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Development of Automated System for Monitoring of Stress-Strain State and Residual Service Life of Pipelines.

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ABSTRACT

The presented paper discusses opportunities for development of a system of forecast, diagnostics, analysis and evaluation of risks of accidents at dangerous production facilities, including pipelines. It is demonstrated that analysis of durability, life-time and reliability of fuel and energy and oil and gas industries must be based on evaluation of stress-strain state with maximum accuracy by means of non-destructive testing (NDT) and diagnostic engineering (DE), including development of automated systems for engineering monitoring. That problem can be successfully solved using experience of development of on-board life-time meter (OSM) of an aircraft (with changes in calculation procedures for application at pipeline equipment) and special type of strain gauges (with implementation of polycrystalline Samarium monosulfide (SmS) films).
Keywords: pipelines, stress-strain state, life-time, monitoring, strain measurements, samarium monosulfide.

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Statement of the problem

Facilities of fuel and energy industry and oil and gas industry (FEI and OGI) operate with high working pressures and temperatures of working medium and in presence of fire- and explosion-dangerous products and raw materials, which causes risks of large-scale anthropogenic accidents and disasters. Only during 2007-2011 there were 84 dangerous accidents, including 41 explosion, 30 fires and 13 accidents with emission of dangerous substances [1, 2] and more than 30% of such accidents took place at pipelines. The total direct material damage for 2011 amounted to more than 1 milliard of rubles.

Among those accidents there were: 13 April 2009 – accident at a main pipeline Severokamsk-Krasnokamsk in Perm krai: oil leak in river Las'va, tributary of Kama river (hole in a pipeline); 19 October 2009 – rupture of "Druzhba" pipeline in Bryansk region with leak of oil (defect of weld joint); 29 August 2012 - accident at main gas pipeline Punga-Vuktil-Uhta-2 in Berezovsk district of Ugra, accompanied with gas ignition (corrosion and stress-induced cracking). In 2012-2014 there were failures and emergencies at pipelines of Ryazan' and Achinsk oil refineries, main circulation pipelines of nuclear power plants etc.

For assessment of potential safety risks it is necessary to take into account that integral index of wear of main production facilities of FEI and OGI in Russia is more than 60% (in some case up to 70-80%).

One of the key direction of "Concept of development of state policy for provision of industrial safety with consideration of necessity for stimulation of innovations for period up to 2020" [3] is increase of reliability and development of systems for forecast, diagnostics, analysis and evaluation of risks of accidents at dangerous production facilities.

Operational reliability of equipment and resulting safety of FEI and OGI facilities must be based not only on traditional kinds of maintenance, such as scheduled preventive maintenance (SPM) or reactive preventive maintenance (RPM), but also on more progressive methods, such condition-based maintenance (CBM) and proactive maintenance (PM).

That issues were reflected in decrees of Security Council (SC) and State Council (SC), federal laws (FL) on industrial safety (IF), on engineering regulation (ER), on safety of hydraulic engineering facilities and nuclear and radiation safety (NRS), on nuclear power engineering and emergency situations (ES). The above mentioned decrees and federal laws as development of the previous domestic regulations (state - GOST and industry OST – standards, building codes (SNIP)) demanded development of technical regulations (TR), national – NST, industry – STO, codes (SP), as well as federal regulations – FNiP.

Scientific and engineering, design, technological and operational security issues must be addressed at all stages of a product life cycle in a context of complex analysis and protection potentially dangerous objects of FEI and OGI from accidents and disasters on a basis of both traditional (analysis of durability, life-time and reliability) and new approaches (evaluation of survivability, security, risk, and protection) [4, 5].

This, in turn, requires deep scientific and methodical research on the topic (based on complex analysis of industrial security criteria of different levels), and to carry out appropriate applied scientific studies and experimental development (ASSED) for development and implementation of technologies and equipment for control (diagnostic and monitoring) of condition of FEI and OGI facilities including pipelines.

Scientific and methodological basis of diagnostic and monitoring of engineering systems

Analysis of durability, life-time and safety of complex engineering systems is based on concepts of main kinds of operation and emergency situations (designed, not designed and hypothetical) defined via parameters such as local stress and deformations ε, number of cycles *N*, temperature *t* and life-time time τ, which vary in a very wide range ($10^0 \leq N \leq 10^{12}$, -270°C $\leq t \leq$ 2000°C, 100$\leq \tau \leq$ 80 years).

