UDC 510.635.8 : 681.51
DOI: https://doi.org/1034169/2414-0651.2025.1(45).97-103

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FORMATION OF POSSIBLE SCENARIOS FOR THE DEVELOPMENT OF ABNORMAL SITUATIONS DURING TESTS OF CONTROLLED MEANS OF DESTRUCTION

The article presents a methodological approach to the formation and development of possible scenarios for the development of emergency situations during the testing of guided weapons by describing their structure and functioning based on logical-probabilistic theory. In this case, the structure of the object under study is described by a function of the algebra of logic, and the quantitative assessment of the operational state is described by a probabilistic function, which allowed the application of the basic theorems of probability theory.

Possible scenarios for the development of emergency situations when using guided weapons were considered provided that their occurrence is due to the failure of one or more components or a violation of the connections between them. As an example of the development of an emergency situation, a possible scenario for the transition to unguided flight of an air-to-air guided missile is given.

Keywords: *probabilistic function, guided weapons, emergency situation, operational state, component, complex technical system, function of the algebra of logic.*

INTRODUCTION

Modern guided weapons (GW) consist of a large number of systems, blocks, assemblies, parts, etc. (component parts), each of which performs its functions, is built on the use of certain physical principles and has connections with other component parts. Their main features are relative independence (connection with the launch platform is lost after launch) and the possibility of only one-time use for its intended purpose. Although the structure of the GW is determined by the combat purpose, they all have common features in the organization of construction and equipment composition – that is, they are typical representatives of complex technical systems (CTS) and can be considered from the perspective of the theory of complex systems in both organizational and functional aspects [1].

Reliability is usually used as an integral indicator of the operational properties of CTS, that is, the ability of the system to maintain its properties and function as intended under certain conditions and for a certain time [2].

Thus, the operational state of the GW, as CTS, is characterized by the ability to perform its functions as intended and is determined by the technical condition of the medium and the connections between them. Loss of operability of one or more medium or violation of connections between them leads to failure of the GW as a whole [2]. When used as intended, the consequence of such an event may be the occurrence of emergency (abnormal) situations (ES) and failure to complete the task.

Thus, the operational state of the GW, as CTS, is characterized by the ability to perform its functions as intended and is determined by the technical condition of the components and the connections between them. Loss of operational capacity of one or more components or a violation of the connections between them leads to the failure of the GW as a whole [2]. When used as intended, the consequence of such an event may be the occurrence of emergency situations (ES) and failure to complete the task. Emergency situations also include situations that are caused by deviations from normal (standard) conditions of use. Their possible consequences are necessarily analyzed when assessing risks, building scenarios for the occurrence and development of accidents, catastrophes, etc. It is obvious that the more complex the system, the more medium-frequency components it contains, the more complex the connections, the more complicated the process of analyzing and predicting its state, and the greater the potential danger it carries.

The basic principles of assessing the reliability and safety of the functioning of the CTS have many common features and, from a mathematical point of view, can be carried out using identical mathematical tools and create the prerequisites for the formation of possible scenarios for the development of emergency situations, identifying the cause and developing measures to prevent or minimize their consequences.

The purpose of the article is to develop a methodological approach to the formation of possible scenarios for the development of emergency situations in the functioning of the GW when conducting tests using logical-probabilistic methods.

RESEARCH RESULTS

The issues of formation and development of possible scenarios of development of emergency situations during testing, along with the theory of reliability, aging are increasingly found in works [3–10], in which they are solved from the position of the theory of STS and the basic provisions of the algebra of logic are applied. At the same time, the means of mathematical logic are used to analyze the structure of STS and ways to increase their reliability are developed on the basis of quantitative assessments of reliability using the theory of probability. Such approaches allow solving the general tasks of creating reliably functioning systems taking into account negative factors, the target function of which is to ensure a working condition in various operating conditions.

At the same time, testing of samples of GW, which is associated with launching (firing), carries risks of abnormal and emergency situations [11, 12]. In most available sources, insufficient attention was paid to the issue of the occurrence and development of abnormal situations during testing of weapons and the features of their construction and functioning as single-use CTS were practically not considered.

