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Evaluation Model of Integrated Safety of Fuel and Energy Complex Facilities

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Abstract**:** ***This article discusses the developed model of monitoring subsystem of automated process control system (APCS) with consideration for stabilizing procedures. In order to develop the model and to describe the conditions of state of the environment as well as detectors of the first level (sensors), a conventional simulated facility of fuel and energy complex (FEC) was selected. Such facility inevitably includes numerous fire and explosion hazardous locations. The formulated evaluation principles of integrated safety of hazardous locations (HL) in the case of implementation of analytical system of strategic planning (ASSP) can become an additional module of automated system of fire and explosion safety (ASFES). Dependence of efficiency and survivability of detectors (transferring data to a decision maker (DM)) on appropriate stabilizing measures (maintenance, verification, overhaul, etc.) was demonstrated. In order to calculate survivability evaluation criterion of the APCS first level equipment, several management objectives were selected (provision of data reliability). Analysis of integrated safety in APCS with N detectors is defined as a task of decrease of integrated quality of fire safety at HL. The proposed model is formalized as an algorithm. The planning objectives are relatively ranked in three stages: arbitrary, ranking based on expert evaluations, and adjustment, correction using the decision matrix method (DMM). Fulfillment of normalization condition for the obtained final evaluations makes it possible to derive evident coefficients less than 1 (on importance scale). Final step of the algorithm is assignment of probability function value to each selected group of measures. On the basis of this probability distribution, the DM can determine the dependence of functional and supporting subsystems of APCS on planning and diagnostics during their operation. The proposed evaluation model of integrated safety based on strategic planning methods would improve the DM management quality at FEC facilities and, as a consequence, improve ASFES efficiency and survivability.***

Index Terms**:** ***fuel and energy complex enterprise, fire safety, fire prevention, hazard locations, hazardous state, sensors, ranking, management objectives, diagnostics, automated process control systems, automated systems of fire explosion safety, mathematical model, algorithm, strategic planning, expert evacuation, decision matrix, evaluation, probability, survivability.***

I. INTRODUCTION

Nowadays the market of industries of FEC varies intensively: amount and geography of goods and services, participants and leaders, technologies, logistics. Importance of this market for global economy in the nearest future can hardly be overestimated. The power engineering industries exert significant influence on stability of national economy. Such influence can be both positive, expressed by increased growth rates and quality, and negative, especially obvious during financial crisis. The development principles of fuel industry are highly important in provision of national strategic safety. FEC facilities in their turn should be based on planning and monitoring of steady and safe operation [1], [2]. The objectives of provision of safety of FEC facilities are determined in [3], the measures of fire safety are also considered. Taking into account inevitable hazards of fires and explosion at FEC facilities, it is necessary to supplement existing and to develop new methods of fire prevention using modern elements of APCS. The ASFES is one of the pioneer systems in Russia comprised of such methods [4]. The authors in [4] present numerous qualitative efficiency evaluations as well as qualitative analysis of the efficiency. The generalized structure of ASFES is based on three automated systems: automated system of fire and explosion prevention (ASPFE), automated system of fire and explosion protection (ASFEP), general purpose automated systems (GPAS), as well as some auxiliary systems [4]. It should be understood that ASFES is a constituent of fire and explosion safety system combining all functional possibilities by means of automated control. The authors assume that the main objective upon provision of integrated safety at FEC facilities is prevention of fire hazards and, as a consequence, prevention of human and material losses. While solving this problem, the authors consider the issue of efficiency improvement of fire protection depending on quality and completeness of data available for DM with regard to HL, subdivision of FEC facilities. The level of data completeness on managed facility is a factor which determines the rate of adoption of correct decision by DM [5]. The major organizational and technical requirements for fire safety of energy facilities are described in [6]. The first level equipment providing information about hazardous situations is comprised of sensors and detectors [7]. The data from such devices are highly important for continuous provision of integrated safety. It is important to evaluate thoroughly the quality of data supplied to DM control panel. The authors in [8], [9] proposed evaluation models of integrated safety formalized in the form of algorithms (including fire safety) at oil refineries. The models make it possible to analyze data required for adoption of decision with regard to the required level of integrated safety.

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In this work the authors consider a subject of wider scale: a conventional simulated facility of FEC. Operability and efficiency of detectors depend on quality and adequacy of stabilizing measures. Then, using mathematical strategic planning [10, 11], the authors will describe another developed detailed model of APCS monitoring subsystem with consideration for stabilizing procedures and present it in the form of algorithm. Such model would allow to increase the DM management quality of ASFES at FEC facilities related with provision of acceptable level of fire and explosion safety.

