From Mir-2 to the ISS Russian Segment

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Introduction

Most of the originally planned elements of the ISS Russian segment were directly inherited from the final version of the Mir-2 space station. The major exception was the Russian-built and US-financed FGB/Zarya module, which despite a long heritage in the Almaz, Salyut and Mir programmes, was introduced specifically for ISS, mainly for political reasons. The FGB kicked off station assembly in November 1998 and after many frustrating delays was joined in July 2000 by the Zvezda Service Module, the original core of Mir-2. The only other element of the Russian segment launched thus far is the Pirs Docking Compartment, which linked up with the station in September 2001. Russia's seemingly never-ending financial problems forced numerous design changes in the remaining add-on elements, most of which will now be built through commercial partnerships with US companies. If the Russian segment is ever completed, it will look a whole lot different from what designers had envisaged in the early 1990s.

The Three Lives of Mir-2 [1]

Mir Back-up

The Base Block of the Mir space station, launched in February 1986, was an outgrowth of the civilian Salyut space stations. Officially known as the Longterm Orbital Stations (Russian acronym DOS), six of these had been launched between 1971 and 1982, four of which actually hosted crews. The first four stations were equipped with one docking port and the last two (Salyut-6 and 7) had two docking ports. They were all designed jointly by the Korolyov design bureau (known successively as OKB-1, TsKBEM, NPO Energiya and since 1994 as RKK Energiya) and a branch of the Chelomey bureau located in the Moscow suburb of Fili. Manufacturing took place at the Khrunichev factory, also situated in Fili.

In February 1976 the Soviet government gave the official go-ahead to begin the development of a next-generation space station with multiple docking ports. This called for the launch of two core modules, namely DOS-7K N°7 (serial number 17KS N° 12701) and DOS-7K N°8 (serial number 17KS N° 12801). Both were supposed to have a guaranteed lifetime of at least three years. This plan also provided some redundancy. In case DOS-7 failed to reach orbit or suffered some catastrophic in-orbit failure, DOS-8 could have been launched as a back-up. The same practice had been followed with all previous civilian Salyut stations, which were all manufactured in pairs to ensure the availability of a spare vehicle should the first one fail (DOS 1&2, DOS 3&4, DOS 5&5-2)

The original 1976 proposals for DOS-7 and DOS-8 involved a core module with a total of four docking ports, two axial ports on either end of the station and two lateral ports on the small-diameter work compartment. In 1978 it was decided to move the lateral docking ports to the front cylindrical transfer compartment and increase their number from two to four. After the Fili branch of Chelomey's bureau joined the project in 1979, the cylindrical transfer compartment was changed into a spherical docking adapter inherited from a cancelled successor of the military Almaz space stations known as Zvezda. In 1981 the Fili branch was incorporated into NPO Energiya and became known as the Salyut Design Bureau (KB Salyut). It separated from NPO Energiya in 1988 and eventually joined with the Khrunichev factory in 1993 to form the Khrunichev State Space Scientific Production Centre (GKNPTs Khrunichev) [2].

The final blueprints for DOS-7 and DOS-8 were finished in early 1982, making it possible for their construction to begin at the Khrunichev plant in Moscow. The hull of DOS-8 was finished in early February 1985. No other major work was done on it until the launch of DOS-7 in February 1986. If something had gone wrong with that launch, DOS-8 could have been sent up as a replacement within about 1 to 1.5 years.

The Giant Mir-2

Until the early 1980s plans for DOS-8 were either to replace DOS-7 in case of a launch failure or to succeed DOS-7 in orbit after it had outlived its usefulness, which was expected to be only a few years after launch. DOS-8 would have become the core of a space station very similar to the original Mir, with the most visible change being the addition of a large cross beam which would have been used to support solar panels and other equipment.

Plans for the Mir follow-on station changed in 1984, when NPO Energiya began devising plans for a giant orbital complex known as the Orbital Assembly and Operations Centre (Russian abbreviation OSETs for *Orbitalnyy sborochno-ekspluatatsionnyy tsentr***). Probably seen as a response to America's Freedom space station, it was supposed to be used primarily as an assembly site for large-scale orbital structures and a repair shop and refuelling station for orbiting satellites. DOS-8 was supposed to become the first element of OSETs and would be followed by several modules launched by the Energiya rocket. During the next two years the goals and timelines for the new station were revised. The build-up would be more gradual, with the actual goals of the OSETs being fulfilled only in the final stage. In December 1986 NPO Energiya came up with so-called Technical Proposals for such a station and on 14 December 1987 NPO Energiya's first deputy general designer Yuriy Semyonov approved the Draft Plan for the orbital complex, which in January 1988 was announced in the Soviet media as Mir-2. The designers also referred to it as 180GK.**

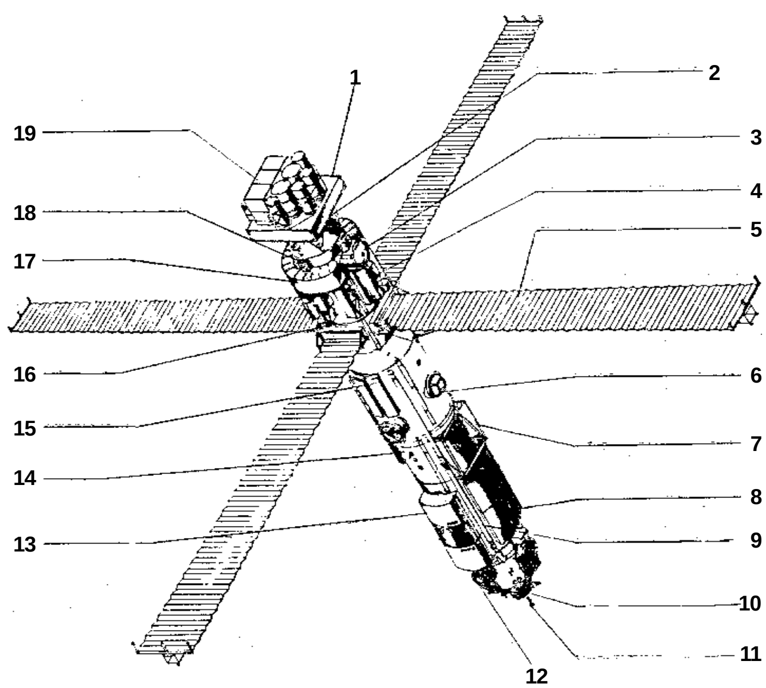
According to the 1987 Draft Plan assembly of Mir-2/180GK was to get underway in August 1993 with the launch of DOS-8, which would act as the living quarters for the crew. The next launch, in October 1993, would have added a 76-tonne core module (MoB) to DOS-8 (Fig. 1). This was to be orbited by the 14A10 booster, a standard Energiya rocket with a new NPO Energiya upper stage based on the venerable Blok-DM, which was to provide the final push to orbit. An alternative option proposed by KB Salyut was the use of a module based on the Skif-DM/Polyus (17F19DM) payload flown on the first Energiya rocket and incorporating an FGB section.

