Karmanov A.V., Telyuk A.S.

DEFINITION OF ACCEPTABLE SAFETY PERFORMANCE FOR MULTI-CHANNEL EMERGENCY PROTECTION SYSTEMS

The paper offers the structure of a cost criterion that may be used as a basis for defining acceptable frequencies and acceptable risk reduction factors for a multi-channel emergency protection system, which maintains a group of hazardous technological objects. The paper also presents an example of defining acceptable safety performance for technological objects involved in the process of preparing products of oil-and-gas wells.

Keywords: *safety, risk, emergency protection system, risk reduction factor.*

Introduction

A system of emergency protection (EP) is used to ensure the safe operation of technological facilities in hazardous industries. Typically, EP is part of a computer-aided manufacturing (CAM) system, and it is intended for insuring automatic transition of a hazardous technological object (TO) into secure state, referred to as "stop", in the event of an incident on it. Generally, incidents arise on TO in case when some of its process parameters fall within the so-called critical area (CA). In this case the further operation of an object is inadmissible, as this can lead to various undesirable consequences, such as loss of products, accidents, etc. Parameters, for which critical areas are defined, hereinafter will be called "critical" parameters.

Let us consider a multi-channel EP [1], with a block diagram shown in Fig. 1.

In general, a multi-channel EP maintains *n* technological objects, where $n \geq 1$. Each *j*-th TO has *m* (j) of critical areas (CA). In case when a corresponding "critical" parameter falls into any critical area, an incident occurs where $m(j) \geq 1$, $j = 1, ..., n$. Each *s*-th CA, where $s = 1, ..., m(j)$, on the *j*-th TO is maintained by one (j,s)-channel of EP, which is a combination of subsystems: $D_{j,s}$, PLC and EU_j. $D_{j,s}$ is a subsystem of sensors of (j,s)-channel. PLC is a programmable logic controller, which has the number of inputs not less than $m = m(1) + ... + m(n)$; it performs cyclic processing of input data to determine the fall of "critical" parameters into the corresponding CA. In case if a parameter fall into the *s*-th critical area on the *j*-th object, the PLC generates a signal (command) to the subsystem of execution units (EU_j), which performs "stop" of the *j*-th object.

Note that each subsystem integrated into the (j, s)-channel of EP can have quite a complex architecture [2], directly affecting the channel reliability. For example, the subsystem of sensors $D_{j,s}$, in general, as

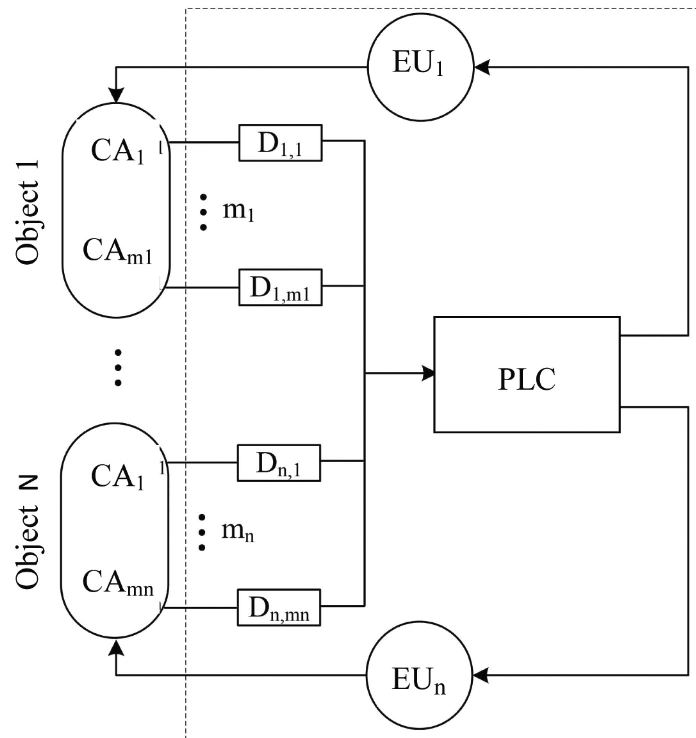

Fig. 1. The structure of multi-channel EP

well as any other subsystem that may have the MooN architecture, where N is the total number of parallel operating sensors (subsystem channels) and M is the number of sensors (subsystem channels) to be in upstate, so that the subsystem of sensors can successfully execute the function of measuring the value of hazardous parameter ($M \leq N$). Thus, the failure of the subsystem occurs if (N-M+1) of parallel operating channels of the subsystem fail. It is clear that the subsystem with the simplest architecture 1oo1 has "lower" reliability than with any other subsystem architecture, but its cost will be lower, all other things being equal.

