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Research Article

Experience of using loose parts monitoring systems at Novovoronezh NPP*

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Abstract

In VVER reactor plants, it is impossible to completely exclude the appearance of loose, loosely fixed and foreign objects in the main circulation circuit. Operational experience shows that early detection and estimation of the parameters of such incidents can provide the time required to eliminate or minimize damage to the main equipment of the reactor plant. For this reason, most modern power units with pressurized water reactors (PWR, VVER) are equipped with a loose parts monitoring system (LPMS). At the units under construction, these systems are laid down as standard ones; the power units put into commercial operation in the Soviet period were also equipped with them. The requirements for them are established by international standards. Ongoing research work in this area is aimed at determining the root cause of the acoustic anomaly and the localization of its epicenter. Also, no less significant are the works aimed at determining the mass of a loose object (LO). The most precise definition of this parameter will make it possible to have an idea of the nature of the LO before its withdrawal from the primary circuit and to conclude about whether this object is accidentally found or it is a detached part of the steam generators, main circulation pumps, internal devices or shut-off and control valves.

Keywords

VVER-440, VVER-1200, technical diagnostic systems, loose parts monitoring system (LPMS), impact event, loose object, KÜS, neural network, artificial neuron, synapse, nuclear power plant, classification, class of events, main circulation circuit, steam generator

Introduction

The presence of loose objects (LOs) moving along the main circulation circuit (MCC) of the VVER coolant poses a real threat to the safe operation of nuclear power plants. Partial or complete blockage of the coolant flow by the LOs can lead to deterioration in heat transfer and possible overheating of fuel claddings, a change in fuel temperature and an increase in the intensity of fuel swelling. The ingress of the LOs into the mechanisms of the operating parts of the control and protection system creates a threat of abnormal operation of the system and/or complete failure, which is confirmed by the incident at the Paks NPP (fragmentation of the platform forgotten during scheduled preventive maintenance and "rubbing of drives" of the ECR (emergency control rod) (Arkadov et al. 2019)). However, one should not think that the presence of the LOs in the MCC is an extremely rare event and is

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associated only with careless work during repair operations. The main reason for the presence of the LOs in the circuit is the destruction for various reasons of the NPP structural units, which is reflected in the specialized section in (Textbook 1992). As a typical example of this class, we should mention the event at the Tianwan NPP in 2006 (Arkadov et al. 2019) with the destruction of the MCP impeller blade at the stage of commissioning Power Unit 1.

Identification and localization of loose, loosely fixed or foreign objects in the coolant circulation circuit are carried out by a specially designed loose parts monitoring system (LPMS): its main functions are to detect and estimate the parameters of such objects. Currently, most reactor plants with pressurized water reactors (PWR, VVER) are equipped with the LPMSs. There are several international standards that define the requirements that any LPMS must meet, namely:

- U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.133 (Regulatory Guide 1.133 1981);
- American Society of Mechanical Engineers (ASME) Standard OM-2017 (Operation and Maintenance 2015);
- International Electrotechnical Commission (IEC) Standard IEC-609887 (IEC 60988 2009).

A large number of studies on these systems that have appeared recently are aimed primarily at solving the problem of localizing the impact site on the NPP equipment. One of the most important functions of the LPMS in diagnosing the reactor plant equipment is the impact source localization (Operation and Maintenance 2015). For effective diagnosis, it is necessary to accurately locate the place where the acoustic anomaly occurs. Should loose or foreign objects appear, it is important to track the paths of their movement along the main circulation circuit as well as the places of their localization.