The first phase of assembly was to be rounded out by June 1994 with the addition of a large truss to carry solar arrays (Fig. 2). The second phase of assembly (1994-1997) would see the launch of three more giant modules (a technological module, a support module and a biotechnological module) and the further expansion of the truss with solar arrays, solar parabolic concentrators and scientific platforms (Fig. 3). In the final phase (1997-2000) Mir-2/GK-180 would be expanded to fulfil the role of the OSETs. This involved the launch of four more giant modules and also the deployment of various types of space tugs. The station would also be equipped with a fuel storage depot and various facilities to repair satellites and assemble large structures in space.

The intended inclination of Mir-2/180GK was 65° to expand remote sensing coverage of Soviet territory. This inclination had also been foreseen for Mir, but one year before the launch of the DOS-7 core module it was changed

Fig. 1 One version of the Energiya-launched core module (MoB) of Mir-2/GK-180. (source: RKK Energiya)

Key:
1. Platform for truss segments;
2. Platform attachment structure;
3. EVA exit hatch;
4. Folded solar panel;
5. Unfolded solar panel;
6. Visual observation post;
7. Attachment structure for truss;
8. Storage room for truss segments;
9. Remote manipulator arm;
10. Axial APAS docking port;
11. Rendezvous antennas;
12. Radial APAS docking port;
13. Propellant tanks;
14. Living compartment;
15. Technological compartment;
16. Transfer compartment;
17. Gyrodin section;
18. Approach and orientation engines;
19. Storage room for truss segments.



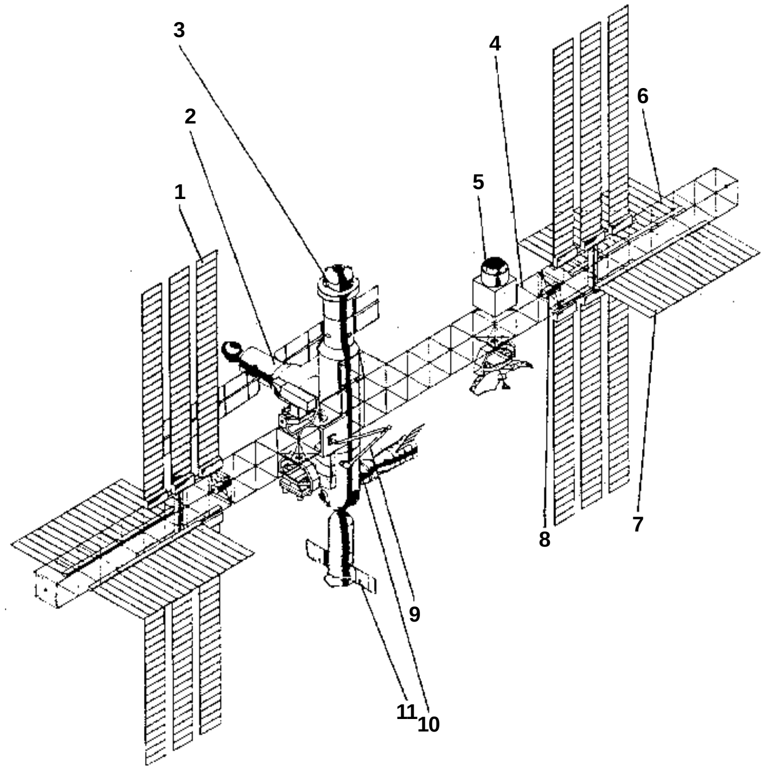


Fig. 2 Mir-2/GK-180 in early stage of construction. (source: RKK Energiya)

Key:
1. Solar panel;
2. 17KS N°128 (DOS-8) module;
3. Core module (MoB);
4. Truss;
5. Rotatable platform;
6. Rotatable section of truss;
7. Radiator;
8. Solar array drive mechanism;
9. Remote manipulator arm;
10. Soyuz-TM vehicle;
11. Progress-MT vehicle.

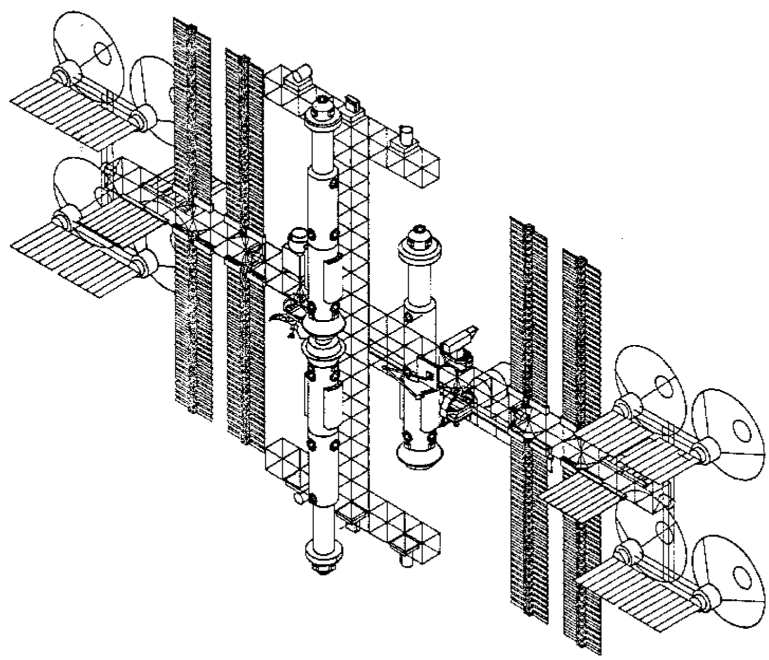


Fig. 3 Mir-2/GK-180 with three large modules. (source: K. Lantratov)

to the standard 51.6° due to mass constraints. Servicing the giant station would be a variety of vehicles: Buran, a Zenit-launched cargo ship derived from Progress and a Zenit-launched reusable crew ferry called Zarya (14F70), essentially an enlarged Soyuz descent module covered with the same heat-resistant tiles as Buran. Alternatives for Zarya were the standard Soyuz-TM or an advanced Soyuz-TM launched by Zenit.

It was not until 25 December 1989 that the plans for Mir-2/180GK were officially sanctioned by a State Commission of the USSR Council of Ministers. By now DOS-8 was expected to go up in 1994 and would receive the giant Energiya-launched module in 1995. In 1990 blueprints were made for the changes that were required to DOS-8 in its role as the living quarters for 180GK. Instead of six passive docking ports of the 'probe/drogue' type, the module would have four androgynous docking ports, two axial and two lateral. The other two lateral docking ports originally foreseen for DOS-8 were no longer needed. One would be turned into a 1 metre diameter EVA exit hatch and the other would simply be covered with a plate. Other planned changes included a new satellite communications system ('Kvant-OK') and modified Kurs rendezvous antennas.