For the major part of applications according to traditional regulations nominal stresses σ and deformationsε are not greater than yield stress and elastic strength $\sigma_{\text{т}}$ ($\sigma_n \leq \sigma_{\text{т}}$), and project situations are related to a field of study of classical theories (strength of materials, theory of elasticity, plasticity and creep).

After a transition to maximum local stresses $\sigma_{max} \geq \sigma_{T}$ and to emergency situations there is a need for analysis of nonlinear relationships of deformation and fracture, and stresses σ_{max} become less informative parameters than deformations ε_{max}. Damage from vibration and fatigue transit into damages from low-cycle fatigue.

Higher increase of σ_{max} and ε_{max} becomes a reason for transfer to not designed and hypothetical accidents and disasters. Theoretical basis for analysis of such situations is static and dynamic nonlinear fracture mechanics, and engineering regulation should be implemented via definition of risks of accidents and disasters $R(\tau)$ and their management for specified parameters $R_c(\tau)$ and [$R(\tau)$].

Thus, systems for control (diagnostics and/or monitoring) of engineering systems must be created on a basis of scientific studies of durability R_σ, life-time $R_{N,\tau}$, reliability $P_{P,R}$, survivability $L_{l,d}$, safety S, risk R and security Z.This is a settled traditional sequence of solvable problems, and each of its phases is mandatory based on a previous. As base parameters of operational effects P^o accepted are operational stresses σ^o, deformations ε^o, number of cycles N^o, time τ^o, temperature t^o, environment Φ^o (radiation, corrosion, electromagnetic field), coefficients of concentration α_σ, intensity of stresses K_I^o and deformations K_{Ie}^o :

$$P^o = \{\sigma^o, \varepsilon^o, N^o, \tau^o, t^o, \Phi^o, \alpha_\sigma, \alpha_\sigma, K_I^o, K_{Ie}^o\} \quad (1)$$

In practice, the most responsible are strength calculations R_σ, which characterize strength limits, where on a basis of stress-strain state parameters "σ^o-ε^o" and characteristics of mechanical properties used parameters are yield strength limits σ_Y, strength limits σ_{ul}, fatigue limits σ_{-1}, long-term strength limits σ_{lt}, tearing-off strength limits S, limits of plasticity ψ, critical coefficients of stress intensity K_{Ic} and deformations K_{Iec}:

$$R_\sigma = F\{\sigma_T, \sigma_B, \sigma_{-1}, \sigma_{\partial n}, S, \psi, \alpha_\sigma, K_{Ic}, K_{Iec}\} \quad (2)$$

Derivative parameters of mechanical properties, structural shapes and loading conditions are such materials' characteristics as long-term plasticity ψ_τ, effective coefficients of stress concentrations K_σ, sensitivity to absolute dimensions ε_σ and cycle asymmetry ψ_σ, variation coefficient υ_σ, speed of cracks' growth by number of cycles dl/dN and by time $dN/d\tau$, sensitivity to environment β_e. In that case stress conditions are written as follows:

$$P^o(\sigma^o, \varepsilon^o) \leq R_\sigma(\sigma_c, \varepsilon_c)\{\psi_\tau, K_\sigma, \varepsilon_\sigma, \psi_\sigma, v_\sigma, dl/dN, dl/d\tau, \beta_c\} \quad (3)$$

At that, stress-strain state characteristics "σ^o-ε^o" are compared with criteria characteristics "σ_c-ε_c" of limiting states.

In order to provide required life-time the following condition must be met:

$$R_{N,\tau,p} \leq R_{N,\tau}^c = \{N^o / N_c, \tau^o / \tau_c, \Phi^o / \Phi_c\} \quad (4)$$

where $R_{N,\tau}^c$ – critical (limiting) value of life-time, which is presented via critical (destruction) cycles N_c, time τ_c or effects of environment Φ_c.