To date, a large number of studies have been carried out on impact source localization methods (GOST R ISO 13379-1-2015, Olma 1985, Szappanos et al. 1999, Kim et al. 2003, Figedy and Oksa 2005, Park and Kim 2006, Park et al. 2006, Choi et al. 2011, Ki et al. 2017, Liska and Kunkel 2017). The traditional and most trivial method localizes the source of the acoustic anomaly up to the equipment controlled by the sensor that first recorded the impact. If there is a recorded effect in more than one channel, the source is localized using the arrival time differences (ATDs) of the leading edge of the wave in two or more measuring channels. One of the most well-known methods using ATDs is the hyperbola intersection method (Olma 1985, Park and Kim 2006), which is implemented in manual mode and requires additional expert knowledge from the system operator. The algorithm has a simple analytical solution for the plane, but it is not adapted for the complex surface of the primary reactor circuit. Another method (Szappanos et al. 1999, Figedy and Oksa 2005, Liska and Kunkel 2017) is based on the search for the closest match to the recorded ATDs calculated earlier. For this purpose, the first circuit is divided into small segments or control points. Taking into account that the velocity of acoustic waves in metal is known, it is possible to preliminary calculate the time of the wave travel from individual segments to the sensors. The obtained ATD values are stored in the database. As soon as an acoustic anomaly is recorded, its location is selected from the database as the closest stored vector to the measured one according to the Euclidean distance. In (Liska and Kunkel 2017), the errors of the localization method and its structural limitations are analyzed. To determine the arrival time, it is necessary to know the acoustic wave velocity. Since it depends on the material, kinetic energy of interaction, mass and shape of the LOs, and other parameters, this method introduces a large uncertainty in the localization of the acoustic anomaly source. The proposed algorithm performs automatically localization to a point on the surface of the primary reactor circuit. It is based on the calculation of the shortest path over the 3D model of the primary reactor circuit surface. The algorithm is flexible and easily adaptable to any pressurized water reactor plant.

KÖRPER ÜBERWACHUNG SYSTEM (KÜS): the first industrial LPDS

In 1992, in accordance with the Consolidated Measures to Improve the Reliability and Safety of Operating NPPs with VVER (SM-90-VVER), Power Units 3 and 4 of NvNPP (VVER-440) as well as Power Units 1 and 2 of KolNPP (VVER-440) were equipped with technical diagnostics systems (TDSs). Due to the lack of domestic TDSs ready to be delivered at that time, it was decided to use imported systems but adapted to the equipment of domestic power units. The choice was made in favor of the solutions of Siemens, Germany, and, in 1992–1993, the following systems were put into operation at the NvNPP site:

- SÜS: vibration control system;
- KÜS: loose parts monitoring system;
- ALÜS: acoustic leak detection system.

The operating principle of the system is based on constant comparison of the root mean square (RMS) value of signals from sensors with two types of thresholds set by the operator: hard-coded (absolute) and constantly calculated depending on the current signal value (relative). When one of these two thresholds is exceeded, the event that caused the local disturbance is recorded. The system records an increase in noise as an impact event, regardless of the reasons for its occurrence: impacts of objects, heating of equipment, cavitation phenomena, etc. Therefore, the cause of the anomaly can only be determined by the system operator, who is supposed to have necessary skills and experience in processing impact-type events (Figedy and Oksa 2005). The delivery of KÜS did not include specialized software for event processing; therefore, at the initial stage of operation, the systems were involved exclusively in collecting information instead of processing it. This circumstance completely nullified the entire effect of the proposed exploitation. Events were recorded in the range from 1 kHz to 10 kHz by a network of sensors installed on the equipment in places where LOs were most likely to appear (Fig. 1).

The processed signal values from all the sensors were entered into a ring memory (short-term storage buffer) with a constant calculation of two RMS values with a software-defined averaging time: short-term RMS (5 ms) and long-term RMS (820 ms). A relative threshold is calculated from the long-term RMS. The short-term RMS is compared with the relative and the absolute threshold. When the signal exceeds one of the thresholds, the event is recorded from the ring memory of the time realizations of all the channels for 50 ms, including 10 ms of the event's history. To calibrate the system, there is an impulse hammer: when it is launched, the operator can apply a calibration blow of a strictly defined pulse and check the system settings by the responses on all the channels (Figedy and Oksa 2005, Liska and Kunkel 2017).