Statements by Soviet officials in 1989-90 indicated that the launch date for Mir-2/180GK kept slipping further and further into the 1990s and financial cutbacks eventually forced these ambitious plans to be scrapped, the first report of cancellation coming in April 1991 [3]. It was necessary to return to the old plans for a more modest 20-tonne core module with add-on modules.

Back to Basics

"Mir 1.5"

One option considered was light-heartedly referred to by some as "Mir 1.5" and called for swapping DOS-7 with DOS-8. In fact, this scenario had already been foreseen in the Mir-2/180GK Draft Plan and, if implemented, would have meant that the giant station would be built without DOS-8. According to Soviet media reports in mid-1991 the idea was to orbit DOS-8 with a Proton rocket and then tow it to Mir with the help of Buran, following which one or more add-on modules would have been transferred to the new core module. The Mir Base Block and the obsolete modules would subsequently have been deorbited with the help of Progress cargo ships [4]. A more elaborate version of this plan was presented by NPO Energiya general designer Yuriy Semyonov at the IAF Congress in Montreal in the autumn of 1991 and envisaged launching DOS-8 in 1994 and keeping it attached to Mir for about two years. During this period Buran would have delivered a prototype biotechnology module called 37KBT. After the transfer of the Priroda module to DOS-8, Mir would then have been discarded, paving the way for the four-year assembly of the Mir-2 complex. During that time Buran would have been used to regularly deliver and return to Earth two operational biotechnology modules known as 37KBT N° 1 and N° 2. A large truss structure with solar panels would have been added, with assembly expected to be complete by 2000 [5].

The 1992 Mir-2 Design

Eventually, the choice fell on another option that had been considered parallel to the "Mir 1.5" plan, namely to launch DOS-8 after DOS-7 had outlived its usefulness and expand it with add-on modules. This would also allow the new station to be placed into a 65° inclination orbit, as had been the intention all along. Launches to it were to be staged from both Baykonur and Plesetsk. Detailed plans for the new Mir-2 station began appearing after the middle of 1992 [6]. On 24 November 1992 they were approved by the Council of Chief Designers, a body including representatives from the various design bureaus involved in the station. Mounted on top of the Base Block would have been a large cross beam known as the Science Power Platform (Russian abbreviation NEP). The NEP was to be outfitted with retractable solar panels similar to those used on Mir's Kristall module and also with solar parabolic concentrators, known in Russian terminology as a 'solar gas turbine installation' and in NASA jargon as a 'solar dynamic power system'. Unlike a photovoltaic system, such concentrators utilise the Sun's heat instead of its light for the production of power. The heat is collected in a receiver which is located near the focal point of a parabolic mirror and power is generated exactly the same way as in a power station on Earth, namely by heating a fluid which in turn rotates a turbine. Since a heat/gas-driven turbine is a much more efficient power converter than a solar cell, the mirror has to be only one fourth the area of a solar array to generate the same amount of power. Other devices to be mounted on the NEP were radiator panels, small engine units (similar to the VDU unit on Mir's Sofora mast) and small rotatable science platforms comparable to the ones on Kvant-2 and the Vega Venus/Halley probes. The ball-shaped multiple docking adapter of DOS-8 was once again to be outfitted with four lateral docking ports as in the original design. All six docking ports were to be of the 'probe-drogue' type.

The add-on modules for DOS-8 represented a radical departure from the bulky 20-ton modules of Mir. The Mir modules themselves had gone through a long evolutionary path ever since the approval of multimodular space stations in 1976. The original idea was to launch small Soyuz-based specialised modules that could regularly be changed out. In 1979, after the design bureau in Fili joined the Mir project, that idea was dropped in favour of the Proton-launched 37KS modules, which consisted of a laboratory section and a heavy space tug derived from the FGB units of the Transport Supply Ships (TKS), originally developed to ferry crews and cargo to Almaz. One of the 37KS modules, Kvant, docked with Mir in 1987, but the others were cancelled in 1983/84 in favour of the 20-ton 77KS modules that eventually flew to Mir as Kvant-2, Kristall, Spektr and Priroda. These were also designed by the Fili bureau (by now called KB Salyut) and based on the FGB.

The proposals tabled for Mir-2 in 1992/93 marked a return to some of the cancelled module concepts for Mir and also eliminated any role for KB Salyut, which in 1993 became part of the Khrunichev Centre. First, they would be much lighter

than the 77KS modules, allowing them to be launched by Soyuz or Zenit rockets. Second, they would be ferried to the station by detachable space tugs, no heavy derivatives of the FGB as in the case of the 37KS modules, but units derived from the propulsion compartment of the Progress-M cargo ship. The four radial docking ports of Mir-2 were to be occupied by a Docking Compartment, a Service Module, a Technological Module and a Biotechnological Module. An alternative plan to launch the latter two with Buran was given up fairly soon as funds for the Russian shuttle dried up after the collapse of the USSR (Fig. 4).

The Docking Compartment had an airlock for spacewalks and an aft androgynous APAS docking port mainly intended for Buran dockings, which would have required it to be temporarily moved to the front axial port of the Base Block. The main functions of the Service Module (not to be confused with the identically named cornerstone of the ISS Russian segment) were to provide attitude control through the use of control moment gyroscopes ('gyrodins' in Russian terminology), to store and distribute power provided by the solar panels and solar parabolic concentrators and to make sure that excess heat from the various modules was transported to the radiator panels on the NEP and the Base Block. It also had an aft docking port to receive Soyuz-TM and Progress-M vehicles. No repositioning of the module was required for such dockings. The Technological and Biotechnological Modules would have been used for the production of pharmaceutical products as well as pure crystals and alloys.

The Docking Compartment weighed about 3-4 tonnes and together with the attached Progress-M propulsion compartment remained within the payload limits of the Soyuz-U rocket. The Service Module and the two production modules were based on a new resupply ship designed for launch by the Zenit booster. An initial version of this Zenit-launched resupply ship, essentially an enlarged Progress vehicle, had been conceived around 1988 and was supposed to fly to the giant 180GK/Mir-2 space station. Known as Progress-MT or 11F615A75 (the standard Progress-M being 11F615A55), it would have had enlarged cargo and propellant compartments [7] (Fig. 5). A slightly modified version for the new Mir-2 appeared on the drawing boards in the early 1990s. Its index was 11F615A77 and it later became known as Progress-M2 (not to be confused with the second vehicle in the Progress-M series) (Fig. 6). The overal mass of the ship was 13.3 tonnes and it was 12.6 metres long. It had a 5.3-tonne compartment combining the functions of the Progress-M propulsion and propellant compartments, the propellant being used to either refuel the station or provide additional fuel to the ship's own engines. Attached to this section would be an 8-tonne cargo compartment (2.3 tonnes empty with a maximum of 5.7 tonnes of cargo) with a docking port. The plan apparently was for Progress-M and Progress-M2 to be used simultaneously to resupply Mir-2.

