Analysis of the concept of a long-term orbital station for the interorbital cargo traffic serving

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The article presents an analysis of the concept of a long-term orbital station operating at low near-equatorial orbit and serving interorbital transport operations in terms of independent economic efficiency. To income earning in the market of launch geostationary vehicles, it is proposed to use the orbital transfer vehicle served by space station. The near-equatorial orbit has a number of advantages in particular the radiation environment, allowing for the application of scientific and technical solutions not previously used in the design of orbital stations. The concept of a promising single-module orbital station with the means for creating artificial gravity and the possibility of increasing the habitable volume by deployment of inflatable rigidizable structures is proposed. The effect of artificial gravity on the comfort and productivity of crew is shown; a possible option of living and working spaces of the station is suggested, if available. The possibility of reducing expenses and increasing revenues in comparison with the implemented projects of orbital stations is shown.

Keywords: *orbital station, artificial gravity, spacecraft, orbital transfer vehicle, economic effect, geostationary orbit*

In connection with the forthcoming completion of the operation of the International space station (ISS), statements were made about its exclusively political value and the revolutionary impact of human activities in outer space. However, in the near future it is of interest to search for activities of the orbital station (OS), allowing to obtain an economic cost effeciency and achieve at least partial payback. The purpose of the study presented in this article was to determine the possibility of making the projected OS cost-effective or at least significantly reducing the cost of the associated use of the station for non-commercial purposes.

The uniqueness of the OS is the availability of long-term weightlessness in ultra-high vacuum and the possibility of physical interaction with operating space vehicle without leaving orbit. However, the highest cost of creating and supplying the OS, coupled with reduced productivity of the crew, hinders the development of orbital tourism and production, leading to an increase in passenger and cargo flows.

The most profitable solution is the redirection of the existing orbital cargo flow through the OS. Orbital Assembly, qualification tests with the possibility of reworking and re-commissioning of the space vehicle with a reusable transfer vehicle, serviced with an OS, can significantly reduce the cost of deploying space systems. The possibility of a return to OS satellite which turned into an unplanned orbit, broken, and in need of refueling or upgrading will free up additional resources for the maintenance of the OS and transfer vehicle by reducing production costs and developing new space vehicle [1].

Currently, most cargo, both by weight and cost, is put into geostationary orbit [2]. In this regard, when optimizing the OS for servicing interorbital cargo flow, it is effective to optimize it primarily for a geostationary cargo flow. Such optimization requires certain technical solutions in both the station itself and in the means of launching serviced by it.

The following requirements are imposed on the interorbital transfer vehicles [3]:

1) maximum efficiency in terms of the working fluid costs;
2) minimum time for launching the space vehicle into the working orbit;
3) maximum service life in outer space;
4) maintainability;
5) minimum cost of development, production, launch and operation.

These requirements are inherently contradictory, and the choice should be based on the final economic efficiency. In the course of the work, the possibility of using a tether system, electric and chemical transfer vehicles was analyzed [4]. The analysis showed that the existing technical level and the state of the market for the launching of geostationary space vehicle is most consistent with a chemical transfer vehicle, according to the main technical solutions, possibly similar to the project of PAO S.P. Korolev Rocket and Space Corporation Energia (RSC Energia) “Leap” [5], except that after aerodynamic braking it returns to the OS, and not to the ground. The prospect of development may be an electric propulsion transfer vehicle capable of transporting space vehicle to the station with subsequent return to the working orbit [6].

To ensure the cost-effectiveness of space vehicle maintenance with the use of fixed assets, it is necessary to reduce the cost of its creation and especially maintenance. Thus, the ISS costs amount to several billion dollars per year [7], and the possible economic effect of the space vehicle prelaunch and maintenance is expected to not exceed half a billion dollars per year, and only with the monopolization of the market [2]. This amount corresponds to the cost of maintaining the Russian segment of the ISS [8] and shows that without a significant reduction in costs it will be impossible to achieve an economic cost efficiency of the project.

Let’s consider possible ways to reduce the cost of creating and maintaining the OS. In all the analyzed variants of the reusable transfer vehicle, the mass of the working body is comparable to the mass of the payload and makes the main contribution to the cargo flow to the station, exceeding its own. The use of the near-Equatorial operating orbit of the OS [9] will allow to reduce it by reducing the characteristic velocity of launching on the GEO [9]. This orbit also has a number of advantages that facilitate the operating conditions of the OS.