The formation of a list of possible failure variants of components and related emergencies is carried out based on the results of a schematic analysis of the design of the GW sample and functional-morphological decomposition with preference for the functional feature, the result of which is the distribution of the causes of malfunctions and damage that lead to the emergence of an emergency situation into groups [13]. The general algorithm for the development and formation of possible emergencies is shown in Fig. 1. It should be noted that the most common is the transition of the GW to uncontrolled flight.

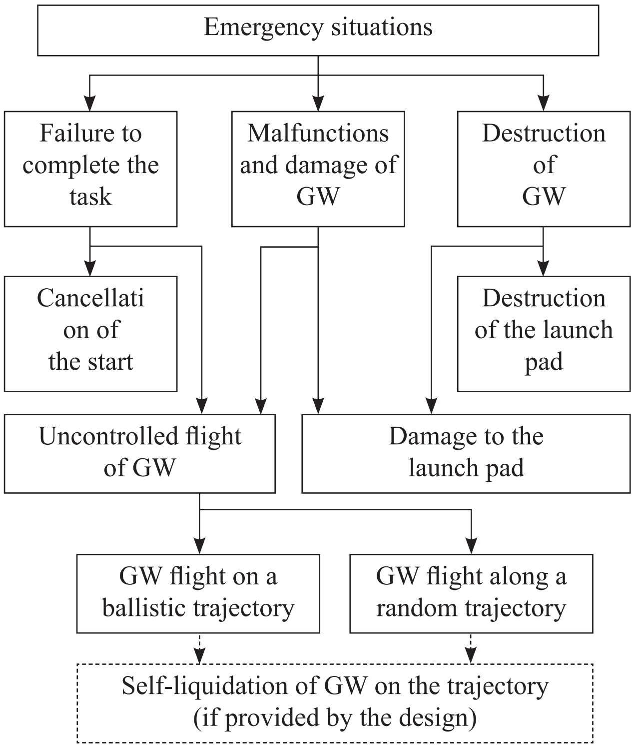


Fig. 1. Algorithm for the development and formation of possible emergency situations

According to the results of decomposition, several hierarchical levels are distinguished, determined by different degrees of abstraction regarding the technical, physical, chemical and other properties of the components and an ordered hierarchical set is formed, which can be represented in the form of a single-root hierarchical graph, table, structured diagram, etc. This allows us to consider the GW as a CTS consisting of separate interconnected systems, which, in turn, can also be divided into subsystems, units, blocks, etc.

To assess the operational state of the GW, we will use the logical-probabilistic method, the essence of which is that their structure is described by the function of the algebra of logic (FAL) [5, 6] and the quantitative assessment of the operational state is carried out by the methods of reliability theory and mathematical statistics [13].

As is known, FAL is formed from statements (random events) that are connected by logical operations (conjunction, disjunction, negation, equivalence, etc.). In this case, statements can take only two values: 0 (false) or 1 (true). In most cases, CTS are described by FAL with repeated arguments or negation arguments, which does not allow direct use of known methods of reliability theory. To transition from FAL to a probabilistic function (PF), it is necessary to replace the logical variables of the function with the probabilities of failure-free operation and the logical operations with arithmetic ones. As a result of the transformation, the PF will act as the probability of the truth of FAL.

