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Methodology for the Creation of an Innovative Scientific and Technical Reserve in the Rocket and Space Industry

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Abstract. The paper analyzes the problem of creating an innovative scientific and technical reserve (STR) in the rocket and space industry. A general methodological approach to the creation of STR is proposed. The main provisions of the STR establishment methodology are formulated. Innovative uncertainty and some limitations are taken into account. Restrictions due to the structure of technological way of life in the economy, the phase of the cycle of economic conjuncture and the general laws of the development of technical systems are analyzed.

Keywords: innovative scientific and technical reserve, rocket and space industry, innovative restrictions, technological paradigm, general laws of the development of technical systems

Introduction

All the outstanding achievements of scientific and technological progress, including the successes of astronautics in the twentieth century, were achieved by advancing and solving problems of the development of science and technology. The basis of all innovations is an innovative scientific and technical reserve (STR), created long before the start of implementation of large projects [1].

The design stage (including the development of customer requirements and the concept of a space system) in real costs does not exceed 20% of the total cost of creating a product. At the same time, the significance of the work performed at this stage reaches 95% [2]. In this regard, the existence of an STR is crucial to the success of a project.

In Russia, the most theoretically developed subjects are the methodologies for creating an STR in the field of weapons and military equipment (WME) [3, 4, etc.]. However, the basic methodological provisions for the creation of an STR in the field of weapons and military equipment are poorly applicable to the creation of rocket and space technology (RST) for the following reasons:

- in the defense field, the problem of goal setting is much easier to solve than the problem of goal setting in space activities;
- the uncertainty of the directions of development of weapons and military equipment is significantly lower than the uncertainty of the directions of development of astronautics;
- space activities directly and indirectly affect many aspects of the society, while maintaining the national defense capability only creates conditions for normal operation of state institutions, organizations, establishments and citizens;
- the methodology for creating an STR for the development of weapons and military equipment does not take into account the limitations imposed by the structure of techno-economic paradigms in the economy, the phase of the economic cycle and the general laws governing the development of technical systems.

There are no countries in the World than have a regulated general procedure for creating an STR in various areas: different enterprises and organizations do it in their own way. As the analysis of the problem shows, the project principle of work organization when creating an STR, and especially goal programming, have significant limitations.

The project approach is limited in the areas of activity where the final result, the required resources and time are determined insufficiently or not at all. In the general case, the creation of an STR is a process, not a project (that is, the work on the creation of an STR should be carried out continuously!). Moreover, the process is creative, initiated by insights of scientists and engineers. Sometimes the creation of an STR can be a project, but only in a small number of cases, then when it comes to the purposeful creation of a basis for solving a specific task. However, in this case this activity can be considered a pre-project research aimed at the implementation of a specific project, rather than development of an STR.

The project approach is fixated on the tasks of managing the design process, involves rigidly defined procedures and, generally speaking, does not require considerable intellectual effort. There is a temptation to resolve the difficulties associated with the development of fundamentally new design solutions, either using the old technological basis, or by making trivial decisions by analogy.

With the wide introduction of the project approach, in combination with the general decline in the level of education, there is a threat of washing out of the creative element, and first of all, at the stage of creating the STR, replacing high-class specialists with managers and executives.

Goal programming in the conditions of accelerating technological development and deepening innovative uncertainties in the development of science and technology can inhibit the creation of an STR that implements truly innovative principles.

Nevertheless, in our opinion, some general directions for solving the problem of creating an STR for the rocket and space industry, not related to the project approach or goal programming, which can serve as the basis for a number of regulatory industry papers, can be proposed.

The purpose of this article is to substantiate the main directions of the methodology for the creation of an STR in the rocket and space industry.

1. The structure of the innovative scientific and technical reserve

In accordance with the definition given in GOST R 57194.1-2016 [5], an innovative scientific and technical reserve (hereinafter STR) refers to promising products of the intellectual activity of enterprises and organizations in the field of science and technology, critical and breakthrough technologies, the development and implementation of which in industrial production and products will lead to an increase in the efficiency of the industry and the introduction of technical systems with new properties and qualities. An innovative STR includes (Fig. 1) a scientific reserve (SR), a scientific and technical reserve (STcR) and a scientific and technological reserve (STlR).