Values N^o, τ^o, N_c, τ_c, in turn, depend on stress-strain state parameters ("σ^o-ε^o") and limiting state ("σ_c-ε_c"). Finally, reliability parameters $P_{P,R}$ by criteria of strength P and life-time $R_{N,\tau,P}$ are defined by the equations (1)-(4), when they are supplemented with probabilistic characteristics of strength, plasticity, operation loading with consideration of coefficients of variation υ of the mentioned characteristics:

$$P_{P,R} = \{P^o, R_\sigma, R_{N,\tau,\Phi}, v\}. \quad (5)$$

Scheme of forecast of safe residual life-time is presented in figure 1.

Thus, according to the equations (1)-(5) and fig.1, the most important parameters for evaluation of safety of engineering facilities are stress strain state "σ^o-ε^o" and ultimate states "σ_c-ε_c", which seriously influence strength, life-time and reliability, which leads to a problem of maximum accurate measurement of these parameters by means of NDT and DE, which can have independent and interconnected tasks [6].

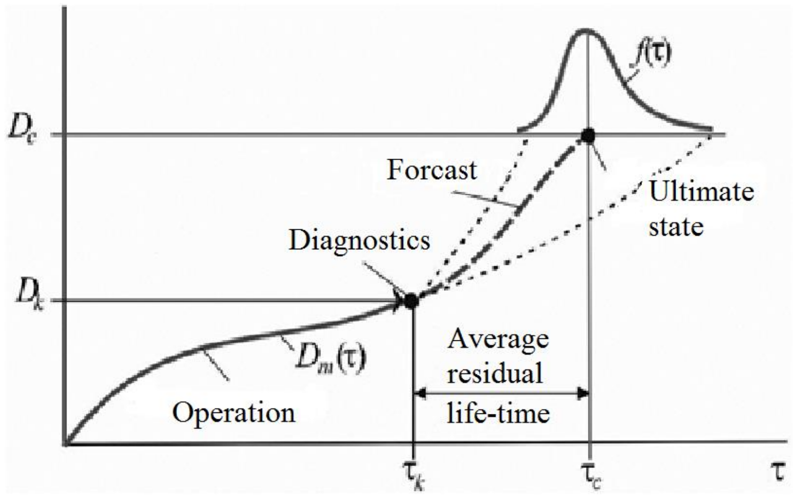

Figure 1: Scheme of forecast of safe residual life-time of structures and equipment

Defectoscopy and diagnostics are traditionally aimed at diagnostics and evaluation of micro- and macrodefects parameters in materials and structures at all stages of their life. In defectoscopy methods and systems based on physical, chemical and mechanical parameters (ultrasonic, X-ray radiography, acoustic emission, colorant, magnetic powder, holography, thermal imaging, strain measurement) are developed and widely applied.

Formation and propagation of defects $\ell(\tau)$ at micro- and macrolevel influence change in time τ of stress-strain state "$\sigma(\tau)-\varepsilon(\tau)$" (Fig. 2).

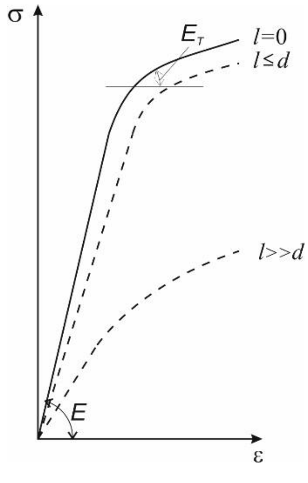

Figure 2: Change of shape of deformation curve with increase of defect's sizes ℓ

If microdefects distributed in volume are developing, it leads to increase of deformation level $\varepsilon(\tau)$ in a case of fixed $\sigma(\tau)$. For an area of insignificant microdefects ($\ell \le d$, *d* - size of microstructure elements) with changes $\sigma(\tau)$ и $\varepsilon(\tau)$ changes of deformation curve "$\sigma(\tau)-\varepsilon(\tau)$" are observed, i.e. decrease of inclination angle (conventional modulus of elasticity*E* in linear area of deformations and hardening modulus E_T in non-elastic area).

Formation and propagation of macrodefects $\ell(\tau)$>>*d*, which are comparable with cross-section sizes of load-bearing elements, for deformation curve "$\sigma-\varepsilon$" leads to rapid decrease of *E* and E_T, also it can lead to disappearance of linear deformation area.

