JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 45, No. 3, May–June 2008

Utilization of Space Stations: 1971–2006

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DOI: 10.2514/1.32772

Manned space stations beginning from orbiting stations *Salyut*, *Skylab*, and *Mir* have been developed as springboards for gradual and consistent increase of human presence in space. The International Space Station Utilization program is viewed as a logical evolution of this fundamental approach when the aerospace industry has transitioned to a new stage of industrial exploitation of outer space. The paper provides an overview of strategic directions of space station utilization. The International Space Station Russian segment is used for graphic review of concrete issues and challenges, and options for their solution with respect to the International Space Station environment are proposed. The paper also provides an overview of the history of space station utilization and focuses on utilization of the International Space Station.

Introduction

ALMOST nine years after the launch of the first International Space Station (ISS) element and seven years after its initial habitation, the ISS partners have made great strides in operating this impressive orbiting research facility. The architecture of the International Space Station originated from U.S. and Soviet/Russian concepts dating as early as 1950s and was influenced by past experience as well as by new innovative concepts and ideas [1].

Sergey Korolev laid out the classic approach to human conquest of space in the 1950s through early 1960s that included space station outposts as a logical step in an outer space exploration [2]: "The development of a heavy orbital station is a necessary stage for long-duration flights in space that allow training humans in space and testing hardware in easily accessible low Earth orbit. It is an important methodological and indispensable step in space exploration. . ."

More than a hundred different space stations had been conceptualized in the years before the ISS came to life operationally [1]. Several space station architectures had been developed and manned in orbit by Russians and Americans before the establishment of the current space station configuration in the early 1990s.

Soviet/Russian *Salyut* and *Mir*, U.S. *Skylab*, and the NASA *Mir* program provided significant lessons in the design, operation, and support of a space station.

This paper will trace some of the engineering origins that were factored into the International Space Station as it is being operated today. Issues and challenges that have been experienced in planning and implementation will be highlighted, as well as many valuable lessons learned with respect to International Space Station operations, integration of international engineering cultures, utilization of station resources, etc.

Formation of Space Station Utilization Directions

Improvement of the space station (SS) utilization process occurred incrementally, based on sequential introduction of advanced engineering into space technology as the space industry faced new scientific, economic, and defense challenges with the evolution of a SS.

Received 12 June 2007; revision received 2 September 2007; accepted for publication 6 September 2007.

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Historical and technical analysis [2] identifies three main stages of a low-Earth-outer-space exploration; each stage can be characterized by certain quantitative indicators (see Table 1): 1) accumulation of knowledge about the space environment and development of human space flight engineering: single and group flights of human space vehicles in 1961–1970; 2) conduct of research in various scientific areas, creation of space vehicle (SV) utilization directions and further improvement of human space flight engineering: development of single-module space stations in 1971–1985; and 3) transition to practical use of space via assembly and utilization of multiple-module long-term space stations such as *Mir* and ISS, from 1986 until the present.

Our analysis covers the second and the third of the aforementioned stages associated with assembly and utilization of human space stations within the last 35 years (Figs. 1 and 2). Figures 3 and 4 show diagrams of the flight duration of all flight-tested space stations.

During the early human space flights, two practical objectives of space vehicle utilization that became mandatory on all subsequent space stations evolved: 1) more precise definition of the space vehicle's operating environment and requirements and accumulation of data about outer space factors affecting the human body and 2) study of the human body in terms of its adaptation to the long-duration space flight environment and improvement of life-support techniques and facilities for the crew.

The first manned docking of the Gemini-8 spacecraft with an unmanned satellite in 1966 and the first automatic docking of unmanned satellites Cosmos-186 and Cosmos-188 in 1967 enabled early development of full-fledged space complexes in a low Earth orbit, with masses exceeding 100 t. In its turn, such development brought about another SS utilization direction; namely, creation and in-flight optimization of next-generation space engineering elements and systems for support of future human space missions.

Goal-oriented scientific and technological research was viewed as a priority in mission planning for early single-module space stations. Two factors of space environment, such as absence of atmosphere and weightlessness (microgravity), became determinative in formulating scientific and research objectives. For this reason, research hardware on *Salyut* space stations and *Skylab* mainly consisted of, in addition to systems for medical and biological research, devices for astrophysical research: the study of the sun and Earth. These stations also witnessed early attempts at space processing and a material science.

Development and assembly of the first multiple-module *Mir* space station [2] significantly expanded capabilities of research programs in various areas of science and technology. Research on *Mir* encompassed practically all modern research, such as 1) deep space research, 2) investigation of the Earth and near-Earth space, 3) investigation of life activity in space (human space habitability), and 4) processing in space. *Mir* research serves as the basis of

Table 1 Main characteristic quantities of manned space vehicles (maximum values per stage)

Characteristic quantity	Stage 1 1961–1970	Stage 2 1971–1985	Stage 3 1986 - p. t.
Number of crew members staying on SV simultaneously	3	5	10
Duration of uninterrupted crew members stay, days	18	236	437
Mass of SV, t	13	90	286
Mass of research equipment, t	0.25	11.3	11.5

the Russian long-term scientific and technological program on the ISS.

Robotic space vehicles proved to be the most effective platforms for the study of the Earth and universe as well as for the application of long-term and precise remote monitoring techniques (e.g., the unprecedented Hubble space telescope mission). Manned stations serve as platforms enabling primarily optimization and improvement of new devices and research techniques, with the assessment of their future use aboard specialized space vehicles (The unprecedented 15-year flight of the *Mir* space station serves as a good example of such an application.)

