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Genesis of dependability of unique safety critical systems

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Purpose. *This article offers to focus on the genesis of dependability of unique safety critical systems specified by low probability of failures, using the example of transformable structures of spacecrafts, in relation to which just the possibility of failures can question the reasonability of their creation. It describes the stage of the life cycle of unique mission critical systems at which the measures taken to improve reliability are the most effective, and the stages at which it is already late to take any measures at all.* **Methods.** *Neglecting the genesis of unique mission critical systems will inevitably lead to failures at the stage of operation, and the failures are caused by errors in design, engineering, modeling, as well as by different manufacturing deviations. In practice up to 80% of cases are predetermined before the start of operation – "at a drafting machine" and in manufacturing departments, when something was not thought through, taken into account and controlled, making an error or foozling. Reliability of future products depends on the quality of the decisions taken under development, which directly depend on the principles, rules and requirements used under design and engineering. These notions are interrelated, they have a concrete meaning. Principles are used to develop design solutions. Rules are intermedia between theory and practice, they often reflect the gained experience that should be considered in new developments to avoid repeating the errors. Reliability requirements at the stage of engineering are formed as the result of application of goal-oriented procedures and analyses, being established in graphic and text form in design documentation: in technical requirements and on a draft, as well as in technical specification. Satisfying these requirements is finally aimed at undoubted performance by a product of its functional tasks with predetermined reliability.* **Results.** *The aspects described in the article, separate the methods of reliability theory which are based on probabilistic and statistical models, with practical engineering methods aimed at the creation of reliable equipment. The field of reliability theory covers the study of behavior of finished products, proceeding from the information about mathematical models that consider stochastic parameters. Real objects in reliability theory are schematized to the models described by probabilistic dependences and having a sampling that can be used for statistical generalization. In practice though, engineers work having no statistics and concepts of probabilistic behavior of a future product, and the collection of methods and algorithms of its operation makes it possible to influence the reliability of real products.* **Conclusion.** *This paper shows that the stages of a life cycle of unique safety critical systems before the stage of operation are strictly differentiated by the efficiency of reliability measures. At each stage it is necessary to use certain reliability algorithms and methods that are specific to this particular stage, which may increase the effectiveness when solving the tasks of reliability of unique safety critical systems.*

Keywords: *unique safety critical systems, transformable structure, spacecraft, reliability, genesis, life cycle of products.*

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Introduction

When creating any technical product the first task is to achieve such output characteristics that a product is capable of performing. But this very achievement does not guarantee that products will always be manufactured serviceable, that they will not lose the functionality after being stored and transported, that they will perform the targets in full scope and will not operate less than it is predetermined.

Inevitable changes of possible states of products under the influence of external factors and internal chemical and physical processes may eventually reduce their output characteristics, as the result of which the expected efficiency may turn out to be unachieved.

Why is it possible? In most cases the modes and conditions of functioning are not properly estimated or considered. Unintentional wrong actions by personnel are not rare during manufacture and operation processes. Sometimes, constructive decisions go ahead of the production technological capabilities, or they are inadequate to the concepts of physical processes that take place under products' operation. In any of the cases the mentioned factors can lead to failures that may turn out to be accidents and catastrophes. If the social and economic losses suffered by human society in case of products' failures, exceed the acceptable critical level, there is a need to ensure the reliability of these products.

For common equipment ensuring of reliability is normally a secondary task that is often solved as if by the way, because usually failures do not have any serious consequences. Reliability in this case is considered in the context of optimizing the financial costs and costs in public image. But there are technical objects that exclude any failures despite inevitable additional financial expenses on the prevention of such failures, because otherwise it may lead to far more losses at accidents. Examples of such objects are unique safety critical systems (USCS), in relation to which just the possibility of failures can question the reasonability of their creation. Here it is important to understand at which stage of the USCS life cycle the measures taken to improve reliability are the most effective, and at which stages it is already late to take any measures at all.