At the initial stage of development of a specific system (space technology product), a previously developed STR can be represented as a network hierarchy of technical components (elements) of a *PBS* (*Product Breakdown Structure*) that are mutually coordinated by interfaces and which are integrated into the target system with the help of support systems. Each of the components of the PBS hierarchy in the life cycle includes the entire set of representations, from computer models to physical implementation.

The STcR includes promising products focused on creating a target technical system that can be described as a hierarchical product structure and is a mutually coordinated network hierarchy of technical subsystems and components integrated into the target technical system using support systems. The STcR is focused on a specific target system, which can be a specific product with a full life cycle, or a conceptual development project of advanced equipment. The result of the creation of STcR can be a research and development report, a system project, a patent, know-how and other innovative scientific and technical products.

The STlR includes advanced products focused on the creation of a support system that advances the target engineering system through its life cycle and is a coordinated network hierarchy of activities performed using current or advanced organizational, technical and technological mechanisms. At the same time, the advancement of the target system by the support systems along its life cycle (LC) is regulated by GOST R ISO / IEC 15288 [6] and GOST R ISO / IEC 12207 [7]. The STlR is a network hierarchy of tasks mutually coordinated by interfaces, a *WBS* (*Work Breakdown Structure*). The tasks are potentially implemented by technical and organizational mechanisms of the support systems for advancing the target system through its life cycle. Maturity, as the ability of a specific technology of a scientific and technological reserve to carry out work to advance target systems, is determined by the *TRL* (*Technology Readiness Levels*).

The result of the creation of STlR can be scientific and engineering products of the same type as in the case of NTNZ, but with an emphasis on technology (How to implement STcR? What production and technological capabilities, technologies, will this be required?).

SR, STcR and STlR in the general case may or may not be interconnected. SR, STcR and STlR can be interpreted as the degree of maturity of the STR: the cause-and-effect (production) dynamics of the creation of the STR can be described as a sequence: general theoretical concept (SR) ® technical solution (STcR) ® implementation tools (STlR).

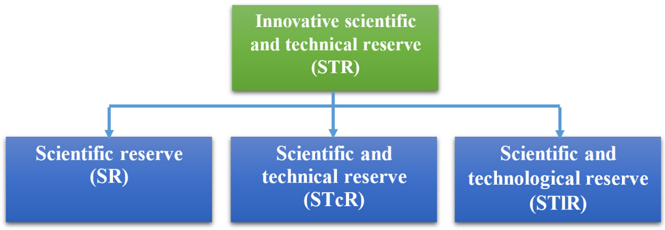

Fig. 1. The structure of the innovative scientific and technical reserve

Lastly, the NZ is the result of fundamental scientific research (new knowledge about phenomena, effects, laws, patterns, etc.) that is not directly related to the existing or advanced artifacts, technical means and technologies. Forms of presenting the SR as a commodity are research reports, articles, monographs and other sources of information in standardized forms, including archives of electronic documentation, designed for machine processing. The scientific reserve is focused on fundamental research and studies that do not directly imply subsequent research and development work (R&D) for the creation of a specific product of rocket and space technology.

Thus, the formation of the STR should be considered as a complex systemic activity that creates the scientific, technical and technological basis for the industry, carried out mainly by research organizations and individual researchers, together with the rocket and space industry and organizations of other industries, necessary for the creation (development, modernization) of various types and products of space technology. The STR includes the results of theoretical and experimental research, as well as exploratory development.

The structural components of the STR are [8]:

- new knowledge obtained in the course of studying the properties of material objects, processes and phenomena in the field of space exploration, including the results of theoretical and experimental research: a knowledge base for the areas of scientific and technical activities;