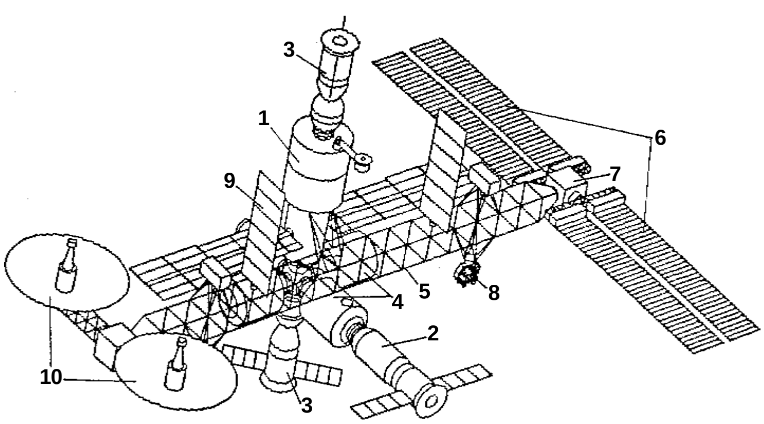


Fig. 4 Mir-2 configuration in 1992.
(source: K. Lantratov)

Key:
1. Base Block (DOS-8);
2. Progress-M2 cargo ship;
3. Soyuz-TM vehicle;
4. Specialised modules;
5. Truss;
6. Solar arrays;
7. Solar array drive mechanism;
8. VDU thruster package;
9. Radiator;
10. Solar parabolic concentrators.

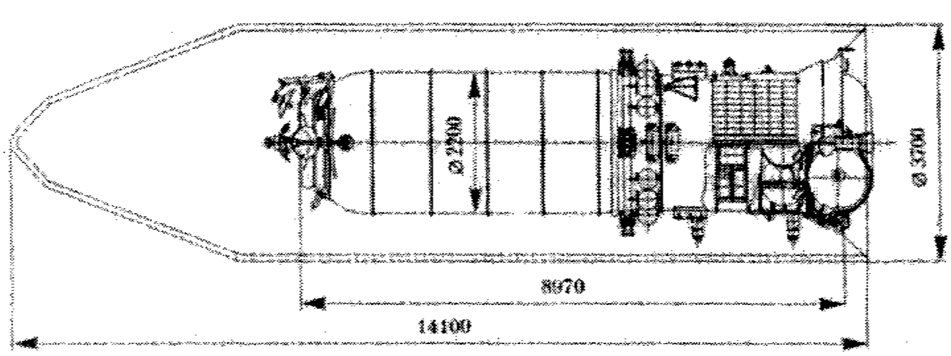
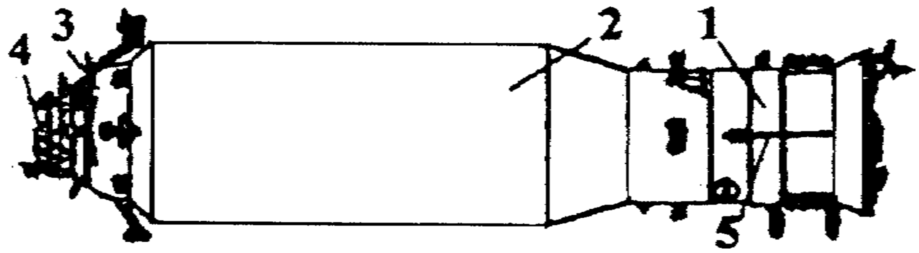


Fig. 5 A version of Progress-MT briefly considered in 1999 for launch by the Yamal rocket.
(source: RKK Energiya)

Fig. 6 The Progress-M2 cargo ship.
(source: Novosti Kosmonavtiki)

Key: 1. Propulsion and propellant compartment;
2. Cargo compartment;
3. Forward section;
4. Docking port;
5. Solar panel.



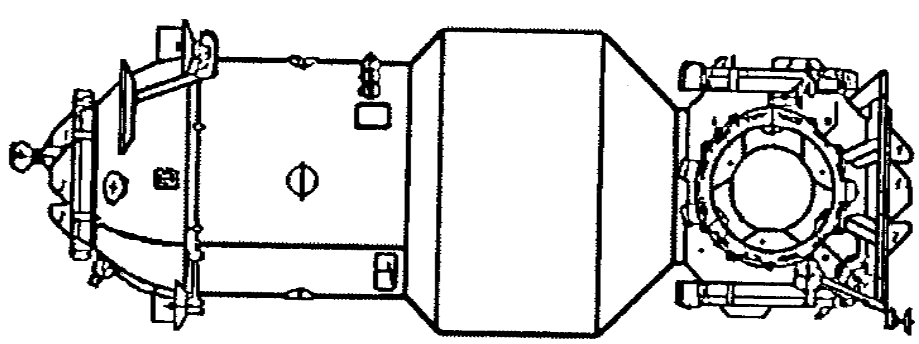
Progress-M2 could easily be reconfigured as a permanent add-on module by changing the 8-tonne compartment into a laboratory. Two other Progress-M2 derivatives were later described for the International Space Station and it is likely that they were originally designed for Mir-2 as well. One was a tanker version in which the 8-tonne cargo compartment would have been replaced by an unpressurised propellant section. This vehicle could also act as a tug for larger modules and payloads. The other was an assembly version that would substitute the 8-tonne compartment for a large structure to be used in station assembly. The module and assembly versions would have discarded their propulsion compartments after reaching the station [8].

According to the 1992 plans construction of the Mir-2 complex was to begin with the launch of the DOS-8 core module in the first quarter of 1996, followed shortly afterwards by the assembly of the NEP truss using several Progress or Buran launches. That same year DOS-8 was to be joined by the Docking and Service Modules, with the Biotechnological Module going up in 1997 and the Technological Module in 1998. The station was expected to remain operational for at least ten years and would be permanently occupied by two to three cosmonauts.

The 1993 Mir-2 Design

Sometime in the first half of 1993 it was decided to expand Mir-2 with two so-called Universal Docking Modules (Russian abbreviation: USM) that provided extra docking opportunities for modules and transport ships and eliminated the need for lateral docking ports on the DOS-8 docking adapter. The USMs were to be launched by Zenit and delivered to the station by a detachable Progress-M2 propulsion compartment. They had about the same length and mass as the other Progress-M2 based modules, but consisted of three sections rather than one long cylindrical compartment. The front section was a small cylinder with a single axial docking port, the middle section was about the same diameter as the Progress-M2 cargo section and the aft section was a square-shaped docking adapter with five docking ports, four lateral and one axial. Most or all of the docking ports were supposed to be of the androgynous APAS type. In the previous Mir-2 design only the Docking Compartment was supposed to have an APAS port (Fig. 7).

