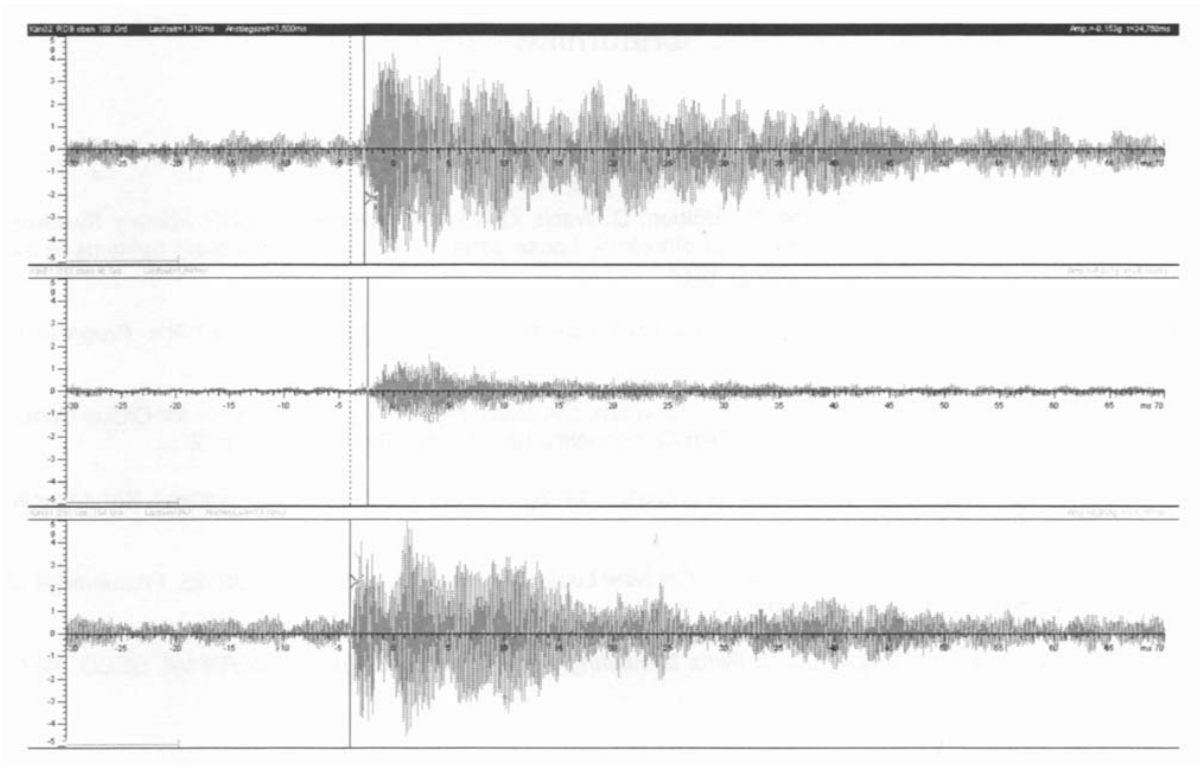
Figure D.3 – Trend and distribution of channel-selective burst-amplitudes



IEC 1525/09

Figure D.4 – Burst signals with determination of delay differences

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