The near-Equatorial orbit (up to the inclination of the reference orbit of the Kourou cosmodrome — about 5.5°) does not pass through the Brazilian magnetic anomaly and, as a result, the level of radiation dose placed on it by the OS is several orders of magnitude lower than that existing on the ISS, and a certain protection against solar flares (according to calculations in the OMERE software package, the annual dose behind the protection of 1 g/cm^2 at an altitude of 500 km does not exceed 0.1 rad). The greater distance to the radiation belts makes it possible to increase the orbit of the OS to 500...600 km and reduce fuel costs for maintaining the orbit. It should be noted that a large linear velocity of the earth's rotation during the launch on the Equatorial inclinations will increase the mass of the payload of missiles launched to the OS.

Such a unique arrangement of the OS permits the following technical solutions:

1) construction of the OS on the basis of modules from inflatable solidified structures [10]. Low exposure dose of radiation exposure allows limiting the inflatable shells as a mass protection, and virtually no atmospheric resistance will not lead to significant loss of the characteristic velocity. The use of such structures will allow to obtain a significant sealed volume of compartments exceeding the volumes under the head fairings of launch vehicles, and will reduce the cost of deploying the OS per unit of working volume;

2) use to maintain the orbit and maneuvers of the OS instead of chemical rocket engines on high-boiling components of engines of lower power Small losses in the characteristic speed of the OS (up to 0.1 m/s per year at an altitude of 600 km) allow the use of such engines in the project. They are much easier and cheaper to produce during testing and can be brought to the required reliability for human space flight programs at relatively low cost in a reasonable time [11];

3) use of industrial-type solar panels without adaptation to outer space, possibly in conjunction with inflatable solar radiation concentrators. In the operating orbit of the OS, radiation degradation of the batteries will be virtually absent, since the accumulated doses are small, as is the concentration of atomic oxygen. Due to the absence of significant atmospheric resistance, the solar radiation concentrator (and other OS equipment) can have an arbitrary shape and cross-sectional area. At the same time, it can protect batteries from ultraviolet radiation by absorbing it [12]. Thus, the unit cost of the OS power supply system can be reduced;

4) use of intermediate reusable cargo vehicle at the final stage of cargo delivery to the OS. Such vehicle will select standardized cargo containers

to be removed by any launch vehicle and deliver them to the OS, eliminating the need for single-use cargo vehicle [13].

The container will be launched by a carrier rocket into an elliptical orbit with an apogee corresponding to the altitude of the orbit of the OS, and independently issue an apogee impulse that brings it into the orbit of the OS with phase mismatch. Due to the small and a priori known value of such a pulse, it can be issued by a solid-fuel engine after passive stabilization of the container. The use of a cargo vehicle that docks with the container and moves it to the OS will allow eliminating the docking system from the container [14].

It should be noted that the low inclination and high altitude of the orbit of the OS will lead to a high precession rate (up to 20°/day) of the container orbit in the absence of aerodynamic divergence of the orbits. Therefore, the characteristic velocity of the cargo vehicle will be significantly lower than in the ISS orbit, including due to the phasing capability. This, in turn, will simplify and reduce the cost of the vehicle. After delivery to the vicinity of the OS, the container will be able to carry out an Autonomous flight for a long time, which will give the OS the opportunity to use goods from a heavy container on demand.

Thus, the specific mass cost of OS supply can be reduced and practically brought to the cost of launching a heavy-class rocket into the reference orbit;

5) the use of typical industrial electrical products. Bottom - Chia radiation dose rates and small debrelease section Proni - penitent through the magnetic field of the Earth of heavy charged particles allow us to calculate the efficiency of electronic components of Industrial class, provided protection against surges of current due to the thyristor effect - that and the backup to bring the reliability up to the required values [12]. This will significantly reduce the cost of electronic OS systems;

6) improved cycle life support systems on the basis of pyrolysis and Sabatier and Bosch processes will obtain at the output the recovered O_2 and H_2O, and gaseous or powder final products. The increased power capacity of the OS will allow to use electricity for decomposition of waste and waste products instead of closing the cycle with the use of chemical reagents [11]. This will simplify and reduce the cost of the equipment of the life support system;