The performance quality of multi-channel EP is evaluated by various parameters of safety. One of the most important parameters is RRF (j,s), a risk reduction factor of (j,s)-channel, where j = 1, ..., n, s = 1, ..., m (j). RRF (j,s) is the ratio of $F_{np}(j,s)$ to $F_p(j,s)$, where $F_{np}(j,s)$ is the frequency (rate) of incidents occurred on the *j*-th TO when a corresponding hazardous parameter falls into the *s*-th critical area, and F_p (j,s) is the frequency (rate) of the so-called "not worked-out" incidents. "Not worked-out" incident occurs when the incident took place but EP did not execute "stop" of TO, for example, due to the failure of one of the subsystems that is a part of the corresponding (j,s)-channel of EP. Thus, each incident caused on the *j*-th TO by the *s*-th CA is either a "worked out" incident, i.e. EP has brought TO to "stop" state, or a "not worked out" incident, i.e. EP has not executed "stop" of TO.

We shall point out the following properties specific to each (j,s)-channel of EP:

1. The value $F_{np}(j,s)$ does not depend on the presence of EP but it depends on TO physical properties.

2. The higher the dependability of (j, s)-channel as a recoverable system is, the smaller the value Fp (j, s) and hence, the higher RRF (j, s) are. The "absolutely dependable" (j, s)-channel has the value Fp (j, s), which is close to zero, however the cost of hardware of "absolutely dependable" (j, s)-channel is very high.

3. RRF (j, s) ≥ 1. If the RRF (j, s) is equal to unity, then the following equation is satisfied

$$F_p(j,s) = F_{np}(j,s). \quad (1)$$

The inverse proposition is also true. Note if the equation (1) is met, we can assume that EP does not maintain the *s*-th CA on the *j*-th TO.

The risk reduction factor RRF (j, s) can be considered as the relation of the rate of F_{np} (j,s) simple stream of incidents that occur on the *s*-th CA on the *j*-th TO, to the rate of F_p (j, s) stream of "not worked-out" incidents. In this case, the stream of "not worked-out" incidents is represented by a simple stream obtained by operation of incident stream rarefaction [3, p.251]. Usually the rate of F_p (j, s) is used to estimate the rate of F_a (j, s) of the accident stream on the *j*-th TO arising from the "not worked-out" incidents over the *s*-th CA, as the following inequality holds true

$$F_a(j,s) \le F_p(j,s). \tag{2}$$

EP is believed to be correctly designed if each of its (j, s)-channel has such a risk reduction factor RRF (j, s) that provides the frequency value F_p (j, s) not more than the acceptable value F_t (j, s). Justified selection of the acceptable frequency F_t (j, s) and, accordingly, RRF (j, s) is a separate task that can be solved based on different criteria [4]. Below you can find the statement and solution of the problem of defining the frequency F_t (j, s) and risk reduction factors RRF_t (j, s), j = 1, ..., n, s = 1, ..., m (j) for a multi-channel EP, based on minimizing the cost criterion that takes into account the costs of development and operation of EP, as well as the expected damage from accidents.

Statement and solution of the problem

Let EP be supposed to be used for T years, then the cost C (A,T) for the development, operation of EP and accident elimination during operation can be represented respectively by the following three summands:

$$C(A,T) = C_1(A) + C_2(A) \cdot T + C_3(A, T), \tag{3}$$

Let us consider the components of the expression (3).

A is a set of data about EP with the following form:

$$A = \{[A_{j,s}, j = 1,\dots,n, s = 1,\dots,m(j)], \tau\}, \tag{4}$$

where $A_{j,s} = A_{j,s} = (A^{(1)}_{j,s}\ A^{(2)}_{j,s}\ A^{(3)}_{j,s})$, $A^{(v)}_{j,s} = [(M^{(v)}_{j,s}ooN^{(v)}_{j,s}), \xi^{(v)}_{j,s}]$, v = 1, 2, 3, τ is the time of EP availability control check. In this case, if v = 1 then the data corresponds to a subsystem of sensors of EP (j, s)-channel; if v = 2 then the data corresponds to PLC subsystem; if v = 3 then the data corresponds to the subsystem of executing mechanism of the (j, s)-channel. The set $A^{(v)}_{j,s}$, where v = 1,2, 3, defines the following information for the v-th subsystem of EP (j, s)-channel:

1.1. $(M^{(v)}_{j,s}ooN^{(v)}_{j,s})$ is the architecture of the *v*-th subsystem, for which, in accordance with the structure of the EP shown in Fig. 1, the following relations hold true:

$$M^{(2)}_{j,s}ooN^{(2)}_{j,s} = M^{(2)}ooN^{(2)},\ M^{(3)}_{j,s}ooN^{(3)}_{j,s} = M^{(3)}_{j}ooN^{(3)}_{j}\,. \tag{5}$$

1.2. $\xi^{(v)}_{j,s} = (\lambda^{(v)}_{j,s}, \alpha^{(v)}_{j,s}, \beta^{(v)}_{j,s})$, where $\lambda^{(v)}_{j,s}$, $\alpha^{(v)}_{j,s}$, $\beta^{(v)}_{j,s}$ are a failure rate, the level of self-diagnostics and the β-factor of one channel of the *v*-th subsystem respectively. [5] In this case, taking into account the structure of the EP, the following equations take place:

$$\xi^{(2)}_{j,s} = \xi^{(2)},\ \xi^{(3)}_{j,s} = \xi^{(3)}_{j}\,. \tag{6}$$

Characteristics $\lambda^{(v)}_{j,s}$, $\alpha^{(v)}_{j,s}$, are usually provided by a manufacturer in the passport of facilities, and they significantly affect its cost. The β-factor, as a rule [5], satisfies the following relation:

$$0 < \beta^{(v)}_{j,s} < 0{,}3 \text{ , } v = 1, 2, 3, j = 1,\ldots,n, s = 1,\ldots,m(j) \text{ .} \tag{7}$$

In view of (5) and (6), the set A can be presented as follows: $A = \{[(A^{(1)}_{j,s}\ A^{(2)}\ A^{(3)}_{j}), j = 1,\ldots,n, s = 1,\ldots,m(j)], \tau\}$. It should be noted that the purpose of the checks carried out at intervals τ, is the control of availability of all EP subsystems, thus, should any subsystem fail, the recovery of its availability is carried out.

2. C_1 (A) is the inventory value, i.e. costs of EP production and commissioning. These costs can be represented in the following sum:

$$C_1(A) = C_{11}(A) + C_{12}(A) + C_{13}(A) + Q(A), \tag{8}$$

where C_{11} (A) is the total cost of all EP sensors, C_{12} (A) is the cost of the PLC subsystem, C_{13} (A) is the total cost of all EP actuators, Q (A) is the total cost of the EP design and commissioning. In particular:

$$C_{11}(A) = \sum_{j=1}^{n} \sum_{s=1}^{m(j)} a(\xi^{(1)}_{j,s}) \cdot N^{(1)}_{j,s} \text{ ,} \tag{9}$$

where $a(\xi^{(1)}_{j,s})$ is the value of one sensor of the (j, s)-channel, $N^{(1)}_{j,s}$ is the number of sensors in the first subsystem of (j, s)-channel;

$$C_{12}(A) = b(M^{(2)}ooN^{(2)}, \xi^{(2)}), \tag{10}$$

where $b(M^{(2)}ooN^{(2)},\xi^{(2)})$ is the cost of PLC with the architecture $M^{(2)}ooN^{(2)}$ and the characteristic $\xi^{(2)} = (\lambda^{(2)}, \alpha^{(2)}, \beta^{(2)})$;

$$C_{13}(A) = \sum_{j=1}^{n} d(\xi^{(3)}_{j}) \cdot N^{(3)}_{j} \text{ ,} \tag{11}$$

where $d(\xi^{(3)}_{j})$ is the cost of one actuator in the third subsystem of (j, s)-channel, $N^{(3)}_{j}$ is the number of actuators.

Note that the costs of $a(\xi^{(1)}_{j,s})$, $b(M^{(2)}ooN^{(2)}, \xi^{(2)})$, $d(\xi^{(3)}_{j})$ strongly depend on the reliability parameters and the level of self-diagnostics, which may be different for various manufacturers.

