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FORECASTING OF LIFE SUPPORT SYSTEMS OPERATION EFFICIENCY FOR ECOLOGICALLY CLOSED MAN-MADE ENVIRONMENT

The problem of spaceflight and manned submersibles life-support systems (LSS) guaranteeing safety and serviceability for a crew during long self-sustaining period modelling on the basis of phenomenological models is discussed in the paper. The analysis of traditional reliability research methods and construction of processes quality criteria has shown their insufficiency for an estimation of life-support systems. The main goal of the paper is to illustrate a method of improving safety and effectiveness of the crew by providing greater habitability. The developed methodological approaches to designing and to operation efficiency forecasting life support systems allow us to increase safety and comfort of the crew in extreme conditions.

safety, reliability, forecasting, life-support systems, closed man-made environment, habitability, phenomenological modelling

Introduction

Evaluating of life-support systems reliability and forecasting their functional condition is one of the major problems of designing ecologically closed environment for manned submersibles and spaceflight. The attention to the problem can be explained by functions which are carried out by the systems and first of all the creation and maintenance of safe and comfort parameters of inside atmosphere. For example, failures of gas supply, regeneration, air conditioning and ventilation subsystems of manned submersible compel a crew for emergency emersions, and violation in the work of automatics (air/gas mixture parameters disadjusting, control elements failures, controllers detuning, etc.) may have latent influence on crew members.

The methodological base is necessary for the purpose of forecasting functional condition and efficiency estimation of life-support systems. Now there is no integral methodology and the mathematical base for an exact all-round estimation of LSS stability and forecasting of their functional condition. The models offered by different authors [1 – 5] do not always allow us to solve the task set. The full description of transfer processes of energy, mass, impulses is difficult, that's why the principle of decomposition of the system preserving the maximum number of inner connections between LSS subsystems is used. In a static condition such an approach provides correct results. However taking into consideration the complex interrelations and inter influence between the various subsystems of LSS, it is possible to assume the use limitation of the decomposition principle at solving the problem of forecasting the functional condition and optimization in dynamic models of LSS.

The absence of direct dependences by unequivocal definition of LSS reliability parameters leads to the necessity of the use of the developed phenomenological models of their empirical values which are developed in an iterative way, for example, expert estimations and analytical calculations based on Quirk's method [2, 5, 6].

One of the possible approaches for the tasks solving of structural synthesis, forecasting the operational condition of LSS and the analyses of constructive and technological parameters stability is the usage of dissipative function and integrated parameter of reliability.

Main section

Traditionally the technical system efficiency criterion K should reflect a ratio between the result (effect) W and expenses C on its achievement and represent a function like $k = k(W, C)$ [2, 5]. It's possible to reject the reduction of different time parameter of useful effect W and expenses C to the common time moment at the expense of LSS should not change essentially their parameters during autonomy.

Estimating LSS efficiency there may be confusion between the concept of useful effect and the performance of a functional task. For LSS the functional task is in maintaining the given parameters or changing them according to the required program set in ecologically closed environment. The physical content of this task solving for manned submersibles is disclosed in bringing in or removal of a certain amount of a heat/cold for compensation of thermal losses/inflows, provision of a certain breathing gas mixture and/or oxygen quantity and removal of CO_2, other harmful impurity for maintaining the required breathing gas pressure and structure. Simple reference of expenses to system heat productivity, breathing gas, oxygen and CO_2 absorbent consumption, will limit the frameworks of decision making. In this connection the concept of useful effect at the given function of system – maintenance (or change) atmosphere parameters in manned ecologically closed environment – should be expanded by a number of parameters – reliability, safety, a level of comfort (indoor quality), etc.

Thus, the useful effect is unequivocally defined by a vector or vector set:

$$W = \left(X_1, X_2, X_3 \ldots X_n\right), \qquad (1)$$

where $X_1, X_2, \ldots, X_n$ - parameters of useful effect.

$$W \in P, \qquad (2)$$

where P is combination set of parameters determined by technical requirements.

According to the recommendations [3, 6] the complex criteria of LSS efficiency can be presented in the multiplicative form:

$$k_{ef} = \prod_{i=1}^{n} \left(Y_i\right)^{\beta_i}, \qquad (3)$$

where Y_i – the particular parameter of LSS efficiency;

β_i – the factor of importance of *i*-parameter,

$$\sum \beta_i = 1. \qquad (4)$$

The factor of importance β_i represents the weighting of the *i*-parameter against other parameters. The factors of importance are defined by various methods: limiting and rating values of parameters, with the help of regressive equations and also an expert method.