In this relation it is worth considering the genesis of USCS reliability on the example of transformable structures (TS), whose main task is to enable long functioning of spacecrafts in space environment by single actuation on orbit [1].

What happens to reliability at the stage of operation of transformable structures

According to GOST 25866-83 the operation of products generally includes use as intended, transportation, storage, maintenance and repair. For opening parts of TS, the operation can be arbitrarily limited by the period from the moment of transfer of a product for storage after factory acceptance and to the opening into operating configuration on low earth orbit. While being in operation TS passes the following stages of the life cycle: storage, transportation, maintenance, preparation for launch at a test range, flight within the scope of a rocket vehicle, placing into orbit, preparation for opening and opening into operating configuration [2].

Let us assume that at any moment of operation τ TS may suddenly fail, and it will not be possible to recover or repair it at subsequent moments of time. Let us define the probability $P_f(t)$, with which this structure will perform its functions within the period of operation up to the moment t. If we assume the TS operating capacity to be a sampling of sequential independent tests with probabilities $P_\upsilon(\tau)$, then the probability of its functioning during the time period t will be:

$$P_f(t)=\prod_{\tau=1}^{t} P_\upsilon(\tau). \qquad (1)$$

From (1) it appears that in the course of time t the probability of TS functioning can increase, it can decrease, or hold constant on level 1.

Decrease $P_f(t)$ is the result of stochastic changes of the state of TS under the influence of external factors (overloads, impacts, jarring, vibrations, fluctuations of temperature, humidity, aggressive environments, etc.), as a consequence of implementation of the following processes:

– degradation of physical and mechanical properties of materials caused by wear, corrosion, deterioration, embrittlement, etc.;

– change of physical and mechanical properties of materials under the influence of freeze-thaw temperatures;

– non-convertible deformations and destructions (plastic deformations, crumbling of contact surfaces, creeping, fractures, etc.);

– deterioration of tribocoupling;

– expression of structural instabilities in form of displacement of fixed parts, loosening in screw joints, changes of freeplays in actuated parts, violation of adjustment, etc.

The next important aspect is solving the issue of initial level of P_0 at the moment that corresponds to the start of operation.

Let us consider the situation at the moment when TS is on hold being ready for operation, i.e. it has already had the full capability to show reliability properties, because the relative position, interrelation and interoperation of the elements inside TS has already been implemented (TS is ready for operation), and the relative position, interrelation and interoperation of TS in external environment and with other objects is provided and expected. This state of TS is a priori predetermined in engineering documentation (ED) by rated parameters μ_i and respective tolerances $\Delta\mu_i$. And the parameters are random variables (dependent or independent of time), that may change within the limits of nonrandom tolerances:

$$\Delta\mu_i=\mu_{i\max}-\mu_{i\min}\,\forall i=\left(\overline{1,n}\right). \qquad (2)$$

Parameters μ_i set:

$$\mu_i\in R^N. \qquad (3)$$

Number of equations N of set (3) corresponds to the number of parameters of the structure, and with the rise of its detalization it may grow, and according to (2) the parameters will always be within the predetermined range:

$$\mu_{i\min}\le\mu_i\le\mu_{i\max}. \qquad (4)$$

If there are no bad errors in ED, and therefore it is not necessary to modify ED at the stage of manufacture, it is considered to be a stationary stochastic model of the object represented in a draft and text form [3]. If a random value of parameter $\mu_i(t)$, predetermined in a stationary model of TS, stays within tolerance $\Delta\mu_i$, TS is considered to be fit for operation. Therefore, the object's readiness for operation is determined by the fulfillment of all ED requirements related to predetermined parameters μ_i, and its performance capability is determined by a random entering the tolerance limits (4). If parameters μ_i go out of the tolerance range it is qualified as a failure. Besides, the possibility of a failure lays in the principle of use of a stationary stochastic model of the object. Due to the fact that the number of equations (3) under the development of ED is always finite with an infinite number of random values, there is a risk of non-consideration of any failure factors.