II. METHODS

According to [12], a gas analyzer is a device for measurement of qualitative and quantitative composition of gaseous mixture. Such transformers of data on concentration of gaseous components are known as sensors [7]. In [13] a sensor of pre-explosive concentrations is defined as a device enabling automatic recording concentrations of flammable gases and vapors. Aiming at the model simplification, the authors will apply the term "sensor" exactly for such meters. Fire detector is a device for data transfer of fire to a receiving instrument [14]. Such detector is not a metering device. Since the detailed general model of sensors and detector is not described in this research, the authors will use the terms "sensor" and "detector" in general sense during description of storing devices and data transfer of the first level of APCS. It follows from the aforementioned definition that in mathematical terms a sensor is a function of several variables. Here and further on the stabilizing procedures are technical maintenance, verification, overhaul, replacement, upgrading of sensors and other first level data sources in APCS. Taking into account the responsibility level of ASFES operators, it is possible to state that a DM managing integrated safety of each HL and overall FEC facility should understand in real time how efficient are all systems including sensors [15]. This should be based on data on stabilizing measures performed before DM shift changeover. It should be mentioned that stabilizing measures are performed under regular operation conditions of FEC facility without limitations of supply and verification of APCS equipment of lower level as well as its other components. Stabilizing measures concerning ASFES equipment are related with schedules of technical maintenance, verification, overhaul, equipment replacement and upgrading, financing, activities of maintenance crews, logging of these activities and emergency events which, without being hazardous, lead to failures of equipment units and components. The time dependence of sensor can be considered as certain curve (see Fig. 1).

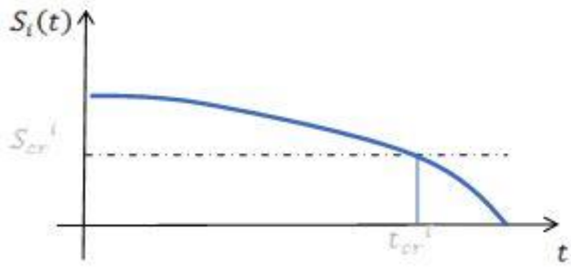

Fig. 1: "Reagent function" of the i-th sensor as a function of time.

Its operation can also depend on some other circumstances, such as weather conditions, operation conditions, periodicity and quality of verifying measures and other stabilizing procedures. Development of general model of sensor operation with consideration for the mentioned circumstances is beyond the scope of this work. Nevertheless, the model which considers the sensor state should account for the schedules of maintenance, overhaul, and replacement of equipment of APCS and its ASFES constituent.

In this sense the operation function of the ASFES i-th sensor should be considered as the following tuple:

$$I_i = \{(x_i, y_i, z_i),\ f_i(S_i(t)),\ S_i(t, U_з(P_j))\}, \quad (1)$$

where (x_i, y_i, z_i) are the spatial coordinates of the i-th sensor at HL; $f_i(S_i(t))$ is the function of environment state evaluation by the i-th sensor; $S_i(t, U_з(P_j))$ is the function of reagent state of the i-th sensor with consideration for the performed stabilizing procedures; $U_з(P_j)$ is the management function of scheduled activates (with regard to the stabilizing procedures) during the j-th time interval; P_j is the vector of management objectives during the j-th time interval.

The management objectives in integrated safety of a FEC facility can be as follows:

- fire and explosion prevention;
- provision of certain quality of fire and explosion protection;
- personnel qualification required for a given safety level;
- provision of required data quality concerning state of systems;
- guaranteed provision of management in difficult situations, etc.

However, in such complicated form it is difficult to analyze sensor operation as a function of special conditions (imposition of sanctions and so on). Hence, it would reasonable to consider simpler dependence. As mentioned above, the major element of sensor as used in this work is reagent or its electron substitution. Its approximate sensitivity as a function of time (or number of applications) is illustrated in Fig. 1. Both time and reagent are the variables determining sensor capability to appropriately determine the amount of explosive substance within the boundaries of responsibility, hence, they could be considered in the predictions. However, in this presentation they can be neglected. Therefore, the function of environmental state evaluation by the i-th sensor can be written as follows:

$$f_i(S_i) = S_i(U_з(P_j)), \quad (2)$$

If the model in [16] is simplified even more and the state of sensor recording part is excluded, then the function of its response can be presented by the dependence on the vector of management objectives irrespective of their time interval. This is quite substantiated since the previously considered blind zones of sensors appear and increase upon their incorrect maintenance, overhaul, and upgrading.

