RELIABILITY OF WELDED STRUCTURE OPERATION. ASSESSMENT AND CONTROL

B.E. PATON[1], **L.M. LOBANOV**[1], **A.Ya. NEDOSEKA**[1], **A.Yu. FEDCHUN**[2], **A.A. YOLKIN**[2] and **B.M. OBODOVSKY**[2]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]Odessa Priportovy Zavod, Odessa, Ukraine

The paper presents the technology and instrumentation for NDT of the condition of welded structures with assessment of breaking load and residual life. The predicted breaking load and residual life are determined during operation at working load. Application of the system in control of equipment at Odessa Priportovy Zavod is described.

Keywords: *welded structures, operating reliability, technical diagnostics, acoustic emission, strength*

Some time ago we dreamt that a time will come, when it will be possible to sufficiently accurately determine the condition of a particular structure, whether it should be put out of service, or it is still capable of operation [1]. Now developments in the field of material strength, diagnostics and prediction of their serviceability, computational and measuring instrumentation have made such a progress that there appeared a possibility of practical implementation of such methods. Developed technologies allow remote assessment from one center and prediction of the condition of an operating structure, whatever its location. This is a significant achievement of science and technology. Monitoring from routine and labour-consuming process is gradually turning into convenient office control. We can already see the future, when continuous monitoring systems will operate in all the high-risk facilities of Ukraine, providing safety and reliability of their operation [2].

Modern progress of engineering led to development of large-sized welded metal constructions, operating under rather complicated conditions. Such objects, primarily, include large-sized storages of hazardous substances, ship hulls, blast furnaces, their air heaters and charging equipment, TV towers, tower-pipes of thermal power plants more than 300–500 m long, power plants proper, bridges, super-capcity walking excavators, tower cranes of shipbuilding yards, compressor units of gas pipelines, etc.

Reliable operation of the above metal structures is mainly determined by load-carrying capacity of their load-carrying parts and welded components. However, calculation of load-carrying capacity of structural elements, providing sufficient reliability, is difficult for a number of reasons.

At present difficulties in assessment of the condition of welded metal structures are overcome in most cases by taking design decisions during their development by specifying high margins for the main strength properties. This not only makes the construction more expensive, but also lowers its technical and cost parameters.

Such an approach involves high time and labour consumption and costs, and does not always yield the desirable results, and it is very difficult to reproduce the entire range of operating conditions at testing of complex structures. Under the actual conditions, a structure can operate in modes essentially different from those accepted at testing and even more so from those used in calculations of its load-carrying capacity.

A means for solving the problem of ensuring safe operation of welded structures is development of information-measuring systems, allowing assessment of structure reliability already at the testing stage, as well as monitoring performance of structures or prototype model directly in operation.

The purpose of this paper is analysis of PWI developments in the field of technology and instrumentation for continuous monitoring of welded structures, as well as realization of these developments in industry.

Current progress of means of computer engineering, radio electronics, applied mathematics, test procedures, science of material strength and continuum mechanics allows solving the problem of continuous monitoring of performance for various types of welded structures.

Operation of information-measurement system requires regular acquisition of real-time data, primarily, on the state of structure components and various kinds of defects, which accumulate during service. In case of availability of data on the structure and appropriate processing of this information, it is possible to quickly assess its load-carrying capacity in real time.

This, in particular, can yield considerable technical and cost benefits in those fields of engineering, where because of a lack of knowledge of actual operating loads, costly full-scale structures are tested to fracture to obtain strength characteristics and develop technical documentation for their batch production.

Overall scope of work in the field of development of «intelligent» structures fitted with continuous monitoring systems with issuing recommendations to

Figure 1. General view of OPZ ammonia storage

service personnel, has increased lately [1–7]. Monitoring systems of this kind should ensure the ability of the structure to provide information on its state, its suitability or unsuitability for further operation, define conditions, at which further operation of the structure remains to be safe.

Beginning from 1978, Odessa Priportovy Zavod (OPZ) started operating four isothermal tanks designed for storage and transfer of ammonia, supplied to the plant by a special pipeline from Toliatti, and further reloaded into tanker partitions [8, 9]. General view of ammonia storage of 34,000 m^3 volume, 52 m in diameter and 21 m height is given in Figure 1.