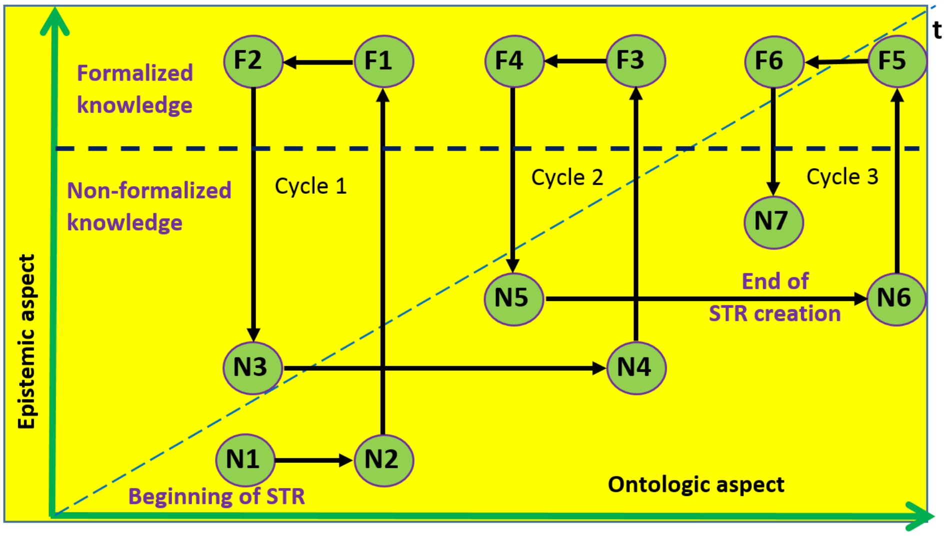

Fig. 2. The spiral of knowledge creation in the dynamics of the development of scientific and technical reserve

- new technical solutions (results of exploratory development), including design documentation, prototypes of new designs, elements and components of space technology (in the general, parts of target systems);

- technological processes and specialized equipment necessary for the development, production and testing of rocket and space technology, including processes and equipment for the design, production and processing of materials, assembly, quality control, testing. This component of the STR exists in the form of relevant regulatory and technical documentation and equipment (in general, supporting systems).

The process of creating an STR can be described by the so-called "knowledge spiral", which shows the transition of knowledge from one type to another. In particular, formalized (conscious) and non-formalized (unconscious) knowledge are distinguished. The creation of an STR is a continuous interaction of implicit and explicit knowledge through various forms of transformation. One of the main conditions driving the "knowledge spiral" (Fig. 2) is the redundancy of the STR. That is why leading countries are paying so much attention to creating a reserve. In the United States, in particular, the commitment to the creation of the STR in advance led to the fact that knowledge became a commodity as well as material objects [9].

The implementation of this principle leads to the fact that the number of research and development activities carried out by an enterprise deliberately surpasses the nomenclature of samples of rocket and space technology to be created. Therefore, when holding tenders for a contract for the creation of a new space technology, there will always be options to choose from. If the tenders are made multi-stage or at least two-stage (for example, the first stage is a tender for the implementation of an advance project or technical proposal, and the second stage, according to the results of the first, is the implementation of the remaining stages of product design), then there is competition, which is based on the STR, in advance created by each of the participants of the competition. Enterprises of the industry, creating an STR, are already competing with each other, although in an implicit form.

In our opinion, the creation of the STR can be financed either at the expense of the enterprise (most likely) or on the basis of budget financing. The amount of financing for creating an STR can be tied to achievements in this area, for example, it can be based on the results of the year: the higher is the volume of STR created, the higher is the next year funding for these purposes. It is imperative to create targeted financial incentives of specific scientists and specialists, developers of the STR.

The current results of the continuous process of creating an STR in the form of specific documents can be combined into an information base such as a depository. The semantic structure of such a depository is presented in fig. 3

The meaning of the term "depository" is that the information base of the STR not only stores STR documents, but also guarantees the copyrights of their developers with all the ensuing consequences. An STR depository contains building blocks that (with appropriate "processing") can be used as the basis for a specific project.

