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Comprehensive Approach for Service Life Assessment of Solid-Propellant Rocket Motors

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Abstract
In this article we propose comprehensive approach for service life assessment of solid-propellant rocket motors. The comprehensive approach is based on the mix between traditional standardized (chemical stability, live-fire, etc.) and the non-destructive methods. This approach is needed to precisely calculate reliability and to compensate mixed results obtained from different parts of lots. Long term in service is the main prerequisite of this mixed results.
The main problem for implementing NDT is the lack of standardization in this area, but in this case the non-destructive methods applications is to provide additional information in order to "transfer" precisely the results obtained from destructive standardized methods over the whole lot.

Keywords: ammunition life cycle, ammunition service life, solid propellant rocket motor, non-destructive testing

1. Introduction

Nowadays, the emphasis in military understanding is on the provision of military capability, to which the weapon systems and ammunitions probably are the most significant and directly referred add of the materiel. From logistics prospective, for ammunitions this is related with establishment of large stockpiles in order to ensure current and future operational or training activities and needs [17, 18]. Being one-shot devices, the most important issue during their life cycle is to ensure their safety during service life[1] and of course their performance. Starting in very early phase (in design and development stages) and continues during service, safety and performance lie on the munitions system reliability. To ensure it, the periodical tests, predominantly destructive ones, plays significant role.
These suggestions is totally valid for tactical missiles. The majority of them use solid rocket motors. Solid rocket motor is one of the important subsystems of tactical missiles which represents beteen 40 and 65% of the total missile mass [12].
During its life cycle, the rocket motor experiences thermal loads under the variation of environmental storage temperature, but also vibrational and impact loads as a result of transportation and service handling. All of these affect on the rocket motor in distinct way depending from:

- Design, materials and used technologies;
- Overall climatic profile;
- Reaction of energetics to real environmental and service handling loads;

[1] The service life is defined as the time that the rocket motor is able to operate reliably, safely, accomplish the setted requirements under the real life loads [12]

– Current service life period.

Negative combination from these factors could lead to irreversible changes in chemical composition and mechanical properties, cracking and other damages, which compromise normal engine performance. As a result, unstable combustion may occur, and worse – destruction or even explosion of the rocket engine. [12, 28, 29, 30, 31].

But rocket motors are designed to function within narrow performance boundaries. In order to guarantee safety and performance we must be able to predict their behaviour, as well as determine their residual life span after the system has been subject to handling and storage under varying conditions which are not always fully recorded.

Service life assessment begins in the development phase and monitoring programs must be developed and implemented during the life span of the system.

The two interacting iteratively paths to produce current service life estimates are used [9].

One path is analytical which assesses the rate of material aging, the effect of material aging on the system (i.e., stability, performance, integrity, etc.) and the statistical probability of system failure during service life. The typical approach is to specify conservative service life period, determinated under harsh environment conditions and severe service loadings. Generally, the base for service life period for the whole system is this of the non-replaceble part with energetic material with the shortest service life period, nevertheless that the designed rocket motor can be used safely longer (Table 1) [21].

Table 1. Expected service life for different tactical missiles components

<table>
<tr><th>Components</th><th>Expected service life, years</th><th>Posible degradation</th></tr>
<tr><td>Pyrotechnics</td><td>20</td><td rowspan="3">- Destruction of pressed or glued joints;
- Depletion of chemical precursors;
- Diffusion;
- Micro and macrocracks generation;
- Moisture.</td></tr>
<tr><td>Composite propellants (sealed)</td><td>20÷35</td></tr>
<tr><td>One or two components propellants (sealed)</td><td>20÷35</td></tr>
<tr><td>Electronic components</td><td>25-30</td><td>- “Electronic” aging;
- Damages after service loads.</td></tr>
<tr><td>Optical components</td><td>>50</td><td>- Damages after service loads;
- Moisture.</td></tr>
<tr><td>Power units</td><td>10-20</td><td></td></tr>
<tr><td>Contact surfaces</td><td></td><td>- Damages of seals;
- Contact corrosion.</td></tr>
<tr><td>Rubber and plastics components</td><td>10-20</td><td>- Damages after service loads;
- Thermal degradation.</td></tr>
<tr><td>Metal components</td><td>>50</td><td>- Damages after service loads;
- Thermal degradation.</td></tr>
</table>