It is possible to identify the following current priority areas of SS utilization: 1) fundamental and applied scientific research programs and experiments and production of high-tech samples in space; 2) development and optimization of advanced utilization hardware and techniques for effective space applications aboard manned and robotic SVs; 3) creation of scientific, technical, and engineering outposts for realization of perspective projects targeting moon and Mars exploration; and 4) provision of high-tech and advertising services in space, including flights of space tourists and implementation of educational and humanitarian projects.

ISS partners have already begun actual work in these areas [3–6]. We would still like to define the priorities, prospects, challenges, and constraints that they face. It appears attractive to provide answers via analysis of the ISS utilization (the most complex SS ever) to be followed by a comprehensive analysis of utilization efficiency on all previous SSs.

ISS Utilization

Our analysis of the ISS activities is based on the assumption that the officially accepted estimated service life of the station is 15 years (it is supposed to run till 2016, although it can be assumed that the term can be extended). The United States, together with the international partners, plans to finish the assembly and begin full-scale utilization of the U.S. segment in 2010 [7,8]. Russia, in turn, has plans to complete the Russian segment (RS) assembly earlier, in compliance with the Federal Space Program for 2006–2015 [9]. The near-term major stage is the addition of the multipurpose laboratory module in 2009–2010. Because of termination of shuttle flights in 2010 and internal financial problems, Russia abandoned its plans to develop the scientific power module designed for launch in the cargo bay of the space shuttle. The next step for Russia includes the addition of a research module (maybe modules) planned for delivery to the ISS after 2011.

The analysis of statistical data based on the number of experiments in 2000–2006 on both segments of the ISS (see Fig. 5) [10,11] reveals the following research priorities: medicine and biology, 104; biotechnology, 59; engineering, 44; educational programs, 29; space-based processing, 27; geophysics, 9; and study of natural resources of the Earth and ecological monitoring, 6.

In response to the U.S. President's Vision for Space Exploration (14 January 2004) [7,8], NASA revised its ISS utilization plans to focus on 1) research of astronaut health and the development of countermeasures that protect the crew from space environment effects during long-duration voyages, 2) use of the ISS as a test bed for research and technology to safeguard vehicle systems and improve operational techniques and procedures targeting future exploration missions, and 3) development and validation of operational techniques and procedures for long-duration space missions.

Currently, the areas of priority research for all ISS partners include the study of the human body and processes of its habitability in space. Medical and biological research mainly pursue further improvement of a human space medical-support system, collection of new data about the mechanisms of human-body adaptation to space environment, an optimization of methods, and countermeasures for its protection from unfavorable flight effects.

Biotechnology research is equally important for the partners from the United States, Europe, and Japan. It focuses primarily on the growth and production of protein crystals of various biological objects such as viruses, bacteria, plant cells, and zooblasts that have specific properties and have a potential for use in medicine, veterinary science, and pharmacology.

All partners also give an equal priority to engineering studies aimed at investigating and enhancing space station structural characteristics, conditions of its maintenance (microgravity environment, acoustic effects, radiation exposure, and micrometeorite situation), and studying structural materials and coatings. New goals of outer space development, primarily exploration of the moon and Mars, require further ISS research pursuing space technology and engineering tasks.

NASA and ESA assign a major priority to experiments with evident applied orientation, including physics of colloids, processes of zeolite formation and crystal growth, determination of transport factors in crude oil, and synthesis of substances during combustion in microgravity.

Among all experiments conducted on the RS ISS so far, of fundamental significance is the Russian–German "plasma crystal" experiment studying plasma-dust crystals and liquids in a microgravity environment.

The interest of scientists from different countries also extended traditionally to other areas of space research such as geophysics, remote sensing of the Earth, and cosmic-ray physics. Experiments in these areas are primarily directed toward optimization of new instruments and research techniques in space flight environment for future use on specialized robotic space vehicles.

Educational programs received particular attention in the ISS utilization program: 27 school and student projects have been conducted so far. With support from space agencies, the ISS has already become a virtual classroom in space for conducting laboratory experiments, excursions, and visual demonstration of physical processes in microgravity.

Commercialization is a unique feature of modern astronautics. In the case of the RS ISS, commercialization is realized, for instance, by rendering high-tech services to various customers: commercial visiting expeditions, conduct of experiments, commercial advertisement, and special actions. Flights of space tourists have become an area of steady business and proved to be a new direction of SS utilization.

Two areas of research have been present on all SSs without exception. These include identification of space vehicle operational conditions using data retrieval about space factors influencing the human body, as well as medical and biological research. Table 2 provides the payload complement on the RS ISS. Within 2000–2006, its mass has increased approximately from 300 kg up to 1.7 t. Medical and biological equipments and instruments account for almost 70% of all payloads. Other areas have been presented more modestly so far. Nevertheless, we can state that the strategy of the ISS utilization is developed and implemented in compliance with the preceding classification of SS utilization areas. There are certain challenges that stand in the way of increasing the scope of ISS utilization.