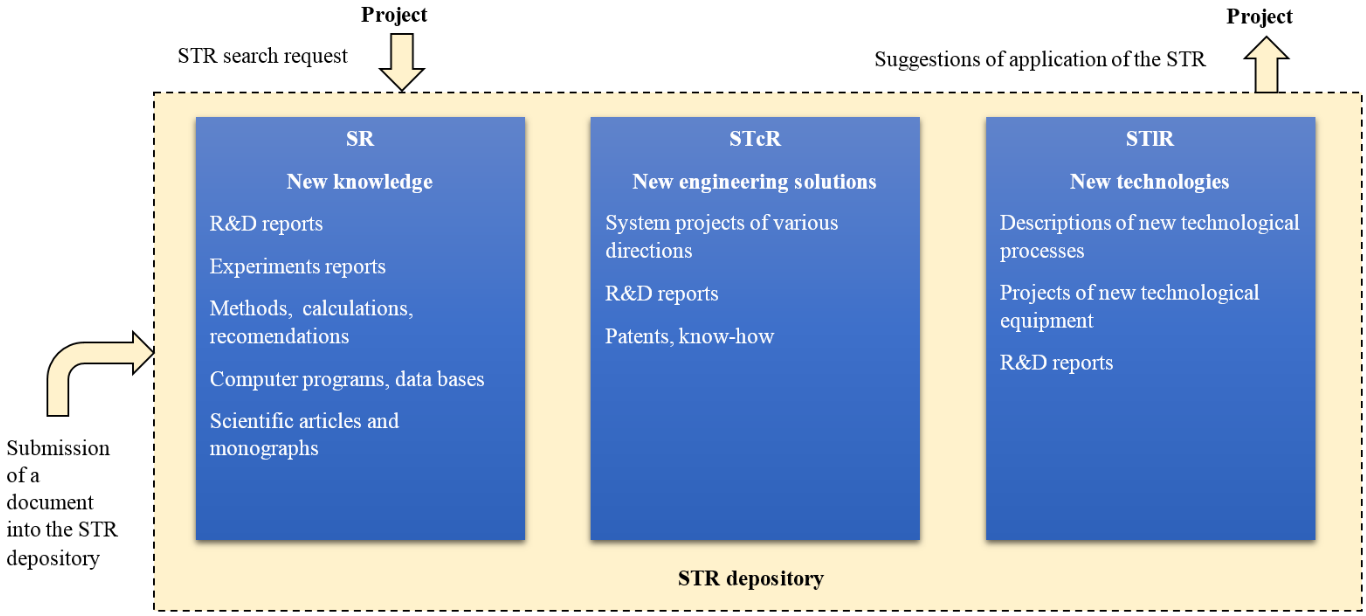

Fig. 3. The semantic structure of an STR depository

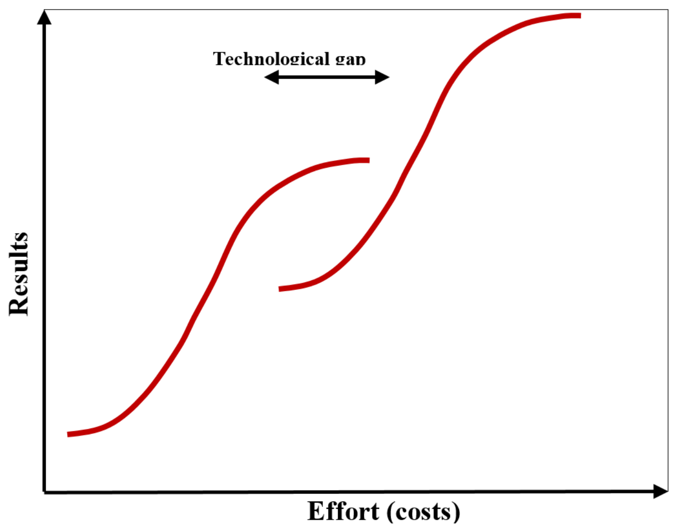

Fig. 4. Illustration of the technological gap concept

2. General principles for the creation of an innovative scientific and technical reserve

The main problem of creating an innovative STR is the so-called innovation uncertainty, which arises as a measure of ignorance of potential directions and opportunities for technological development, in particular, taking into account possible technological gaps that break the momentum of the development of science and technology (Fig. 4). The technological gap in the development of a technical system is understood as a qualitative leap in the dynamics of the target (forecast) characteristics of the system, a gap in its evolutionary development due to new achievements of basic science or new design solutions. Development of any technical system sooner or later reaches a level where, in spite of the efforts made, its characteristics hardly improve. As an example, a liquid rocket engine can be given: its technical evolution has reached the limit: any design solutions are able to raise the specific impulse by no more than 10-15%, but the costs increase geometrically. In such a situation, further development of the system is possible only on the basis of a technological gap. A technological gap eliminates the innovation uncertainty.