7) the use of reusable descent vehicles. Ensuring reusable lander will significantly reduce the costs incurred in providing the asset. There is a large domestic and foreign experience in solving this problem. It should be noted that the landing fields of the vehicles working with the Equatorial OS can be entirely located in the ocean, which facilitates their reusability and rescue operations [15];

8) ensuring the reusability of the last stages of launch vehicles. The last stages of the rockets that put the cargo into their orbit and remained docked to the cargo container can be delivered to the OS by means of a transfer vehicle. By separating their valuable small parts (avionics, turbo - pump unit, engine nozzle head, etc.), the cost of which, according to Arianspace (France), is up to 80% of the stage cost [16], the OS crew will be able to return them to Earth in the descent vehicle. In combination with the achieved reusability of the first stages, this will lead to a significant reduction in the cost of goods launching;

9) creation of artificial gravity. Artificial gravity on Board the OS will solve many medical and biological problems, improve the performance of the OS crew and reduce the time spent by pilots on medical and domestic procedures, as well as use standard ground equipment in OS systems and in scientific and production equipment [17]. This will significantly reduce the cost of the station and additional equipment, as well as the cost of working man-hours in orbit.

Presumably, the implementation of the above advantages of the near-Equatorial orbit after the development of appropriate technologies will ensure the profitability of the project and return on investment, even with incomplete market coverage. Unfortunately, the current level of economic models in the rocket and space industry makes it impossible to estimate with certainty the cost and timing of the creation of new equipment, so it is not possible to calculate the payback period of the project.

To assess the feasibility and effectiveness of the proposed technologies, an estimated design of the OS was carried out and its various options with and without artificial gravity were analyzed. Depending on the amount of initial funding available and the required payback period, the rational OS configurations will vary significantly.

So, the least up-front costs will be characterized by a variant of the OS, which is a virtual replica of the base module of the ISS. However, with long-term operation, the associated costs will not ensure payback, only a partial presence of the project in the market of launch on GEO and return at the expense of profit only a small share of public spending on human space flight exploration is possible.

The implementation of the OS version using all the described methods of cost reduction will give hope for the actual monopolization of the market and full cost recovery for several years, even in the conditions of static market volumes at a reduced price. The option, including the creation of artificial gravity on Board the OS, was worked out in more detail.

It should be noted that it is advisable to increase the functionality of the OS in these conditions by increasing the number of Autonomous modules of the station-“clouds”, rather than modules as part of one OS. As the most promising option, an Autonomous residential module with a means of providing artificial gravity in the form of a counterweight unit equipped with a propulsion system and connected by a tether system with a residential module and with a docking Assembly located in the center of gravity of the OS was developed. The crew of such an OS will be three people, and the cargo flow will not exceed the cargo flow of the OS type “Mir” or “salute”. If necessary, the counterweight unit can be replaced by a second residential module (figure 1).

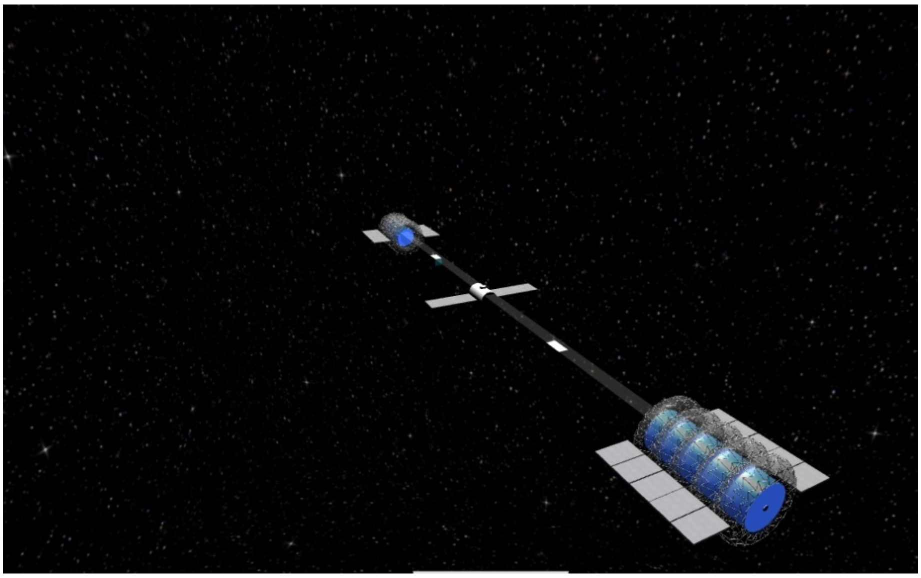


Figure 1. The appearance of the symmetric version of the OS*

Analysis of the OS and crewed space vehicle structures shows that the OS should include the following main systems [18]:

– on-board control system, including a central computer, motion control systems and on-board complex, command and measurement, radio telemetry and navigation systems;

– the system of life support, including the system of gas composition, means of water, food and food storage, means of medical care and hygiene and a set of means of crew support;

– power supply systems including solar panels, orientation system, batteries and control and monitoring equipment;

– thermal management system

– docking system

– fire detection and fire extinguishing system

– television system.

* Figure was prepared by T.V. Volkova using the 3D visualization software.

In addition to the main systems, the structure of the residential module and on-board equipment should include radiation protection, micrometeorite protection, server-router, computers with the necessary peripherals, on-board communication facilities, beds with the necessary equipment, rescue equipment, scientific and experimental equipment and other service equipment at the request of the customer.

Mass analysis of the design and on-Board systems is a very voluminous and complex process involving both the evaluation calculations and the study of prototypes, and can not be described in detail in the article.

Therefore, below is only the final mass summary (values are in kilograms) obtained from the analysis of prototypes at the level of technologies for creating existing ISS modules:

Frame with inflatable blocks	1560
Micrometeorite protection	2120
Thermal management system	2338
Radiator	287
Drive	102
Screen-vacuum insulation	238
Heat pipe and the coils	151
Aggregates	1377
Coolant	285
Supply system	278
Solar panels , kg	152
Orientation system , kg	30
Rechargeable batteries, kg	65
Control and monitoring equipment, kg	30
Life support system	2884
On-board control complex	308
Motion control system	50
Onboard complex control system	50
Command and measurement system	30
Radio telemetry system	50
Passive docking guidance system	78
Navigation system	20
Central computer	30
Docking ports	574
Radio engineering docking system	78
Others	72
Total (residential module)	13237
Block-counterweight	500
Tether system	1200
Mobile docking station	300
Transport unit (Elevator)	200
Total (OS)	<15500

When creating the design of the OS, the key value will be the ability to increase the working and residential volumes of the module while maintaining its permissible mass for launching by the existing carrier in one launch by deploying a large inflatable structure on its frame. This technology will be a logical continuation of the experiment on deployment in April 2016 as a part of the ISS of an inflatable residential module BEAM, the sealed volume of which can be increased after launching into orbit [19]. This will allow the creation of a single-module OS with sufficient working volume on a single-start scheme.

From the already worked out methods of transformation of a large-size space structure (mechanical [20], rotary [21] and pneumatic [22]) to create a large-size OS module, a pneumatic one is best suited, since such a module initially has closed cavities in which a constant internal pressure is maintained. In addition, this method makes it possible to obtain a structure with a minimum mass (due to the use of composite and film materials) and a minimum volume occupied in the Packed state. The pressurization of the Packed structure was first performed in 1960 on the “Echo-1” satellite [22]. It was later implemented several pilot programs to boost space structures. Over the past 10 years, on the basis of developments made by NASA in the 1990s under the project TransHab [10], the company Bigelow Aerospace was launched into space three inflatable modules.

The relatively low rigidity of the structural elements of the inflatable structure and the need to maintain a constant internal pressure in it significantly reduce its reliability. Therefore, after supercharging the structure, its shape is proposed to be fixed with the help of hardenable materials.

Of all the variety of materials to be cured [22], the most promising for the creation of the OS module are materials to be cured during heating and materials with curing impregnation [23].