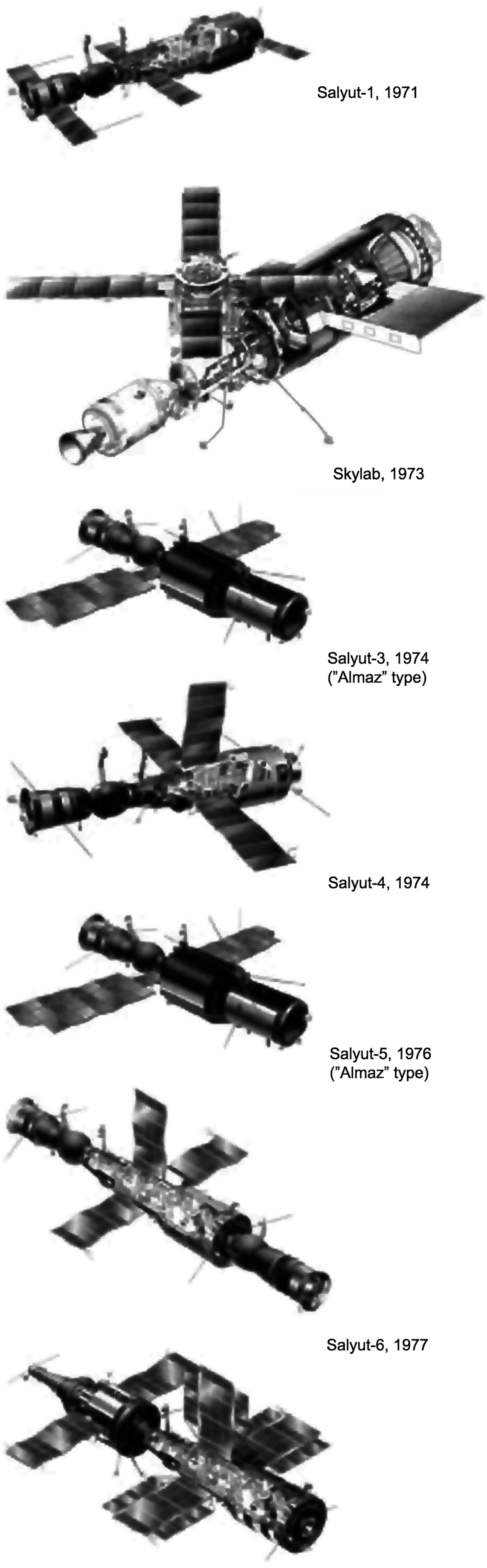

Fig. 1 Single-module manned space stations (1971–1985/1987).

Fig. 2 Multiple-module long-term space stations.

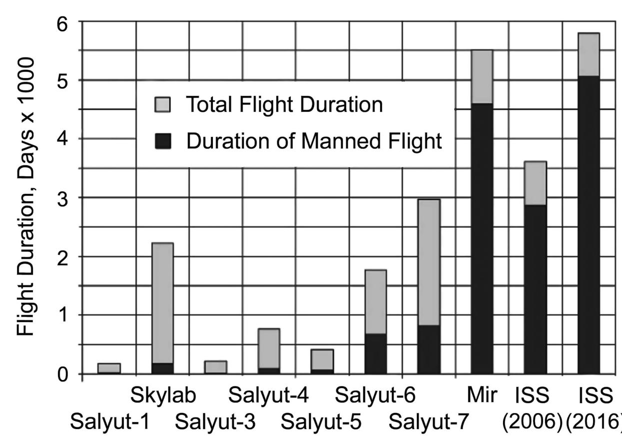

Fig. 3 Flight duration of space stations.

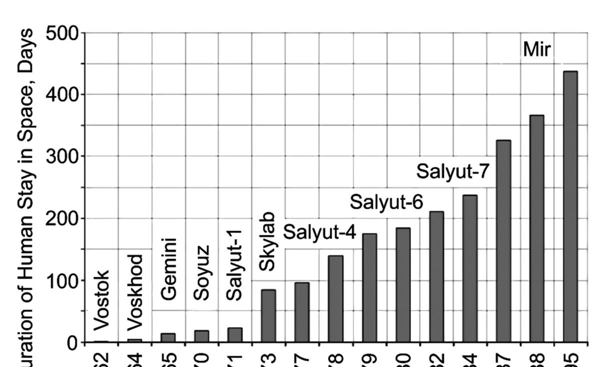

Fig. 4 Increase in duration of human stay in space.

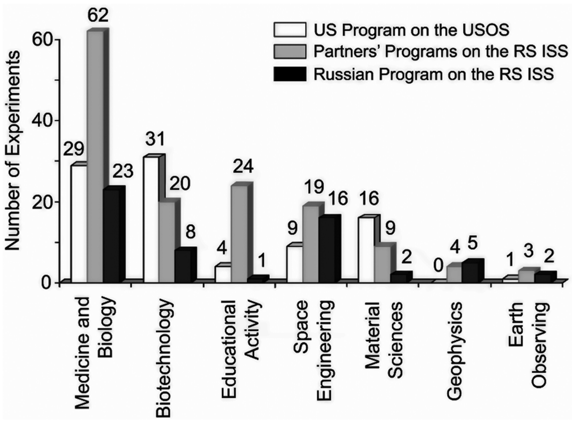

Fig. 5 **Distribution of scientific experiments on the ISS (USOS in the U.S. orbital segment).**

Challenges of Space Stations Utilization

We have witnessed consistent improvement of SS capabilities (see Figs. 6–9). However, onboard resource constraints posed a fundamental challenge for utilization on early single-module stations. Station resources were overwhelmingly allocated to flight operations. Such constraints primarily included 1) limited volumes for accommodation and storage of research hardware inside the station and a few workstations outside, 2) cargo traffic parameters for hardware and consumable materials delivery and return of research results to Earth, 3) limited availability of power for utilization purposes, 4) limited channel capacity for control and communication, and 5) limited crew time allocated for operations with research equipment. *Skylab* was possibly the only exception during its nominal flight phase. The station was sensitive primarily to cargo traffic limitations.