Volume of ammonia transfer was equal to about 5 mln t per year, including 1 mln produced directly in the plant.

Ammonia production, storage and overloading belong to the hazardous production sphere. Therefore, in 2002, when the specified term of operation of storage and equipment of the plant was over, a meeting of scientific-technical board of the plant was conducted, in which the need to take additional measures to ensure their further safe operation was noted. Meeting of scientific-technical board took a decision to develop a 10-year plan of fitting the plant with continuous monitoring systems of the main productions, based on advanced monitoring technologies allowing timely assessment and prevention of an emergency situation with process equipment, without interrupting its operation. In keeping with the plan, work on development of such instrumentation and its mounting on structures of the main productions using ammonia was started.

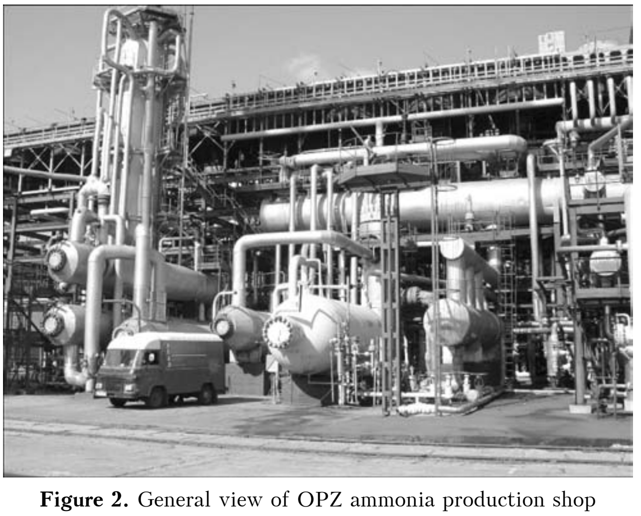

Figure 2. General view of OPZ ammonia production shop

The first diagnostic system for ammonia storage monitoring, based on acoustic emission (AE), was developed by PWI together with Videoton Company, Hungary. The system was mounted on ammonia storage ST-4 and commissioned in 2003. During the next three years continuous monitoring equipment was mounted on three more storages, and in 2006 and 2007 such instrumentation began operating in ammonia production shops (Figure 2).

Figure 3 gives a block diagram of the technology providing a solution for the defined problem. Technology is based on information coming from AE transducers. There are two data-processing modules. The first module is that of preprocessing, where measurement data are brought into a format, required for analytical module operation. In the second module the data are step-by-step converted into values predicting the breaking load and residual life of the operating structure. The technology further envisages specialist training for operation of monitoring equipment, development together with the state bodies of normative documents required for operation. Measuring components of the instrumentation are certified, and required documents are issued. The entire package of work accompanying supply of diagnostic equipment, is sufficient for successful practical operation in the enterprises and plants.

Diagnostic system put into operation in OPZ storages already at the start of its functioning has found propagating microdefects in the region of welding ammonia pumping pipe holders to the case of storage cylindrical shell. Defects were found in locations, which were not subject to control earlier according to current normative documentation, and were sites, where more serious damage can form later on, accumulating with time. Thus, a qualitatively new approach to monitoring the state of structures demonstrated its effectiveness directly after commissioning of the monitoring system. Development of instrumentation and technology for monitoring the storage condition allowed for modern achievements in the field of science of the strength of materials, and in the field of computational and measuring instrumentation.

Many years of PWI activity in the field of development of AE-based information-measuring systems, as well as experience of Videoton Company in the field of instrumentation development, allowed designing, manufacturing and commissioning conmmercial control-diagnostic equipment for long-time continu-