Fig. 7 The Universal Docking Module with APAS docking ports.
(source: Novosti Kosmonavtiki)



USM N°1 was to be attached to the front docking port of DOS-8 and USM N°2 to one of the lateral docking ports of USM N°1. The Biotechnology and Service Modules would be docked to the lateral ports of USM N°1 and the Technology Module plus a new Remote Sensing Module to the lateral ports of USM N°2. There would now be two Docking Compartments, one attached to USM N°1 and the other to the aft port of the Base Block. This gave cosmonauts more flexibility in perfoming spacewalks, making it possible to easily gain access to any part of the orbital complex. Another novelty was the installation of two pressurised sections on the NEP with gyrodins and storage batteries [9] (Fig. 8).

Given the new international climate Mir-2 would probably not have remained an all-Russian venture. In the summer of 1992 the European Space Agency began expressing interest in participating in the project, which would have given ESA a back-up option for pursuing its man-related space efforts in case the politically fragile Freedom project fell victim to

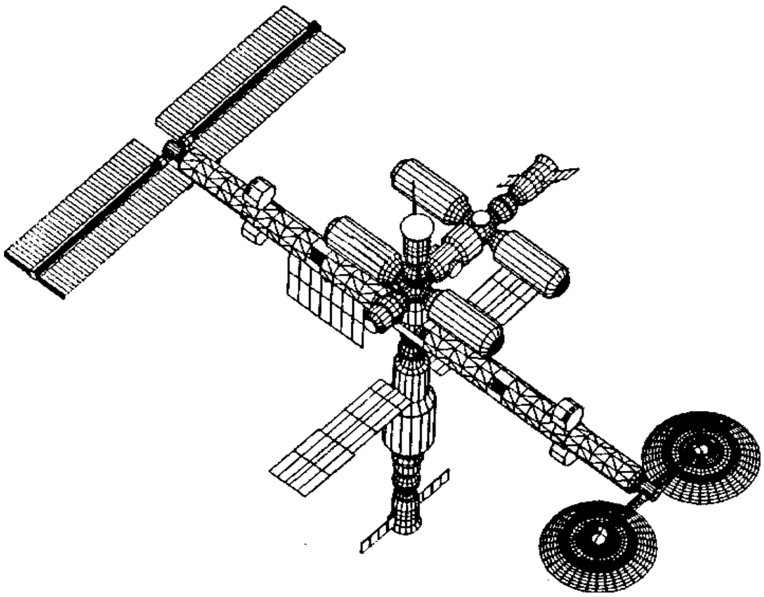


Fig. 8 Mir-2 with two Universal Docking Modules. (source: RKK Energiya)

budget cuts. ESA showed particular interest in the 65° inclination of the Mir-2 complex. One early option studied was to fly the so-called Euro-Russian Technological Complex (ERTC) in conjunction with Mir-2. This was a European-Russian version of the Man-Tended Free Flyer (MTFF), a free-flying element of the Columbus programme that was no longer seen as a viable option for Freedom. It would have been delivered to the station either by a Progress-M or Progress-M2 propulsion compartment [10]. In November 1992 the ESA ministerial meeting in Granada gave the go-ahead for expanding Euro-Russian space co-operation, one aspect of which was to be joint work on the Mir-2 station. Co-operative ventures studied in the following months were the modernisation of Progress and Soyuz vehicles, a jointly built EVA spacesuit and a robotic arm called ERA (European Robotic Arm) [11]. Another potential partner was Japan, although no concrete proposals seem to have been worked out for Japanese contributions to Mir-2.

Merging Mir-2 with Freedom

Early Discussions (March-September 1993)

The first discussions on Russian participation in the Freedom project began in late 1991 and focused exclusively on the use of Soyuz-TM as an interim crew rescue vehicle for the joint US/European/Canadian/Japanese space station (see Soyuz section). US-Russian space co-operation got a further boost on 17 June 1992 when US President George Bush and Russian President Boris Yeltsin signed an agreement on joint manned flights during their first summit in Washington. This provided the basis for an agreement between NASA and the Russian Space Agency, signed in Moscow on 5 October 1992, in which the details of those flights were worked out. The plan was for a Russian cosmonaut to fly a mission aboard the US Space Shuttle in 1994 and for a US astronaut to spend about 90 days aboard the Mir space station in 1995, with the Space Shuttle performing a rendezvous and docking with Mir to bring back the US astronaut at the end of his mission.

The first move towards an actual merger of the Freedom and Mir-2 programmes seems to have come in early 1993. On 11 February 1993 NPO Energiya officials received an invitation from Boeing to discuss various aspects of US/Russian space co-operation. A delegation of NPO Energiya headed by general designer Yuriy P. Semyonov arrived at the Boeing headquarters in Seattle on 5 March 1993 for a week of joint discussions on 12 possible areas of co-operation. One of these was the creation of an international space station comprising elements of both Mir-2 and Freedom [12]. Russian Space Agency director Yuriy Koptev reportedly also discussed this option in a meeting with NASA Administrator Dan Goldin in Washington that same month [13].

On 15 March, just one day after the NPO Energiya team returned to Russia, Semyonov and Koptev sent a joint letter to Goldin outlining their proposals for such a station. It would orbit at an inclination higher than 50°, a compromise between the planned 28° inclination of Freedom and the 65° inclination of Mir-2. They stressed that the merger of the two space stations would be cost-effective for both sides. Under the Semyonov/Koptev proposal the Russian segment would consist of four Mir-2 elements: the DOS-8 Base Block, a Universal Docking Module, a

Docking Compartment with airlock and the Service Module. The Universal Docking Module would act as the interface between the Russian and US segments. Soyuz-TM and Progress-M vehicles would be used to ferry up crews and cargo. Station assembly was to begin with three Russian launches (DOS-8, the Universal Docking Module and the Docking Compartment) after which a Canadian robot arm would be deployed to assist in further assembly activities. These would include the addition of the US Lab, the US Hab and the European and Japanese modules. A total of fourteen assembly flights would be needed to complete the station. The station would be able to house a permanent three-man crew by the sixth flight in 1997 and would be continuously manned by nine astronauts in 2000. By contrast, the Freedom plans called for *beginning* permanent occupation in 2000 [14].