Another contributor to enhanced multiple-module SSs' utilization effectiveness was improved repair and maintenance procedures due to extensive experience gained in previous *Salyut*, *Skylab*, *Mir*, and shuttle–*Mir* programs [2,12]). This knowledge made possible in-flight recovery after most complex failures (including contingencies). It is appropriate to mention here that the heroism displayed by astronauts and cosmonauts during SL-2 (Ch. Conrad, J. Kerwin, and P. Weitz) and SL-3 (A. Bean, O. Garriott, and J. Lousma) missions to *Skylab* in 1973; *Soyuz* T-13 (V. Dzhanibekov and V. Savinykh) mission to *Salyut*-7 in 1985; *Mir*-22/NASA-4, *Mir*-23/NASA-5, and *Mir*-24/NASA-6 (V. Korzun, A. Kalery, J. Linenger, V. Tsibliev, A. Lazutkin, M. Foale, A. Solovyev, P, Vinogradov, D. Wolf) missions on *Mir* made it possible to sustain the stations and continue their utilization after extraordinary failures and damage.

Another contributing feature is the system of regular traffic to the station using Progress-class robotic cargo carriers. This system proved to be adaptive to any changes in the SS operations program and to be highly efficient toward extending mission duration. Space station cargo delivery has increased from 22 t on the *Salyut*-6 station during its almost five-year life span to 170 tons on the *Mir* station in its 15 years and already 68 tons on the ISS during its first five years of existence.

Another positive current development is the space station's mission-planning approach, providing for integrated long-term crew mission planning and short-term visiting crew planning (Fig. 10).

Table 2 **Payload complement on the RS ISS (2006)**

Research direction	Part of the payload complex, %
Medicine and biology	35
Material sciences	7
Biotechnology	14
Space engineering	33
Geophysics, Earth observation	6
Education	5

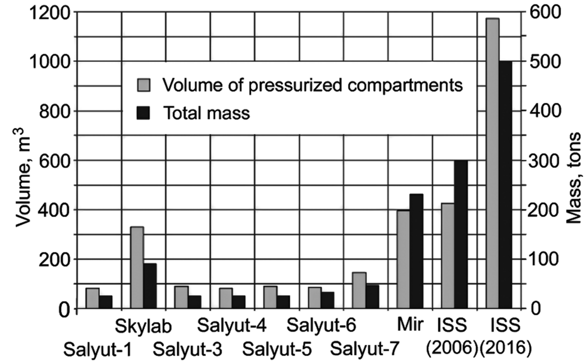

Fig. 6 **Change in SSs' pressurized modules by volume and mass.**

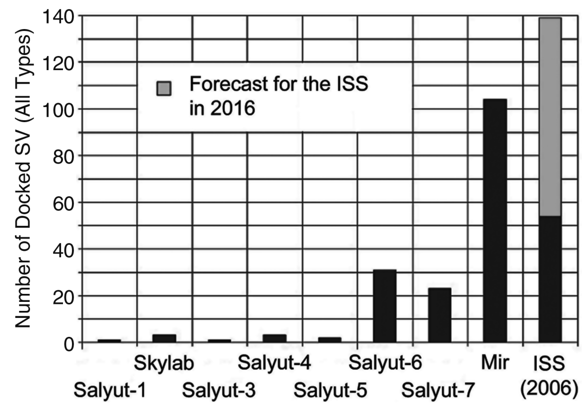

Fig. 7 **Number of arrived/ docked space vehicles.**

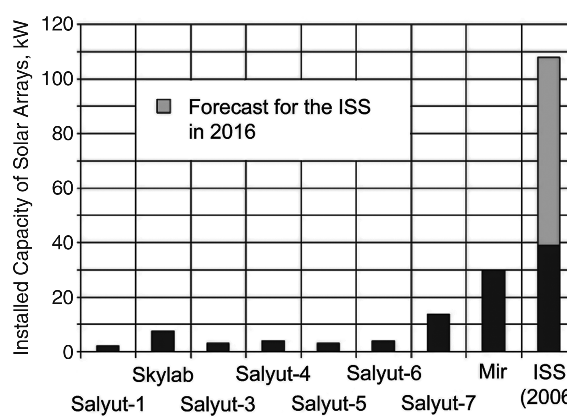

Fig. 8 **Change in the solar array capacity.**

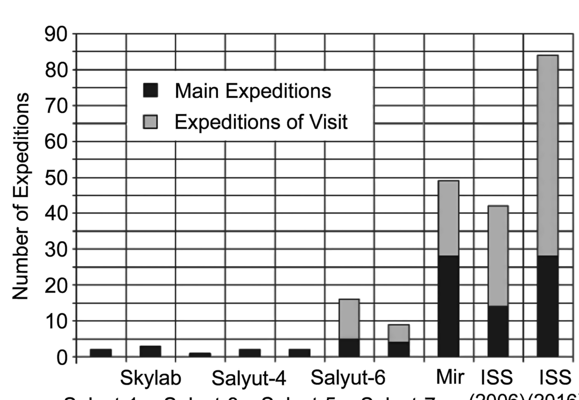

Fig. 9 **Number of expeditions.**

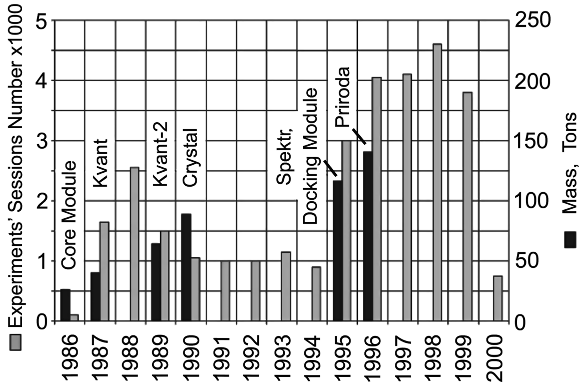

Fig. 10 **Number of experiment sessions on the SS *Mir* and increase in the station mass.**