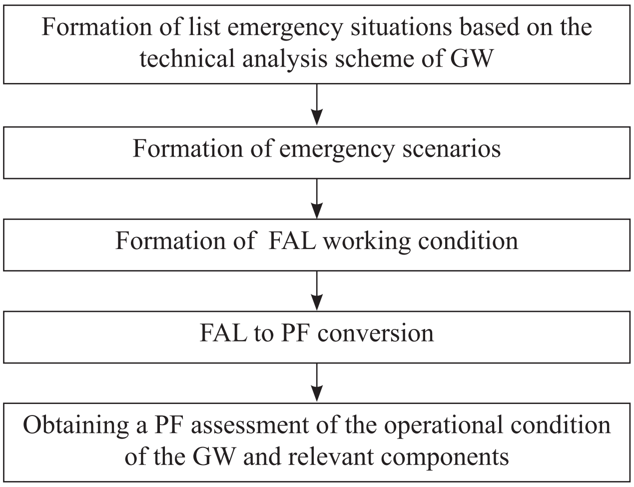
Thus, using FAL, it is possible to describe the conditions of the GW's operability, which will allow us to identify such components and their connections, due to which a failure (loss of operability) may occur, which will lead to an emergency situation. Taking into account the above, we will describe the FAL of the operability of the GW in the form of a structure that can be in two states – operable ($y = 1$) or inoperable ($y = 0$). In this case, the state of the system (y) depends on the state of its components (x_i), which can also be in operable ($y = 1$) or inoperable ($y = 0$) states. The values $x_1, x_2, ..., x_i, ..., x_m$ of binary variables and determine the GW state vector as a whole. Therefore, in the general case, the FAL of the operability of the GW can be written as

$$y(x_1, x_2, ..., x_i, ..., x_m) = y(X). \quad (1)$$

The procedure for assessing the operational state of GW using logical-probabilistic theory approaches is shown in Fig. 2.

In principle, there are two approaches to analyzing possible scenarios for the development of emergency situations [6].

The first approach consists in analyzing the development of events, starting from the moment of the emergency situation and until the detection of failures of those components that will lead the GW to an inoperable state, that is, the analysis of the accident is carried out «from the end to the beginning». In this case, the reasons (events, a



F i g . 2. Procedure for assessing the operational condition of the GW

combination of several events) that lead it to such a state are analyzed. In the process of analysis, a logical scheme is also built, which contains all possible combinations of events. A logical function is built based on the logical scheme, the arguments of which are the primary events.

The second approach involves analyzing the development of events in the reverse direction – from the moment of failure of a component to the beginning of the development of an emergency situation. After the initial failure is determined, a scenario of its development within the system is formed based on the existing connections between the components. Thus, the system's reaction to the failure that has occurred is determined. The second approach also solves the problem of finding ways for the system to transition to an inoperative state under the condition of any initiating event, that is, it represents an analysis of the accident «from beginning to end».

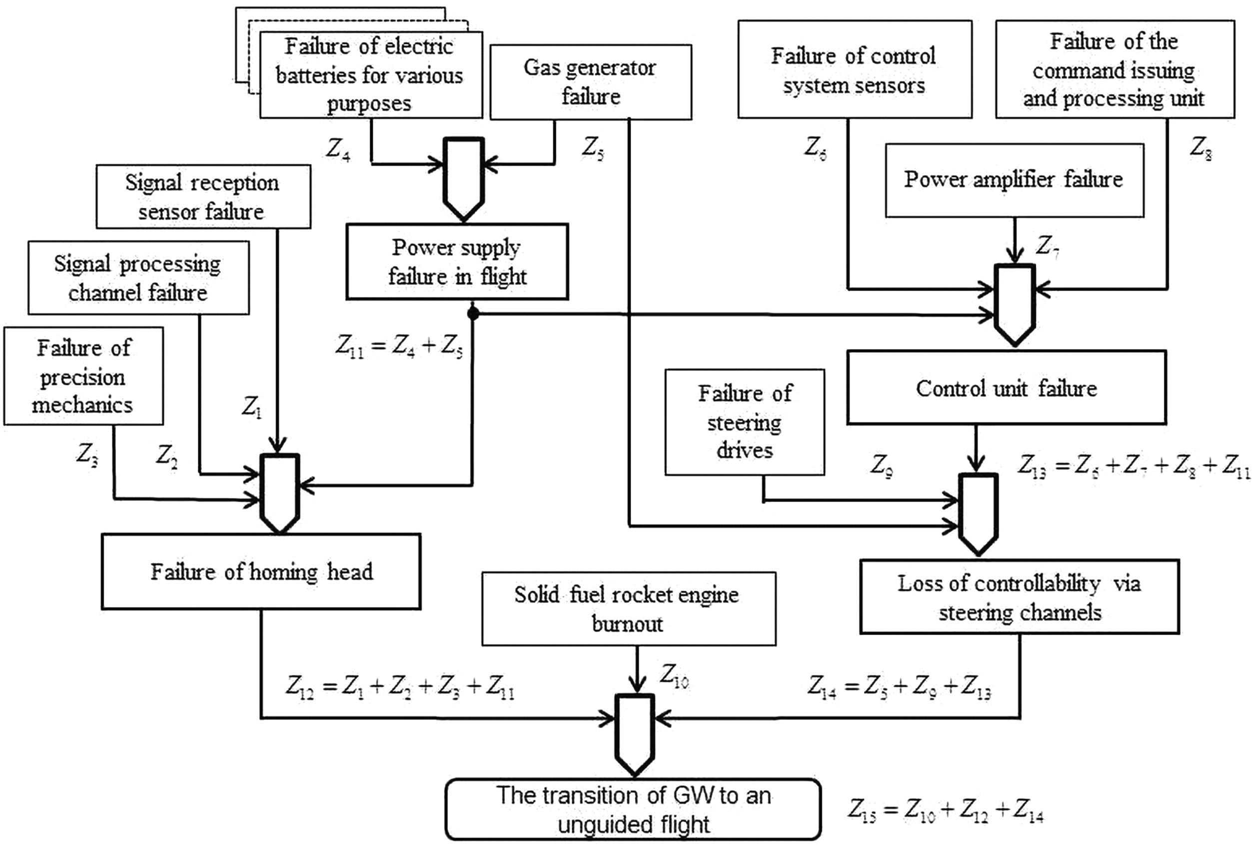
It should be noted that the formation of emergency scenarios occurs in chronological order, even when events occur with a small difference in time.