3. C_2 (A) are the annual operating costs of EP. The basic cost of field operations is due to carrying out EP availability control checks, which are held at intervals τ, where τ is the time interval, usually a multiple of one month. In this case, control checks are usually carried out by a specialized engineering organization. The annual cost of these control checks depends on the amount of work and the frequency of their implementation. This value C_2 (A) may be defined by the following expression:

$$C_2(A) = \left(w_2(M^{(2)}ooN^{(2)}) + \sum_{j=1}^{n} \left[w(M^{(3)}_{j}ooN^{(3)}_{j}) + \sum_{s=1}^{m(j)} w(M^{(1)}_{j,s}ooN^{(1)}_{j,s}) \right] \right) \cdot \frac{12}{\tau} \text{ ,} \tag{12}$$

wherein $w_v(M^{(v)}_{j,s}ooN^{(v)}_{j,s})$ is the cost of one check of the *v*-th subsystem with the architecture $(M^{(v)}_{j,s}ooN^{(v)}_{j,s})$, v=1,2,3; τ is the interval calculated in months, $12\cdot\tau^{-1}$ is the number of control checks per year.

4. C_3 (A, T) is the expected damage from accidents at the time interval [0, T], which, in view of inequality (2), can be estimated as follows:

$$C_1(A) = \sum_{j=1}^{n} Y_j \cdot \sum_{s=1}^{m(j)} F_p(A_{j,s}, \tau) \cdot T, \tag{13}$$

where Y_j is the average damage due to one accident on the *j*-th TO, $F_p(A_{j,S}, \tau) \cdot T$ is the average number of "not worked-out" incidents by (j, s)-channel at the time interval [0; T]. Note that the value Y_j of the average cost of an accident on each technological object is calculated according to standard methods; see for example [6]. Also note that the relation (13) is a consequence of the fact that PLC as a part of EP operates in real time mode, i.e. the time required for detection and response of (j,s)-channel to an incident is less than the time before occurrence of hazardous consequence (accident) [1].

Before stating the problem of finding acceptable values F_t (j, s) and correspondingly risk reduction factors RRF_t (j,s), j = 1, ..., n, s = 1, ..., m (j), we shall indicate that for any fixed aggregate A there is an algorithm G [1] for computing the values $F_p(A_{j,s}, \tau)$, i.e. $F_p(A_{j,s}, \tau) = G(A_{j,s}, \tau, \omega)$, where $A_{j,s}$ of G Fp (Aj, s, τ), i.e. Fp (Aj, s, τ) = G (Aj, s, τ, ω), where Aj, is the component of the aggregate A, ω is a set of indices that affect the value $F_p(A_{j,s})$ and the set is estimated by constants. These indices can be:

1) the time limit for recovery of CAM failed elements, including EP,

2) the rate F_{np} (j) of incident occurrence on the *j*-th TO etc. For example, in JSC Gazprom the limit recovery time should not exceed 4 hours; $F_{np}(j) \leq 1$ [1/year], j = 1, ..., n. In these circumstances, the task of finding acceptable rates F_t (j, s) and, accordingly, risk reduction factors RRF_t(j, s), minimizing the cost C (A,T), can be summarized as follows:

one shall find such values $F_t(j,s) = G(A^t_{j,s}, \omega)$ and $RRT_t(j,s) = F_{np}(j,s) \cdot F_t^{-1}(j,s)$, j = 1,…,n, s = 1,..., m (j), for which the following equation holds true:

$$C_э(A^t,T) = \min\{C_э(A,T) \mid A\in \Xi\}, \tag{14}$$

where $C_э(A,T) = C(A,T) \cdot T^{-1}$ is the annual cost for EP system development and operation and elimination of accidents during T years of EP operation, is a set possible aggregates of A type.

In particular, in applied calculations the set Ξ can be represented as a finite set of the following form:

$$\Xi = \{A = \{ [(A^{(1)}_{j,s}\ A_{j,s}^{(2)}\ A^{(3)}_{j,s}),\ j = 1,\ldots,n,\ s = 1,\ldots,m(j)],\ \tau\} \mid A^{(v)}_{j,s}\in \Xi^{(v)}_{j,s},$$

$$v = 1, 2, 3,\ \tau \in \Theta \}, \tag{15}$$

where $A^{(v)}_{j,s} = [\,(M^{(v)}_{j,s}ooN^{(v)}_{j,s}),\ \xi^{(v)}_{j,s}\,]$, $\xi^{(v)}_{j,s} = (\,\lambda^{(v)}_{j,s}, \alpha^{(v)}_{j,s}, \beta^{(v)}_{j,s})$;