Thus, before the operation there is always a risk with probability γ, that not all parameters μ_i under engineering will be properly considered, and those parameters predetermined in ED will be within the respective tolerance under operation $\Delta\mu_i$.

Let us assume that all TS parameters are independent in terms of reliability, and non-consideration of any of them, or going out of the range of tolerance will lead to a parameter's failure. The event specifying the readiness of TS to perform without failures shall be indicated as H, and the event specifying the occurrence of a failure in case realization of risk with probability γ, shall be indicated as A, then:

$$P(H)+P(A)=1,\ \mathrm{P(A)}=\gamma,$$

$$\mathrm{P(H)}=1-\gamma. \qquad (5)$$

According to formula (5) initial reliability of TS before operation $P_0=P(H)$ is always less than one. And after TS functioning during the period t, its reliability with consideration of (1) and (5) is:

$$P(t)=P_f(t)\cdot P(H) \qquad (6)$$

Formula (6) makes it possible to consider TS reliability not only as the result of performance of its functions without taking into account the genesis of its origin, but also as the result of the process that leads to an occurrence of this reliability. Thus, a value of TS reliability index determined in a technical task (TT) for the development, shall be defined by formula (6), which presumes the consideration of operational conditions, as well as of engineering and manufacturing prerequisites for failures as the result of the following factors:

– imperfections of design and engineering methods, engineering errors, violations of normative technical documentation, violations of engineering rules;

– imperfections and errors of technologies applied;

– defects and errors of manufacture, installation, violations of technological processes of manufacture, running in friction joints and adjustment, deterioration of parameters as the result of the required testing.

Moreover, if in case of readiness to function without failures indicated as event H, normal functioning of TS shall be indicated as event B, the reliability (6) of TS functioning TK during the period t should be interpreted as conditional probability:

$$P(t)=P(B|H).$$

Based on the mentioned above, reliability should be considered and estimated not only at the stages of the life cycle of the product which is ready for operation, but also in the cases when it is under manufacture or exists in form of the models such as:

– information models under design;

– graphical models under engineering;

– models of technological process under preparation of manufacture.

During the course of sequential modeling and manufacture of the product throughout the life cycle, its expected initial reliability at the start of operation tends to decrease due to the impendence of formation of prerequisites to failures, as the result of modeling errors and as the result of different deviations under manufacture.

The correctness of formula (6) is confirmed by the results of studies carried out by Rome Air Development Center in order to improve the standard of US defense department related to reliability MIL-HDBK-217 [4]. The studies were based on the analysis of data about accidents and incidents at 300 American and European spacecrafts related to 2500 facts of failures for the period from early 1960s till January, 1984. The following factors were accepted as the causes of TS failures: engineering errors – 34,4%, underestimate of environmental conditions – 25,3%, defects of components – 10,8%, quality of manufacture – 8,9%, conditions of operation – 6,9%, other – 2,2% and unknown – 11,5%. In fact, not less than in 79,4% of cases, TS failures were predetermined before the start of operation – "at a drafting machine" and in manufacturing departments (when something was not thought through, taken into account and controlled, making an error or foozling).

Thus, the expected TS reliability at the start of operation is generally always less than one with a tendency to decrease during operation. Moreover, engineering and technological causes that predetermine failures before start of operation prevail over the causes of failures occurred as the results of factors affecting during operation.

Formulas (1) and (5) do not contradict with the TS reliability being "close to one" – фактически "zero point nine repeating": 0,(9)=1 in the interval of operation from 0 to t. If we suppose that under design, engineering, technological development and manufacture there was no error (i.e. there are no reasons for failures), hypothetically, initial reliability of the object at the start of operation may be maximum possible, that does not contradict with the idea of developing failure-free objects.

What happens to reliability before the start of operation of transformable structures

The product development and launching into manufacture in accordance with GOST R 15.201-2000 consists of the following stages:

1) Elaboration of tactics and technical task for development engineering (DE);

2) Implementation of DE (incl. the development of engineering (ED) and technological (TD) documentation in accordance with GOST 2.103-68 and GOST 3.1102-81, respectively);

3) Launching into manufacture (incl. the preparation and mastering of manufacture, production and qualification tests).