In this case it would be reasonable to consider the function of environmental state evaluation by certain single sensor as a function of vector of management objectives:

$$I_i = f_i(P), \quad (3)$$

where $P = \{P_1, P_2, \dots, P_K\}$ is the vector of planning objectives (provision of information reliability) upon management of integrated safety at FEC facility. As follows from Eq. (3), the function of sensor operation is a multidimensional function. Herewith, it is not necessarily a Boolean. However, the objectives do not convert sensor to working state. They only regulate the main trends. The trends are followed by tasks of various levels and priorities which are converted into specific measures and procedures involving maintenance, replacement or overhaul. This is accompanied by multilevel tree of sensor operation variables determining its activation in tough situation. Inverse problem can be related with evaluation of stabilizing measures performed at FEC facility and their influence on dependences which determine blind zones of sensors. In each specific case stabilizing measures should be financed. Though, by virtue of certain reasons such financing can be partial or even zero. In this case the measures will not be carried out. Now let us analyze the efficiency of implementation of management objectives with regard for stabilizing measures with consideration for the methods described in [9]. Let us summarize the management objectives in Table 1. In order to identify them and the coefficients of the model, the authors will consider the importance scale of each objective.

Table 1. Evaluation of management objectives at FEC facility

Designation	**Description**	**Coefficient value determined by expert**	**Coefficient value according to significance scale**
$\alpha_1{}'$	Fire and explosion prevention	β'	$\gamma_1{}'$
$\alpha_2{}'$	Required quality of fire and explosion safety	β'	$\gamma_2{}'$
$\alpha_3{}'$	Required quality of data on system state	$\beta_3{}'$	$\gamma_3{}'$
$\alpha_4{}'$	Guaranteed response rate in complicated situations	$\beta_4{}'$	$\gamma_4{}'$
$\alpha_5{}'$	Personnel qualification required for a given safety level	$\beta_5{}'$	$\gamma_5{}'$

None of the objectives summarized in Table 1 is related directly with Eq. (3), however, the actions of personnel aimed at their achievement inevitably result in stabilizing measures. In general case the number of these objectives is *K*. In fact, the management of integrated safety at FEC facility is impossible without reliable information of the first level of APCS presented by sensors. Herewith, it is obvious that upon implementation of digital twins [17], the number of sensors is doubled by at least an order of magnitude in comparison with their initial number. It follows form the latter consequence that the amount of actions by personnel with regard to rearrangement of detectors increases proportionally. Upon such sharp increase in the scope of stabilizing activities, the overall survivability of APCS decreases, their thorough planning is required. On the basis of calculations in [9], let us perform the algorithm steps of APCS monitoring subsystem with regard to equipment upgrading and stabilizing measures. At the first step let us calibrate the management objectives in Table 1 using the preset importance scale considering that:

$$\sum_{i=1}^{K} \gamma_i = 1, \quad (4)$$

where Q_i is the calculated i-th coefficient according to the importance scale of K possible values.

Then, on the basis of selection of coefficient evaluations by experts, let us adjust the data on the coefficients and calibrate them again [18]. The integral quality factor in the developed model will characterize general efficiency of personnel activities at HL (HL cluster) on stabilizing measures.Then, let us normalize the coefficients determined by experts:

$$\sum_{i=1}^{K} \beta_i = \Psi, \quad (5)$$

where β_i is the value of the i-th objective proposed by experts; K is the number of objectives according to the importance scale.

Then, it is possible to write for γ_i:

$$\gamma_i = \beta_i \,/\, \Psi, \quad (6)$$

The coefficients β_i selected by experts are processed by methods specifying the expertize quality. Then, each group of activities is assigned to the value of probability function calculated as follows [19]:

$$P(\alpha_j) = 1 - \sum_{i=1}^{K} \vartheta_i * \gamma_i, \quad (7)$$

where K is the number of objectives involved in the calculations; γ_j is the importance coefficient of objective for which the calculations are carried out; θ_i is the coefficient of objective existence for a group of measures:

$$\theta_i = \begin{cases} 0, \text{ no objective} \\ 1, \text{obective exists} \end{cases}, \quad (8)$$

Existence of 1 in Eq. (7) is stipulated by Eq. (4).

Using such probability distribution, while operating functional and supporting APCS subsystems, the DM can determine their dependence on planning and diagnostics. On its basis, it is possible to establish operation algorithm of APCS monitoring subsystem with consideration for stabilizing measures (Fig. 2).