The Russian proposal came at a time when the Freedom project was running into ever deeper trouble. Originally approved by President Reagan in 1984, it was seriously over budget and still several years away from its first launch. On 18 February, less than a month after taking office, President Bill Clinton had ordered yet another redesign of Freedom and directed its cost to be reduced by more than half and to advance the construction schedule. On 9 March NASA Administrator Dan Goldin set up a redesign team that was to present various options for the redesign to Clinton by early June.

Meanwhile, officials from the White House, NASA and the Defence, Commerce and State Departments had begun debating the possibility of further involving the Russians in the station effort, possibly in response to the Koptev/Semyonov letter. Both Clinton and Vice-President Al Gore reacted favourably to the idea when they were briefed about it on 1 April. During a summit between Clinton and Yeltsin in Vancouver on 3-4 April the Russians were officially invited to offer advice on the station redesign effort. Another outcome of the summit was the formation of a high-level commission led by Gore and Russian Prime Minister Viktor Chernomyrdin to chart the course of US-Russian co-operation in energy and space. Officially called the Russian-American Commission on Economic and Technological Co-operation, it became informally known as the Gore-Chernomyrdin commission [15].

From 22 April to 5 May a Russian delegation including Koptev, Semyonov, Polukhin (KB Salyut), Utkin (TsNIIMash) and Grigoryev (IMBP) was in the United States to discuss the use of Russian experience in the space station redesign with NASA, White House and Defence Department officials. Members of the delegation proposed two variants of co-operation. One would see the joining of Freedom and Mir-2 into a single station pretty much in the same way that Koptev and Semyonov had outlined in their 15 March letter to Goldin. Another possibility would be separate stations that would use the same transportation and rescue systems, which would still require them to be launched into the same inclination. The Russian officials stressed that they were nearing a decision on full-scale Mir-2 production and therefore needed to know soon whether they would be invited to take part in the international station. However, it soon dawned upon them that they had come to the US with too high expectations. NASA officials made clear that a combined station was beyond the scope of what the redesign team was studying. Instead, they consulted the Russians on the possibility of using the Proton rocket to launch large elements of the station (such as the European and Japanese modules). The Russians were also invited to evaluate the cost of building the primary American modules and their life support systems, with final outfitting taking place in the US. The delegation was confronted with widely differing opinions on the level of Russian involvement in the station and left the US with mixed feelings on the prospects of co-operation [16].

Faced with an early June deadline to present its report to the White House, the station redesign team simply did not have the time to integrate the radical Russian proposals into the options it had singled out by this time. Shortly after its formation in March the team had been bombarded with ideas from all sides. At least one of these had been for Freedom to be assembled in a 51° inclination orbit so that it could share rescue and supply vehicles as well as other components with Mir and/or Mir-2, allowing people and cargo to be ferried between the two stations [17]. While the team kept the 51° inclination orbit open as an option, the three redesign plans that emerged from their studies by late April limited Russian co-operation to the use of the Soyuz-TM lifeboat and Russian docking systems. At that point the team stopped accepting major changes to the three options so that NASA analysts could examine the price tag of each before the deadline expired [18].

Option A (nicknamed 'austere') was a scaled-down version of Freedom with the possible inclusion of a Lockheed propulsion unit ('Bus-1'), probably used on the advanced KH-11 spy satellites. Option B (nicknamed 'baseline') represented a minimal departure from the Freedom design and Option C (nicknamed 'the can') called for a single-launch core station that could later be expanded with additional modules. Clinton eventually picked a combination of Options A and B, a decision announced by the White House on 17 June. He also called for sweeping management and contract reforms and keeping spending under $11 billion over the following five years, a $4 billion reduction from the original estimates.

Important questions such as the station's inclination and Russian involvement remained unsettled and many Congress members continued to have second thoughts about the still impressive cost. Later that month an amendment aimed at shutting down the project was rejected in the House of Representatives with the narrowest possible margin (216-215).

NASA's redesign team, renamed the transition team, was now tasked with working out the technical and managerial details of the revamped station before 7 September. As the team got down to work, one of the major political stumbling blocks towards expanding Russian co-operation on the station was overcome. After intense negotiations in Washington between US and Russian officials in mid-July Moscow agreed to abide by the Missile Technology Control Regime, an international accord that limited sales and the transfer of rocket parts and technology. In May 1992 the US government had accused Russia of violating this agreement by selling cryogenic upper stages to India. In letters to Yeltsin and Chernomyrdin in mid-June 1993 Clinton and Gore had linked space station and commercial launch co-operation with Russia's acceptance of anti-proliferation guidelines. This drew an angry response from the Russians and reportedly led to the postponement of the first meeting of the Gore-Chernomyrdin commission, originally scheduled to take place in Washington in mid-June. The agreement, signed by Koptev and US Undersecretary of State Lynn Davis on 15 July, allowed Russia to sell the stages to India, but stipulated that controls be applied on the amount of technology transferred with the hardware. With this hurdle out of the way, the stage was set for the signing of two more key agreements the following two days. On 16 July Koptev and assistant US Trade Representative Peter Allgeier approved an accord to allow Russia into the commercial launch market and on 17 July Koptev and Goldin agreed to study the feasibility of further co-operation in the Shuttle/Mir and space station programmes by 31 August. The agreements would have to lead to a major new US-Russian co-operation pact to be signed by Gore and Chernomyrdin in Washington in early September [19].

On 27 July Goldin met with the chiefs of the European, Japanese and Canadian space agencies in an attempt to allay their fears about increased Russian co-operation in the space station. At the same time, NPO Energiya manager Yuriy Semyonov, appearing at a symposium in Virginia, voiced the hope that the resolution of the export disagreement would open the way for the combination of Russian and international station efforts. Two days later a team of Russian aerospace industry technicians and government representatives began arriving in the US for a month of brainstorming with the station transition team under the agreement reached between Koptev and Goldin on 17 July. The 26-member team included representatives from NPO Energiya, the Khrunichev Centre, TsNIIMash, Star City, IMBP, the Scientific Research Institute of Thermal Processes (NIITP) and the Russian Space Agency. Although a complete merger of Freedom and Mir-2 was supposed to be only one of the options to be discussed, it evolved into an ever more attractive idea as the weeks progressed. Not only would it lead to major cost savings, it was also felt that it would lessen the temptation for some Russian companies to violate international missile proliferation guidelines.

By the end of the month the Russian team produced a 137-page report in which it concluded that Russia could provide about $2.5 billion worth of services and hardware to the station and save the US an estimated $7 billion in expenditures on the programme [20]. On 26 August Goldin and Koptev once again discussed the ambitious plans for co-operation and reportedly agreed to work together on an international space station that would supersede the revamped programme approved by Clinton in June [21]. Finally, on 2 September Gore and Chernomyrdin signed a space pact in Washington calling for a phased station effort. Phase One would see the expansion of Shuttle/Mir operations, with Mir being available for up to two years of aggregate US astronaut time on board. Phase Two would be aimed at 'the use of a next-generation Russian Mir base block together with a laboratory module and the Shuttle' to provide an interim human-tended science capability. According to the agreement, 'successful implementation of this phase could constitute a key element of a truly international space station'. The pact called for working out a detailed plan for such an international station before 1 November [22].