After completing the analysis using one of the above approaches, a logical diagram is built that contains all possible scenarios for the development of emergency situations and allows you to graphically display the logic of failures in the GW. According to this diagram, a logical function is built, the arguments of which are the events present in the scenario. In some cases, it is necessary to take into account the possibility of operation of individual subsystems in the situation that develops before their regular connection.

As a rule, it is convenient to present FAL in disjunctive normal form (DNF), with each conjunction representing the path of the loss of performance, i. e. the scenario of the development of an emergency situation. As an example, Fig. 3 shows scenarios of the development of emergency situations, which leads to the transition to unguided flight of an aircraft guided missile of the «air-to-air» class of short/medium range. In this case, the «from beginning to end» approach was used. In this case, expression (1) will have the form

$$y = z_{13} \vee z_{14} \vee z_{15} .$$

To assess the probability of occurrence of emergency scenarios, we will move from FAL to PF, as which we



F i g . 3. Possible scenarios for the development of an emergency situation – the transition of an aircraft guided missile into uncontrolled flight will use the probability of failure-free operation, which will allow us to apply the basic theorems of probability theory. For the analysis of sequential, parallel and tree-like structures, the formula of total probability can be used.

After constructing possible scenarios of the development of emergency situations (construction of FAL), the probability of their implementation is estimated. Next, the impact of each component on the development of each of the possible scenarios is assessed by translating FAL into PF, the arguments of which are the corresponding probabilities of failure-free operation included in the logical schemes. The probabilities of failure-free operation of the components included in the studied GW are determined by expert methods taking into account the construction of their structural and functional reliability schemes [1], according to design and technical documentation, relevant characteristics of similar products, etc. At the end, by substituting the corresponding probabilities in PF, the probability of the final event is calculated.

For example, the FAL of the transition to uncontrolled flight of an aircraft guided missile (Fig. 3) as a result of the failure of the homing head has the form

$$y_{hh} = z_1 \vee z_2 \vee z_3 \vee z_{11},$$

that is, its normal operation depends on the technical condition of the signal reception sensor, signal processing channel, precision mechanics and power supply, and the probability of its trouble-free operation is calculated as

$$P_{hh} = P_{SRS} \cdot P_{SPC} \cdot P_{PM} \cdot P_{PS},$$

wherein P_{SRS}, P_{SPC}, P_{PM} and P_{PS} – the probability of failure-free operation of the signal reception sensor, signal processing channel, precision mechanics, and power supply, respectively.