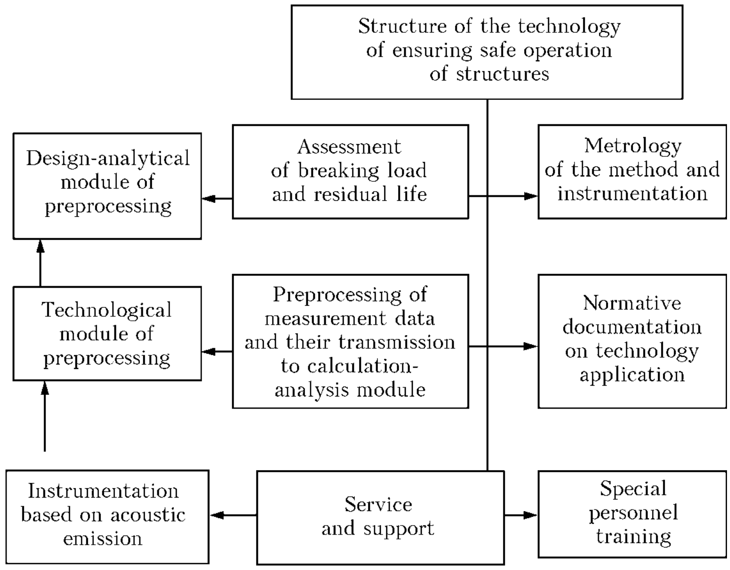

Figure 3. Schematic of technology of EMA-3 system control

ous monitoring. By now, four ammonia storages and equipment of two shops for its production have been fitted with it.

Calculation-analytical work on development of diagnostic continuous monitoring system was preceded by investigations of the stressed state of individual components of storage case structure. Walls of cylindrical storage tanks are made of sheets of low-carbon steel of A-537C1 grade (ASTM) of varying thickness, decreasing with its height. It was necessary to assess the storage case and shop equipment with detection and classification of zones with different levels of the stressed state and defects. In particular, it was established that during more than 20 passed years of storage operation the residual welding stresses in welds did not undergo any essential changes, and reached, similar to the initial state, the yield point of materials being welded (σ_y = 360 MPa for steels accepted for case manufacture). Figure 4 shows summary residual welding stresses and stresses caused by load from tank filling with liquid ammonia in the chime weld area. As is seen from the Figure, maximum stresses are concentrated in welds, where they reach the yield point in a narrow band of 10–12 mm at tension.

Figure 5 gives a typical block-diagram of a continuous monitoring system, developed specially for monitoring ammonia storage and equipment of shops for its manufacturing, with data transmission to plant diagnostic center and for larger distance through the Internet. The diagram includes 57 information chan-