The second path is system surveillance which includes system observation and system trend analysis. As a result, the service life estimate may predict a minimum service life (safe interval) that will likely be extended on testing at a later period. All aspects of service life issues for solid rocket motor will be addressed including chemical and physical aging mechanisms, methodology and techniques for determining service life, application of the service life methodology and techniques to systems and non-destructive test methods. For these paths, except non-destructive methods, existing system of standards and best practices [9].

Most of them is based on the destructive methods – live firings, chemical analyses, aging, mechanical tests, etc. [21]. In turn, the non-destructive methods (NDT) methods are powerful tool for many industry areas, but due to their inherent limitations and complementary nature of different types, many of them need to be applied depending on their suitability as a service life estimation tool [14].
Unfortunatelly, they aren't so popular tool (except the visual methods) in service life of ammunitions (except the production phase) (see Fig. 1), following to the main problems for implementing NDT for qualification of the ammunition – the scope and lack of standardization. For inspection at various stages of its production and service life of the rocket motors for instance:

- NDT methods such as radiography, ultrasonic testing and dye-penetrant testing are being employed for the inspection of hardware,
- Magnetic methods for shells and mortar bodies [36],
- Ultrasonic testing is applied for checking the bond-line integrity of case, ammunition elements and insulation layer [10, 23] and
- X-ray radiography is employed for evaluating both the integrity of propellant mass and the bond-line integrity of propellant and insulation [4, 26].

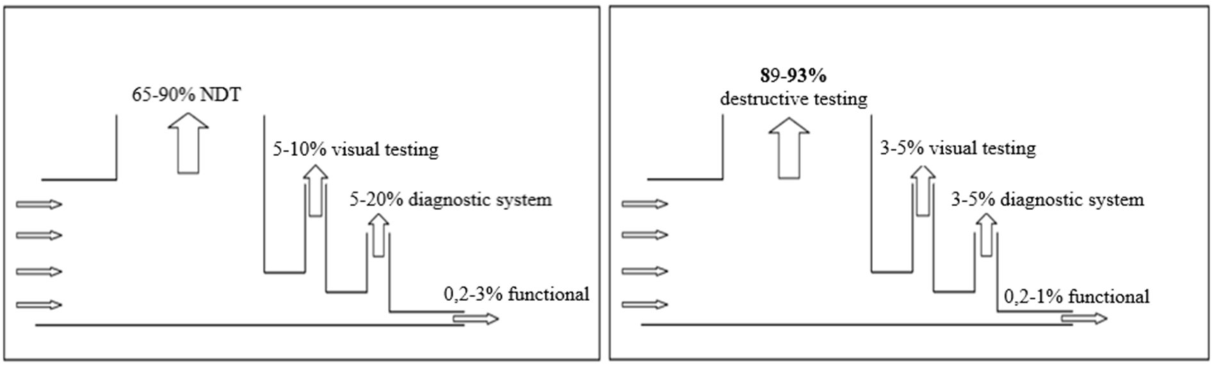

Fig. 1. Coverage of different methods in the industry (left) and in ammunition life cycle (right) (Adapted by [20])

This was compensated in previous studies [10, 12, 14, 15] and in thesis [21], where some non-destructive methods were verified and this is stimuli for proposal in this study a methodology incorporated standardized destructive and non-destructive methods.

