Reliability assessment of automatic process control systems for the production of concentrates of MD1 and MD2 nanostructures in terms of providing thermal vortex enrichment

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Abstract. As part of the project to create a comprehensive resource-saving technology for the associated production of nanostructure concentrates, the reliability of the software package "Automated control system for the technological process of obtaining MD1 and MD2 nanostructure concentrates" was evaluated in terms of providing thermal vortex enrichment. The calculation of the reliability of the system was performed to assess the level of reliability and quantitatively determine the reliability indicators for the implementation of the functions of ACS TO 2.12. The object to be calculated was identified, the goals and objectives of the calculation at this stage, the nomenclature and the required values of the calculated reliability indicators were determined, the calculation method was selected that is adequate to the features of the object, the goals of the calculation, the availability of the necessary information about the object and the source data for the calculation. The initial data for the calculation were obtained and pre-processed; the values of the reliability indicators of the object were calculated. From a comparison of the calculation results with the reference values of the integral safety level (SIL) in accordance with IEC 61508, it follows that the maximum safety level of the ACS TO 2.12 SIL 2, the system availability is 98.97%, and the system uptime is 2 years. The probability of a dangerous failure of the PAZ system is $1.31 \times 10^{-4}$, which corresponds to a high value of the integral safety level (SIL 4).

1. Introduction

As part of a series of works on the processing of aluminium and silicon waste [1-7], including of the project to create a comprehensive resource-saving technology for the associated production of nanostructure concentrates [8-13], the reliability of the software package "Automated control system for the technological process of obtaining MD1 and MD2 nanostructure concentrates" was evaluated in terms of providing thermal vortex enrichment.

The design reliability assessment of the system was made on the basis of and taking into account the requirements of RD 50-34.698-90, GOST 27.301-95, GOST 24.701-86, IEC 61508.

According to paragraph 1.2 of RD 50-34.698-90 it is allowed including additional sections and information in the document, to combine and exclude sections.

According to clause 3.1 of GOST 27.301-95, reliability calculation is a procedure for determining the values of object reliability indicators using methods based on their calculation from reference data on the reliability of object elements, according to data on the reliability of objects - analogues, data on properties materials and other information available at the time of calculation [14-17].
2. Purpose and composition of the calculation of system reliability

The calculation of the reliability of the system was performed to assess the level of reliability and quantitatively determine the reliability indicators for the implementation of the functions of ACS TO 2.12.

According to paragraph 1.4 of GOST 24.701-86, the reliability level of industrial control systems depends on the reliability and other properties of its technical support (a set of technical means), software and personnel involved in its operation. In connection with the implementation at the automation facility of measures to protect software from infection with software viruses, measures to protect software and hardware of ACS TO 2.12 from unauthorized access and measures to protect against unauthorized or incorrect actions (errors) of users, a design assessment of the reliability of the system made only taking into account the reliability of the complex of technical means.

According to paragraph 4.3.2 of GOST 27.301-95, the calculation of reliability at any stage of the types of work includes:

- identification of the object to be calculated;
- determination of the goals and objectives of the calculation at this stage, the nomenclature and the required values of the calculated reliability indicators;
- the choice of a calculation method that is adequate to the features of the object, the purposes of the calculation, the availability of the necessary information about the object and the source data for the calculation;
- obtaining and pre-processing the initial data for calculation, calculating the values of the reliability indicators of the object and, if necessary, comparing them with the required ones.

Object identification was carried out according to the main classification attributes (Clause 3.3 of GOST 27.003-90). According to paragraph 3.3 of GOST 27.003-90, the main features by which the products are divided when setting requirements for reliability are:

- certainty of the purpose of the product;
- the number of possible (taken into account) the state of the product for performance during operation;
- mode of application (functioning);
- the possible consequences of failures and (or) reaching the limit state during application and (or) the consequences of failures during storage and transportation;
- the ability to restore working condition after failure;
- the nature of the main processes that determine the transition of the product to the ultimate state;
- the possibility and method of restoring the technical resource (service life);
- the possibility and need for maintenance;
- the possibility and need for control before use;
- the presence in the composition of products of computer technology.