The long-term operation of KÜS at NvNPP 3 and 4 has shown the correctness of the algorithms underlying the system operation as well as the reliability of the technical means. Quite eloquent is the fact that the KÜS systems put into operation in 1991–1992 at KolNPP 1 and 2 are still working. However, the LPMSs of the first generations had significant drawbacks, the main of which included:

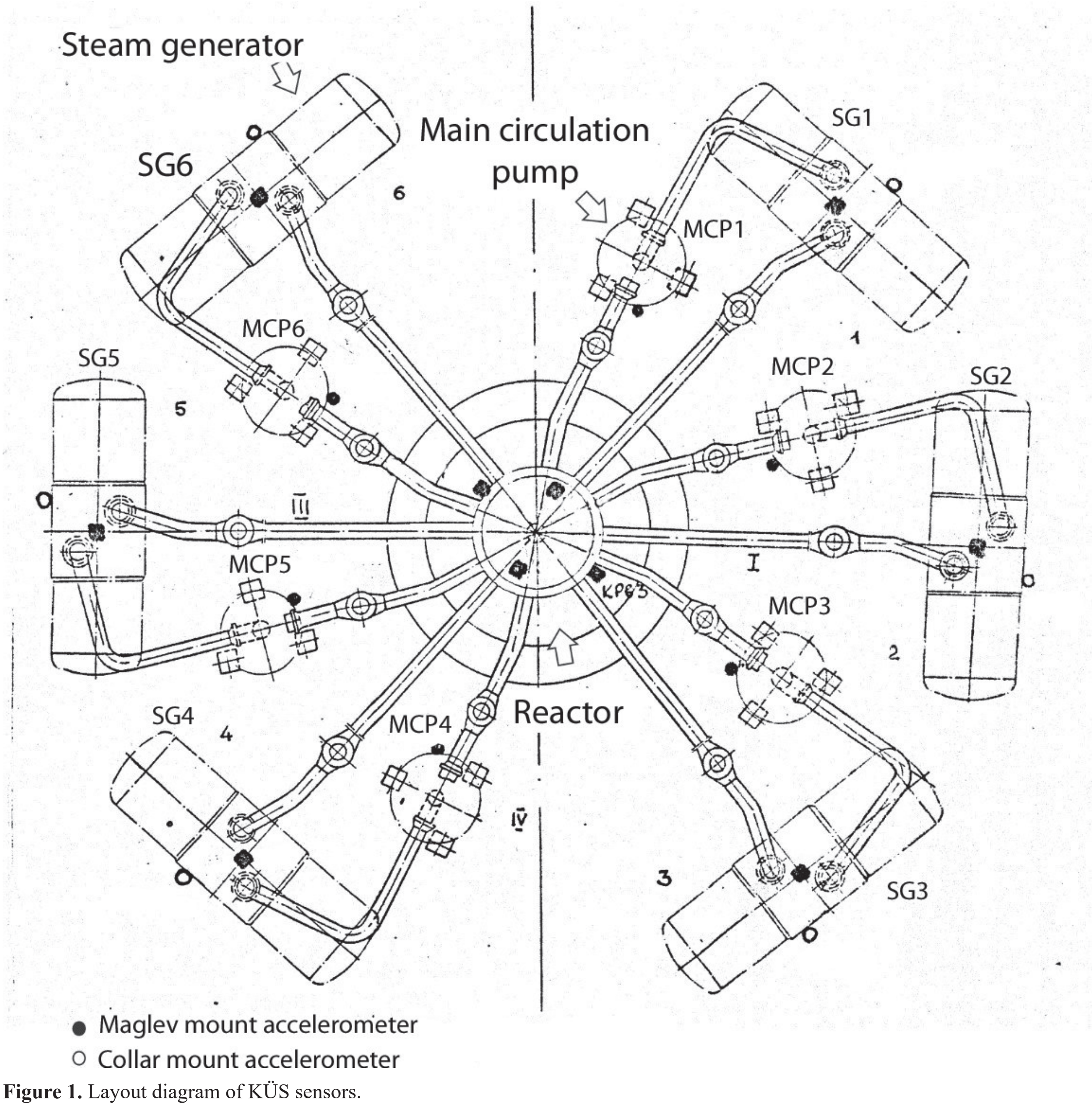

Figure 1. Layout diagram of KÜS sensors.

- the impossibility of working without the operator when detecting impact-type anomalies;
- the lack of algorithms for the impact site localization;
- the lack of algorithms for the LO impulse (mass) determination;
- the non-uniformity of calibration effects on loops (one impulse hammer on one loop);
- the lack of an embedded database on impact anomalies; and
- the lack of information exchange with organizations providing engineering support.