The methodology of the continuous creation of the STR becomes particularly important in connection with the impending problem of singularity (Problem 2045)[1], illustrated by the Panov–Snooks curve [10]: there is a pronounced tendency for the innovation uncertainty border to approach the duration of the R&D stages [11]. In our case, the problem of singularity can be interpreted as the desynchronization of the duration of the cycles for creating an innovative STR, the development of technologies (from TR=0 to TR=9) and the lifetime of a space technology product. The technological gap will occur long before the end of the product life cycle.

[1]Technological singularity is a hypothetical moment, after which, in the opinion of supporters of this concept, technical progress will become so fast and complex that it will be inaccessible to human understanding. Reality, apparently, will not be so intimidating. It is possible to talk about the threat of singularity, about the asymptotic approach to it. In any case, the information explosion will be somewhat stretched in time.

In this regard, firstly, the process of creating an STR, resolving innovation uncertainty, should be continuous, and secondly, it should be ahead of the current R&D projects. At the same time, the method of selection of critical technologies stops working in its pure form: all technologies fall into the category of critical ones.

At first glance, taking into account all the above, the task of creating an STR can be characterized by the idiom "Go I know not wither and fetch I know not what." Nevertheless, the task can be successfully solved if the following principles are put in the basis of the methodology for creating an STR, (Fig. 5):

1. The general directions for the creation of an STR should be determined based on objectively existing critical system conflicts in the development of rocket and space technology and space activities in general. As a rule, overcoming such conflicts is accompanied by a discontinuity in the smooth evolutionary development of a technical system, a technological gap. However, there may be several directions of technological gaps. In such cases, is proposed to consider the most acceptable way to overcome conflicts the one that best meets the expectations of the society [12]. In this way, the level of innovation uncertainty can be reduced.

It should be noted that focusing only on the technological environment in the process of identifying critical conflicts and choosing ways to resolve them is unproductive. It is necessary to take into account the synchrological[2] nature of potential conflicts in all social environments [13].

I.e., in determining the prospects and directions for the development of the space technology, the humanitarian issues of working with social environments are involved, which in general terms corresponds to the ideas of the VII technological paradigm[3] [14, 15].

2. Definition of the corridor for creating of an innovative STR in the field of technological and economic opportunities [16], determined by the technological paradigm in the economy and the phase of the cycle of the economic conditions[4].

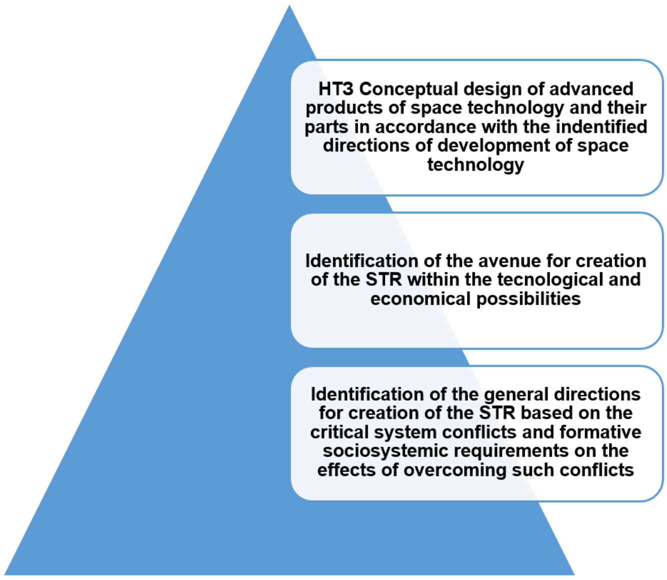

Fig. 5. Methodological principles for the creation of an STR

3. Conceptual design of advanced space technology products, their components, instruments, systems and units in accordance with previously identified fields for creation of an innovative STR. Conceptual design, generally speaking, should be the initial stage of the project to create a specific space technology product. However, within the framework of the creation of an STR, conceptual design tasks are not practically specified; they should be much more redundant and extensive compared to pre-project research tasks.

The proposed principles for the creation of an STR respond to the main challenges of the time, take into account the predicted changes in the technological base of the space technology, such as technological gaps and the impending problem of singularity.