As had been the case in June, the transition team did not have enough time to include the Russian proposals into the revised station plan it was to present to President Clinton by 7 September. What Clinton got on his desk instead was a 37-page plan for a station known as 'Alpha', based largely on the Option A design produced during the redesign work in the spring. A key feature of the station was that the basic configuration remained unchanged regardless of how much Russian hardware would be used. It would maintain the same arrangement of the US, ESA and Japanese modules, the Canadian manipulator arm, the truss and the solar arrays and radiators. That basic configuration could then be complemented in three different ways. In the first two, either the Lockheed Bus-1 or Russian FGB space tugs could be added to provide propulsion, guidance, navigation and control (Fig. 9). In the third option the basic Alpha could be combined with Mir-2 hardware, with the Russians becoming full-fledged partners in the station [23].

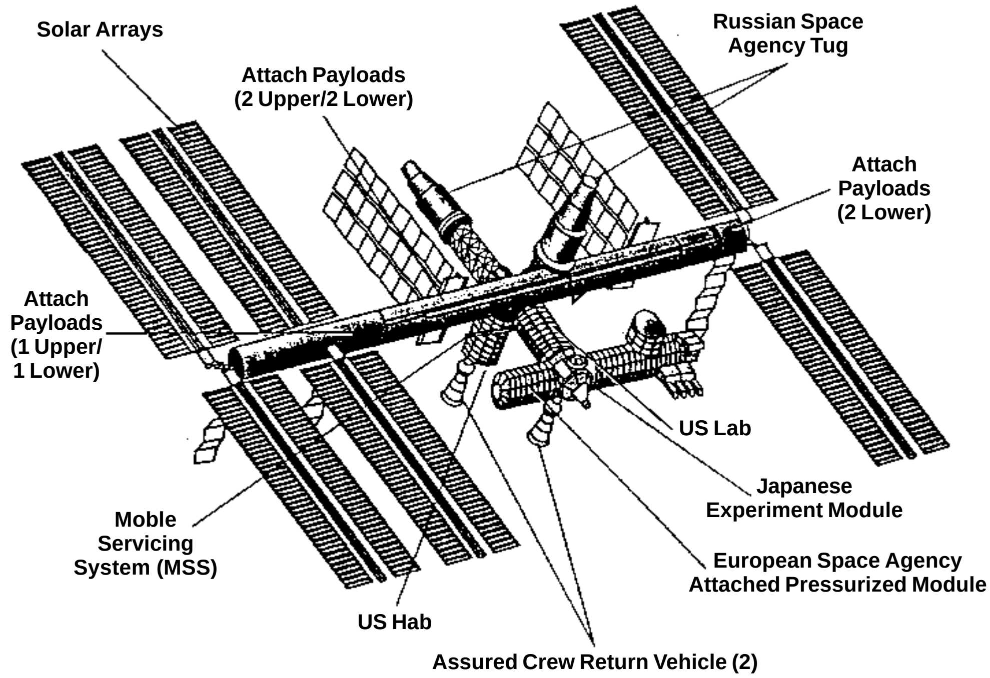


Fig. 9 Alpha concept with two FGB tugs. (source: NASA)

Reaching a Final Concept (September 1993-September 1994)

In the plan for the joint station presented by the Russians on 26 August 1993 the Russian segment was to consist of the following Mir-2 elements (Fig. 10):

- the Base Block
- three Universal Docking Modules
- the Docking Compartment (with airlock)
- the Service Module
- three Research Modules (a technological, a biotechnological and a remote sensing module)
- a downsized version of the Science Power Platform with two solar parabolic concentrators

Notable in the plan was the heavy reliance on Russian elements in the early stages of construction and the ability to have a permanent crew on board from the very start. The first five launches would all be Russian. Assembly was to begin in late 1996 with the launch of the DOS-8/Mir-2 Base Block, which was to be boarded immediately by a three-man resident crew ferried up by Soyuz. Subsequently, two Universal Docking Modules were to be docked in tandem to DOS-8 to permit further expansion of the Russian segment and to provide an interface with the US segment. In the next step the Docking Compartment was to be hooked up with UDM Nr. 2. It was to act as the berthing place for the first US Space Shuttle assembly mission, which was to attach the US Node-1 to UDM Nr. 2, setting the stage for the construction of the 'Western' side of the station. The zenith port of UDM Nr. 1 would later be occupied by the Science Power Platform, which required two Russian launches, and the nadir port was to receive UDM Nr. 3. This in turn was to serve as the core for the final four Russian modules (the Service Module and the three Research Modules). Assembly of the station was to be finished by late 2000 [24].

Now that the Gore-Chernomyrdin commission had given approval to come up with a firm design for the station, Russian and US experts got down to working out the details. An idea that soon emerged was to replace the two Universal Docking Modules in the longitudonal axis of the station by a single FGB tug. It seems that the NASA transition team had already been informed about the FGB's capabilities during the August negotiations with the Russians and it was seen as a potential alternative to the Lockheed Bus-1 in the Alpha design even if the Russians were not to become full partners. Not only was FGB expected to be cheaper, unlike Bus-1 it could be refuelled in orbit. In late September a delegation of NASA and US industry officials was given more information about the FGB during a visit to the Khrunichev Centre in Moscow. On 4 October a Khrunichev representative presented a plan for integrating the FGB into the international space station during a meeting with NASA, Boeing and NPO Energiya

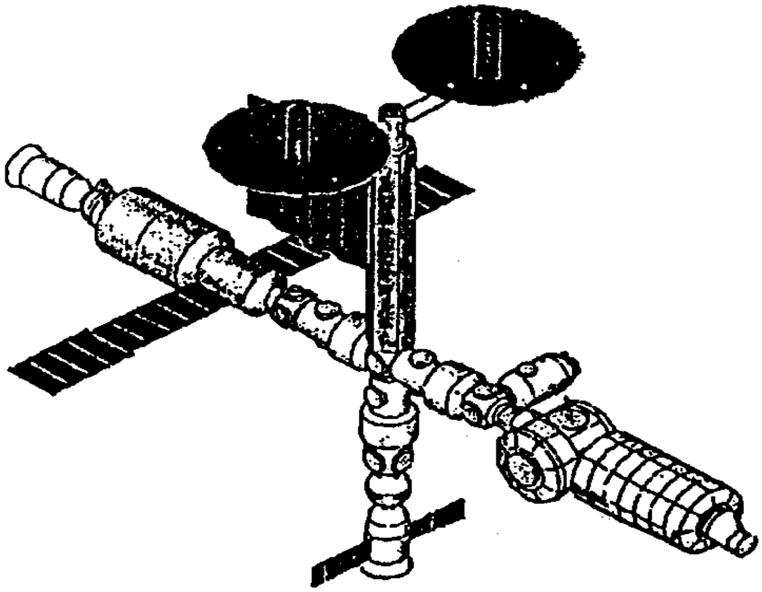


Fig. 10 ISS configuration with three Universal Docking Modules proposed by Russia in August 1993. (source: Novosti Kosmonavtiki)

officials at the Russian Space Agency headquarters in Moscow. The plan was accepted that same month. FGB was to become the first building block of the station and would take care of guidance, navigation, control and station reboosting during the early stages of assembly. Since the FGB had not been planned to be built as part of Mir-2, NASA agreed to pay for the construction of the vehicle.