2. Comprehensive approach for service life assessment of solid rocket motors

2.1. Justification of combined use of classical and non-destructive methods for service life assessment of solid rocket motors

The current approach is periodically to test in field environment whole tactical missile. The fuzes from different lots is subjected to laboratory testing. The rocket motors itself is not subjected to laboratory or field testing (except air-to-air missiles) and chemical analysis is not performed on regular basis, due to unreliable equipment.
The negative combination from this unefficient approach for surveillance and testing, lack of environmental records and the age of tactical missilles often "produces" mixed results (see fig.2) when classical approach is used, based only on sampling of some numbers from one lot. It is well a fact that the input elements, units and aggregates change their characteristics [4, 5, 27], and for munitions, producers tie the aggravable deadlines of the individual with the

prescribed lifetime. The term aging is marked by the generalized change in mechanical and chemical factors as compared to properties immediately after production.

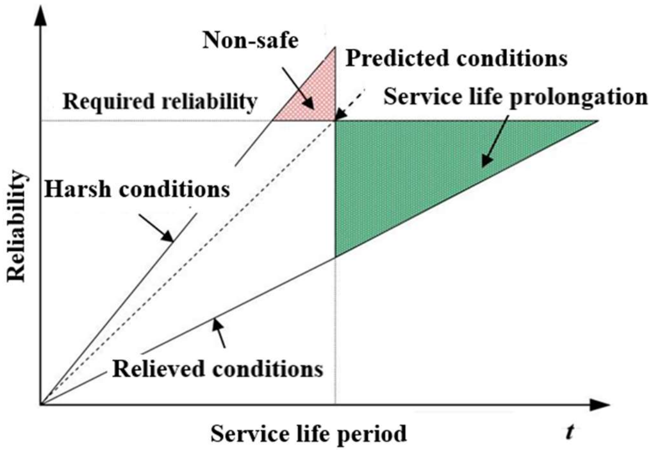

Fig.2. Different service life expectations for different specimens from one lot

Usually, the associated problems during the service life are related to explosives in rocket motors (solid propellant and pyrotechnics). During the service life they change their properties [10], the integrity of solid propellant is disturbed, the bond-lines are disintegrated, and defects like cracks, voids and depletion appear (fig. 3 and fig. 4). Also during the service life, the continuing changes in chemical composition are appeared. In detail, the aging processes in different energetic materials and their displays is described in [20].
The pyrotechnics are even more vulnerable, mainly because the trend to absorb the moisture.

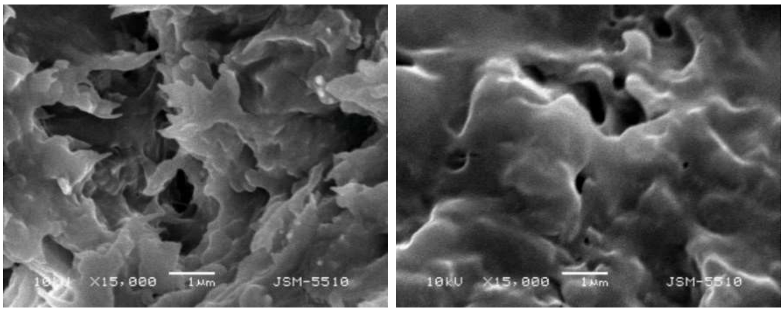

Fig. 3. "Sharpening" and "rounding"

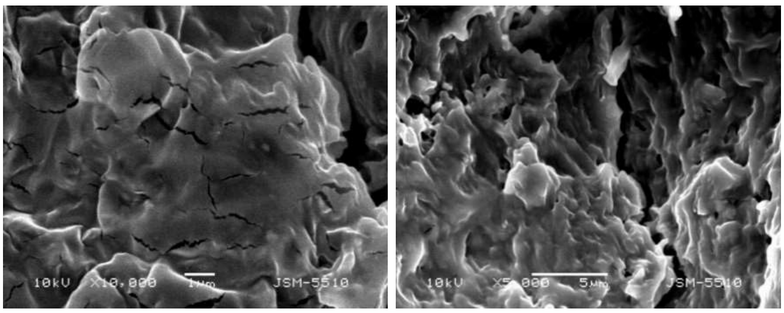

Fig. 4. Micro and macro cracks

Complexity of these can affect negatively on performance and safety during service life.