By definiteness of destination, the ACS TO 2.12 is a product for a specific purpose, having one main application for the intended purpose - for work at the facilities of RUSAL ITC LLC.

According to the number of possible (taken into account) the states of the products according to their working capacity during operation, the ACS TO 2.12 refers to products of type I, which during operation can be in two states - working or non-working.

According to the application regime, ACS TO 2.12 refers to products of continuous long-term use.

According to possible consequences, ACS TO 2.12 refers to products whose failures or transition to the ultimate state do not lead to catastrophic (critical) consequences (without threatening human life and health, insignificant or "moderate" economic losses, etc.)

If possible, the restoration of a working state after a failure, the technical equipment that is part of the ACS TO 2.12 are recoverable (repaired), single-functional products. ACS TO 2.12 refers to the restored (repaired), multifunctional products. By the nature of the main processes that determine the transition of the product to the limiting state, ACS TO 2.12 refers to aging and worn out products at the same time.
If possible, and the method of restoring the technical resource (service life), ACS TO 2.12 refers to products repaired in not impersonal way (a repair method in which the restored components belong to a specific product instance).

Whenever possible and necessary for maintenance during operation, the ACS TO 2.12 is a serviced product for which periodic maintenance is provided.

ACS TO 2.12, by possible (necessary) of conducting control before use, refers to products that are not controlled before use. To ensure high reliability of the ACS 2.12 as the system as a whole and its individual components (subsystems, modules) and also to prevent the occurrence of the emergency operations support staff, technical and software subsystems shall be performed requirements of diagnostic of the work of APCS.

Diagnostics is carried out by personnel providing maintenance and operation of ACS TO 2.12 tools, in accordance with the organization's regulations for scheduled preventive maintenance and repair work (PPR), as well as automatically built-in technical diagnostic tools. ACS TO 2.12, includes software for monitoring the state of technical means, diagnostics and testing for detecting and localizing technical equipment malfunctions in the normal mode of operation (without disruption) with the ability to display the state of technical means and provides:

a) performance check and failure detection of technical means;
b) t search roubles with depth to a single element or group of replacement elements;
c) signaling of a failure and the results of health checks;
d) automated (automatic) monitoring of the functioning of hardware and software of industrial control systems at all levels of the hierarchy with fixation in event logs (audit logs), including:

1) means of monitoring the operability of communication channels with technical means initiating information exchange, registration of "inaccessible" devices;
2) checking the incoming information for compliance with the format and range of acceptable values;
3) monitoring the functioning of all subsystems and services;
4) notification of operational and operational personnel in case of failures of a bad nature (failures).

Due to the presence of computer equipment in the ACS MOT 2.12, it refers to products with failures of a bad nature (failures).

The goals of calculating reliability are established by clause 4.2 of GOST 27.301-95. The destination of calculating the reliability of the system is indicated above.

The list of evaluated reliability indicators (in accordance with GOST 24.701-86) includes:

- the average operating time of the system to refuse to perform the i-th function (average time to failure of the i-th AF ACS) - MTTF;
- the average recovery time of the ability of the system to perform the i-th function after failure (average recovery time of the i-th AF ACS) - MTTR;
- the probability of failure of the system to perform the i-th function (the probability of failure-free operation of the i-th AF ACS) for a given time P_i;
- the failure rate of the system in the implementation of the i-th function (failure rate of the i-th AF ACS) \( \lambda_i \);
- the coefficient of readiness of the system to fulfill the i-th function (readiness coefficient of the i-th FP ACS) – KG.

According to clause 4.5.1 of GOST 27.301-95, reliability calculation methods are divided into:

- the composition of the calculated reliability indicators (PN);
- according to the basic principles of calculation.

According to clause 4.5.2 of GOST 27.301-95, the methods of calculation differ in the composition of the calculated indicators:

- reliability
- maintainability,
- durability
- persistence,
- comprehensive indicators of reliability.
According to clause 4.5.3 of GOST 27.301-95, according to the basic principles of calculating properties that make up reliability, or complex reliability indicators of objects, they distinguish:

- forecasting methods,
- structural calculation methods,
- physical calculation methods.