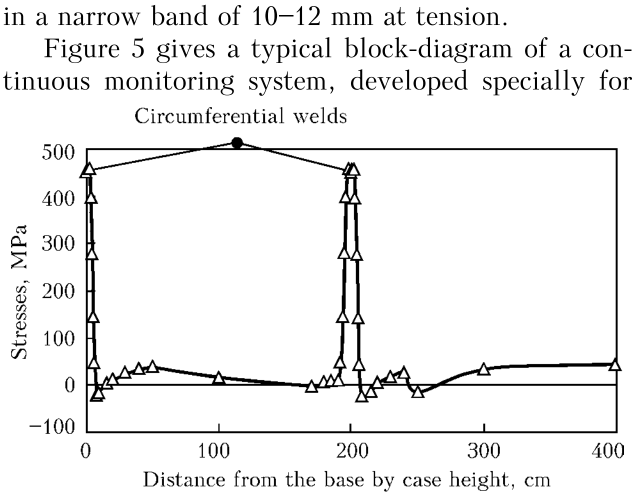

Figure 4. Total stresses in the storage case shell

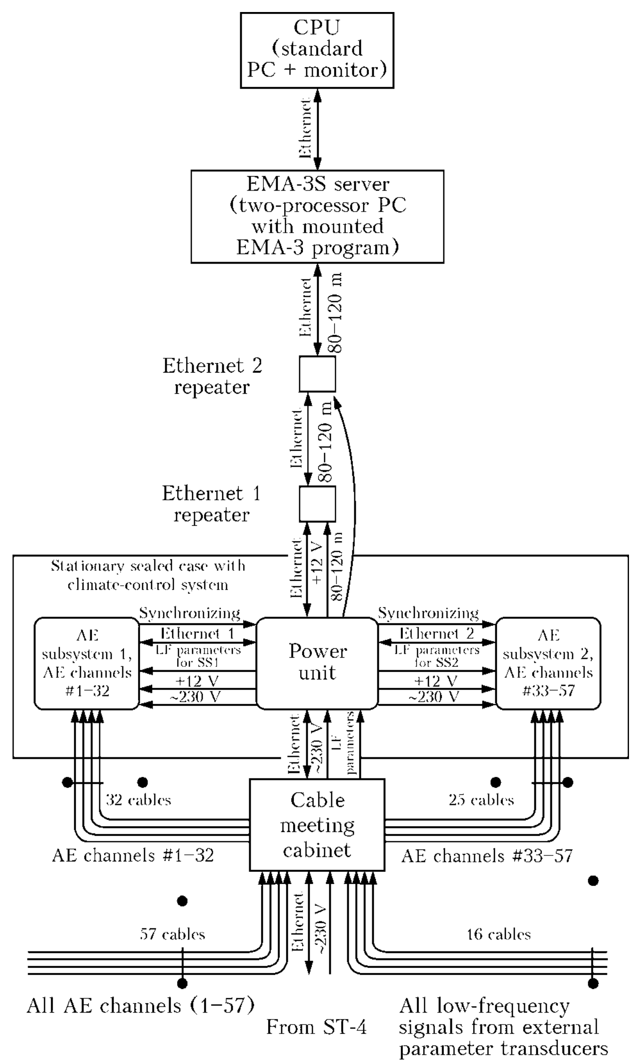

Figure 5. Typical block-diagram of the system of continuous monitoring of OPP equipment

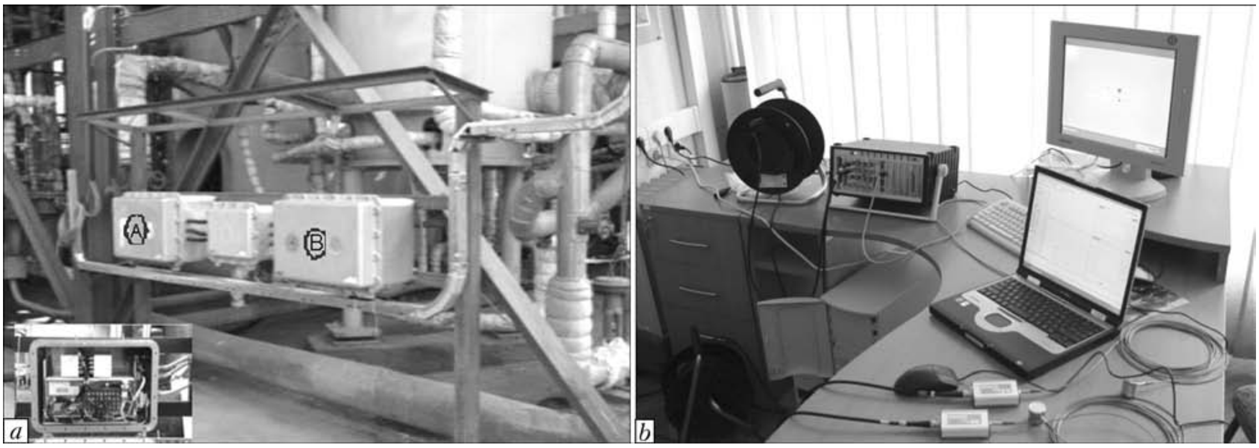

Figure 6. Stationary (*a*) and mobile (*b*) variants of diagnostic system of EMA family

nels in each storage (48 acoustic and 9 additional channels, including standby channels), continuously monitoring about 4 × 3500 m^2 of storage surface.

Data of measurements come by communication channels to two modules fitted with measuring and computer systems, where data preprocessing is performed. Considering that the modules operate continuously in open air, climate-control inside the modules is envisaged to ensure normal service conditions. Then data come to the central server via communication lines, and the server performs the main data processing with issuing of a decision on the state of the controlled objects. In particular, predicted breaking load and residual working life of structures of storage cases are calculated. Data are displayed on a computer monitor in the central diagnostic center of the plant.

Conducted preliminary investigations and calculations allowed detecting storage case areas, which should be monitored with increased care. General views of a stationary system EMA-3S of continuous monitoring, mounted in ammonia production shop, as well as mobile system of EMA family, are shown in Figure 6. Figure 7 shows the schematic of successive processing of diagnostic data, coming from the controlled objects.