To monitor these changes during service life in this study we propose comprehensive methodology for evaluation of rocket motors of tactical missiles.

2.2. Comprehensive approach for service life assessment of solid rocket motors

Schematic view of methodology for evaluation of rocket motors of tactical missiles that has been followed in this study is showed in Figure 5.

For expensive and complex systems, the number of sampled units for destructive full-system tests, which are considered the gold-standard measurements of the performance of the system, may necessarily be small and it's hard task to make conclusions for whole lot performance based on the full-system test result of several test samples [21].

Fortunately, there are other sources of information on the system or component level and in this methodology we incorporate many other types as an alternate sources of information – from functional tests on component level to non-destructive testing, that practically could be performed on the whole lot. Logically, the relative proportion of data available from these alternate sources may reduce the need from full-system and in our case subsystem tests, and can enhance precision of evaluation.

The key aspects of this approach will be explained in some detail in this paper are: (1) how non-destructive methods can be added to "classical" destructive methods to produce single informative platform and (2) a unified methodology for precisely evaluating solid propellant rocket motors system level that combines with prediction up from the component level data, but for clarity of presentation we will not go into details for incorporation of data because this process we described well before – in [17] and [21] the author demonstrate Bayesian approach to incorporate data from different sources and here we present only the results on sub-system level. Also, due to same reasons, the sub-system decomposition process is not detailized here.

The proposed methodology is divided into two brances – "destructive" and "non-destructive". "Destructive branch" includes performance tests, all applicable standardized and validated methods, described in standardized documents (mainly STANAGs and allied publications) and specialized documentation – manuals, guidances etc.

The "non-destructive branch" combines different techniques. Two of them (Ultrasound technique implementation for aging characterization and X-Ray technique for defects characterization) are validated by the author in [21] and here only cursory notes are added. The rest non-destructive tests are well-known [4, 10, 23, 26].

The proposed ultrasound technique, based on different propagation velocities for different aged samples. The technique is well described in [21, 22] and here we will not go into details. This technique may give significant advantage, because other known techniques is based on chemical composition changes and related with destruction of the solid propellant. Otherwise using this ultrasound technique could be automated easily, it's fully non-destructive and hence all the motors in the lot could be subject on testing. The ultrasound technique is proposed as an additional tool in existing system of standards for service life qualification of solid rocket propellants. The method is partially proof for propellants include nitrate esters on micro level by electronic scaning microscopy. Of course, this technique have to be verified for more solid propellants and the future verification within the framework of more complex program is needed to develop the overarching tool.

Some notes regarding X-Ray technique proposed by authors. It is verified by medium power industrial system with film with passable quality for relatively small rocket motors with thin metal case [12, 21]. The results obtained showed possibility for detection of flaws with diameter less than 0,7-0,8 mm, that is not perfect but fully acceptable result for the designed purposes. Understandable, the limitations of x-rays (and γ-rays) in the control of materials with a small atomic number in the presence of materials with a large atomic number (a clasic example is metal-lined explosives) still exist and we can not expect to detect relatively small defects.