Based on the above requirements, in accordance with clauses 4.5.1 - 4.5.3 of GOST 27.301-95, the following methods for calculating the reliability of ACS TO 2.12 are applied:

- methodology for the composition of calculated reliability indicators;
- method of complex indicators of reliability;
- structural calculation method.

The calculation procedure contains:

- information about the object, ensuring its identification for calculating reliability;
- nomenclature of calculated payloads;
- initial data for calculation and sources of their receipt.

3. Composition of factors taken into account in the calculation, accepted assumptions and limitations

According to paragraph 1.5 of GOST 24.701-86, the reliability level of ACS TO 2.12 depends on the main factors listed below:

a) the composition and level of reliability of the used technical means, their interconnection in the structure of the reliability of the complex of technical means (CTM);

b) the composition and level of reliability of the software used, their content (capabilities) and the relationship in the structure of software (software);

c) the level of personnel qualification, organization of work and the level of personnel reliability;

d) the rationality of the distribution of tasks solved by ACS TO 2.12 between the CTM, software and personnel;

e) modes, parameters and organizational forms of technical operation of the CTM;

f) the degree of use of various types of redundancy (structural, informational, temporary, algorithmic, functional);

g) the degree of use of methods and means of technical diagnostics;

h) the real operating conditions of ACS TO 2.12.

Assumptions and Limitations

The properties of informational, mathematical, linguistic, metrological, organizational and other types of software affect the reliability of process control systems indirectly, through the functioning of hardware and software and personnel, therefore, when solving issues related to the reliability of process control system, they do not separately take into account are.

As indicators of the reliability of the ACS TO 2.12 software, the intensity of program restarts (reboots) and their duration should be used. The values of the intensity and duration of restarts (reboots) of the software should be estimated based on the results of monitoring the operation of ACS TO 2.12 during trial operation. To increase reliability, it is recommended to reserve individual components of ACS TO 2.12 and use redundant information.

The terms of reference and design solutions for ACS TO 2.12 provide requirements for the number, qualifications and training of personnel. In this regard, the factor affecting the level of reliability - listing c) a list of the main factors of the level of reliability - can be excluded from the calculation.

The factor affecting the level of reliability - listing d) of the list of the main factors of the level of reliability - can be excluded from the calculation due to the high degree of automation and functional completeness of ACS TO 2.12.

A factor affecting the level of reliability - listing e) a list of the main factors of the level of reliability - can be excluded from the calculation due to the sufficient requirements for the modes, parameters and organizational forms of technical operation of the KTS ACS TO 2.12 presented in the terms of reference.
Factors affecting the level of reliability - lists e), g) and h) of the list of the main factors of the level of reliability - can be excluded from the calculation due to the many tools and methods used in the ACS TO 2.12 for diagnostics and backup of all types of support, as well as channels communication, channel-forming equipment and power supply of technical equipment.

ACS TO 2.12 includes the following redundant hardware:
- redundant communication channels and channel-forming equipment;
- redundant power supplies;
- redundant server hard drives;
- uninterrupted power supply of technical equipment.

Redundancy ensures the reliability of ACS TO 2.12 in emergency situations:
- in the inoperative state of technical equipment;
- when the communication channels are inoperative;
- when the channel-forming equipment is inoperative;
- during short-term power outages (no more than 0.5 hours) and voltage deviations from the nominal no more than ± 20% in the power circuits of technical means;
- during power outages (for a period of more than 0.5 hours).

In case of emergency in the ACS TO 2.12 provides:
- a) the integrity and correctness of the information;
- b) the implementation of the procedure for restoring the required amount of information for all levels of the hierarchy of industrial control systems after power is restored.

When calculating reliability, the following assumptions and limitations are made:
- when calculating the reliability indicators of structural elements of the automatic process control system, the exponential law of the distribution of uptime is used;
- architecture of measuring transducers and actuators 1001; flame control sensor and PLC modules - 1002;
- the average recovery time of the ability of the system to perform the i-th function after failure (average recovery time of the i-th AF ACS) - MTTR is 8 hours;
- the average probability of a dangerous failure (probability of failure to perform the protection function by the system) $R(t)$ is calculated taking into account failures of the actuator type failure and false operation;
- when implementing the protection function, the proportion of dangerous failures such as malfunctioning and false operation of actuators is 2% and 1%, respectively;
- the inter-testing interval for measuring transducers and execution devices was adopted for 3 years;
- reliability calculations are performed according to the functions of measurement, regulation and protection for the entire safety circuit - from the sensor to the actuator;
- project assessment of the integral safety level (SIL) is carried out for each safety circuit and for the system as a whole.
- a design estimate of the system reliability was performed for the system operation interval (T1) - 1 year.