Considering importance and wide range of changes of parameters E and E_T and shape of deformation curve "$\sigma - \varepsilon$", there are high requirements for methods and equipment of defectoscopy, for strain measurement it is resolution for estimation of defects $\ell(\tau)$ and deformations $\varepsilon(\tau)$. Diagnostics in a whole and, in particular, DE according to the equations are related to wider and more multiparameter estimation of conditions of loaded and damaged zones of load-bearing elements, including $\sigma(\tau), \varepsilon(\tau), D(\tau), K_I(\tau), t(\tau), N(\tau), \Phi(\tau), \ell(\tau), \alpha_\sigma, K_\sigma(\tau), K_I(\tau)$. At the same time, in DE, which is a basis for evaluation of parameters of strength, life-time, reliability and survivability, the key goal is definition of deformation curves "$\sigma - \varepsilon$" taking into account $N(\tau), \Phi(\tau), t(\tau), \ell(\tau)$.

Currently, there are several systems for monitoring of engineering condition of equipment of thermal power plants (TPP) and nuclear power plants (NPP), as well as for pipeline transport (PT) that were developed and are in operation, however, these systems belong to RPM group, which is traditionally used in Russia. For realization of more advanced forms of PM it is necessary to create systems for monitoring and forecast of residual life-time of equipment on a basis of effective methods of NDT and DE.

One of perspective direction of solution of that problem is development of automated monitoring systems (AMS) for engineering conditions of facilities on a basis of special kind of strain gauges.

Development of monitoring systems on a basis of strain gauges

Requirement for creation of systems for monitoring and prediction of residual life-time of equipment is stated, in particular, in [7]: "For the most dangerous parts of line part design documents / documentations must provide special safety measures, which decrease risk of accident", at that, one of main parameters was specified as "monitoring of engineering condition of pipeline".

Let's accept, that "diagnostics" is identification of defects and forecast of their propagation. "Monitoring" - is "survey of engineering condition of unit or block of units (of structure, machinery, assembly, mechanism) for definition and forecast of moment, when they reach their limiting state" [8]. That implies not only systematic control and analysis of individual parameters, but also a generalized model of a facility's condition, which allows to take into account history of individual loading of components and important part of equipment, form generalized complex parameters of structural condition in a whole and in each moment of time to know, which part of life-time of a facility is used and what was speed of damage accumulation. Term "residual life-time" means remaining running time of equipment after a moment of control of engineering condition (or repair), during which its main parameters are meeting requirement of regulation documentations (engineering, operation and safety parameters). With ability to accurately measure residual life-time it is possible to make a forecast for change of engineering condition of equipment, prevent its destruction and reasonably establish time intervals between costly inspections.

However, analysis of literature on scientific and practical issues of the problem, existing means of monitoring mainly works after the event, when cracks or damage had already appeared, and that's why there are terms like "leakage monitoring", "corrosion monitoring" etc. Often under "monitoring" is understood as a system for registration of results of periodic defectoscopy of certain parameters. Moreover, certain principles of physics, which methods of NDT and DE are based on, are related with limitations, which complicate or prevent their application as a mean of continuous monitoring.

Recently, for life-time evaluation there is a tendency for "transferring from defectoscopy to DE methods, which are based on combination of fracture mechanics, physical metallurgy and NDT" [3]. That tendency is complicated not only by low efficiency of existing methods and means of control, which don't allow to carry out quality evaluation of oil and gas pipelines, but also by absence of adequate algorithmic and methodological basis of evaluation and prognosis of residual life-time of an equipment using its current condition, which are based on systematization of information on diagnostics parameters of operation and level of wear off.

Solution to a problem can be found with consideration of the fact that one of the most important issues in problem of provision of durability, life-time and safety of modern powerful equipment and machinery is always definition of stress-strain state of structural elements during operation.

In the authors opinion, in that field the experience of creation by Russian scientists and engineers of a system for evaluation of an aircraft life-time, which is based on measurement of structures' deformation during operation, can be successfully applied [9, 10]. The method requires installation of strain gauges at a structure, which number is maximally reduced with remaining of capability of working on large number of critical parts of a structure.

OSM system consisted of

- sensors, which were picking up changes of nominal relative deformations during operation in several parts of a structures, situated in force vicinity of local "points", which were critical from a point of view of speed of fatigue accumulation; for that three component strain gauges of set, which allow to evaluate all three components of nominal stresses in a field of plane stress-strain state.
- transformers, which transformed electrical signals of strain gauges into form, which was suitable for further calculations of required witness-factors;
- calculator, which calculated values, which were planned to use as witness-factors, using a specified algorithm;
- indicators, which provided fixation of obtained values of witness-factors.