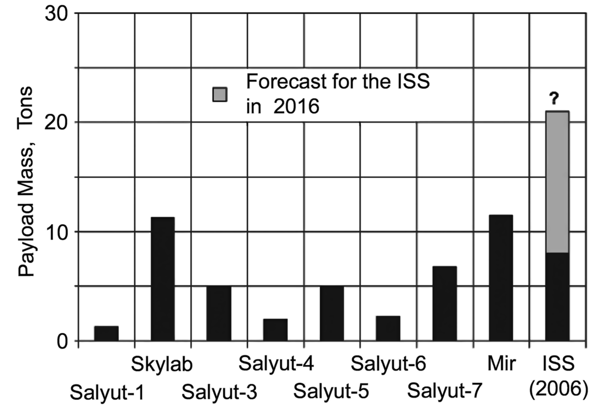

Fig. 11 **Payload mass on SSs.**

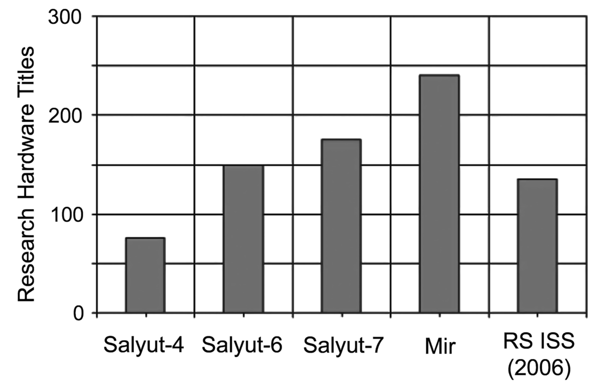

Fig. 12 **Number of research hardware titles on some Russian SSs.**

This approach made possible the adjustment of research programs planning to change priorities and availability of research hardware, thus enhancing the efficiency of space station utilization.

However, even the ISS, which is considered to be the most sophisticated SS in history, has also been facing certain resource constraints so far. In addition, the incremental approach of modular space station buildup that seemed to be so efficient created a new challenge for integrating the SS assembly with utilization planning and implementation. [8,13].

It is known that the concept of incremental modular assembly of SS enables stage-by-stage construction and flexible buildup driven by funds allocation for construction and availability of payloads. On the other hand, such an approach also accounts for possible changes in the original construction plans. It is also known [2,14] that the assembly of the first multiple-module *Mir* space station was stretched out for ten years instead of three, as planned originally. It was undoubtedly one of the reasons behind SS *Mir* utilization intensity decline (see Figs. 2 and 10) for almost five years, from 1989 to 1994.

The design of the ISS (1996 version) provided for completion of the station assembly with habitation of a long-term crew of three crew members within five years after the launch of the service module in 2000. Then the plans were adjusted to a ten-year operation period with the crew of six (originally seven, before NASA decision to terminate the Crew Return Vehicle program). However, the *Columbia* accident brought about significant corrections to the schedule of the ISS deployment, and for three years, until the STS-121 mission in July 2006, the ISS was inhabited only by two crew members. This development diminished the utilization efficiency of the ISS, without any doubt [3,4,15,16].

The efficiency of research activities on a SS is a direct function of the complement of onboard research hardware and the duration of its operation. In turn, research hardware is treated on a SV as another payload with a certain mass. Criterial dependences defining expenses for creation and operation of aerospace systems usually include mass as a basic parameter that can be optimized. It is not just an aviation tradition. It is well known [17] that an increase in mass of a payload by 1 kg makes a carrier heavier by 40–80 kg; accordingly, the cost of a space vehicle ascent/launch is a function of its mass. Therefore, the mass of a SS payload complement impacts many design options of a space station and influences utilization opportunities.

Payload mass increase and the number of research hardware facilities achieved so far on space stations appears quite modest (Figs. 11 and 12) at the background of more dynamic positive changes in SSs' general operating characteristics (see Figs. 6–9).

It would be true to assume that in the process of the ISS development, a number of elements and mass of a payload complement on both segments should increase significantly. Unfortunately, periodic changes in the station architecture, largely due to a continuous reduction in the number of modules, make this assumption without merit.

One of the most serious challenges, probably typical for all SS, is lack of crew time to support SS research. In this respect, the ISS differs in no way from its predecessors. Only during short-term 8–10-day expeditions (so-called expeditions of visit) that take place every six months on the RS ISS when the integrated crew increases up to five crew members (since September 2006, up to six), the situation changes substantially for the better. A short-term crew member can conduct as many experiments in one week as a long-term crew member in six months (Figs. 13 and 14), because the long-term crew member's primary focus is to maintain the station habitat by performing planned and unplanned tasks and conduct personal care [18].

