Reliability of life support systems depending on the degree of their biologisation

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Abstract. Long-range and long-duration autonomous missions of manned transport systems have different objectives depending on the environment. They can be tasks of studying and mastering the depths of the world ocean, Arctic and Antarctic multi-purpose missions, etc. The most complicated of such missions may be manned flights to planets with the purpose of their exploration during long stays. Reliable technologies of life support systems (LSS) of autonomous transport systems (ATS) mastered in space missions can be fully or fragmentarily used in missions of other habitats. The reliability of any long-term manned missions depends on the degree of LSS autonomy, the level of its biologisation, and the efficiency of integrated closed biotechnological cycles. With the help of unmanned interplanetary vehicles, the presence of water reserves on Mars has been proved, the Mars atmosphere has been studied, and methane, the origin of which is yet to be discovered, has been discovered, all of which will undoubtedly contribute to the exploration of the planet. This indicates the possibility of organising human life on Mars and contributes to the preparation of a manned mission with the mission of thorough exploration of the planet. Biotechnology has long ago mastered in Earth conditions biosynthesis of animal microbial protein on the basis of methane, water, and air. If the LSS ATS of the Martian manned mission includes closed biotechnological cycles with the participation of these substances, they will make it possible to provide food for the ATS crew not only at the stage of a long flight to Mars, but also on its surface at the initial stage of colonisation, including the use of planetary resources. The purpose of this paper is to analyse and identify ways to improve the reliability of ATS during long-duration and extended manned missions when there is no possibility of resupply in the LSS.

1 Introduction

Autonomous missions outside the usual human habitat are impossible without LSS of varying degrees of sophistication. ATS in deep-sea navigation or in high-altitude flight are equipped with LSS, providing the crew with breathing and feeding capabilities and creating acceptable living conditions. As the autonomy period increases and the distance from the launch base increases, increasingly multifunctional, more advanced and reliable LSS are required. Orbital ATS missions differ from interplanetary missions primarily in their ability to resupply and

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return spent materials and life wastes. Orbital space station missions are entirely designed for resupply. Recently, the LSS has developed systems for water regeneration, air purification from carbon dioxide, greenhouse systems and systems for growing microalgae, higher plants and biological objects are being investigated. Thus, apparently, there will be a gradual and non-alternative biologisation of LSS, allowing to create on board ATS the habitat conditions, maximally close to terrestrial ones, which in the long term will turn this trend into a possibility to create such LSS, which will be able to provide a long-duration manned ATS flight.  

Reliability of life support systems is positioned as one of the most important conditions characterising an autonomous transport system, which determines the efficiency and safety of long-term and long-range missions. The development of ATS with the increasing complexity of their tasks requires from LSS not only high efficiency, but also reliability. This fact confirms the increasing role of reliability as one of the main technical characteristics of both ATSs and their LSSs. The modern strategy of LSS development is characterised by an increase in the volume of tasks they perform, which undoubtedly leads to changes in reliability. It is of practical interest to assess the feasibility of technical implementation of one or another additional function of LSS, including increasing the degree of biologisation, by the criterion of reliability itself. This is especially important when the additional function itself has no alternative solution. The solution of this problem implies the use of the functional feasibility factor, which should take into account not only all the main characteristics of the base or orbital LSS based on delivery and storage, but also additional ones based on closed biotechnological cones. When calculating reliability it is important to assess the accuracy of primary information and its statistical basis, which is possible in case of serial production and mass operation and difficult to do in case of single production or small series of products. One of the ways to estimate the accuracy of reliability calculations can be the application of the Mellin transform, closely related to the Fourier and Laplace transforms. On this basis, let us consider ways to obtain distributed reliability of typical LSS circuits and their optimisation taking into account self-adjusting additional biologisation circuits.

The reliability of an LSS is considered as the property of the system to perform a given function, depending on a large number of factors, the main ones of which include:
1. The scope of functions performed by the LSS and the algorithms used to solve them;
2. The required duration of system operation;
3. The structure of the LSS;
4. Requirements for the accuracy of LSS operation and the limits of acceptable changes in the main parameters;
5. Reliability of circuits included in the LSS;

On the other hand, ensuring the established level of reliability correlates with certain limitations such as weight, cost, energy consumption, etc. Thus, when designing promising LSS it is necessary to consider possible variants according to dependencies of reliability of fulfilment of the set functions and taking into account limiting factors and choose the most acceptable one.