In a course of development of OSM the two following important problems were successfully solved: a) optimization of the system - the procedure of "correct" selection of number and places of installation of sensors is defined; b) setting up of the system - for each sensor (or group of sensors) an algorithm of signal processing during calculation of witness-factors for all "serviced" critical points is created.

That kind of system can become an effective tool for monitoring of condition of pipeline on a condition that highly sensitive strain gauges will be created, because the realization of strain measurement method is the best mean for definition of stress-strain state in real-time in any time period [11].

Strain gauges have the following important features: measurements of deformations wit different sizes of a base (from 0.5 to 20 mm); distance measurements in larger number of points; measurement in a wide range of temperatures; measurements with unfavorable conditions of environment; changes of multicomponent deformations at local parts. They have light weight, wide frequency range, including static deformations and low reaction threshold, high reliability and comparatively low cost.

However, there are two parameters that didn't allow to widely use tensoresistors (TR) and tensoresistor sensors of mechanical values (TRMV). Strain sensitivity factor (KT) of the major part of metals is not big and equal to, approximately, 2 (($\Delta R/R)/(\Delta L/L)$) = 2), therefore standard output signal of TRMV – 2 mV/V – requires significant strengthening. From the other point of view, energy consumption of TR and TRMV is too big: with resistant of tensor bridge of 400 Ω and power supply voltage of 5 V one channel consumes 12.5 mA.
TR based on semiconductors don't have that disadvantages, among them elements of special interest are those based on Samarium monosulfide (SmS), which were firstly studied in Engineering physics institute of A.F. Ioffe ame, where effective methodology for growing of SmS monocrystal was developed. SmS has the following advantages:

- KT for T=300°K reaches 260 (Ω/Ω)/(m/m), piezoresistance compression coefficient – $6 \cdot 10^{-3}$ MPa^{-1};
- temperature coefficient of resistance (TCR) of SmS can be changes in a wide range by means of doping with europium and selenium, as well as by means of various modes of evaporation and condensation;
- it has linear characteristics, which simplifies mathematical processing of results of measurements and calibration of sensor, i.e. increases accuracy of measurements;
- refractory and thermostable material (T_{melt}=2300°C), which results in high stability for penetrating radiation: changes of parameters of film structures on a basis of SmS with γ-radiation up to doses of 10^{10} roentgen do not exceed 1%, and operability remains at radiation intensity of 10^{6} roentgen /hour;
- presences of phase transition semiconductor-metal; a method for transfer of deposited polycrystalline film of SmS into metal compound exists, which results in possibility to adjust tensor

bridges without introduction of additional regulating elements.
- thermal coefficient of linear expansion (TCLE) of SmS has the same value as steel, which allows to avoid unnecessary temperature stresses at elastic steel elements;
- there is possibility to form polycrystalline films of SmS on any substrate, which can operate at temperature of 300°C.

In studies [12, 13] there are results of studies and engineering development, which demonstrate possibility of achieving required values of sensitivity and measurement accuracy by the proposed sensor on a basis of SmS.

Considering aforementioned, let's discuss in details solution of the problem of monitoring of complex parameter (of engineering condition) of pipeline equipment on a basis of stress-strain state measurements.

In a course of operation, a pipeline is loaded with internal pressure, which causes circular σ_φ and axial σ_x stresses, which change proportionally to a value of pressure. A pipeline is also subjected to bending and torsional loads, which are caused by deformations of soil, which a structure is placed in or with which it is connected through foundation stands. Bending stresses (in two planes) and torsional stresses are combined with pressure-induced stresses, which results in main stresses σ_Γ in a cross-section of a pipe, which are changing in time and results in fatigue damage. Even small cyclic changes can cause a significant accumulation of damage with time. Therefore, continuous monitoring of these stresses in real-time is necessary, as well as calculation of used part of a life-time on a basis of strain measurement data.