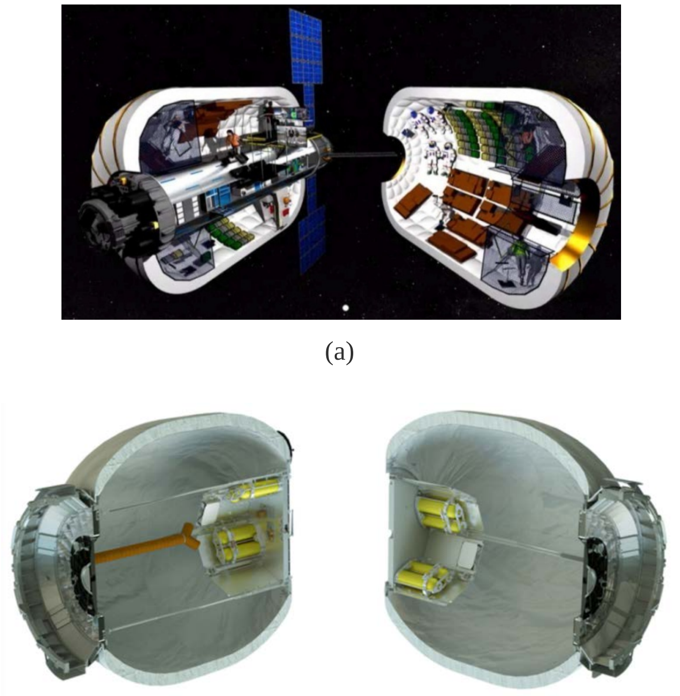
The first group is a polymer composite material having a matrix (binder) and reinforcing elements (filler). The structure which is prepared on the Earth is packaged and, in the prepreg state, transported into space, where it is unpacked and inflated and then cured by heating (for less than an hour) from the internal heat source.

The materials of the second group are impregnated with a special substance, which, when one of its components evaporates, provides solidification. Curing occurs not in the process of chemical reaction, but as a result of removal of a low-molecular volatile solvent or a temporary plasticizer from the composition of a rare-mesh polymer matrix of a polymer composite material [22]. The plasticizer evaporates in space under vacuum, i.e. without additional energy costs. As a basis, various technical fabrics are used for the construction of various forms, and as a matrix (impregnation) — gels of thermoplastic polymers (for example, systems based on aqueous solutions of polyvinyl alcohol).

To create a power set that fills the cavities after their supercharging, the most effective use of materials that foam when exposed to vacuum or when heated [22].

In the TransHab project, a rigid Central (axial) truss, as well as the upper and lower bottoms, on which docking units were installed, were provided for fixing the most massive units and assemblies [10]. The design was inflated only in the radial direction.

The BEAM module has no rigid central (axial) design and is inflated in both longitudinal and radial directions [18]. The equipment responsible for pressurization and the docking station are attached to the rigid front and rear bottoms (figure 2).



(a)

(b)

Figure 2. One of the concepts of the layout of the TransHab module (a) and the layout of the experimental residential module BEAM (b) [24]

To improve the safety of the crew, in the design of the station two compartments are considered: a central cylindrical core with a diameter of about 4 m and support a torus-shaped, attached at the central and having an outer diameter of 9 m. Both compartments are hermetically sealed.

For the greatest reliability of the soft shell it is necessary to have a multilayer with additional layers of sealing. In addition to these layers, there are layers of screen-vacuum insulation (EVTI), providing passive thermal protection of the module, and layers that protect against micrometeorites and small-sized space debris. To ensure the maximum volume, it is more efficient not to use the built-in protection [10], but to install the hinged protection during the operation of the module.

Nomex can be used as an internal barrier (protective) layer; this material is resistant to fire and wear. This is followed by a number of alternating layers of capton, ensuring tightness, and Kevlar, providing structural strength. The outer layer-EVTI protects the Kevlar from ultraviolet radiation, under the influence of which this material is highly degraded, and provides passive thermal protection. When using curing impregnations, capton layers reinforced with Kevlar [25] can be used, which simultaneously provide both tightness and strength. To remove the plasticizer, it is necessary to provide drainage channels, which can be provided, in particular, by multi-row weaving of aramid fibers or by adding a corrugated layer [10].

A significant difference between the proposed project and the BEAM and TransHub modules is the use of centrifugal forces to create artificial gravity. It is known that weightlessness causes the need for a period of adaptation to it before the cosmonaut begins work, and also has a long-term negative impact on the human body, including causing muscle atrophy, metabolic disorders and cognitive decline [16].