4. Initial data

According to paragraph 4.6.1 GOST 27.301-95 sources of source data for calculating the reliability of the object can be:
- standards and specifications for the constituent parts of the facility, the components used in it for inter-industry use, substances and materials;
- Guides on the reliability of elements, the properties of substances and materials, the standards for the duration (labor, cost) of standard maintenance and repair operations and other information materials;
- statistical data (data banks) on the reliability of analogous facilities included in their composition of elements, the properties of substances and materials used in them, on the
parameters of maintenance and repair operations collected in the process of their development, manufacture, testing and operation;

- the results of strength, electrical, thermal and other calculations of the object and its components, including the calculation of reliability indicators of the component parts of the object.

In the table 1 shows the passport and reference reliability indicators of measuring transducers and actuators, taken into account when calculating the reliability of the system.

| No | Device type | SIL | $\lambda_i$, h$^{-1}$ | MTTF, h | $P_i$ | $kg$ |
|----|-------------|-----|----------------------|--------|-------|------|
| 1  | Measuring transducer temperature Metran - 2700 (Sensor) | 1   | 1.6·10$^{-4}$ | 6000   | 0.248 | 0.9986 |
| 2  | Pressure transducer Rosemount 3051S (Sensor) | 2   | 0.5·10$^{-6}$ | 150000 | 0.957 | 0.99994 |
| 3  | Pressure transducer Metran55 (Sensor) | 2   | 0.5·10$^{-6}$ | 150000 | 0.957 | 0.99994 |
| 4  | Flow converter Rosemount 8800 (Sensor) | 2   | 0.5·10$^{-6}$ | 100000 | 0.957 | 0.99992 |
| 5  | Flow converter Schmidt Flow Sensors SS (Sensor) | 2   | 0.65·10$^{-6}$ | 100000 | 0.994 | 0.99992 |
| 6  | Level switch Vegawave 61 (Sensor) | 2   | 0.6·10$^{-6}$ | 40000  | 0.994 | 0.99980 |
| 7  | Flow detector Flow Jaw (Sensor) | 1   | 1.6·10$^{-4}$ | 10000  | 0.248 | 0.99992 |
| 8  | Frequency converter Micromaster 420 (Sensor) | 2   | 0.4·10$^{-6}$ | 50000  | 0.996 | 0.99984 |
| 9  | Drive MEO (Actuator) (Sensor) | 1   | 0.15·10$^{-5}$ | 80000  | 0.987 | 0.99990 |
| 10 | Current Position Alarm Sensor | 1   | 0.65·10$^{-5}$ | 100000 | 0.945 | 0.99992 |
| 11 | Flame detector | 1   | 6.66·10$^{-5}$ | 18000  | 0.943 | 0.99955 |

Table 2 shows passport and reference indicators of reliability of elements and modules of a programmable logic controller, taken into account when calculating the reliability of the system.

| No | PLC module | SIL | $\lambda_i$, h$^{-1}$ | MTTF, h | $P_i$ | $kg$ |
|----|------------|-----|----------------------|--------|-------|------|
| 1  | CPU 1214C (CPU) | 3   | 3078·10$^{-9}$ | 236520 | 0.9735 | 0.999966 |
| 2  | SM 1221 (DI) | 3   | 1600·10$^{-9}$ | 625000 | 0.9861 | 0.999987 |
| 3  | SM 1222 (DO) | 3   | 4400·10$^{-9}$ | 227273 | 0.9624 | 0.999965 |
| 4  | SM 1231 (AI) | 3   | 3000·10$^{-9}$ | 333333 | 0.9742 | 0.999976 |
| 5  | Communication processor (CP) | 3   | 2400·10$^{-9}$ | 416667 | 0.9793 | 0.999981 |
| 6  | Power machine (SF) | 3   | 300·10$^{-9}$ | 333333 | 0.9973 | 0.999997 |
| 7  | Power Supply (PS) | 3   | 7407·10$^{-9}$ | 135000 | 0.9375 | 0.999941 |
| 8  | Uninterruptable power source (UPS) | 3   | 237·10$^{-9}$ | 4211412 | 0.9979 | 0.999988 |
| 9  | Operator station (APM) | 3   | 999·10$^{-9}$ | 33333 | 0.9913 | 0.9928514 |