For the reflection of the level of LSS conformity on the maintenance of comfort and safe conditions required in manned submersibles closed living compartments the following criterion is offered:

$$k_{ef} = \frac{p(\tau)^{\beta_1}\, \omega(\tau)^{\beta_2}\, \psi(\tau)^{\beta_3}}{M} \to \max, \qquad (5)$$

where $p(\tau)$ – probability factor of non-failure operation of life support system;

$\omega(\tau)$ – probability factor of atmosphere characteristics maintenance in the required range of safety parameters;

$\psi(\tau)$ – probability factor of required distribution of environment parameters maintenance inside closed living compartments or pressures chambers;

M – LSS mass.

Depending on the concrete conditions of a comparative analysis it is possible to use the various simplified or modernized forms of the suggested formula.

One of the major and at the same time most complex question at forecasting LSS functional condition is determination of its reliability parameters. The limiting failure rate $\left[\lambda_c(\tau)\right]_{per}$ or allowable value of probability factor of non-failure operation $\left[p_c(\tau)\right]_{per}$ as functions $\lambda_c = \lambda_c(\tau)$ and $p_c = p_c(\tau)$ should be given in specifications of the developing product. Values λ_c and p_c may be given numerically for necessary autonomy of life support system. Predicting a LSS functional condition, it is necessary to provide the required conditions of reliability, i.e. to design such a system, at which $\lambda_c < \left[\lambda_c(\tau)\right]_{per}$ or $p_c > \left[p_c(\tau)\right]_{per}$ during all the self-sustaining period. Usually the value λ_c for prospective time of operation should be put on the diagram. The calculated curves $\lambda(\tau)$ of suggested LSS variants should be put on the same diagram. And it could be seen from the diagram what kind of system satisfies required reliability condition.

If the design with the required reliability may not be carried out by elementary methods because of any limiting factors (dimensions, mass, volume, cost, i.e.), the reservation is used to maintain the required reliability level. Analyzing life support system on the basis of its functional condition forecasting models preventive steps for neutralization of destabilizing factors are developed. It is carried out in two ways: Protection from destabilizing factors, the creation of the elements, capable of normal functioning at critical loadings on the system; Abatement of destabilizing factors themselves.

A statistically normal distribution $\lambda(\tau)$ is typical for units and aggregates, the failure of which occurs due to deterioration, friction, action of corrosion and erosive processes. An exponential distribution takes place in cases with prevailing sudden failures, and the influence of deterioration and ageing of units and details is insignificant.

It is possible to distinguish as the main forecasting LSS functional condition factors (the maintenance of which parameters directly influences serviceability and health of crew members) probability factor $p_r(\tau)$ of providing the crew with required comfort conditions and probability factor $p_s(\tau)$ to secure life saving conditions for crew members in closed living compartment. The fulfillment of the following conditions is necessary:

$$p_r(\tau) \geq [p_r(\tau)]_{per} \text{ and } p_s(\tau) \geq [p_s(\tau)]_{per}, \quad (6)$$

where $[p_r(\tau)]_{per}$ − minimally allowable probability factor of required comfort conditions maintenance for the period of LSS autonomy τ;

$[p_s(\tau)]_{per}$ − minimally accepted probability factor of safe conditions maintenance for LSS operating period.

The calculation of values $p_r(\tau)$ and $p_s(\tau)$ are calculated on the basis of structurally functional schemes of reliability. All LSS elements are divided into two groups according to failure consequences: the elements with accepted failures or those which result in an output of dependent internal parameters of atmosphere and lead to the discomfort of crew members; and the elements with non-accepted failures or such which result in an output of parameters beyond the limits safe for the life of crew members. For defining $p_r(\tau)$ into the structural-functional reliability scheme, two groups of elements and those reserve units which may provide the required conditions in case of failures of basic elements are included. For defining $p_s(\tau)$ into the structural-functional scheme, a group of elements with non-accepted failures and all reserve and emergency units which may provide safe conditions for crew members life, are included.

With the help of structural-functional schemes the equations for definition $p_r(\tau)$ and $p_s(\tau)$ are made taking into account all the required on LSS restrictions.

In table 1 some results of the calculations based on a suggested method are presented. Thus for defining $p_r(\tau)$ the time τ_r of LSS autonomy was assumed to be 1000 hours, and for calculations $p_s(\tau)$ $\tau_s = 250$ hours. Reliability of heat supply subsystems was assumed to be identical and it was not taken into account.

According to the probability of non-failure operation $p(\tau)$ it is possible to judge the potential of dissipative function for LSS, and according to its change − the expenditure of this potential.

As there is insufficient information for determining probability of non-failure operation during the development of prospective units for forecasting a LSS functional condition it is proposed to replace $p_r(\tau)$ and $p_s(\tau)$ for Quirk's indexes of reliability IR^k [5].