These factors significantly reduce the efficiency of the crew on board the OS, require the installation of additional equipment at the station and the maintenance of significant maintenance of the ground infrastructure (including specialized centers for the design of systems designed to work in weightlessness, to prepare the crew for weightlessness and rehabilitation after its impact). The possibility of creating artificial gravity using the rotation of the OS has long been scientifically justified. Unlike earlier projects, artificial gravity can now be created by autonomous small space vehicle used as counterbalance blocks having their own propulsion system and rotating around the axis [11].

Centrifugal artificial gravity differs from the earth's influence of Coriolis accelerations, the presence of a gradient of gravity and its dependence on the relative speed of motion in the rotating coordinate system of the station. The effect of these effects imposes a restriction on the bottom dimensions of the OS.

In the proposed OS concept, the residential module is supposed to be oriented vertically relative to the line of action of artificial gravity. This arrangement will help to reduce the movement of the center of gravity of the axle in the transverse direction and increase the weight of the axle due to inertial loads.

In the architectural and planning solution of living and working spaces of OS it is necessary to consider regularities of construction of internal space, proceeding from ergonomics of activity of crew not only in the mode of artificial gravity, but also partially in the mode of microgravity. The anthropomorphic metric should be taken into account on the basis of the specific activities of the crew carried out in these modes [26].

The single-module OS will be output by one start as a sealed rigid cylindrical block $D4\times11$ m with five-span air-supported hardenable shells taking the form of a torus D_{max} = 9 m after automatic pressurization (figure 3). It is produced after insertion into a working orbit. At the same time, the block-counterweight separates from the OS block, pulling the Central docking Assembly on the cables and twisting the OS in a rotational motion and creating artificial gravity.

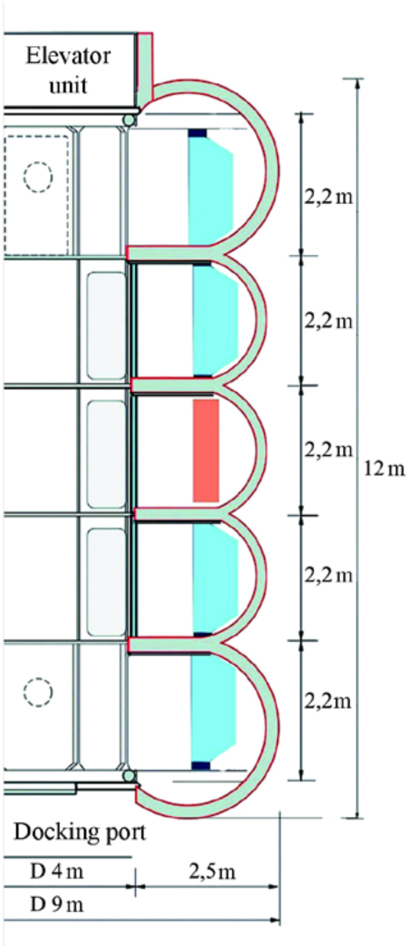


Figure 3. External layout of the residential module*

When receiving human space flight expeditions, the OS will have to stop the rotation to dock the vehicle to the residential module that provides emergency evacuation. Unwinding, braking and correction of the orbit of the OS can be carried out by wated based electric arc rocket engines,

* Figure was prepared by T.V. Volkova

mounted on a residential module and a counterweight. The process will take about a day. Cargo vehicles are joined to the Central docking Assembly, exposed to the cables in the center of gravity of the OS. In this case, the vehicle must align the speed of rotation with the speed of rotation of the axis. To ensure transport operations from the docking station to the residential module and back to the OS, a mechanical vehicle moving along the tether system is provided.