3. The main provisions of the methodology of creating an innovative scientific and technical reserve in the rocket and space industry

Identifying of critical system conflicts

Identifying critical system conflicts and forming socio-system requests for the effects of overcoming these conflicts in the rocket and space industry is a rather difficult task due to the impossibility of its formal solution. Table 1 presents some preliminary results of expert identification of critical system conflicts and forming socio-system requests for the effects of overcoming them in the rocket and space industry.

[2]Synchrological - establishing the relationship between phenomena and processes occurring at the same time in different parts of one state or in several states.

[3]VII technological paradigm is called socio-humanitarian or cognitive. Its main feature is the convergence of nano-, bio- and information technologies, aimed at transforming human consciousness into a productive force (conscious control of reality, creation of new realities: technological, cultural, social).

[4]This refers to the phases of economic cycles of different periodicity: Kondratiev, Kuznets, Kitchin, Zhiglyar, etc. The main of them is the Kondratiev cycle (Kondratiev waves).

Table 1 - Results of the expert identification of critical system conflicts and the forming socio-system requests for the effects of their overcoming in the rocket and space industry

<table>
<tr><th>No.</th><th>Critical system conflict</th><th>Possible socio-system request for the effects of overcoming the conflict</th></tr>
<tr><td>1</td><td>The conflict between the biological nature of man and the factors of outer space</td><td rowspan="2">The pursuit of space expansion, including the industrial exploration of space, the transfer of polluting and dangerous industries into space, the development of the mineral resources of planets and asteroids, the efficient use of solar energy, the colonization of the solar system.
Striving for sublimation of such human qualities as passionarity and aggressiveness in solving problems of research, exploration and use of space</td></tr>
<tr><td>2</td><td>The conflict between the unclear goal-setting of space activities and the large resource costs for the space exploration and space expansion</td></tr>
<tr><td>3</td><td>The conflict between the demand for space products and space services and the high cost of space technology products</td><td>Striving for the availability of the entire range of space services anytime and anywhere</td></tr>
<tr><td>4</td><td>The conflict between the high speed of development of science and technology and the impossibility of spacecraft modernization during orbital flight</td><td>The desire to receive higher quality space services</td></tr>
</table>

Definition of the corridor of technological development

The possible directions for creating an innovative scientific and technical reserve in any field, including the rocket and space industry, are limited by the existing and advanced structure of technological paradigms in the economy, the phase of the economic cycle and the general laws governing the development of technical systems.

In the long term (10–30 years), Kondratiev cycles [17], which are directly related to innovation, apparently have the greatest influence on the development of technology (Fig. 6). Since the beginning of the twenty-first century, after the global crisis of 2001-2002, the fifth technological paradigm and the corresponding Kondratiev cycle entered a downward phase. At the same time, began the development of the first generations of technology of the 6th technological paradigm, which will become predominant in the advanced countries in 2020-2050s. The total duration of Kondratiev cycles (Kondratiev long waves) ranges from 45-60 to 50-70 years. The problems of the 6th technological paradigm with respect to space activities are considered in [18, 19].

Based on the theory of large cycles of the economic situation, it can be expected that on the downward wave of the Kondratieff cycle, the depth and duration of economic crises will increase. Their peak may fall on the beginning of the 2020s, after which the reverse trend will prevail.

In general, in the next 25 years, the avenue of the technological development of the space industry, due to the current economic structure and the associated innovation cycle, is characterized by a generally favorable economic environment.

As the key factors for the development of the space technology products of the 6th technological paradigm, one can identify from five to twenty of the most promising breakthrough technologies of the beginning of the 21st century, including:

- computer-controlled processes of production and operation of rocket and space technology at all stages of its life cycle;
- microminiaturization and multifunctionalization of information and communication, sensor and actuating devices with a high degree of accuracy;
- autonomous intellectual modules and spacecraft (SC), including multi-agent spacecraft systems;
- alternative and combined energy sources, ways of highly efficient energy transportation, energy saving, compliance with environmental standards;
- biotechnological development in the interests of manned space flight;
- nanotechnology of a wide range of applications;
- implementation of the bionic principles (life-technologies) of creating space technology, etc.