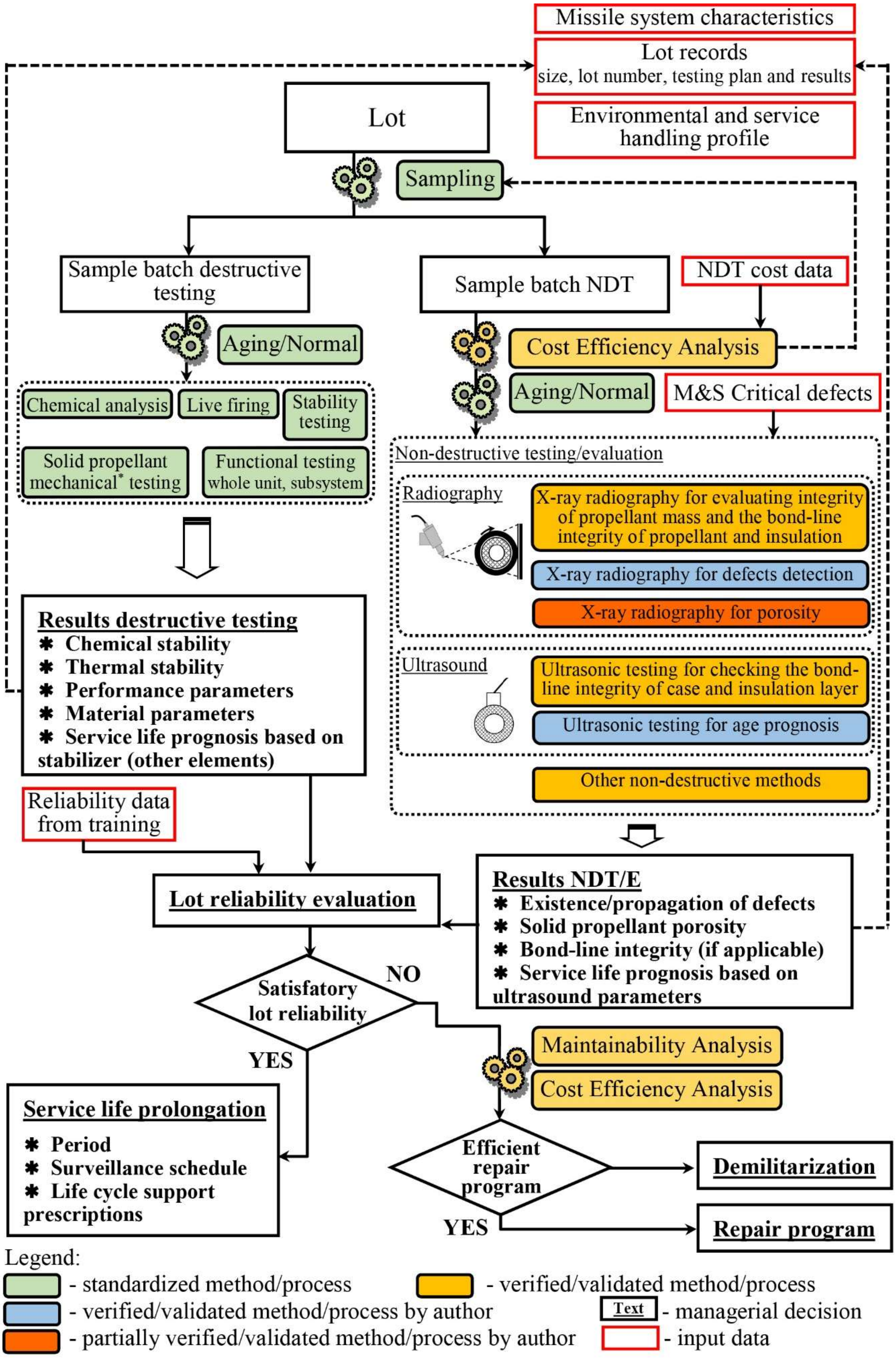

Fig. 5. Comprehensive approach for service life assessment of solid-propellant rocket motors

Fig. 6. Verification testing bet: a) solid propellant; b), c) and d) artificial flows; e) X-ray system; f) sample with X-ray film (Copied from [21])

Fig. 7. X-Ray film from rocket motor unit (Copied from [21])

3. Selected results

The results from reliability calculation on sub-system level is shown on Figure 6. The proposed methodology and Baesian approach are used for reliability calculation. The distinguished difference between prior and posterior reliability curves is observed, mainly due to implementation of non-destructive techniques.
Performed cost-efficiency analysis (subject on other article) showed that the (expected) whole cost of the performed test X-ray and ultrasound test is between 0,01 and 0,1 times of price of one unit in dependence of the type of the rocket. Nevertheless, one of the directions for future development, as well as improving sensitivity, precision and productivity of the NDT methods) remains the cost reduction.