Elements of ACS TO 2.12 ensure their operation in the following modes:

a) normal mode (automatic, manual);

b) emergency mode (emergency).

Elements of ACS TO 2.12 operate in climatic conditions of 4 categories according to GOST 15150-69.
Information about the typical operation model of ACS TO 2.12 is set out in the relevant sections of the documents:

- Explanatory note;
- Description of the complex of technical means;
- Description of the organizational structure.

5. Methodology and calculation of reliability indicators

Methods for calculating the reliability of ACS TO 2.12 are defined above.

According to clause 4.7.1 of GOST 27.301-95, the adequacy of the selected calculation method and constructed calculation models for the goals and objectives of calculating the reliability of an object is characterized by:

- the full use in the calculation of all available information about the object, the conditions for its operation, the maintenance and repair system, the reliability characteristics of the components, the properties of the substances and materials used in the object;
- the validity of the assumptions and supposition adopted during the construction of models, their influence on the accuracy and reliability of estimates of PN;
- the degree of correspondence of the level of complexity and accuracy of the calculated models of the object reliability to the available accuracy of the initial data for calculation.

Based on the above requirements, the selected calculation method should be considered reasonable (adequate).

Regulatory and technical document according to which the calculation is carried out is GOST 27.301-95 Reliability in technology. Reliability calculation. The main provisions.

A brief description of the calculation method

In accordance with the composition of the reliability calculation, the following reliability indicators are subject to calculation: failure rate $\lambda(t)$ probability of failure-free operation for a given time interval $p(t)$, availability factor $K_g(t)$. The calculation of these reliability indicators was carried out for the structural elements of ACS TO 2.12 and the functions performed by it. When assessing the functional reliability of ACS TO 2.12, structural calculation methods are used, based on the representation of the object in the form of a logical (structural-functional) diagram describing the dependence of the states and transitions of the object on the states and transitions of its elements, taking into account their interaction and the functions performed by them in the object with subsequent descriptions of the constructed structural model with an adequate mathematical model and calculation of the object's PN from the known reliability characteristics of its elements. Structural methods are the main methods for calculating the indicators of failure-free, maintainability and complex PM in the process of designing objects that can be disaggregated into elements whose reliability characteristics at the time of the calculation are known or can be determined by other methods (forecasting, physical, according to statistical data, collected during their use under similar conditions) (paragraph 2.1 of GOST 27.301-95).

For systems with a series connection of elements, the probability of failure-free operation is equal to:

$$P(t) = \prod_{i=1}^{n} p_i$$ (1)

with the exponential law of the distribution of FBG elements:

$$P(t) = e^{-\lambda t}$$ (2)

with this law, the mean time between failures of the system is:

$$T = \frac{1}{\lambda} = \left(\sum_{i=1}^{n} \lambda_i\right)^{-1} = \left(\sum_{i=1}^{n} \frac{1}{T_i}\right)^{-1}$$ (3)

For systems with redundancy (parallel connection of elements):
\[
P(t) = 1 - \Pi_{i=1}^{n} (1 - P_i)
\]  

For an unloaded reserve in the case of an exponential distribution at $\lambda_1 \neq \lambda_2$, the probability of failure-free operation is:

\[
P(t) = e^{-\lambda_1 t} + \frac{\lambda_1}{\lambda_2 - \lambda_1} \left( e^{-\lambda_1 t} - e^{-\lambda_2 t} \right),
\]

\[
MTTF = \frac{\lambda_1 + \lambda_2}{\lambda_1 \lambda_2}.
\]

With $\lambda_1 = \lambda_2$, the probability of failure-free operation:

\[
P(t) = e^{-\lambda t} (1 - \lambda t),
\]

\[
MTTF = \frac{n}{\lambda}.
\]