The proposed model can be formalized in the form of algorithm which can be written as the following sequence:

1. Selection of planning objectives (data reliability) in APCS for management of integrated safety $\alpha = \{\alpha_1, \alpha_2, \dots, \alpha_Z\}$.
2. Initial ranking of objectives (arbitrary).
3. Ranking of objectives by X experts and obtaining of K variants of expert evaluations: $\beta_j = \{\beta_1{}^j, \beta_2{}^j, \dots, \beta_K{}^j\}$ for the j-th expert.
4. Evaluation, adjustment, and correction of planning objectives in order to provide data reliability in APCS obtained by expert ranking: $\beta = \{\beta_1, \beta_2, \dots, \beta_K\}$.
5. Normalization of objective rank (obtaining of coefficients less than 1 according to the importance scale): $\gamma = \{\gamma_1, \gamma_2, \dots, \gamma_Z\}$.
6. Calculation of probability distribution function for each coefficient of objective impotence: $P(\alpha_j)$ by Eq. (7).

According to definition, strategic planning for DM is the procedure of decision selection under uncertainty conditions concerning a set of actions (consumption of resources, safety provision, evaluation measures), which is reasonable from the point of view of maximum achievement of the major objective [10], [11]. This objective can be determined by the function or its fixed value. This value is usually a certain number defining maximum or minimum of target objective (integral quality factor) on the basis of which the DM makes decision concerning reliability of APCS data provision and overall survivability of ASFES.

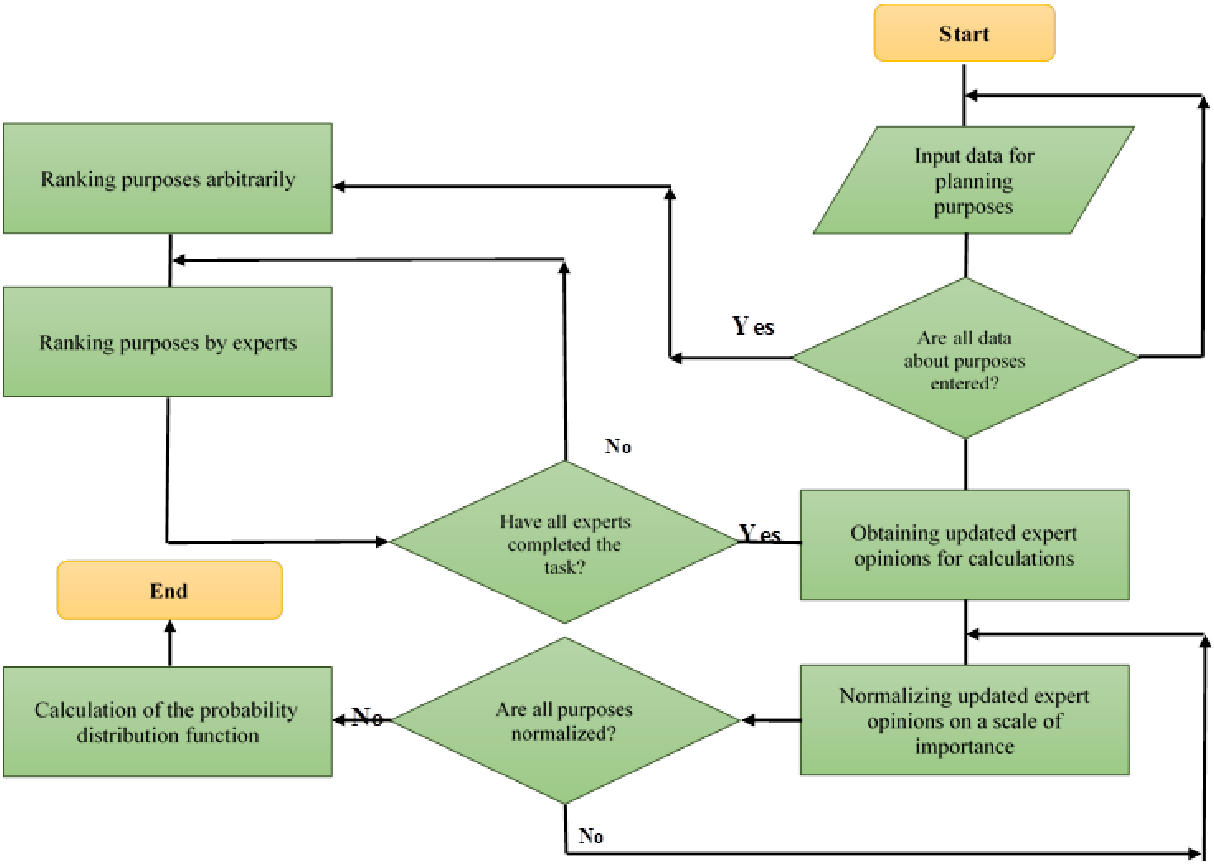

Fig. 2: Algorithm of APCS monitoring subsystems with consideration for stabilizing procedures