It is obvious that the probability of a guided missile going into uncontrolled flight due to a homing head failure and the occurrence of a corresponding emergency situation is equal to

$$P_{UF\ hh} = (1 - P_{hh}).$$

In a similar way, it is possible to calculate the probability of a rocket going into uncontrolled flight caused by failures of the control unit, gas generator, burnout of a solid fuel engine in flight, etc.

For organizational and technical systems and high-dimensional CTS, well-known methods of FAL and PF conversion are used, of which the most convenient for practical application are the orthogonalization method, the recurrent method and the path-building method [6]. The most complex of them from the point of view of calculation is the orthogonalization algorithm, which is based on the conversion of FAL into orthogonal DNF. It is proposed to be used in the case when the probabilities of events have approximate values, since the total calculation error will be smaller due to the fact that the probabilities are added when performing the conversion.

The recurrent algorithm is based on calculations using the tabular method using the multiplication theorem of event probabilities. In these tables, the columns are the number of possible combinations of conjunctions and the rows are the number of elements in the system. This algorithm is the least computationally cumbersome due to the lack of the need for additional function transformations and is most efficient if the number of DNF members does not exceed 10. In the path building algorithm, the relative probability of impossibility of all previous paths is used when calculating the probability, i. e. some variables are replaced by 1, which significantly simplifies further calculations.

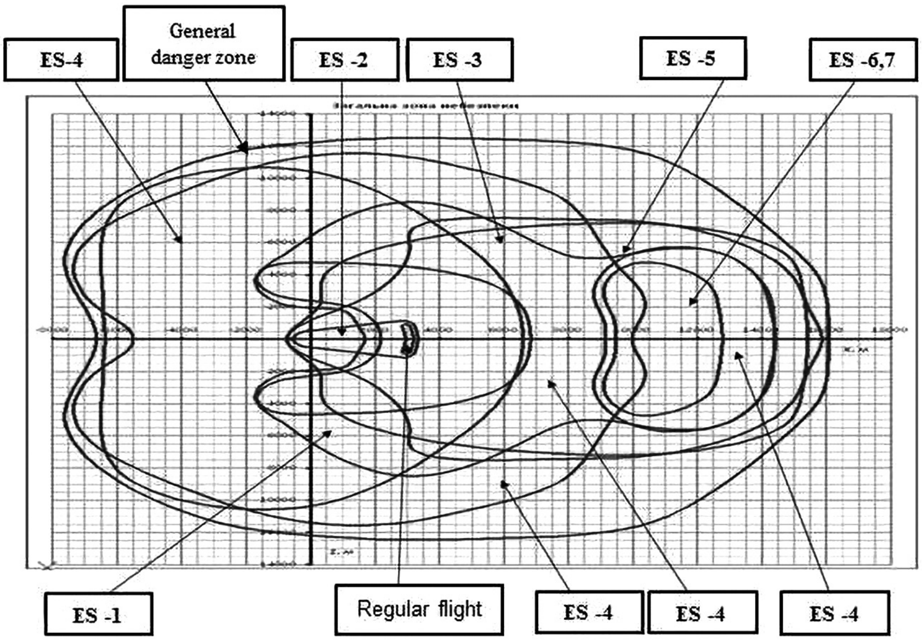
To make a decision on the adoption of GW of domestic and foreign production into service (admission to operation), it is usually necessary to confirm their individual tactical and technical characteristics. The results of such tests can also be used to refine the algorithm for the combat use of GW. In this case, appropriate flight tests are carried out at the training grounds of the Armed Forces of Ukraine, which requires the calculation of the danger zone, the geometric dimensions of which are determined by the set of possible variants of their abnormal operation.