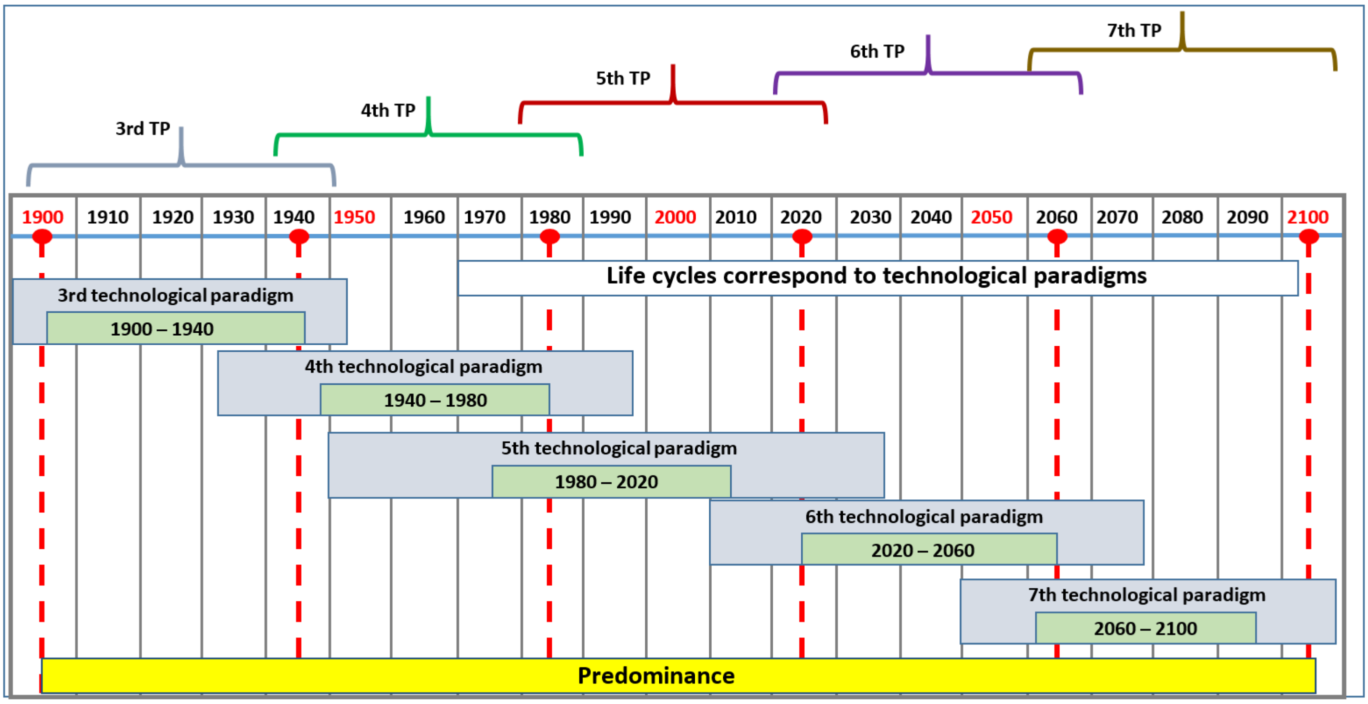

Fig. 6. Dynamics of change of technological paradigms [19]

Conceptual design

Conceptual design complements and specifies the general directions for the creation of the STR. Conceptual design is carried out by industry research and design organizations, individual scientists and specialists.

Examples of possible directions of conceptual design when creating the STR in the rocket and space industry are presented in Table 2.

As methods of conceptual design in the process of creating the STR, the following can be used:

- heuristic methods;
- methods of iterations (sequential approximation);
- decomposition methods;
- methods of inducing questions;
- various brainstorming technologies;
- methods of the theory of inventive problem solving (TIPS);
- methods of functional cost analysis, etc.

The most promising methods of conceptual design are the methods of TIPS, based on the general laws governing the development of technical systems [20]. In this case, under a concept we understand the description of the way to achieve a goal. Concepts include physical or functional principles of action, principles of change, principles of conflict elimination, improving pairs of interrelated indicators of a technical system, as well as sets of optimal values of parameters of system elements. Description of the concept should be sufficient for the development of design solutions.