The need to improve the efficiency of LSS ATS in the performance of long-range missions, requires the inclusion of additional functions, which leads to the complexity of the system, and, consequently, to a decrease in its reliability. In this sense, efficiency and reliability act as antagonists to each other, which leads to the need to incorporate more complex LSS design algorithms that incorporate probability theory methods and take into account the integration of interconnected devices operating on different principles but performing the same function.
2 Materials and methods

Table 1. Required mass of LSS components for Martian expeditions

<table>
<thead>
<tr>
<th>Name of LSS components</th>
<th>Weight per 1 person/day, kg</th>
<th>Weight per 6 persons. 1 day, kg</th>
<th>Weight per 6 persons. 50 days, kg</th>
<th>Weight per 6 persons. 100 days, kg</th>
<th>Weight per 6 persons. 500 days, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>0.96</td>
<td>5.76</td>
<td>288.0</td>
<td>576.0</td>
<td>2880.0</td>
</tr>
<tr>
<td>Water</td>
<td>16.9</td>
<td>101.4</td>
<td>5070.0</td>
<td>10140.0</td>
<td>50700.0</td>
</tr>
<tr>
<td>Drinking</td>
<td>2.5</td>
<td>15.0</td>
<td>750.0</td>
<td>1500.0</td>
<td>7500.0</td>
</tr>
<tr>
<td>Shower, wash</td>
<td>4.5</td>
<td>27.0</td>
<td>1350.0</td>
<td>2700.0</td>
<td>13500.0</td>
</tr>
<tr>
<td>For laundry</td>
<td>7.0</td>
<td>42.0</td>
<td>2100.0</td>
<td>4200.0</td>
<td>21000.0</td>
</tr>
<tr>
<td>Technical, ACS flush</td>
<td>0.6</td>
<td>3.6</td>
<td>180.0</td>
<td>360.0</td>
<td>1800.0</td>
</tr>
<tr>
<td>For vitamin greenhouse</td>
<td>0.3</td>
<td>1.8</td>
<td>90.0</td>
<td>180.0</td>
<td>900.0</td>
</tr>
<tr>
<td>Dishwashing</td>
<td>2.0</td>
<td>12.0</td>
<td>600.0</td>
<td>1200.0</td>
<td>6000.0</td>
</tr>
<tr>
<td>Food</td>
<td>1.75</td>
<td>10.5</td>
<td>525.0</td>
<td>1050.0</td>
<td>5250.0</td>
</tr>
</tbody>
</table>

This amount of additional cargo creates problems not only at mission start-up but also in flight. Therefore, it is necessary to add additional functions to the LSS to ensure the emergence of renewable resources from waste produced in closed biotechnological loops. The necessary addition of some efficiency-enhancing functions, such as closed loops of minerals, oxygen, methane, organic matter, etc., if certain conditions are fulfilled, including circuit logic of connection, can give the LSS an increase in reliability. Figure 1 shows the structural diagram of combining a number of biotechnological cycles claiming to be included in LSS as an additional function [2].

The numerous biological cycles of different substances interrelated with each other and with terrestrial processes, which continuously occur in the biosphere of the Earth, harmoniously perform the main task: the maintenance and development of multispecies life. Artificial maintenance of adequate living conditions for the crew during long-term autonomous missions requires a reliable and effective LSS on board ATS, based on nature-like biotechnological cycles integrated into a closed multifunctional circuit. The examples of the main biotechnological cycles that provide acceptable living conditions for the ATS crew are given below:

Food – exometabolism of the crew – methane digester – nutrient medium – fermenter and phototrophic link – biomass, higher plants: cereals and vegetables – food


Oxygen – fermenter – crew – carbon dioxide – photobioreactor, phototrophic link – oxygen

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We can also describe other, merely biotechnological cycles; the main principles and
requirements for their integration into the closed LSS of autonomous transpor
tion systems are the maximum operational reliability, low weight and small dimensions, low power
consumption, high efficiency, ergonomics, and serviceability.

Fig. 1. Diagram of the closed multifunctional integration loop for the LSS of ATS based on the
biotechnological cycles

The closed multifunctional loop for integrating biotechnological cycles is a set of basic
apparatuses, systems, devices, and material flows synergistically performing different
functions aimed at accomplishment of the main task: life support of the ATS crew.

The work of the closed loop integration should be considered separately for each specific
biotechnological cycle, since the devices, systems and material flow for each cycle can be
simultaneously engaged in different structures of the schematic diagram and perform
different functions.

The control system and auxiliary devices are not shown in the figure.