At the stages of product development and launching into manufacture from the point of genesis of reliability, it makes sense to consider the following stages of the product life cycle:

– development of TT – determination of requirements for the output products;

– design (technical proposal, basic design, technical detailed design) – coordination and validation of requirements for products;

– development of ED – implementation of the requirements for the product in technical documentation for its manufacturer;

– development of TD – coordination of ED requirements ED with manufacturing capabilities производства;

– manufacture (product launching into manufacture) – finished product output.

As it was noted in [5], reliability at the stage of the product development and launching into manufacture is expressed as capability. In accordance with this thesis, there is no capability of the future product to express reliability at the moment of start of TT development. If we use the term *"conditional probability of failure-free operation"* of the product, it will be equal to zero (there is nothing to talk about). Under the TT development the requirements are elaborated in relation to the conditions and modes of operation of the future product, under which the product will actually have to express the property of reliabilityв. By this time it is necessary to collect the data about external environment and loads, carry out basic research of characteristics of structure materials, work out the key technologies of manufacture. With correct statistical samplings there is the possibility to deviate from the stochastic dependence of change of the products parameters, by transferring the reliability tasks to a deterministic approach. The most known example is the assuring structural integrity with a use of safety factors. The more justified and accurate these requirements are in TT, the higher the conditional probability of failure-free operation is.

Based on the TT requirements, at the design stage the operating principles of the future product are built, technical decisions are elaborated, the product's characteristics and functioning algorithms are optimized, design models and methods of parameter calculation are specified.

Design stage is the most important in terms of reliability of the future product, as here it is possible to take such technical decisions that allow for choosing rational design-layout schemes, reduce the uncertainties of the product's states and eventually improve reliability. For instance, using thermal isolation in pads of mounting of continuant structures leads to the exclusion of the possibility of distortion of action elements of a clamping system in non-stationary field of freeze-thaw temperatures [6]. Another example may be a shift of weld in a lining tube of metal high-pressure vessel from the area of maximum voltages, that leads to a reduced influence of technological defects in welds (in particular, due to the occurrence of oxide scabs on the surface of weldments), and to the growth and stabilization of safety factors values [7].

The ability of the future product to express reliability changes at the stage of ED development, as well, but the growth of conditional probability of failure-free operation is limited (ED is developed on the basis of technical decisions already taken at the design stage, and it is difficult to correct design errors at engineering). Potentials of reliability improvement are connected with the possibilities to correct and clear out engineering "trifles", occurred as the result of poor attention, incorrect choice of parameters and decisions, incompetence, hit-or-miss working, lack of qualification of design engineers, etc. [8]. Principal results of engineering are clear and accurate requirements for manufacture of products that exclude any understatements, ambiguity of understanding and interpretation. By the moment of completion of ED development the conditional probability of failure-free operation of the product achieves the maximum level possible for this development (it means that a developer should have instilled all his knowledge, skills and experience, i.e. he cannot go as much long way anymore).

Reliability of future products depends on the quality of the decisions taken under development, which directly depend on the principles, guidelines and requirements used under design and engineering. These notions are interrelated, they have a concrete meaning.

A principle is a basic truth, going without saying, which appears from established logic and forms a general strategy of actions. Principles are used to elaborate design solutions to be *"intermediate or final descriptions of a design object, necessary and sufficient for consideration and determination of further direction or completion of a design stage"* [GOST 22487-77, article 7]. Number of principles is limited by key factors each of which expresses physics of any condition affecting reliability. Essence of these conditions is objective and unshakeable, for instance, the number of functional elements should be minimal, during operation the product should not break down, drives should have enough energy to perform predetermined shifts, etc. A principles is a theoretical basis for further reasoning, decisions and actions, it has no specific guidance in relation to the ways of implementation, it just should be like this, and not otherwise. Principles are implemented with a use of rules that flow out of principles. These rules determine the principles and specify their application.