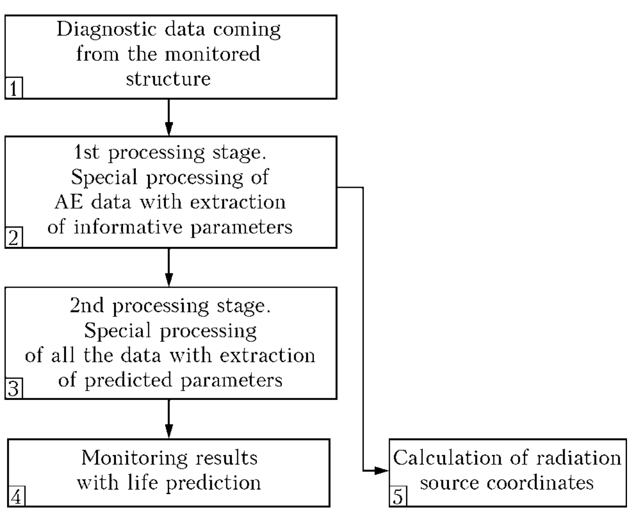

Figure 7. Stages of data processing by AE-based diagnostic instrumentation

Metrological characteristics of the instrumentation are specified by the following parameter sets: electronic modules of instrumentation; measuring transducers for set measurement of AE event coordinates; module of breaking load prediction.

The most serious technical requirements are made of module 1 (1st stage of processing), which transmits initial data to module 2 (2nd stage of processing). Module 1 is connected to measuring instruments and transducers, mounted on the object.

Accuracy of prediction of breaking load and residual life depends on reliability and accuracy of the data coming to module 3 and further on to modules 4 and 5. While modules 3–5 are quite well established in the world practice, organizing operation of module 2 is associated with considerable difficulties of data extraction with the set probability and accuracy before its subsequent transmission to module 3. Presented considerations lead to fundamentally new, very serious requirements to construction of diagnostic equipment architecture and its certification procedure. For systems of AE monitoring of EMA family, certification by four parameter sets is envisaged. Final stages of certification are stages of changing the coordinates of AE sources and determination of breaking load.

Technology of AE monitoring of operation of OPZ storages and equipment. EMA-3S system conducts the monitoring process in a continuous and automatic mode. Each measuring system EMA-3S uses a separate control computer, which stores files of conducted measurements. Data are stored at intervals set by the operator. Recommended data storage interval is 0.5–2 h.

The program uses measurement results for calculation of breaking load and residual life of the monitored structures, the data on which are stored in the database, and displayed in the numerical and graphic form on the computer.

Figure 8 shows the working window of EMA-3S program. The right upper part of the window displays real time graphs showing the current load and tempo of continuous AE appearance, which characterize the overall condition of the object of control and accumulation of minor damage. Indicator of predicted breaking load and hazard warming is located in the upper left quarter of EMA-3S program test window. At normal condition of metal, the indicator is green, and there is no prediction of breaking load. If a higher acoustic activity is detected during measurement, the indicator changes colour according to the warning level (change of band colour is accompanied by a short sound signal): 1st warning — yellow colour; 2nd warning — orange colour; 3rd warning — red colour, divided into two levels — hazardous and emergency (Table). At prediction of breaking load by the system, the indicator displays the predicted value (shown by lower and upper values in the error range of not more than ±15 % at 0.95 probability) and coordinates of the hazardous location. The lower right quarter of EMA-3S program test window shows the schematic of the tested object, for instance, for ammonia storages in the form of a scan of side surface carrying AE transducers. Locations of appearance of acoustic emission activity are noted by flagged rectangles. Rectangle colour indicates the amplitude level of the last AE event in keeping with EMA-3S program settings, and flag colour indicates the level of the state criticality in keeping with the above colour scale for the 1st–3rd warnings.

The lower left part of EMA-3S window displays data on AE level in the graphical form by active measurement channel (blue colour) and acting load in conditional units (mv) (1 mv = $5.6 \cdot 10^{-3}$ kg/cm^2 (red)). Shape of curves shown in the graph at normal condition of the structure should be horizontal or regularly inclined.

Calculation of breaking load and residual life of ammonia storage is performed automatically. Results of AE monitoring are displayed on the control computer. Data obtained during monitoring are accessible via the Internet for its periodic analysis by specialists and its use at formation and improvement of standards for prediction of breaking load and residual life. In case of development of a situation complex for structure state analysis, additional work on its evaluation is performed. For instance, more precise evaluation of ammonia storage condition is performed after interruption of loading-unloading process and other operations, creating acoustic noises and electric interference in the tank case.