Domestic LPMS

NvNPP-II 1 and 2 (VVER-1200) are equipped with TDSs of domestic design based on the technical solutions of JSC "NTC Diaprom". The TDS includes the following systems:

- VCS: vibration control system;
- LPMS: loose parts monitoring system;
- ALMS: acoustic leak monitoring system;
- HLMS: humidity leak monitoring system; and
- MDS: multipurpose diagnostic system.

The principle of operation and event recording for this system, as well as for KÜS, is based on comparing the RMS values of the signals received from the sensors with the absolute and relative thresholds set by the system operator. When a signal is received that one of the thresholds is exceeded, an event recording process occurs, during which digitized signals from all the channels involved in the event, 60 ms long, are recorded in a structured form on the hard disk. In addition to acoustic noise signals, the reactor performance parameters, which are important for determining the state of the controlled equipment, are stored on the hard disk; they are received via the local network from the MDS (Figedy and Oksa 2005, Liska and Kunkel 2017).

The LPMS includes 20 sensors installed on the equipment and pipelines of the primary circuit, which record an acoustic signal in the range from 1 kHz to 20 kHz. To diagnose the performance of the channels, four impulse hammers are used (one for each loop). Fig. 2 shows the location of the sensors and impulse hammers.

The recorded events are processed and analyzed by the application software supplied with the system. This software is written for the operating system on the Linux kernel and performs the following functions:

- determining characteristic parameters of acoustic noise signals for each measuring channel;
- classifying events;
- determining (localizing), based on the classification results, the component of the reactor plant that is the noise anomaly source; and
- saving the results in the database.

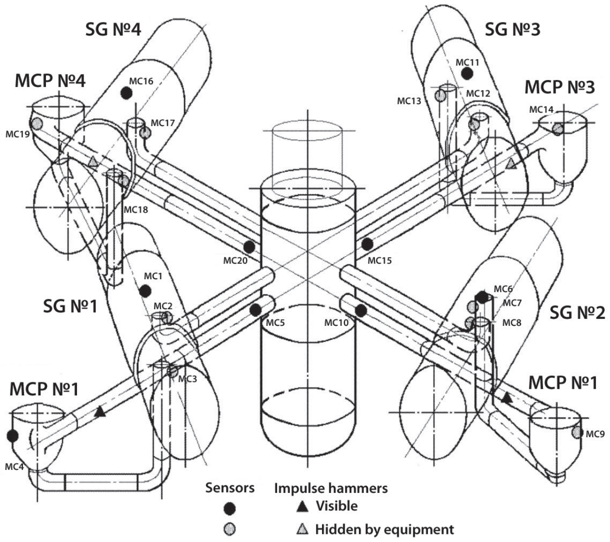

Figure 2. Layout diagram of LPMS sensors.

Events are classified and localized based on user-created classes. When creating classes, the user specifies which reactor component is associated with the occurrence of events of a given class. Based on this, localization is carried out. A generalized message about a registered event with reference to the results of its localization is sent to the MDS and further to the upper unit level system (UULS). An event that does not match any of the classes is marked as "unknown".

The LPMS operator can perform processing and delayed analysis of events already recorded on the hard disk. While performing a delayed analysis, the operator can specify the start time of the acoustic burst, create a new class or edit an existing one.

The LPMS software provides a wide range of event processing and analysis functions, including:

- maintaining a database of classes;
- plotting RMS and envelopes;
- conducting a cross-correlation analysis; and
- conducting a spectral analysis.

The new generation LPMS is equipped with functional software that provides an extensive set of event processing and analysis tools. The LPMS software developed for the Linux kernel can be used in conjunction with domestic operating systems. Due to the fact that the LPMS operated at NvNPP-II 1 and 2 was created by a domestic company, it is possible to receive the developer's engineering support (Page 1961). Despite the impressive list of advantages, the LPMS has a number of disadvantages, including:

- a large number of recorded interference;
- the lack of sensors directly on the reactor pressure vessel; and
- the lack of algorithms for the LO impulse (mass) determination.

At the moment, JSC "NTC Diaprom" is developing the next generation of LPMS software using algorithms of artificial neural networks.

Brief description of the operating principle of artificial neural networks

Over the past decade, artificial neural networks (ANNs) have found wide application in many fields of science and technology. This mathematical apparatus is so versatile that it can be implemented both in software and in hardware. The ANNs are based on an artificial neuron (Haikin 2006) consisting of an array of synapses, a summation unit, and a nonlinear transformation unit (Fig. 3).