The created OS, in addition to its main purpose, can be used to solve some other tasks. They may include space tourism. The American company Bigelow Aerospace justified the prospects of the orbital tourism market and attracted significant funds [27]. The proposed OS will provide a lower cost of human stay in orbit by reducing the cost of the OS itself and transport operations, as well as greater safety due to lower radiation and due to the ocean placement of landing fields; orbital transfer vehicle operations:

a) the orbital injection of a vehicle into orbit than from a geostationary orbit. The less expensive orbital insertion of the OS and transport using a transfer vehicle can ensure the cost - effectiveness of delivering cargo to other near-earth orbits through the OS instead of using a single-use launch vehicle. It is possible to deliver the cargo directly by transfer vehicle to the target orbit or to a high orbit with subsequent correction of inclination and aerodynamic or electromagnetic braking;

b) work with Autonomous modules. The presence of an interorbital transfer vehicle allows to expand the functionality by using Autonomous free-flying modules transported to the place of work and returned from there by the transfer vehicle [28]. Scientific equipment can be placed on the Autonomous modules , orbital production, etc. In the presence of a high-speed communication line, the crew of the OS will be able to control the Autonomous module in real time. At the same time, the proximity of the OS will allow for an operational visit to the Autonomous module in situations requiring the physical presence of a human;

c) provision of expeditions to the moon and deep space on the orders of space agencies. The station's interorbital transfer vehicle can be used to deliver automatic vehicle and other cargo to the moon or to another point in near-earth space. The provision of human space flight expeditions will require the use of a long —stay residential module transported by an electric propulsion transfer vehicle, or a crewed unit used in conjunction with a liquid rocket engine transfer vehicle. It should be noted that the liquid transfer vehicle is potentially able to provide launching on the flight trajectories, in particular through the vicinity of the Lagrange points of the Earth — Moon system [29]. In this case, its fuel reserve is sufficient for self-return (400 m/s for maneuvers plus aero- or magnetic braking at the ground) [30].

The creation of such an OS can be performed by the Russian Federation independently if funding is available. In case of international cooperation, as the experience of the ISS operation shows, the distribution of the contribution and coordination of actions will be required. This can significantly increase the overhead and time to build a long-term OS.

The proposed composition of developers in the case of the Russian national program is given below:

head organization — by the decision of the state customer;

complex analysis of the project — FSUE TsNIIMash;

research programme — Space Research Institute of the Russian Academy of Sciences;

experiments with artificial gravity — Institute of Biomedical Problems of Russian Academy of Science;

the OS body design — PAO S.P. Korolev Rocket and Space Corporation Energia + Russian research Institute of aviation materials (FSUE VIAM, RF SRC);

the main developer of the control system — The Scientific and Production Center of Automation and Instrumentation named after N.A. Pilyugin or Moscow Development Design Office «Mars»;

head developer of power supply system — JC VNIIEM Corporation;

main developer of the thermal regime support system — RSC Energia;

head developer of life support system — RSC Energia;

head developer of orbital transfer vehicle — RSC Energia;

head developer of liquid interorbital transfer vehicle — Lavotchkin Association;

head developer of electro-jet inter-orbital transfer vehicle — JSC Information Satellite Systems named after Academician M.F. Reshetnev.

It should be noted that the need to reduce the cost of creating an OS can make a rational model of work, when enterprises of the aviation or defense industry are involved in solving private problems, and the experience of solving space problems is transferred to them by the parent organization. The practice of implementing such programs abroad shows significant reduction in cost and timing time of [31].

Supply of the Russian national OS can be made from Kosmodrom “Sea start” by the carrier rocket “Sunkar” which loading capacity allows bringing OS in the offered configuration [32]. For the launching of crewed vehicle, however, serious improvements are needed as a modification of the method of launch and the rocket itself.

There are two main options for international cooperation:

1) the involvement of the BRICS countries and the involvement of the Brazilian Alcantara launch site;

2) the existing cooperation on the ISS and the use of Kourou, where you have deployed the pad carrier rocket "Soyuz-STB", to finalizing certification for the human space flight launches and launch vehicles of the series "Arian". It is also possible to create a floating platform of the "San Marco" type in the coastal waters of the Equatorial States (Nauru, Kiribati, etc.). In any case, the decision to create such a station, despite its predominantly economic orientation, will be mainly political [33].

Summarizing the above, we can draw the following conclusion. The project described OS has the ability to improve cost efficiency and therefore significantly differs from previously implemented OS projects.

Ways to achieve this were reasonable scientific, technical, architectural and layout solutions, together giving a significant reduction in the required costs.

Thus, the goal of the study has been achieved and shows the possibility of obtaining such an economic cost efficienty of the OS project, which makes it cost-effective and significantly reduces the necessary costs while simultaneously using the station for solving non-commercial tasks.

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