Scheme of measurement of stresses in four point on a circumference of a pipe allows to separate stresses, which depend on internal pressure and stresses depending on bending and torsion. In that case it is possible to calculate values of moments, which are bending and twisting a pipe, and compare them with acceptable values in real-time. At that, extension meters will not cause significant time delay there will be a possibility to register both slowly change stresses, caused by creep of soil, and fast changes caused by earthquakes. It is important to take into account changes of temperature, both for calculation of fatigue damage and definition of ultimate states of a pipe. Considering aforementioned, pressure sensor, temperature sensors and liquid flow speed sensors must be added to a pipeline.

In selected cross-sections of a pipeline it is planned to install for units of relative deformation sets on a basis of SmS (relative deformation lower measurement limit is 10^{-7}, measurement accuracy is 0.05%). Relative deformation sets must be placed outside, symmetrically on a surface of a plain in points, which are offset at ±45°from a horizontal axis of a plane, from left and right from a vertical axis of a plane. Each relative deformation set has three sensors, which allows to measure deformation in the following directions: parallel to a pipe axis (ε_1), perpendicular to a pipe axis (ε_2) and inclined at 45° to a pipe axis (ε_3) (Fig. 3).

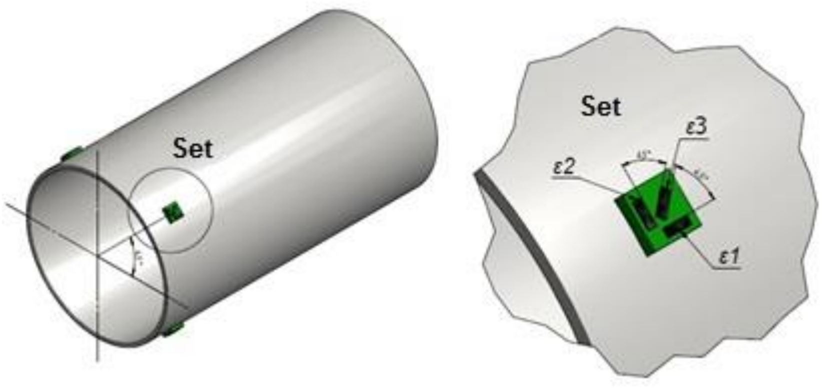

Figure 3: Scheme of placement of relative deformation sets relatively to a surface of a pipe

Bending moments and shear forces (in two planes), as well as torque, working in a pipe cross-section, are defined on a basis of signals of all four relative deformation sets.

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Each set contains thin film deformation meter bridge made from semiconductor SmS. A set must lower measurement limit of relative deformation from 10^{-7} and provide measurement accuracy of 0.05%. It will allow to more accurately calculate residual life-time of a given piece of a pipe, define bending moments and shear forces (in two planes), as well as torque, working in a pipe's cross-section. All calculations can be carried out at a site using local microprocessor, which has a required number of input channels for analogue signals from relative deformation sensors and temperature sensors. Microprocessor memory will store calibration curves of sensors and programs for thermal compensation of signals.

A set of newly developed components will include, aside from developed extension meters, probe-pressure meter, heat-loss anemometer, sensor of hydrodynamic weights type and system for data acquisition and processing. A system's highly sensitive sensors will be produces using polycrystalline SmS films.

On a basis of the mentioned measurement tools it is possible to create AMS, which allows to plan pipeline inspections with local application of any methods of NDT and DE, in a case speed of damage accumulation will increase a specified level before formation of microcracks. Accurate measurement of stresses, static and total pressure, flow speed in various cross-sections will allow to monitor accumulation of fatigue damage, accumulation of deposits on walls (by means of changes of hydraulic resistant of a pipe) and detect leaks.

Methodology for calculation of life-time use (and evaluation of a residual life-time) of a structure for an important power engineering and pipeline equipment, which is based on evaluation of stress-strain state on a basis of results of strain measurements, was proposed in studies of N.A. Mahutov [14-16]. Calculated value of individual use of a life-time, in turn, will allow to evaluate engineering condition of a tested object with high accuracy and carry out justified planning of time periods of its control and repair taking into account speed of accumulation of fatigue damage. It will result in improvement of operation efficiency, increase of life-time of a facility for more than regulated time period and increase of safety in FEI and OGI.

CONCLUSIONS

Problem of increase of reliability and development of system for forecast, diagnostics, analysis and evaluation of risks of accidents at dangerous production facilities is especially topical in FEI and OGI, in particular, for pipelines.