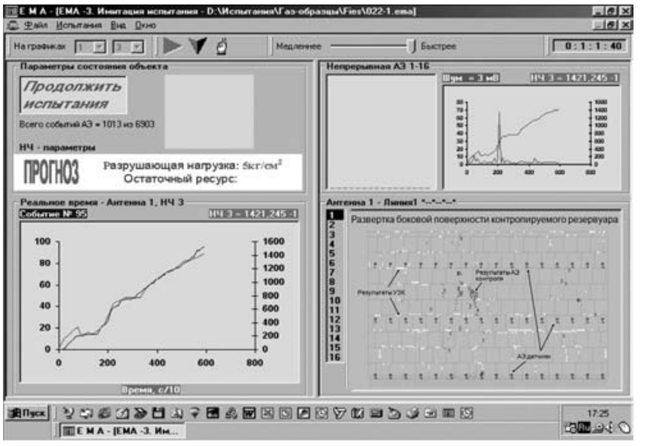

Figure 8. Variant of working window of EMA-3S system

If required, ammonia storage is kept idle for some time and a decision on its condition is taken by readings of indicators in EMA-3S program. Tentative criteria of tank case performance assessment are given in the respective normative tables for the first 10 min of tank monitoring during testing.

In case of development of a critical situation by the table, items 3, 4, the necessary measures for unloading of ammonia storage should be taken.

EMA-3S automated system of continuous AE monitoring has the following built-in means for ensuring continuous operation:

• UPS;

• instrumentation for following the operation of AE measurement subsystems;

• special devices for forced recharging of AE subsystems;

Personnel actions at different indication on EMA-2S system display

#	Indicator readings in the left upper corner of the display	Personnel actions
1	Green band	Normal mode. Operation can go on
2	Yellow band	Attention. At appearance of predicted breaking level of filling and its exceeding the working level by more than two times. Operation can go on
3	Brown band	Assess the predicted breaking level of filling by indicator readings. At predicted level exceeding the working level by more than 30 %, interrupt operation. Conduct additional analysis of received data in keeping with the instructions
4	Red discontinuously pulsating band	Interrupt operation. Conduct additional checking of the strength of storage case in keeping with the instructions
5	Red continuous band or continuously pulsating band	Emergency situation. Interrupt operation. Urgent relieving of load

*Change of band colour is accompanied by short sound signal.