The average probability of a dangerous failure $R(t)$ when performing the protection function:

\[
R(t) = \lambda_D \cdot t_{CE} = \left( \frac{\lambda_{DD}}{\lambda_D} + \frac{\lambda_{DU}}{\lambda_D} \right) \cdot t_{CE}
\]

\[
t_{CE} = \frac{\lambda_{DU}}{\lambda_D} \left( \frac{T}{2} + MTTR \right) + \frac{\lambda_{DD}}{\lambda_D} \cdot MTTR
\]

where: $\lambda_{DU}$ is the intensity of dangerous failures; $\lambda_{DD}$ is the false alarm rate of failure.

In accordance with clause 3.3.2 of GOST 27.003-90 for products having a channel construction principle (communication systems, information processing, etc.), the requirements for reliability and maintainability can be set per one channel or per channel with channels that are not equal in efficiency.

The reliability calculation of ACS TO 2.12 by measurement functions was made for one channel for measuring temperature, pressure, flow, level (in accordance with the initial data of table 1). Structural-functional schemes for calculating the reliability of the measurement channel are presented in figure 1 and 2. Designations of circuit elements are given in table 1-2.

Figure 1. Structural-functional diagram for calculating the reliability of the channels for measuring temperature, pressure, flow, signaling the position of the actuator, the frequency of the drive.

Figure 2. Structural-functional diagram for calculating the reliability of the channels for measuring the level, signaling the flame on the burner.
A generalized structural and functional diagram of calculating reliability for temperature, flow, pressure and protection channels for controlling the gas supply to the burner is shown in figure 3. Designations of circuit elements are given in table 1 and 2.

The calculations are performed according to the expressions 1-10 above. The results of calculating the functional reliability of ACS TO 2.12 are shown in table 3.

![Figure 3. Structural - functional diagram for calculating the reliability of the emergency protection channel, the channels of temperature, flow, pressure.](image)

| Function Name                               | SIL | MTTF, h | λf, h⁻¹ | kg   |
|---------------------------------------------|-----|---------|---------|------|
| 1 Temperature measurement channel           | 1   | 5132    | 1.98·10⁻⁴ | 0.9981 |
| 2 Pressure measurement channel              | 2   | 28293   | 3.534·10⁻⁵ | 0.9997 |
| 3 Channel for measuring gas, air flow       | 2   | 28293   | 3.534·10⁻⁵ | 0.9997 |
| 4 Channel for measuring the flow of raw materials | 2   | 28173   | 3.549·10⁻⁵ | 0.9997 |
| 5 Level measurement channel                 | 2   | 26285   | 3.8·10⁻⁵  | 0.9996 |
| 6 Actuator position signaling channel       | 2   | 24187   | 4.1·10⁻⁵  | 0.9996 |
| 7 Channel for measuring the frequency of operation at water | 2   | 28373   | 3.524·10⁻⁵ | 0.9997 |
| 8 Flame alarm channel                       | 2   | 10137   | 9.8·10⁻⁵  | 0.9992 |
| 9 Temperature control channel               | 1   | 4874    | 2.05·10⁻⁴ | 0.9963 |
| 10 Pressure control channel                 | 2   | 21929   | 4.56·10⁻⁵ | 0.9996 |
| 11 Channel for regulating the flow of raw materials | 2   | 27859   | 3.589·10⁻⁵ | 0.9997 |
| 12 Level control channel                    | 2   | 25316   | 3.95·10⁻⁵ | 0.9996 |
| 13 PAZ system                               | 2   | 10050   | 9.9·10⁻⁵  | 0.9992 |
| 14 ACS TO 2.12                              | 2   | 17566   | 5.69·10⁻⁵ | 0.9897 |

6. Conclusion

From a comparison of the calculation results (table 3) with the reference values of the integral safety level (SIL) in accordance with IEC 61508, it follows that the maximum safety level of ACS TO 2.12 SIL 2, the system availability is 98.97%, and the system uptime is 2 years. The probability of a dangerous failure of the PAZ system is 1.31·10⁻⁴, which corresponds to a high value of the integral safety level (SIL 4).

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