Security issues must be addressed at all stages of a product life cycle in a context of complex analysis and protection of objects of FEI and OGI from accidents and disasters on a basis of both traditional (analysis of durability, life-time and reliability) and new approaches (evaluation of survivability, security, risk, and protection) [4, 5].

For that evaluation of stress-strain state by means of NDT and DE, including development of ASM of engineering condition and residual life-time of facilities, with maximum accuracy is of significant importance. That problem can be successfully solved using experience of development of on-board life-time meter (OSM) of an aircraft (with changes in calculation procedures for application at pipeline equipment) and special type of strain gauges (with implementation of polycrystalline Samarium monosulfide (SmS) films). On a basis of values measured by ASM it is possible to evaluate used life-time (in hours of a pipeline operation with normative loading conditions) and residual life-time.

It will allow to achieve ASM characteristics, which would significantly exceed world's level, which will allow to expect wide application of ASM.

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REFERENCES

[1] Lebedeva, M., Bogdanov, A., & Kolesnikov, Yu. (2013). Analysis of statistics on emergency situation at

oil-processing and petrochemical industry facilities. Internet-journal "Technologies of technoshphere safety", 4(50). Retrieved from http://www.academygps.ru/img/UNK/asit/ttb/2013-4/20-04-13.ttb.pdf.
[2] Accidents and injuries at oil and gas industry facilities. (2015). Information bulletin of Rostekhnadzor. Special Issue. Moscow: SEC IS.
[3] Concept of development of state policy for provision of industrial safety with consideration of necessity for stimulation of innovations for period up to 2020. (n.d.). Retrieved from http://www.docs.cntd.ru/document/902354089.
[4] Safety issues in Russia. Legal, socio-economic and scientific and engineering aspects, vol. 1-47. (1998-2015). Moscow: IHSF "Knowledge".
[5] Federal code in a field of industrial safety "General requirements for justification of safety of production facility. (2015). Documents of interindustrial application on issues of industrial safety and protection of natural resources. Series 03, Issue 73. Moscow: SEU IS.
[6] Kluev, V. (2003). Non-destructive testing and diagnostics: Handbook. Moscow: Mechanical engineering.
[7] Federal code in a field of industrial safety "Safety rules for dangerous production facilities of main pipelines". (n.d.). Retrieved from http://www.rg.ru/2014/01/06/truboprovod-site-dok.html.
[8] Monitoring systems for equipment of dangerous production facilities. General technical requirements. Standard of "Rostehexpertiza" association, association of specialists of petrochemistry and oil processing and SEU RISKOM (SA 03-002-05). (2005). Moscow: Chemical engineering.
[9] Selikhov, A., Raikher, V., & Leibov, V. (1991). The Methodology of, and Experience in Providing the Structural Integrity of Aging Aircraft. International Conference on Aircraft Damage Assessment and Repair, Melbourne, Australia.
[10] Miodushevsky, P., & Podboronov, B. (1991). FALC – On Board Fatigue Life Counter (Fatigue Meter). International Conference on Aircraft Damage Assessment and Repair, Melbourne, Australia.
[11] Rudachenko, A., & Saruev, A. (2011). Studies of stress-strain state of pipelines. Tomsk polytechnic university. Tomsk: Publishing house of Tomsk Polytechnic University.
[12] Melone, G., Miodushesky, P., Rizzi, L., Vasanelli, L. (2007, June 26-27). Miniaturised thin film temperature sensor for wide range of measurement. Advances in Sensors and Interface, IWASI 2007, Bari, Italy.
[13] Miodushevsky, P. (2002, October 7-8). Samarium sulphide SmSx thin film sensors. Deutsche IMAPS-Konferenz, München, Germany, 141-146.
[14] Mahutov, N. (2008). Durability and safety. Fundamental and applied research. Novosibirsk: Science.
[15] Mahutov, N. (2005). Structural durability, life-time and anthropogenic safety. In two parts. Part 1 – Criteria of durability and life-time. Part 2 – Justification of durability and life-time. Novosibirsk: Science.
[16] Mahutov, N., Frolov, K., & Dragunov, Yu.G., et al. (2008). Problems of durability and safety of water-water reactors. Series "Studies of stress and durability of nuclear reactors". Under ed. N.A. Mahutov and M.M. Gadenin. Moscow: Science.