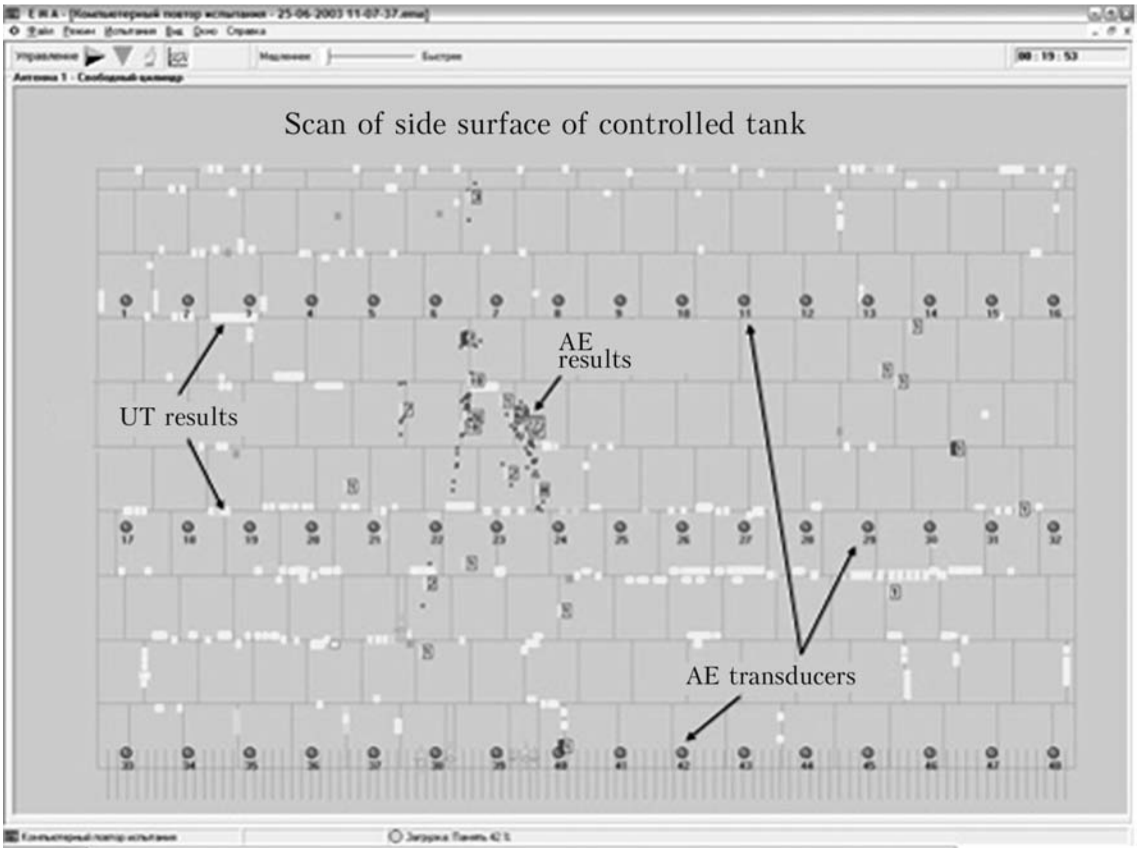

Figure 9. Scan of side surface of storage of 3500 m^2 area on the monitor screen (points show sites of fatigue damage accumulation)

• upper-level soft robots for ensuring uninterrupted operation of EMA-3S and STIntegrator programs, performing their forced restarting in case of failures or malfunctions.

Operation of all the above means as a complex ensures uninterrupted operation of the system in the normal mode and in the majority of contingencies.

The term of regular technical inspection of monitored structures and equipment can be assigned by the actual condition, based on readings of EMA-3S system of continuous AE monitoring.

The system is designed for uninterrupted operation in the continuous monitoring mode for 16 years.