Research activities on the ISS have appreciably less crew-time allocation than expected, because of a much higher priority attributed to service operations such as personal care and habitat maintenance. To illustrate, the minimum program requirement for ISS utilization operations (i.e., research activities) is 20 h/week; however, these activities are typically assigned a lower priority than those needed for habitat maintenance and personal care tasks. It is estimated [18] that each crew member spends an average of more than 1.9 h per work day and, in addition, 1.8 h per rest day performing ISS maintenance tasks. Because of the potential gravity of system failures, habitat maintenance must have high priority on a space vehicle; unfortunately, this demand frequently conflicts with other required

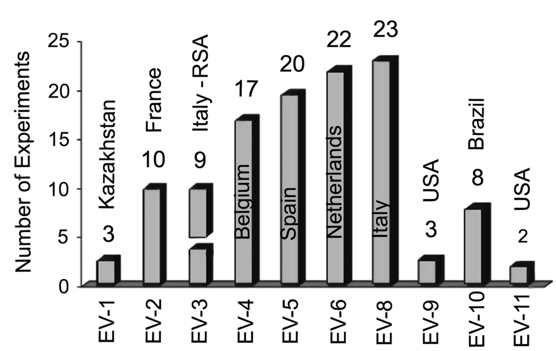

Fig. 13 **Number of experiments performed by short-term crews on the RS ISS (RSA is the Republic of South Africa).**

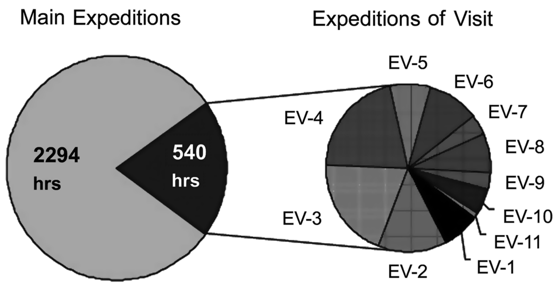

Fig. 14 Ratio of crew-time allocation to support experiments on the RS ISS.

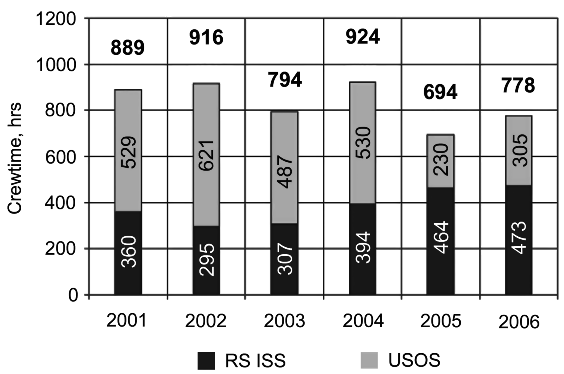

Fig. 15 Time spent by crew for payloads operations on ISS within 2001–2006.

mission operations. Therefore, to successfully meet overall goals of future space missions, design and operational decisions need to concurrently address issues of time required to conduct maintenance tasks and, accordingly, to optimize crew-time allocation based on realistic expectations.

As a result, crew time assigned for activities with payloads does not increase with the growth of the payload complement and, on the contrary, tends to reduce (see Fig. 15). As of October 2006 (expedition ISS-13), it averaged 13–14 h per week. This tendency appears to be stable, without serious prospects for improvement. The main reason behind this is the reduction of a long-term crew from three to two members in 2003. Such crew-time allocation increased only after addition of ESA astronaut T. Reiter to the long-term crew of ISS-13–14 in July 2006 (STS-121 mission). If NASA meets its shuttle flight schedule through 2010, then the crew time assigned for ISS utilization tasks may reach the level of 2002. However, it is equally important to understand how further station assembly with all ensuing challenges will affect this parameter.

Although the payloads complement mass on the RS ISS for the first five years grew almost 3.2 times, the time intended for research activities increased only by 20% (Fig. 16). Accordingly, the efficiency of payload use decreases, thus causing concerns of the ISS program management, because all international partners appear to be unable to implement their research programs in the planned scope.

Generally speaking, this issue is not specific to the ISS: it emerged on previous SSs and, most likely, will occur on future multiple-module orbital stations.

The history of astronautics demonstrates [2,14,18] that crew time for habitat maintenance exceeded planned time for two reasons: greater time consumed by maintenance tasks than originally expected and the need to address new unexpected and unscheduled maintenance tasks. To illustrate, maintenance time allocated for *Skylab* housekeeping increased from the planned 0.75 h per crew member per day to an actual average of 1.1 h, and unscheduled maintenance on the station increased the crew time needed for habitat maintenance to roughly 4 h (the situation was similar on the *Mir* space station). To perform these additional maintenance operations, crew time was diverted from other scheduled activities, such as sleep, during some *Mir* missions or they were carried out during handover and visiting periods when more crew members were available to

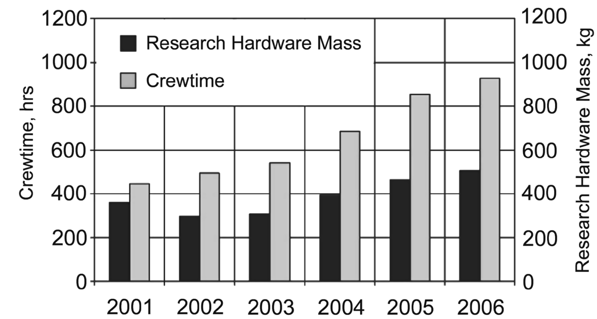

Fig. 16 Ratio of research hardware mass and crew time on the RS ISS.

assist. Notwithstanding such unplanned time consumption every day, each *Skylab* crew member was still engaged in scientific research and medical experiments 6.1 h per day [18], whereas this figure does not exceed 2.5 h on the average on the ISS (including medical operations, U.S. science, and Russian science).

The analysis of the ISS crew time spent on maintenance tasks shows that at the moment, all reserves supporting an increase in research activities and conduct of experiments with the existing number of long-term crew members have been exhausted (see Table 3). Any further increase will definitely impact ISS crew members' daily routine. Under the circumstances, crew members perform a significant part of work, largely due to their high sense of duty and discipline, during their rest time or on days of rest, in accordance with a task list. However, the abnormality of such a situation is obvious to everyone.