$$\Xi^{(v)}_{j,s} = \{\ A^{(v)}_{j,s} \mid M^{(v)}_{j,s} = 1,\ldots, k_1,\ N^{(v)}_{j,s} = 1,\ldots, k_2,\ k_1 \leq k_2,$$

$$\xi^{(v)}_{j,s} = \xi^{(v)}_{j,s}(1), .., \xi^{(v)}_{j,s}(r^{(v)}_{j,s})\ \}, \tag{16}$$

where k_1, k_2 are integers defining a set of architectures used for all subsystems of each channel of EP, $r^{(v)}_{j,s}$ is the number of different types of technology that can be used by designers for construction of the *v*-th subsystem of EP (j, s) –channel, Θ = {1, ..., 12} [months] or {3, 6, 9, 12} [months].

The problem (14) for the set Ξ can be solved on PC by the method of exhaustion.

An example of calculation of acceptable safety performance

Let us consider a part of the process of the absorption dehydration of associated petroleum gas, which is implemented on two processing units: an absorber and a degasser. "Critical" parameters of these units have the critical areas listed in Table 1. It is assumed that the units will be maintained by a multi-channel EP system over a period of T = 10 years.

Table 1. The list of processing units and their critical areas

J	Technological units	s	Critical areas of parameters
1	Absorber unit (column)	1	Gas pressure loss ДP=0.02 [MPa]
		2	Liquid level (lower) L_L=300 [mm]
		3	Liquid level (upper) L_H=800 [mm]
2	Degasser unit	1	TEG level (lower) L_L=300 [mm]
		2	TEG level (upper) L_H=750 [mm]

The average damage due to accidents: 1) for the absorber unit amounts to Y_1 = 3000 thousand rubles, 2) for the degassing unit amounts to Y2 = 1800 thousand rubles.

EP will have the structural schematic shown in Fig. 1 where n = 2, m (1) = 3, m (2) = 2, m = 3 + 2 = 5. Each set $\Xi^{(v)}_{j,s}$ defined for the *v*-th subsystem of EP (j, s)-channel where v = 1, 2, 3, j = 1,2, s = 1, ..., m (j) is defined by the following parameters:

$k_1 = 2$, $k_2 = 3$, $\xi^{(1)}_{1,1}(1) = (8.3\cdot10^{-6}$ [1/h], 0.6, 0.1),
$\xi^{(1)}_{1,1}(2) = (6.7\cdot10^{-6}$ [1/h], 0.7, 0.1), $\xi^{(1)}_{1,2}(1) = \xi^{(1)}_{1,3}(1) = \xi^{(1)}_{2,1}(1) = \xi^{(1)}_{2,2}(1) = (10^{-5}$ [1/h], 0.7, 0.1),
$\xi^{(1)}_{1,2}(2) = \xi^{(1)}_{1,3}(2) = \xi^{(1)}_{2,1}(2) = \xi^{(1)}_{2,2}(2) = (1.25\cdot10^{-5}$ [1/h], 0.6, 0.1),
$\xi^{(1)}_{1,2}(3) = \xi^{(1)}_{1,3}(3) = \xi^{(1)}_{2,1}(3) = \xi^{(1)}_{2,2}(3) = (10^{-5}$ [1/h], 0.4, 0.1),
$\xi^{(2)}(1) = (2\cdot10^{-6}$ [1/ч], 0.8, 0.05), $\xi^{(2)}(2) = (2.5\cdot10^{-6}$ [1/h], 0.8, 0.05),
$\xi^{(3)}_1(1) = \xi^{(3)}_2(1) = (1.42\cdot10^{-5}$ [1/h], 0.15, 0.1),
$\xi^{(3)}_1(2) = \xi^{(3)}_2(2) = (1.1\cdot10^{-5}$ [1/h], 0.2, 0.1), $\xi^{(3)}_1(3) = \xi^{(3)}_2(3) = (8.3\cdot10^{-6}$ [1/h], 0.1, 0.1).