The closed multifunctional integrated circuit of biotechnological cycles includes:

- Fermenter for aerobic cultivation of protein biomass of animal origin based on the
  association of methanotrophic, hydrogen and heterotrophic bacteria.
- Photobioreactor for growing the biomass of microalgae with simultaneous transformation
  of carbon dioxide into oxygen.
- Centrifuge for separating the biomass from the culture liquid.

Fig. 1 shows a schematic diagram of the proposed closed multifunctional integration loop
for the LSS of ATS based on the above biotechnological cycles.

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Methane digester with the functions of recycling exometabolism of the crew and phototrophic waste, as well as obtaining biogas, trace elements and soil. Unit for biogas separation into carbon dioxide and methane. Phototrophic element for the cultivation of higher plants, with the function of biotransformation of carbon dioxide into oxygen. At the same time, minimum stocks are needed, but only as an inviolable reserve for the period of maintenance and recovery operations.

The set of functions performed by modern LSS of orbital ATSs is characterised by the set of functions $S = \{S_1, S_2, S_3, \ldots, S_n\}$, where $S_i$ defines multiple functions; $S_1$ – gas supply system; $S_2$ – water supply system; $S_3$ – sanitation system; $S_4$ – solid waste management; $S_5$ – thermal management system.

Depending on the purpose of the ATS, closed biotechnological loops are added to the given set of functions performed by the LSS, thereby increasing the degree of biologisation of the LSS ATS. In general, both the set of functions and the set of additional loops can be considered unordered. Various attributes can be used to order their set and establish a hierarchy of function realisation. Changing the volume of LSS tasks to be solved affects its reliability and changes other parameters of the system. One of the signs of ordering the set of functions can be the increment of the generalised LSS quality criterion, and taking into account that separate characteristics of the system have different physical nature and dimensions, the most convenient is the relative dimensionless LSS quality criterion. The classical way to increase reliability and ensure fault tolerance is the use of redundancy, in this case – the inclusion in the LSS of additional functions solved by closed biotechnological circuits.

The vector of characteristics for functions $i$ of the considered family of sets can be given by the matrix $Y_i$:

$$Y_i = \begin{bmatrix} y_{1i} \\ y_{2i} \\ \vdots \\ y_{ni} \end{bmatrix}$$

where $n$ is a number of system characteristics.

For each of the characteristics, a function $f_k(y_{ki})$ giving a relative assessment of this characteristic can be constructed. The aggregate of relative evaluations of all characteristics is represented by a matrix $X_i$:

$$X_i = \begin{bmatrix} f_1(y_{1i}) \\ f_2(y_{2i}) \\ \vdots \\ f_n(y_{ni}) \end{bmatrix}$$

Functions $f_k(y_{ki})$ for a limited range of performance variation $y_{k \text{ max}} - y_{k \text{ min}}$ can be chosen to be linear:

$$x_{ki} = f(y_{ki}) = -a_{ki} + b_{ki}y_{ki},$$
For the model under consideration, all characteristics are negative, these can include failure probability, weight, failures, etc. The maximum values can be the values of LSS characteristics that are in operation and have shown the best results. The maximum values may be chosen based on the prospects of implementation or assumed to be zero. Under the above assumptions, the functions $f_{ki}(y_{ki})$ are non-decreasing with a range of variation $0 \leq f_{ki} \leq 1$. In this case, the lower bound corresponds to reliable, ideal systems.

If each of the relative assessments is given a different influence coefficient defined by the matrix-string:

$$a_{i} = \begin{vmatrix} a_{1i} & a_{2i} & \ldots & a_{ni} \end{vmatrix},$$

then the total relative evaluation for the $i$-th function will be expressed as follows:

$$r_{i} = \sum_{k=1}^{n} a_{i} x_{ki} = \sum_{k=1}^{n} a_{i} x_{ki},$$

The set of influence coefficients $a_{i}$ must satisfy the condition:

$$\sum_{k=1}^{n} a_{ki} = 1 = 1.$$

In the case of not favouring individual characteristics, the coefficients $a_{i}$ for all characteristics:

$$a = 1$$

Evaluating each of the LSS tasks to be solved, we obtain the vector of evaluations $r$ in the form of a matrix:

$$r = \begin{bmatrix} r_{1} \\ r_{2} \\ \vdots \\ r_{n} \end{bmatrix},$$

here $n$ is the number of tasks to be solved by LSS.

In general, influence coefficients defining the importance of each function can be set for individual tasks:

$$\beta = \begin{vmatrix} \beta_{1} & \beta_{2} & \ldots & \beta_{n} \end{vmatrix},$$

To obtain the feature, by which the set of functions is ordered, we use the average estimation of the form:

$$R_{j} = \frac{\sum_{i=1}^{n} (1 - \sum_{k=1}^{n} a_{ki} x_{ki}) \beta_{i}}{\sum_{i=1}^{n} \beta_{i}}$$

where $o = 1,2,3,\ldots, n$.