As the payload complement and work procedures get more sophisticated, an experiment gets more labor-intensive and longer, thus affecting an absolute value of an experiment in a particular field (Table 4). The solution of this problem most likely lies in the area of improving equipment ergonomics, simplifying interfaces and procedures, device and systems maintenance, and, ideally, the maximum possible automation.

It is possible to radically solve the issue of a crew-time deficiency only after increasing the total number of crew members. For the existing station, this number should not be less than six. The year 2009 appears in various ISS program documents as the most likely date when this level of habitation on the ISS will be attained [8,13].

There are other constraints that impede more intensive utilization of the ISS and SSs in general. Such constraints include limited power

Table 3 Distribution of the ISS-12 crew time per operation on an average work day (example)

Operations types	Crew-time distribution, %
Onboard systems maintenance	26
Docked SVs maintenance	14
Onboard crew training	2
Research activities	**18**
Medical operations	11
Extravehicular activity	10
Inventory, public affairs, planning and coordination, other service operations	19

Table 4 Average values of crew time per one session of an experiment for six years of the RS ISS

Research area	Average crew-time expenses per session of an experiment, h
Medicine and biology	2.00
Material sciences	2.23
Biotechnology	1.49
Space engineering	2.45
Geophysics	0.70
Earth observation	0.21
Cosmic rays	0.54
Education	1.01

available for science hardware, data throughput, mass and volumes of payloads, and kits with the experiment result to be returned to Earth.

One of the main challenges of the *Mir* space station was a chronic deficiency in electric power [2]. Notwithstanding the fact that the capacity of its solar arrays (SA) was large enough (more than 30 kW), their mutual shading hampered required generation levels of electric power. This challenge will be addressed on the ISS by deploying four pairs of SAs on the U.S. segment (see Fig. 2); currently, research equipment power consumption on both segments cannot exceed more than 1.5 kW.

Insufficient capacity of communication channels on the Russian segment and a lack of Russian relay satellites also have a toll on the RS ISS utilization program. Investigators have limited control capability of their research hardware with regard to its status control and downlink of telemetry and scientific data. Use of the U.S. segment engineering capabilities has helped out Russian scientists so far. However, the preceding challenges constrain the expansion the RS ISS payload complex.

When shuttle missions were discontinued from 2003 to 2006 [2,16], the task of regular cargo delivery to the ISS became critical for the U.S. segment, whereas return of space experiment results (videotapes, films, electronic data carriers, technological, medical, biological, and biotechnological kits and containers) proved to be very critical for both segments.

The analysis of statistical data [10,11] showed that from 2000 to 2006, the share of returned time-critical cargoes increased on average from 15 up to 60%. Time-critical cargoes are understood as being the result of research with a strictly limited shelf life during their stay aboard a SV and are largely associated with biological, medical, and biotechnological experiments. Results of nanotechnological experiments were recently added to this critical category of cargoes. All stowage zones in the *Soyuz-TMA* descent capsules have been subjected to extensive revision to make them better accessible for accommodation of cargoes. As a result, flight support equipment has been improved to facilitate access and retrieval of cargo at the landing site. These measures allowed the Russian partner meeting its commitments not only in compliance with the national space research program, but also for dozens of commercial projects. However, the challenge of returning more than 50 kg of payloads and the crew of three in the *Soyuz* appear to be insurmountable from the engineering point of view. The situation may be improved only by developing a new Russian reusable human space vehicle. This activity has already started at S. P. Korolev Rocket and Space Corporation Energia (RSC Energia) [19]. The design specs of the new space vehicle provide for return of about 500 kg of payload and the crew. Another challenge is associated with research hardware accommodation on the SS. It is known that scientific hardware on early orbital stations was installed into the space vehicle before flight. As space stations systems' longevity grew (in particular, due to regular transport and engineering maintenance of stations using Progress cargo vehicles), SS life span increased to 15 years. During such a duration, research requirements vary and it may be necessary to provide an opportunity for in-flight replacement of space hardware. The more new equipment that is delivered, the more difficult it is to integrate it into the structure of the existing SS, primarily because of volume constraints. In fact, it is impossible to remove stationary hardware installed earlier. Consequently, another challenge arises: that is, the inevitable littering of a station due to accumulation of unused hardware and kits in storage locations. To track hardware, most advanced technology and techniques are being used on the SS. Nevertheless, some pieces, including experiment results, may be lost, to be found only by accident months later. It is quite difficult to estimate how much valuable time the crew will waste in search of some misplaced hardware they may need.

Full-scale implementation of replaceable payloads approach providing for installation/replacement of payloads on universal workstations resolves the issue of lack of workstations on the RS ISS. This approach is used in the U.S. segment modules and it is incorporated in new modules of the Russian segment.

We also face challenges in the area of station planning and engineering support. Studies of planning methodology and development of integrated program algorithms with regard to the formation of science programs for each increment, and planning of experiments in the environment of constantly changing ISS configurations are few and far between. Lack of such knowledge results in excessive time spent on extra coordination of cyclograms of mission operations and difficulties in implementation of large-scale research activities on the ISS segments, aggravated by assignment of resource quotas. A major adverse contributor to this issue is the human factor, including bureaucratic apparatus. Because a person should be treated as an element of the large ISS support system, the complexity of these issues can be addressed only in a systematic and consistent way at all levels of hierarchy.