III. RESULTS AND DISCUSSION

The sensor operation function depends on three types of time: total time of sensor operation from the point of its installation, its operation time from the point of its last verification, and activation time upon dangerous changes in environment. The equation for the i-th sensor is as follows:

$$I_i = f_i(t^1{}_i, t^2{}_i, t^3{}_i), \quad (8)$$

Taking into consideration that in consideration of this model, the activation circumstances of sensors depend on verification and stabilizing measures, as well as they are also responsible for overall time of sensor operation, it is possible to use only the time $t^2{}_i$ as the main parameter in Eq. (8), and the equation can be rewritten as follows:

$$I_i = f_i\big(P_1(t^2{}_i), t^2{}_i, P_3(t^2{}_i)\big), \quad (9)$$

where $P_1(t^2{}_i)$ is the planning objectives of stabilizing procedures which increase the operation time of sensors; $P_3(t^2{}_i)$ is the planning objectives of stabilizing procedures which provide their reliable activation.

Both trends of activities of APCS personnel imply performance of measures included into overlapping but not coinciding sets. It would be reasonable to combine them in unified planned assignment on provision of reliability of the first level data in APCS. Then:

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$$I_i = f_i(P_i(t),t)\ , \quad (10)$$

Equation (10) is not obligatory Boolean. Deviation in activation of sensors upon dangerous changes in environment (the second state of HL) should be considered as the surface area under the function of environment evaluation by sensor during the time t. Then, for criterion of survivability evaluation of the first level of APCS in the j-the cluster, it is possible to write as follows [19]:

$$w_j^{\,P} = \sum_{i=1}^{N_j} \int f_i(P_i(t),t)\, dt \ \ ,\ \ j \in \{1,2,\dots,M\}\ \ , \quad (11)$$

where M is the number of the considered clusters.

The integral quality factor will be preset by the vector :

$$W_{03}^{\ P} = \{w_1^{\,P}, w_2^{\,P}, \dots, w_M^{\,P}\}\ , \quad (12)$$

where $w_i^{\,P}$ will be calculated by Eq. (11).

Equation (11) evaluates criteria of information reliability provided by the DM to APCS as a function of stabilizing procedures. The lower is the $w_j^{\,P}$ in each of M clusters of HL, the higher is the level of APCS survivability, and the higher is the data reliability obtained by the DM from the sensors concerning environment. The stabilizing measures depend on plans of measures of several levels (implemented both for overall FEC facility and with regard to its constituent parts or HL), control quality of their execution, as well as appropriate financing.The monograph [20] presents the conceptual model of management information system of fire safety at distributed facilities of large-scale company as exemplified by housing and utilities sector. The proposed algorithms can be supplemented by the aforementioned evaluation model of integral safety aimed at increase in reliability and completeness of the information provided to the DM. Information reliability provided by the DM to APCS as a function of stabilizing procedures of certain HL at FEC facility can be presented in the form of chart where the most vulnerable locations are highlighted by color. In the case of information ASSP included in ASFES, such information can be predicted automatically. It can be presented to the DM in the same mode. Similarly, it is possible to account for not performed planned measures which strongly impact total protection. In addition, Eqs. (10) and (11) can account for financial and other aspects of planning (predictions of time of repairing crews and auxiliary departments as well as other provisioned resources) which exert influence on overall level of APCS survivability.

IV. CONCLUSION

Therefore, aiming at appropriate and high-quality diagnostics of the first level detectors of APCS in order to improve its survivability and ASFES constituent, it would be reasonable to apply methods of strategic planning [10, 11]. The use of ASSP as ASFES constituent would improve significantly the management by a DM at a FEC facility, hence, would improve overall survivability of APCS.

Long term planning objective at a simulated facility is provision of integrate safety and, hence, improvement of APCS survivability, namely: decrease in integrated quality performance of fire safety at HL. The developed model of DM informing on data accuracy transferred to APCS, due to stabilizing measures and strategic planning methods [10], [11] (calculation of relative values of management objectives in integrated safety, adjustment of objectives using decision matrix, distribution of hazard probabilities) would improve significantly the ASFES survivability.

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