The analysis of the possible behavior of the GW both in normal flight and in the event of one or more failures is carried out based on the results of the study of the corresponding mathematical model, which is based on the known equations of motion of the center of mass and motion around the center of mass. The adequacy of this model and its accuracy are confirmed by the corresponding flight tests. At the same time, a search is made for such combinations of possible failures, at which they take maximum values. The far boundary of the danger zone is determined by the energy-ballistic characteristics of the GW and the near boundary corresponds to the flight range at the maximum deflection of the aerodynamic rudders, as well as a possible engine burnout, which can cause a significant transverse thrust moment. The lateral boundaries of the danger zone are determined by the ballistic flight range at the corresponding deflection of the aerodynamic rudders and also a possible engine burnout. The total danger zone is formed by combining all partial zones, with reference to the start point and direction to the target.

As an example, Fig. 4 shows partial and total danger zones, which were calculated by the State Enterprise State Kyiv Design Bureau «LUCH» when organizing the testing of one of the GW types. Based on the results of mathematical modeling, trajectories, speeds, coordinates of the impact points and other parameters used to determine them were calculated. The set of impact points (taking into account the radius of the fragmentation) form partial danger zones caused by the corresponding emergency situations (ES1 – ES7).

CONCLUSIONS

It is proposed to form a list of possible GW emergency situations based on the results of functional-morphological decomposition with preference given to the functional feature, the result of which is the distribution of causes of malfunctions and damage that lead to emergency situations into groups. To assess the operational state of the GW sample, a logical-probabilistic method is used, with its structure described by a function of logic algebra and the operational state by methods of reliability theory. After the



F i g . 4. Partial and total danger zone calculated for GW tests

analysis is completed, a logical diagram is constructed that contains all possible scenarios of emergency situations and allows graphically displaying the logic of failure occurrence. A logical function is also constructed using this diagram, the arguments of which are the events present in the scenario.

The presented methodological approach to the formation of possible scenarios of the development of emergency situations during GW tests allows us to assess the probability of their occurrence and the obtained PF of failure-free operation and the corresponding assessment of their elements allow us to identify a list of events and components whose impact on operability is the greatest. Their significance and role in possible scenarios of the development of emergency situations should be used when developing and calculating danger zones during flight tests of weapons of various purposes. The results of such tests can also be used to refine the algorithm of combat use.

The proposed methodological approach was used by specialists of the State Enterprise State Kyiv Design Bureau «LUCH» to calculate danger zones when organizing control flight tests of a number of KZU of foreign production and of our own development and production.

REFERENCES

1. Kredentcer, B.P., Lanetky, B.N., Lapitsky, S.V., Liubarets, A.A., Odnoralov, I.V., Shatrov, A.N. & Shichanov, M.A. (2018), "Osnovy voenno-technicytskih reshenii. Teoriia i prilogeniia. Vol. 4. Monografia: Sintez sistemy podderganiia ispravnosti sredstv porageniia." Dmitry Burago Publishing House. K.: 332 p.
2. Zubarev, V.V., Kovtunenko, A.P. & Raskin, L.G. (2005) "Matematicheskie metody otsenki i prognozirovaniia tehnicheskih pokazatelei ekspluatatsionnykh svoistv radioelertronnykh system." Monografia. Knygkove vydavnytstvo NAU. K.: 184 p.
3. Sevriugina, N.S., Prohorova, E.V. & Dikevich, A.V. (2012) "Modelirovanie neshtatnyh situatsiy pri otsenke nadegnosti spetstehniki". Zbirnik Harkivskogo nacionalnogo avtodorognogo universitetu, №57. Pp. 90—96.
4. Mirsky, G.O. (2018) "Osoblyvosti otsinuvannia bezvidmovnosti i bezpeky apparatno-programnyh kompleksiv." Materialy mignarodnoi konferentsii "Radiotehnicni polia, signaly i systemy." KPI im. Igoria Sikorsky. Pp. 66—68.
5. Paul R. Halmos. (1956). The Basic Concepts of Algebraic Logic. The American Mathematical Monthly. Vol. 63. No. 6. Pp. 363—387. https:// doi.org/10.2307/2309396.
6. Ryabinin, I.A. (1997). Logic-probabilistic theory of safety of complex systems. Intern. Conf. on Informatics and Control (ICI&C97). Proc. Vol. 3. Pp. 1069—1075.
7. T. Parhizkar, J.E. Vinnem, I. B. Utne & A. Mosleh. Supervised Dynamic Probabilistic Risk Assessment of Complex Systems. P. 1: General Overview. Reliability Engineering & System Safety. Vol. 208. April 2021. https:// doi.org/10.1016/j.ress.2020. 107406.
8. Johnson, C.W. A probabilistic logic for the development of safety-critical, interactive systems. Intern. J. of Man-Machine Studies. Vol. 39. Iss. 2. August 1993. Pp. 333—351.
9. Zavgorodnii, V.V. & Zavgorodnya, G.A. (2018). Method of representation of knowledge about the assessment of risk of appearance of technogenic accidents. Bull. of Kremenchuk Mikhaylo Ostrohradskyi Nat. Univ. 4 (111). Pp. 43—48. 10.30929/1995-0519.2018.4.43-48.
10. Ernest J. Henley, Hiromitsu Kumamoto. Reliability engineering and risk assessment. Prentice Hall. Inc., Englewood Cliffs. N.J. 07632. 1981. 528 p.
11. Luk'anchuk, V., Nicolaev, I., Lanetky, B., Terebuha, I., Vasilev, V. & Fomenko, D. (2021). "Osobennosti gosudarstvenykh ispytanii zenitnogo raketnogo kompleksa srednei dalnosti s ispolzovaniem tehnologii virtualnogo poligona." Mater. Konf. "Débats scientifiques et orientations prospectives du diveloppement scientifique." Zb. naukovih pratc ΛΌΓΟΣ. Pp. 115—120. https://doi.org/10.36074/logos-05.02.2021.v2.35.