A rule is a consistency that serves as a guidance that is based on stable interrelations between conditions, on prescribed procedures or norms of activity. Principles and rules exist objectively, independently of us. Deviations from principles and rules break the way it is.

Let us consider the example showing the difference between principles and rules. Energy redundancy of TS opening drives is the principle of performance capability of rotating structure under the conditions of uncertain environment, as well as dispersion of physical properties of the materials and technological tolerances of the components and assembly units of structures. Values of energy redundancy are determined by the rules related to the choice of correlation between the moments of drive forces and the moments of resistance forces in a swivel head for specific types of drives that take into account the current resistances, rate of response of opening structures, combination of the worst factors, etc. [9]. A principle indicates how it should be (necessary to ensure energy redundancy), and a rule specifies how it actually should be performed (for example, correlation between the margin of a drive moment and the moment of resistance forces shall be not less than three to have the worst combination of factors, correlation of the margin of a drive moment should be ensured in any angular location of a swivel, etc.).

It is not possible to build rules without principles. Rules are used to develop design and engineering solutions.

Rules are intermedia between theory and practice, they often reflect the gained experience that should be considered in new developments to avoid repeating the errors. This experience can be applied in form of the wording “our grandfathers used to do it like this”, or expressed in the provisions on normative and technical documentation. Unfortunately, it is very difficult to trace how justifiably and effectively the rules are used, they should be at least formalized and written down as, for example, in paper [10], besides, there are no rules for the new developments. In terms of reliability assurance, following the rules is a necessary, though insufficient condition.

Reliability cannot be achieved “by default”, it can be assured only as the result of strict fulfillment of the requirements aimed at the stability of the predetermined properties of the objects. Basis to assure reliability is the fulfillment of the requirements as a realized need to observe the conditions that should be strictly followed at the manufacture. A requirement is a need or expectation that is predetermined, normally supposed or is obligatory [GOST ISO 9000-2011, article 3.1.2].

Reliability requirements at the stage of engineering are formed as the result of application of goal-oriented procedures and analyses [11], being established in a graphic and text form in design documentation: in technical requirements and on a draft, as well as in technical specification. Satisfying these requirements is finally aimed at undoubted performance by a product of its functional tasks with predetermined reliability. But the fulfillment of ED requirements when launching the product into manufacture cannot increase the conditional probability of failure-free operation of the product, as nobody sets such goals for production men. And there are enough reasons to derogate from ED requirements under manufacture, violate technological processes and technological discipline, use means and methods of nondestructive control at the manufacture insufficiently or inefficiently, etc., all this inevitably leads to defects.

The task set at the stage of finished-product output is “not to do much harm” to the quality and reliability when embodying a draft and textual model into a finished product, and the maximum task is that a developer, technologist and manufacturer are “on the same page”. That is why it is necessary to have ED requirements being expressed in TD without deviations and interpretations, but at the manufacture being fulfilled with tolerable deviations [12]. At the stage of TD development and product launching into manufacture, the conditional probability of failure-free operation of the future product decreases naturally to the values of the initial level of reliability P_0 at the start of operation.

Change of reliability of transformable structures at the life cycle stages

If according to (6) we base on the fact that failure reasons occur, exist and develop starting from the very early stages