Table 1

Reliability Characteristics of LSS Elements

LSS Elements	Failure rate, $\lambda \cdot 10^6$, h^{-1}	Required probability for maintenance of habitability, $p_r(\tau)$	Probability of maintaining safe conditions, $p_s(\tau)$
CO_2 scrubber	0,1	0,9999	0,9999
Dehumidifier	1,0	0,9990	0,9997
Cooler-heater	1,0	0,9990	0,9997
Recuperative heat exchanger	1,2	0,9988	0,9997
Circulative Blower	22,2	0,978	0,9945
Absorber	0,1	0,9990	0,9999
Magnetic gas valve	6,7	0,9933	0,9983
Magnetic water valve	0,11	0,9998	0,9998
Regulative valve	9,32	0,9907	0,9977
Temperature and humidity control valve	10,95	0,9891	0,9973
Fan (indoor unit)	62,0	0,9399	0,9846

A traditional Quirk's method is not appropriable for the reliability analysis of compound units, but only for separate elements. That's why it was modified with the purpose to apply it at the reliability analysis of LSS complex, including both sequential and parallel functional connections. All the LSS elements should operate properly for the normal operation of the system with sequential functional connections. Therefore, according to the reliability theory, parameter IR^k for sequential systems is defined as follows:

$$IR^k = \prod_{i=1}^{n} \left(IR^k \right)_i . \qquad (7)$$

The failure of all the elements of the system is necessary for the failure of the whole system with parallel functional connections. Therefore, according to the theory of reliability, parameter IR^k for parallel systems is defined as follows:

$$IR^k = 1 - \left[\prod_{i=1}^{n} \left(1 - \left(IR^k \right)_i \right) \right] . \qquad (8)$$

To define the numerical values of Quirk's reliability indexes the following recommendations are offered: $IR^k = 0,999$ − for a case of the greatest reliability of LSS elements; $IR^k = 0,990 \ldots 0,980$ − for a case of average reliability of LSS elements; $IR^k = 0,900$ − for a case of the least reliability of LSS elements.

For defining the reliability index IR for a life support system consisting of n elements, having their own indexes of reliability $(IR)_i$, it is possible to use the formula:

$$IR = \frac{\sum_{i=1}^{N} (IR)_i}{n} . \qquad (9)$$

Then the criterion to be used for forecasting the LSS functional condition, which takes into account as an example the characteristics of mass, will look like:

$$k_{ef} = \frac{1}{M} k_s \sum_{i=1}^{N} (IR)_i \Big/ N \rightarrow \max , \qquad (10)$$

where k_s − the factor of safety accepting value from 0 up to 1 according to the consequences of unit failure;

$(IR)_i$ − reliability index of i-element;

k_s takes into account an estimation of safety B_i of the concrete unit or subsystem in points, and the general limit number of points of safety B :

$$k_s = B_i / B . \qquad (11)$$

To define k_s it is possible to accept in general the following estimations in points: 1 − the failure of an element conducting to deterioration of breathing gas mixture composition (for example, allocation of smoke, other caustic substances), that requires individual emergency protection and possible crew evacuation; 2 – the allocation of undesirable gases and aerosols which should be absorbed by special regeneration units and which sharply increase loading on them; infringement of thermal balance and increase of loadings on LSS heat exchange equipment owing to failure of conditioning unit, etc.; 3 – do not influence the composition and parameters of breathing gas and crew comfort. Thus, at the absence of influence on composition and parameters of breathing gas mixture $k_s = 1$ at the being of accepted $B = 3$.

In some cases it is possible to simplify the being of k_{ef} replacing k_s by the coefficient of failures:

$$k_f = n_k / \sum n_i , \quad (12)$$

where n_k − quantity of failures on examined units (subsystems);

$\sum n_i$ – total number LSS elements failures.

A dissipative function (i.e. function describing irreversible processes) is offered for the correct estimation of life support systems stability and the analysis of ways for formation and functioning of existential structures [7].

The delimitation of stability of the stationary condition will be carried out by a method of step-by-step casual influences of time and space in a range ±10% from stationary values. Stable LSS operation is characterized by the negative value of a dissipative function. The prevalence of local areas with negative function characterizes the ability of the system to be self-organizing. The positive value of a dissipative function means instability of a LSS, infringement of hierarchical connections, and needs for the revision of models or analyses methods.

Conclusion

Updating of phenomenological models of life support systems according to the described methods enables us to improve the methodological base for the development of fundamentals of life support systems design, to develop the specification method for optimum parameters of life support systems based on the deduced criteria at the working ranges of internal and external environmental parameters, to research the stability of optimum parameters and to forecast a life support system functional condition after a certain time of its operation.

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