12. Julian Salomona, Niklas Winnewissera, Pengfei Weia, Matteo Broggia & Michael Beer. Efficient Reliability Analysis of Complex Systems in Consideration of Imprecision. Reliability Engineering & System Safety. August 2021. https://doi.org/10.1016/j.ress.2021.107972.
13. Yerko, V., Kryzhanivskyi, Y., Liubarets, A. & Shatrov, A. Methodical bases of processing the results of research on guided and unguided missiles solid fuel engines. Intern. Scient. and Pract. Conf. Theory and Practice of Science: Key Aspects. July 19–20, 2023 in Roma, Italy. Pp. 353—361. https://doi.org/10.51582/Interconf.19-20.07.2023.033.

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ФОРМУВАННЯ МОЖЛИВИХ СЦЕНАРІЇВ РОЗВИТКУ НЕШТАТНИХ СИТУАЦІЙ ПРИ ПРОВЕДЕННІ ВИПРОБУВАНЬ КЕРОВАНИХ ЗАСОБІВ УРАЖЕННЯ

У статті наведено методичний підхід щодо формування та розвитку можливих сценаріїв розвитку нештатних ситуацій при проведенні випробувань керованих засобів ураження шляхом описання їх структури та функціонування на основі логіко-ймовірнісної теорії.

Для оцінки працездатного стану керованого засобу ураження застосовується логіко-ймовірнісний метод, при цьому його структура описується функцією алгебри логіки, а працездатний стан – методами теорії надійності. Після завершення аналізу будується логічна схема, яка містить усі можливі сценарії розвитку нештатної ситуації та дозволяє графічно відобразити логіку виникнення відмов. За цією схемою також будується логічна функція, аргументами якої є події, що присутні в сценарії.

Можливі сценарії розвитку нештатних ситуацій при застосуванні керованих засобів ураження розглядались за умови, що їх виникнення обумовлено відмовою однієї чи декількох складових частин або порушенням зв'язків між ними. У якості прикладу розвитку нештатної ситуації наведено можливі сценарії розвитку переходу у некерований політ авіаційної керованої ракети класу «повітря-повітря».

Ключові слова: *імовірнісна функція, керовані засоби ураження, надійність, нештатна ситуація, працездатний стан, складова частина, складна технічна система, функція алгебри логіки.*

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The article was received by the editorial board on 09.01.2025.