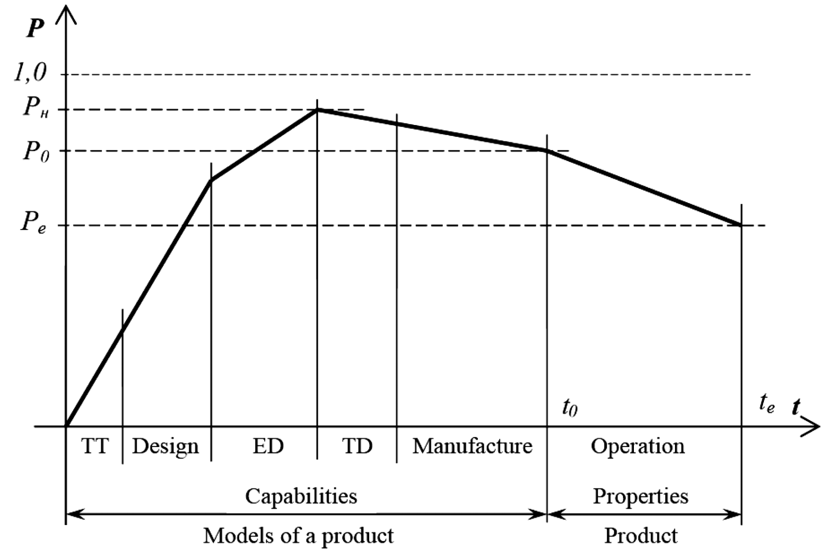

Fig. Graph of change of probability of failure-free operation (conditional probability) of USCS by the life cycle stages of the TS life cycle, the conditional probability of failures can be represented by the graph given below.

The graph shows that at the end of operation of TS t_e the reliability P_e has the lowest value determined by (1). The product is considered to assure the predetermined reliability P_{prd} if the following equation is fulfilled:

$$P_e > P_{prd}.$$

Drop of the product's reliability within the time interval from t_0 to t_e is consistent with the idea of the behavior of products, based on the widely known U-shaped curve if the product's reliability during its service life [13]. This curve defined the change of the probability of failures under operation. The probability of defect is considered to be high in the initial period of operation due to fundamental errors made under design, manufacture defects or incorrect assembly. Then there comes the period of wear accumulation, during which the failure probability is comparatively low. After the wear achieves a specific level, failures rise sharply again.

For TS there is no long mean time to failure, as well as the respective degradation and deterioration, as it is represented by a classic U-shaped curve, because the operation of TS is performed in the short run during the period of the opening of spacecraft's mechanisms when being under preparation for operation. TS operation totally fits in just with the first section of U-shaped curve. But, as TS refer to USCS specified by low probability of failures, failures at the stage of operation should be minimal, i.e. by the start of operation probabilities of failures caused by design, engineering and manufacture errors should be excluded, or minimized.

According to (6), by the start of operation the initial reliability P_0 is always lower than one, and before the moment of time t_0 the product is specified by the ability to express the property of reliability, and then it specifies this property of reliability. Division of reliability into the ability and property allows for separate consideration of the tasks of practical engineering and the tasks of reliability in the classic presentation of reliability theory.

As it follows from the figure, the ability of the product to express the property of reliability when passing the stages of the life cycle changes significantly. Passing the life cycle stages has different impacts on the initial level of reliability by the start of operation. The graph illustrates the tasks set at different stages of the life cycle under the development and manufacture of TS:

– under the development of TT – to complete fundamental studies of characteristics of structural materials and get all necessary information about external influences and loads;

– under design – to assure the maximum possible level of reliability using efficient technical solutions;

– under the issue of ED – at least not to permit loss of reliability achieved under design, and и, as maximum, to improve reliability by correcting the design errors and setting clear and strict requirements for TS manufacture;

– under the issue of TD – not to alter the reliability requirements in ED;

– under manufacture – not to permit deviations from the requirements in ED and TD.

Conclusion

The aspects related to the genesis of USCS reliability described in the paper, separate the methods of reliability theory with practical engineering methods aimed at the creation of reliable equipment. The field of reliability theory covers the study of behavior of finished products, proceeding from the information about mathematical models that consider stochastic parameters. Real objects in reliability theory are schematized to the models described by probabilistic dependences and having a sampling that can be used for statistical generalization. In practice though, engineers work having no statistics and concepts of probabilistic behavior of a future product, and the collection of methods and algorithms of its operation makes it possible to influence the reliability of real products in a wide range.

This paper uses the example of TS to show that the stages of USCS life cycle are strictly differentiated by the efficiency of reliability measures. At each stage it is necessary to use certain reliability algorithms and methods that are specific to this particular stage, which may increase the effectiveness when solving the tasks of reliability of unique safety critical systems.

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