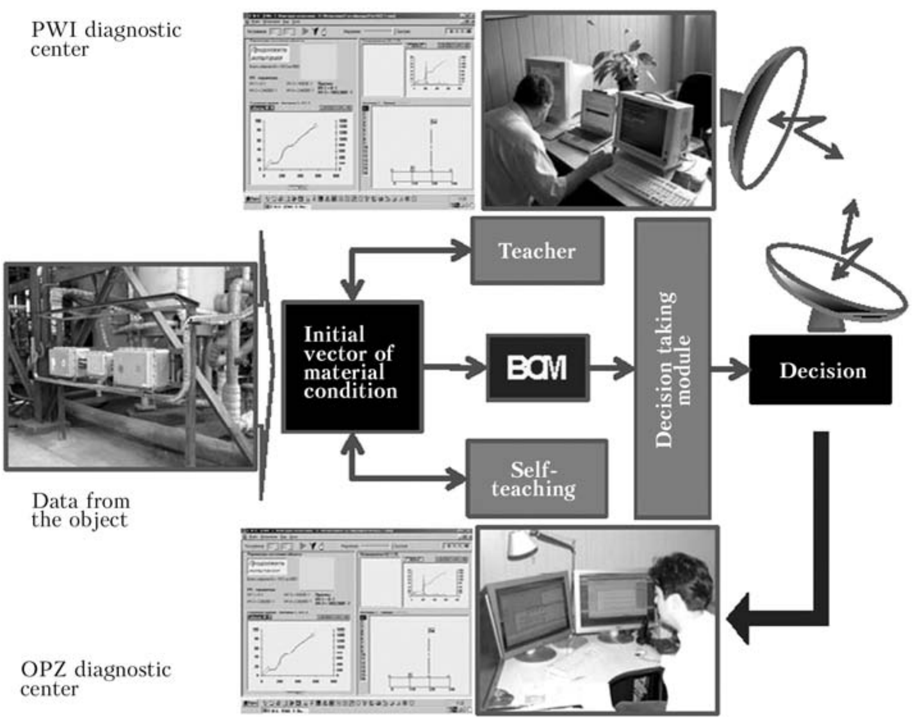

Figure 10. Remote control of operation of monitored structures

Figure 9 gives the scan of the side surface of ammonia storage of the total area of 3500 m^2, extracted from the working window of EMA-3S system program. As was noted above, four such storages are controlled by 48 × 4 AE transducers. Also strain and filling level gages are mounted, which in their totality make up the material state vector. Analysis of the material state vector at each moment of tank operation allows taking a decision on the breaking load and residual life of the storage. In Figure 9 the black round dots in the middle part of the expanded side surface of the tank are seen more clearly. They mark the sites of AE clusters, where service damage is accumulated. These areas coincided with the sites of fastening the brackets of pressure pipeline making oscillatory motions as a result of non-uniform operation of the pump pumping up the ammonia.

The possibility of remote control of the process of monitored structure operation becomes highly important. The control center can be located at any distance from the controlled object, including considerable distances. Such a possibility has great importance and sense. If required (for instance, in mastering new control technologies), consultative assistance can be quickly provided by highly qualified experts to the staff of plant diagnostic centres, located at another often quite remote site. Figure 10 shows the schematic of the technology operating in the mode of remote control of the monitored structure operation, organized jointly by OPZ and PWI. Specialists of the analytical center in Kiev can observe the same readings of control monitors, as the staff of control units of the plant. This enables discussion of control results and taking joint weighted decisions on them.

State of storage cases by the data of the continuous monitoring system. Ammonia storages, as was noted above, were manufactured and put into operation in 1978. Time of specified operation for such structures is usually taken to be equal to 20–25 years. During this period absence of any considerable influence of inner destructive processes running in structure materials at normal operation modes is assumed.

With time, however, negative processes of damage accumulation in materials begin to be manifested in the form of individual microdamage spikes. On the one hand, defects present in the materials, which did not manifest themselves earlier during acceptance testing due to high initial properties of materials, begin to become active. On the other hand, structural transformations on the micro- and macrolevels result in initiation and development of new defects, which gradually form cluster sites. Continuous control system showed permanent in time and not hazardous at this moment of operation spikes of acoustic activity in materials of storage cases, which is indicative of continuous running of changes, associated with operating life process. The above circumstances require that operation of storage cases in the post-specified period was accompanied by stricter control of material condition, which is exactly what is provided by the continuous monitoring diagnostic system.

1. Paton, B.E., Kudryavtsev, I.V., Nedoseka, A.Ya. et al. (1974) Some ways of construction of automatic information-measuring systems for diagnostics of welded structure reliability. *Avtomatich. Svarka*, **9**, 1–5.
2. (2007) 15 years ago (based on the paper of Academician B.E. Paton and Prof. A.Ya. Nedoseka on Concept of Technical Diagnostics of Pipeline Transport, published in journal «Tekhnich. Diagnostika i Nerazrush. Kontrol», **3**, 1992). *Tekhnich. Diagnostika i Nerazrush. Kontrol*, **4**, 6–10.
3. Paton, B.E., Lobanov, L.M., Nedoseka, A.Ya. (2003) Technical diagnostics: yesterday, today and tomorrow. *Ibid.*, **4**, 6–10.
4. Paton, B.E., Nedoseka, A.J. (1999) Diagnostic of designs and safety of an environment. In: *Proc. of Int. Conf. on Human Factor and Environment* (July 19–20 1999, Lisbon, Portugal). IIW.
5. Harris, D.O., Dunegan, H.L. (1972) Verification of structural integrity of pressure vessels by acoustic emission and periodic proof testing. In: *ASTM STP 515: Testing for prediction of material performance in structures and components* (Philadelphia, PA: ASTM), 158–170.
6. Nedoseka, A.Ya. (2001) *Principles of design and diagnostics of welded structures*. Ed. by B.E. Paton. Kiev: Indprom.
7. Kharebov, V.G., Borodin, Yu.P., Shaporev, V.A. (2006) System of complex diagnostic monitoring of hazardous industrial objects. *V Mire Nerazrush. Kontrolya*, **4**, 13–17.
8. Obodovsky, B., Fedchun, A., Nedoseka, A. (2006) Application of permanent acoustic emission monitoring of four ammonia storage tanks. *Ammonia Technical Manual*, 23–24.
9. (1998) *PB-03-182–98: Safety rules for on-land storages of liquid ammonia*. Moscow: Gosgortekhnadzor.