Currently, new varieties of computer-aided design (CAD), focused on conceptual design - CAI-systems [5] are being created. Distinctive features of CAI systems include:

- management of innovative activity of the enterprise;
- development of concepts (technical ideas);
- management of patents of the enterprise.

The main function of CAI systems is concept design. The conceptual design method combines all known invention strategies and covers the entire concept development cycle. It uses complex formal algorithms and a large base of general technical and scientific knowledge [1]. However, it should be noted that numerous development projects of CAI-systems (inventing software) could not significantly increase the productivity of creative activities due to the lack of a formal method that covers all stages of the concept development: from the choice of the initial goal to the definition of the areas for application of the developed concepts.

[5]CAI – Computer Aided Invention – the search for innovative solutions using a computer.

Table 2 - Examples of possible directions and objects of conceptual design when creating the STR in the rocket and space industry

No.	Conceptual Design Directions	Conceptual Design Objects
1	Putting space objects into the Earth orbit and departure trajectories	New ways of launching space objects to the Earth orbit and departure trajectories. Constructive layout of the launch vehicles. Reusable launch vehicles. Platforms for launching payloads of up to several thousand tons. Small and micro-sized launch vehicles for launching small (ultra-small) spacecraft.
2	Rocket engines	Thermochemical rocket engines: - detonation liquid rocket engines (LRE); - LRE with a central body; - one-component LRE, including using micro- (nano-) encapsulated fuel. Nuclear rocket engines: - impulse engines; - heterogeneous gas-phase engines. Thermonuclear rocket engines. Electric propulsion engines: - ion engines; - plasma engines, including engines with free plasma confinement. Cross-media engines (atmosphere - space). Rocket engines on new physical principles (anti-gravity, control of the space-time continuum, etc.).
3	Manned space flight	Ensuring the safety of long-distance space flight and comfortable habitability of manned spacecraft. Emergency crew rescue. Means of landing on the planet (return vehicles). Closed-circuit biological life support systems. Technologies of hibernation (anabiosis) during long-distance space flights. Avatar technologies for extravehicular activity and planetary exploration.
4	Remote sensing of the Earth from space	New ways of sensing the Earth from space. Ultra-compact optical systems. Distribution of the target function of Earth sensing among a cluster of small (ultra-small) spacecraft.
5	Space communications, broadcasting and retransmission	New ways of transmitting (relaying) data through space communication channels. Methods of reception and transmission of weak signals with levels comparable to or lower than the level of natural noise. Quantum communication. Communication between spacecraft. The distribution of the objective function of communication, data transmission and relaying in a cluster of small (ultra-small) spacecraft.
6	Space navigation	Methods of precision space navigation for terrestrial consumers. Navigation methods in high near-earth orbits ($H > 2000$ km), including geostationary orbit. Deep space navigation methods: - within the solar system; - outside the solar system. Methods of navigation on the surface of the planets.

Conclusion

Thus, the main features of the new methodology for creating an STR in the industry have been formulated, taking into account the existing innovation uncertainty and limitations arising from the structure of technological paradigms in the economy, the phase of the cycle of economic situation and the general laws governing the development of technical systems.

The proposed methodology can be used as a basis for a new research and production system for the rocket and space industry, designed to give impetus to its further innovative development.

The main provisions of the developed methodology should be reflected in the regulatory and methodological documents of the industry, paying particular attention to the creative, informal, systemic nature of the creation of the STR, the grassroot initiative, the need for targeted incentives for this process, careful observance of copyright, as well as the requirement of redundancy of the STR in relation to those R&D projects, which are aimed at the creation of specific space technology products.

The creation of the STR should be based on informal heuristic procedures and CAI systems, which makes it possible:

- to determine the general directions of the creation of the STR, taking into account the critical system conflicts and sociological demands for the effects of overcoming these contradictions;

- to identify the areas of technological and economic opportunities that set the "corridor" for the creation of the STR, taking into account the current and future technological paradigm in the economy and the phases of the cycle of the economic situation;

- to predict at the conceptual level the design profile and the main characteristics of promising design solutions in accordance with the previously identified directions for the creation of the STR; the procedures of the conceptual design can be based on the methods of the theory of inventive problem solving (TIPS), based on the general laws governing the development of technical systems.

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