Summary

In this study we propose comprehensive approach for service life assessment of solid-propellant rocket motors based on the mix between traditional standardized (chemical stability, live-fire, etc.) and the non-destructive methods. Because of the lack of standardization of non-destructive methods in this neurological area, their usage is as an additional tool, improving awareness.
The initial results are encouraging and implementation of these methods definitely improved accuracy of evaluation and practically could nullify existence of mixed results obtained from different parts of lots in performance tests.

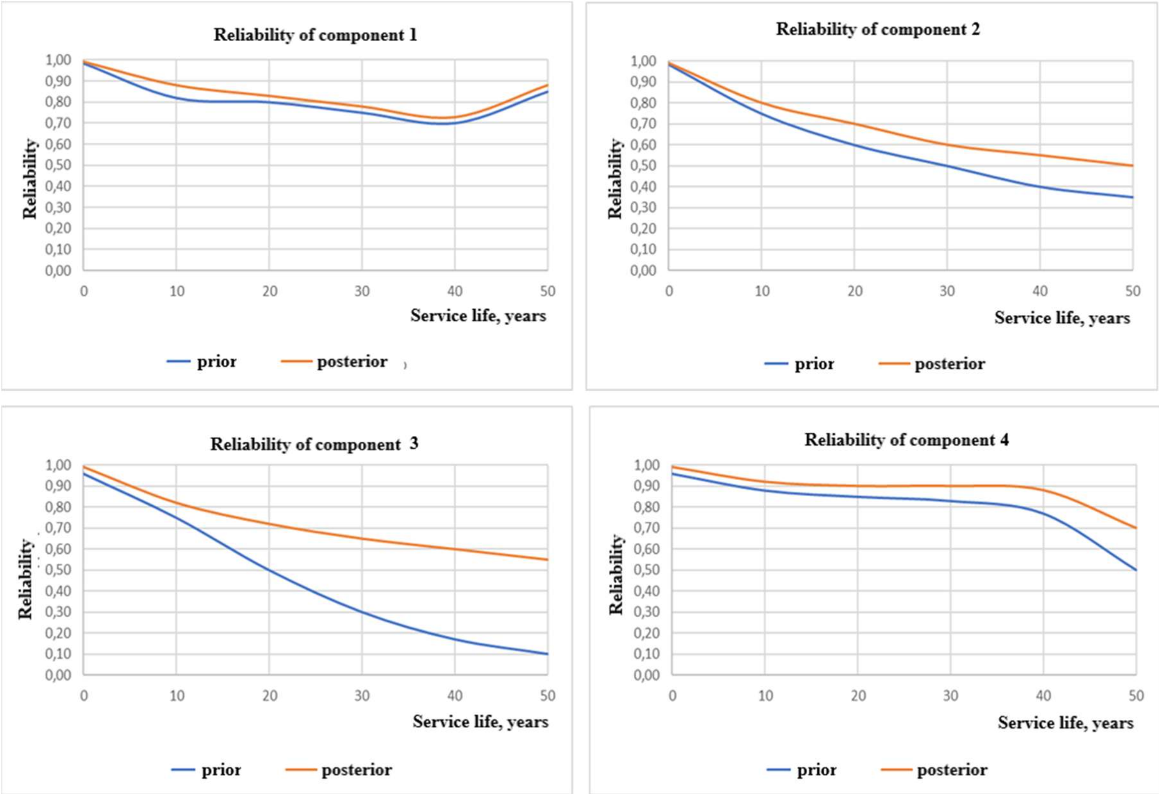

Fig. 8. Prior and posterior distributions for the reliability of the main elements of the rocket motor

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