Mission design and operations planning experts are familiar with dozens of specific constraints and issues affecting SS utilization efficiency. To illustrate, there are constraints associated with astronomical observations of objects from the ISS that require a certain position of an object relative to the station, the sun, and the moon; constraints with regard to the lateral distance of an object from the line of the ISS flight during Earth observations: light-to-dark and meteorological conditions in the area of observation. Material science and nano- and biotechnology experiments require a certain level of microaccelerations. Certain experiments may impose specific time and duration constraints during the conduct of measurements (season and day), periodicity of sessions, etc. A complex of mathematical models defining the ISS structure and onboard systems, physical conditions onboard, crew operations, and the ISS ground control loop is used to identify and account for such constraints.

Hardware failures and human errors are common reasons that reduce the efficiency of any large system. The ISS utilization is also accompanied by failures of research hardware and by errors of humans on Earth and in space. Data about off-nominal situations during utilization of the RS ISS (see Table 5) suggest a conclusion that the functioning of service systems has a significant impact on the ever-increasing number of research hardware facilities and units and their integration onboard modern SSs.

The analysis of issues affecting the scope of SS utilization prompts a need for monitoring and forecasting SS evolution as a system at a design stage, with a view to better understanding each stage of its evolution. During the *Mir* orbital station mission, a need emerged to integrate modern SS calendar utilization operations with overall station operations at a given stage or period ("a closed-loop control principle" at a strategic level).

Forecast of the ISS status at any given period of time and assessment of implementation feasibility, including science tasks, is necessary to increase research output. This approach allows reducing overall expenditures by optimizing experiment cost and making it more affordable. We can use the example of the *Mir* space station to illustrate the importance of this approach. The program of research activities aboard the *Mir* space station in 1997–1999, which included 214 experiments, was put together using a "calendar strategy" and was approved in 1997. The analysis of its implementation and completeness conducted at the end of 1999 at RSC Energia demonstrated that only 136 experiments (62% of the program) had actually been completed. It was discovered that considerable expenses had been incurred on a number of experiments that never ended up on the space station for a variety of reasons, in spite of the large amount of work done.

The preceding data suggest a way for improving station efficiency parameters by integrated monitoring of the ISS assembly and utilization. Such monitoring can be implemented using recently

Table 5 Causes of off-nominal situations during implementation of science programs on the RS ISS during 2001–2006

Research equipment failures	34%
Service systems failures	26%
Software bugs and failures	7%
Maintenance errors (crew and ground personnel)	33%

developed mathematical techniques for an integrated assessment of the project status.

The fundamental challenge before science on the ISS is to perform experiments that provide key answers in time to shape design decisions for future exploration. To create exploration vehicles for missions to the moon and Mars, it is necessary to test materials, foods, and medicines to ensure their reliable performance in space environment. The ISS is a testbed for research and technology that will insure that vehicle systems and operational procedures are mature enough for future exploration missions. The ISS is also a unique training ground to build the operational knowledgebase required to safely conduct future exploration missions and to foster the growing synergy among science, engineering, and operations communities, thus reinforcing the value of such a testbed. It is a prototype of a spaceport for long-duration space voyages [8,20,21].

Conclusions

It is possible to reduce the entire set of issues lowering the efficiency of SS utilization to two basic groups in terms of the degree of their commonality for different generations of orbital stations and possible ways of their solution:

1) Problems inherent to all SSs are generally associated with a deficit of crew time for implementing utilization tasks due to

a) A priority for supporting service operations that are predominant over any utilization tasks for any human space vehicle and are driven by the requirement of crew safety.

b) Unplanned time spent to address off-nominal situations such as failures of systems and units and departures from a mission plan.

2) Issues inherent to modern multiple-module SSs are

a) Periodic changes of SS configuration and overlap of SS utilization tasks with SS construction operations.

b) Deficit of onboard resources for research equipment, arising due to a conflict between the actual pace of SS construction and implementation of planned tasks.

c) Varying research requirements that are frequently incompatible with the station's operational environment for implementation and may lead to a conflict of operational planning.

The first group of issues can be only addressed by further improvement of space technology as a whole and station systems in particular, increase in their reliability, and careful accumulation and application of long-duration human space flight experience.

Solution of the second group of issues in many respects depends upon the system and planning rationality of the SS development and utilization process. A balanced integration of SSs' construction and utilization processes in the environment of resource constraints is a key factor in attempting to increase specific system effectiveness. Acknowledgement of this requirement will lead to an integrated approach to various strategies of the ISS utilization process planning, wide application of mathematical simulation methods for status forecasting of station parameters during any specified time frame, and with a view to fulfilling research programs. This approach has already made possible the transition toward continuous monitoring of the ISS segments operating environment and will eventually help introduce sophisticated evaluation mechanisms to verify project status using efficiency parameters established by customers.

One can conclude that the developers of both ISS segments understand how to address the aforementioned challenges. They have already undertaken significant analytical and practical steps to pinpoint weak areas of station operation methodology and have made corrections and adjustments that lead to continuous improvement of space station operational efficiency parameters.

Acknowledgments

We acknowledge the contributions of Sergey Savelyev and Galina Shamanina of the Space Stations Utilization Center at the Rocket and Space Corporation Energia in Korolyov, Moscow region, for providing factual data about the RS ISS utilization for statistical analysis and securing the approval for public release of the data. We also acknowledge Yuri Ulybyshev of the Space Ballistics Department at the Rocket and Space Corporation Energia for his input and fruitful discussions during paper preparation. We thank the Associate Editor, Andrew Ketsdever, for constructive comments and help in preparation of the paper. Special thanks to an aerospace consulting expert Vladimir Fishel for substantial editing of the paper to improve the text.

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