If there is no preference for any of the functions performed by the system ($\beta_{1} = \beta_{2} = \beta_{n} = 1$) and none of her characteristics ($a = 1$), then the estimation takes the form:
Let us take the increment of the dimensionless quality (efficiency) criterion of a system with a large number of functions relative to its value for a system with a smaller number of functions as the functional feasibility coefficient:

\[ \Delta R_j = R_n^0 + j - R_n^0 \]

To determine the functional feasibility factor, one should proceed either from the minimum number of functions to be performed by the system or from the number of functions corresponding to some basic system \( N_0 \). Let us consider the case when only one function is added, and the evaluation is presented in the following form:

\[ R_n^0 + 1 = R_n^0 + r N_0 + 1 \sum_{i=1}^{N_0} \beta_i \]

\[ N_0 + 1 \sum_{k=1}^{n} a_k N_0 \]

Determining the increment of the estimate when introducing one additional \( N_0 \) function, we obtain an expression for the functional feasibility coefficient:

\[ \Delta R_1 = R_{N_0+1} - R_{N_0} = \beta_{N_0+1} \left( r_{N_0+1} + 1 - R_{N_0} \right) \]

\[ \sum_{i=1}^{N_0} \beta_i \]

The acceptance condition for the technical realisation of an additional function is defined by the following inequalities:

\[ \Delta R > 0; \]

\[ r_{N_0+1} > R_{N_0} \]

Analysing the obtained condition, we can conclude that the addition of a low-importance function that is of great importance \( r_{N_0+1} \), gives a positive value of \( \Delta R \), i.e., the best system. At the same time, adding an important function, but with a small value of \( r_{N_0+1} \), which means a decrease in reliability, leads to a negative value of \( \Delta R \), i.e. leads to a worse system.

For example, it is necessary to determine the feasibility of an LSS to fulfill an additional function that is solved by one of the closed biotechnology loops under the following propositions:

1. The quality of the LSS is characterised by two indicators (\( n = 2 \)):
   - accuracy, which is determined by the probability of the parameter exceeding the limits of the established tolerances \( g_t \);
   - reliability, defined by the probability of failure \( g_n \).

The resulting relative estimates will be as follows:

\[ x_t = a_t + b_t g_t = -0.5 + 25g_t \]

\[ x_n = a_n + b_n g_n = -1 + 20g_n \]

We consider only one LSS function \( N_0 = 1 \) by the simplest algorithm, for which \( g_t = 0.06 \), \( x_t = 1 \), \( g_n = 0.06 \), \( x_n = 0.2 \).
2. No preference is given to both the accuracy and reliability characteristics and the functions performed by the LSS
\[ a = \frac{1}{2}, \quad \beta = \frac{1}{2} \]

Under these assumptions, a generalised quality assessment of the baseline LSS \( R_{N0} = 0.4 \).

Let the onboard methane recycling function [3] be added to improve LSS efficiency, leading to the following absolute and relative performances:
\[ g_1 = 0.4, \quad x_{t2} = 0.5, \quad g_n = 0.1, \quad x_n = 1 \]

To assess the feasibility of implementing the onboard methane processing function, we need to calculate the following \( r_{N0} + 1 \) according to the formula
\[ r_2 = 0.25 \]

Since \( r_2 < R_{N0} \), the implementation of the considered additional function is inexpedient due to a significant decrease in the reliability of the LSS. It is possible to estimate to what level the reliability should be increased in order to obtain a higher quality assessment of the corrected LSS compared to the basic one. To solve the above problem, taking into account the assumptions made, using the proposed approach, we obtain
\[ g_{n2} = 2 - x_{t2} + a_n - 2R_{N0}/20 = 0.085 \]

Thus, implementation of an additional onboard methane processing function is feasible if the reliability of the LSS is greater than 0.915. Similarly, the reliability of including other biological and biotechnological functions in the ATS LSS can be assessed.

3 Conclusions

Long-duration ATS missions are impossible without incorporating closed biotechnological cycles into the LSS. The effectiveness of ATS is in direct dependence on the degree of biologisation of their LSS. Closed biotechnological cycles in LSS, which fulfil the functions of substance regeneration, should be waste-free. The biotechnological regeneration cycles included in the LSS should not reduce the reliability of the LSS.

References


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