Each synapse has a weight coefficient that characterizes the strength of the synaptic connection, similar to a biological neuron.

The input signal passing through the synapse is amplified or attenuated, depending on the value of the weight coefficient. Further, in the summation unit, the values of the input signals are added. If the value of the sum exceeds a certain threshold, then a neuron excitation signal is generated at the output of the non-linear transformation unit, which is transmitted to the next neuron. The value of the threshold depends on the selected activation function (Golovko 2001).

Thus, the ANN consists of an array of artificial neurons that form a multilayer structure that converts the input signal into an output signal in accordance with a given function (Fig. 4).

The value of the weight coefficients is determined during the training of the neural network. ANNs, the weight coefficients of which change their value during operation, are self-adaptive. Such networks are able to adjust their work depending on changes in external and internal conditions.

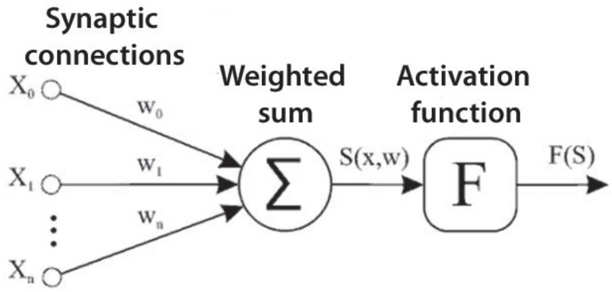

Figure 3. Block diagram of an artificial neuron.

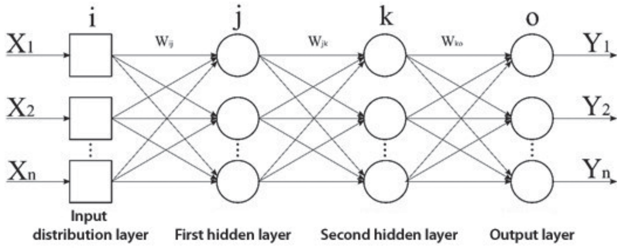

Figure 4. Block diagram of an artificial neural network.

Applying the neural network analysis in LPMS software

JSC "NTC Diaprom" is currently developing a new generation of LPMS software, which includes improved mechanisms for analyzing recorded events and neural network data processing. As part of testing, recorded events at NvNPP-II 1 and 2 were loaded into the database of this software.

The ANN algorithm in this software calculates the probability that an event belongs to one of the following types: "acoustic anomaly", "impulse noise" or "no effect".

Assigning an event to one of these types determines the further analysis algorithm. The operation algorithm and structure of the ANN is hidden from the operators and does not require their intervention in the network. Due to this limitation, the software can be used by an operator without skills in working with the mathematical apparatus of the ANN.

Before using the software for a full-fledged analysis of events, work was carried out to train the ANN, within the framework of which a predictive analysis of the databases of events recorded at NvNPP-II 1 was performed (Page 1961, Zheng et al. 2008).

The use of ANNs at one of the most important stages of event analysis improves its quality and the probability of determining the root cause of an acoustic burst.

In addition to neural network processing, the new generation of LPMS software has a more extensive set of tools and functions that make it possible to improve the quality of the analysis being performed. The event classification mechanism has also been improved (Fig. 5).

The created classes are applied not only to new events, as in the previous version of the software, but also to those already recorded in the archive. This feature is provided by the improved data storage system.

Another distinctive feature of this version of the software is the ability to interface the LPMS with the integrated system for diagnosing motor-operated valves, which makes it possible to determine, with the maximum probability, the events, the root cause of which was the valve actuation (Dijkstra 1959, Lavielle 2005, Maksimov et al. 2018, Maksimov and Pereverzintsev 2019, Truong et al. 2020).

Summing up, we can say that the combination of neural network processing and improved event analysis tools upgrades the quality of the analysis and increases the likelihood of determining the cause of an acoustic anomaly and its localization.