Cost quantities used in the formation of functional (3) have the following values:
$\xi^{(1)}_{1,1}(1)$ = 17 thousand rubles, $a(\xi^{(1)}_{1,1}(1))$ = 20 thousand rubles,
$a(\xi^{(1)}_{1,2}(1)) = a(\xi^{(1)}_{1,3}(1)) = a(\xi^{(1)}_{2,1}(1)) = a(\xi^{(1)}_{2,2}(1))$ = 37.5 thousand rubles,
$a(\xi^{(1)}_{1,2}(2)) = a(\xi^{(1)}_{1,3}(2)) = a(\xi^{(1)}_{2,1}(2)) = a(\xi^{(1)}_{2,2}(2))$ = 24.6 thousand rubles,
$a(\xi^{(1)}_{1,2}(3)) = a(\xi^{(1)}_{1,3}(3)) = a(\xi^{(1)}_{2,1}(3)) = a(\xi^{(1)}_{2,2}(3))$ = 24 thousand rubles,
$b(\xi^{(2)}(1))$ = 96 thousand rubles, $b(\xi^{(2)}(2))$ = 90 thousand rubles, $b(M^{(2)}ooN^{(2)}, \xi^{(2)}) = b(\xi^{(2)}) \cdot N^{(2)}$,
$d(\xi^{(3)}_1(1)) = d(\xi^{(3)}_2(1))$ = 24 thousand rubles, $d(\xi^{(3)}_1(2))=d(\xi^{(3)}_2(2))$ = 33 thousand rubles,
$d(\xi^{(3)}_1(3)) = d(\xi^{(3)}_2(3))$ = 30 thousand rubles.

The set $\Theta = \{3, 6, 9, 12\}$ [months.], $\omega = \{ F_{np}(1,1) = F_{np}(1,2) = F_{np}(1,3) = 1/3$ [1/ year] $F_{np}(2,1) = F_{np}(2,2) = 1/2$ [1/year], MTTR = 4 [h]}, where MTTR is mean time to recovery of any EP subsystem.

The cost of each subsystem control check: $w_1(M^{(1)}_{j,s}ooN^{(1)}_{j,s}) = w \cdot N^{(1)}_{j,s}$, $w_2(M^{(2)}ooN^{(2)}) = w \cdot N^{(2)}$, $w_3(M^{(3)}_j ooN^{(3)}_j) = w \cdot N^{(3)}_j$, where w = 1 thousand rubles.

The calculation gives the following solution of the problem (14):

$A^t = \{[A^{(1)}_{j,s}\ A^{(2)}\ A^{(3)}_j$, j = 1,2, s(1) = 1,2,3, s(2) = 1,2], $\tau\}$, $\tau = 9$ [months],

$A^{(1)}_{1,1} = [(1oo2), \xi^{(1)}_{1,1}], \xi^{(1)}_{1,1} = (8.3\cdot10^{-6}$ [1/h], 0.6, 0.1),

$A^{(1)}_{1,2} = [(1oo2), \xi^{(1)}_{1,2}], \xi^{(1)}_{1,2} = (10^{-5}$ [1/h], 0.4, 0.1),

$A^{(1)}_{1,3} = [(1oo2), \xi^{(1)}_{1,3}], \xi^{(1)}_{1,3} = (10^{-5}$ [1/h], 0.4, 0.1),

$A^{(1)}_{2,1} = [(1oo2), \xi^{(1)}_{2,1}], \xi^{(1)}_{2,1} = (10^{-5}$ [1/h], 0.4, 0.1),

$A^{(1)}_{2,2} = [(1oo2), \xi^{(1)}_{2,2}], \xi^{(1)}_{2,2} = (10^{-5}$ [1/h], 0.4, 0.1),

$A^{(2)} = [(1oo1), \xi^{(2)}], \xi^{(2)} = (2\cdot10^{-6}$ [1/h], 0.8, 0.05),

$A^{(3)}_1 = [(1oo2), \xi^{(3)}_1], \xi^{(3)}_1 = (8.3\cdot10^{-6}$ [1/h], 0.1, 0.1),

$A^{(3)}_2 = [(1oo2), \xi^{(3)}_2], \xi^{(3)}_2 = (8.3\cdot10^{-6}$ [1/h], 0.1, 0.1).

In this case, the stream of "not worked-out" incidents per EP channel has the following rates:

$F_t(1,1) = 9 \cdot 10^{-4}$ [1/year];

$F_t(1,2) = F_t(1,3) = 10^{-3}$ [1/year];

$F_t(2,1) = F_t(2,2) = 1.5 \cdot 10^{-3}$ [1/year].

EP channels have the following risk reduction factors:

$RRF_t(1,1) = 390$;

$RRF_t(1,2) = 332$;

$RRF_t(1,3) = 332$;

$RRF_t(2,1) = 332$;

$RRF_t(2,2) = 332$.

Costs **$C_э(A^t, T) = 72.7$) = 72.7 thousand rubles / year.**

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