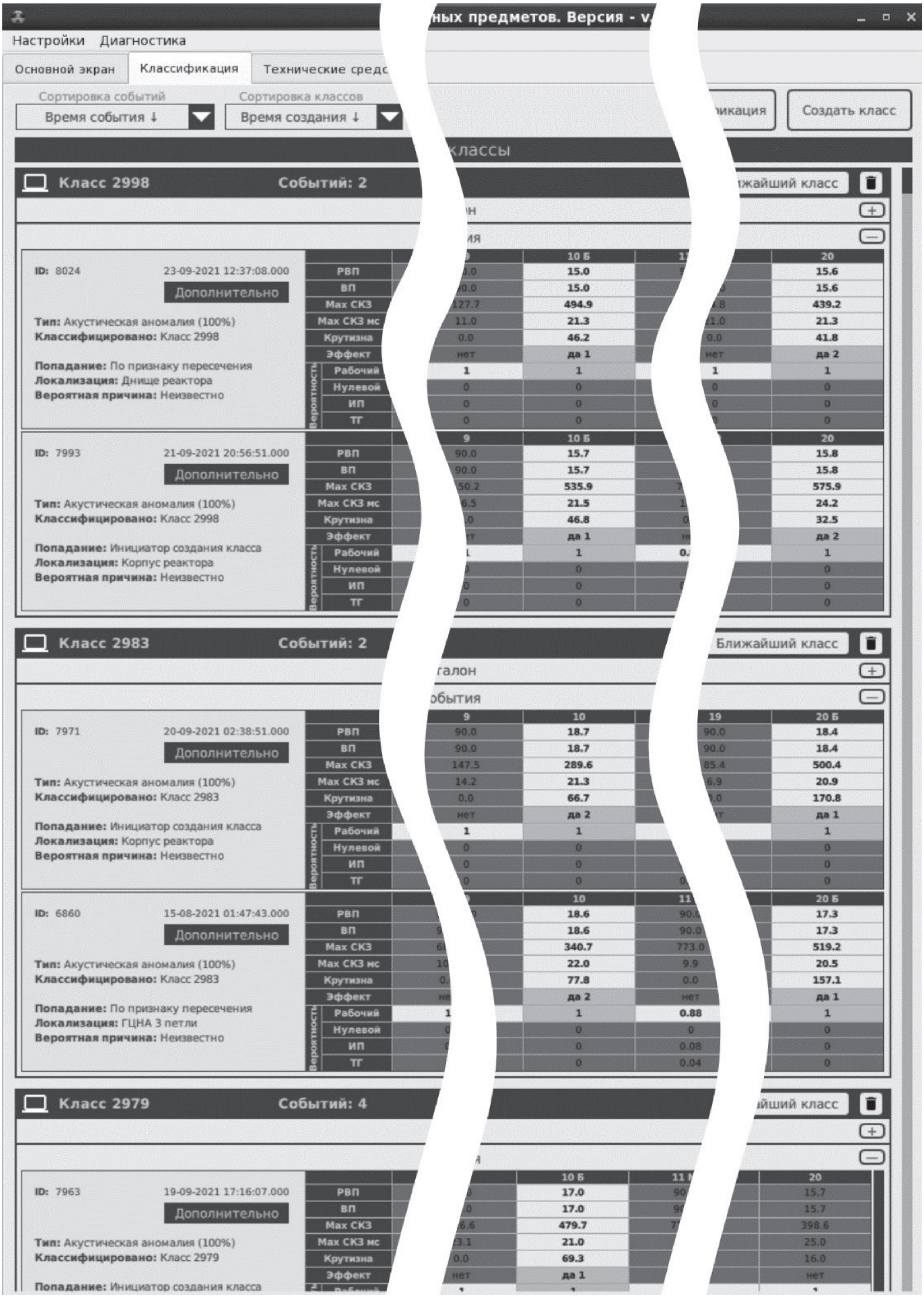

Figure 5. Result of event classification (screen form with cut out channel values that do not record events).

Conclusion

Operating experience has proven the high importance of the LPMS. Since early detection and estimation of the parameters of LOs can provide the time required to eliminate or minimize damage to the main equipment of the reactor plant, and the identification of loosely fixed objects helps prevent their complete detachment.

From generation to generation, the LPMSs have been refined and upgraded, both in hardware and software. Improving the tools for analyzing recorded events and using ANN algorithms makes it possible to more accurately determine the root cause of an acoustic burst and localize it.

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