From an engineering standpoint, there was no compelling need to include the FGB into the ISS. As DOS-8 was supposed to take over most of the FGB's critical functions just months after the latter's launch, station assembly might just as well have been kicked off with the DOS-8 launch as the Russians had proposed in the first place. Clearly, politics played an important role in this decision. With the US footing the bill for its construction, the first element of the station would now essentially become a joint Russian/American module and therefore somewhat alleviated the heavy emphasis on Russian launches in the early stages of assembly, something which the US side had clearly not been comfortable with. On the other hand, the choice of the FGB also solved an internal dispute within the Russian space industry itself. Ever since the early 1970s, NPO Energiya had delegated a significant portion of the design work on its DOS space stations to the Fili branch of Chelomey's bureau. When that bureau became part of Energiya as KB Salyut in 1981, it acquired an even more important role by taking on the design of Mir's add-on modules. However, after having separated from Energiya in 1988, KB Salyut was virtually sidelined for Mir-2, a situation which did not improve after it became part of the Khrunichev Centre in June 1993. Under the international space station assembly plan put forward in late August 1993, virtually all the Russian elements were to be both designed and built by NPO Energiya. Khrunichev's role was confined to that of a subcontractor to Energiya in building the former Mir-2 Base Block. Not satisfied with playing second fiddle to Energiya, Khrunichev Centre director Anatoliy Kiselyov reportedly urged his designers to come up with a plan to increase the centre's involvement in the station. The FGB, both designed and built by Khrunichev, perfectly fit the bill [25].

Another change made to the Russian segment in the autumn of 1993 was to delete the two solar parabolic concentrators from the Science Power Platform. According to the original Russian proposals these were to have been mounted in the early stages of assembly, but NASA engineers doubted they could be developed in such a short time. They also feared it would be difficult to dissipate the heat produced by the concentrators' turbines, something which could only be achieved with huge radiators. A NASA proposal to decrease the capacity of each concentrator from 10 kilowatts to 2-3 kilowatts was turned down by the Russians on the grounds that the whole idea of the concentrators was to produce large amounts of energy. The final compromise was to indefinitely postpone the installation of the 10 kWt concentrators and deploy them at a later stage on the US truss rather than the Science Power Platform. Instead, the Science Power Platform would be equipped with standard solar arrays producing roughly the same amount of power as the solar concentrators. There were plans to test the technology for the solar parabolic concentrators in the Shuttle-Mir programme, but eventually the concentrators were dropped altogether from the ISS design [26].

The resulting 'Addendum to the Space Station Alpha Programme Implementation Plan' was officially approved by

Goldin and Koptev on 1 November and presented to the White House the same day. The details were outlined at a press conference by Goldin and Koptev three days later. The Russian segment (also known as 27KSM) now consisted of the following elements:

- the FGB Energy Block
- the Service Module (NASA and Russian acronyms: SM)
- the Docking Compartment (NASA acronym: DC, Russian acronym: SO)
- one Universal Docking Module (NASA acronym: UDM, Russian acronym: USM)
- the Life Support Module (NASA acronym: LSM, Russian acronym: MZhO)
- three Research Modules (NASA acronym: RM, Russian acronym: IM)
- the Science Power Platform (NASA acronym: SPP, Russian acronym: NEP)

Rather confusingly, the former Mir-2 Base Block was now renamed the Service Module, the same name that had been used for one of the Mir-2 add-on modules. What used to be the Mir-2 Service Module was now replaced by the Life Support Module, a module with additional life support systems for the Russian segment. Assembly was now slated to begin in May 1997 with the launch of the FGB Energy Block, followed one month later by the Docking Compartment. In July 1997 NASA was to add the Node-1, with the Russians putting up the Service Module later that same month. The Science Power Platform, requiring one US and one Russian launch, was now to be mounted on the zenith port of the FGB, with the zenith and nadir ports of the Service Module to be occupied by the Life Support Module and the single remaining Universal Docking Module respectively. Assembly of the whole station was expected to be finished in October 2001 [27] (Fig. 11).

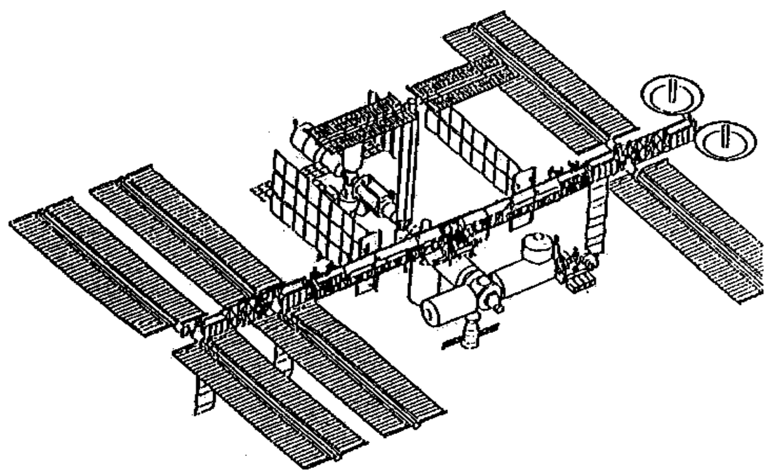


Fig. 11 ISS configuration as proposed in November 1993. Note the SPP on the zenith port of the FGB and solar parabolic concentrators on the main truss. (source: Novosti Kosmonavtiki)

One more change in the Russian segment took place before the end of 1993. The Science Power Platform was moved from the FGB to the Service Module's zenith docking port and all launches needed to assemble it would now be performed by the Russians themselves [28]. The Life Support Module, originally supposed to occupy the Service Module's zenith port, was transferred to the FGB nadir port, with the Docking Compartment moving from the FGB nadir to the FGB zenith port.

In the weeks after the 4 November announcement two major political hurdles were overcome that cleared the path for full Russian participation in the station. On 29 November the White House won backing for the plan from key congressional leaders. Many within Congress had expressed second thoughts about Russia's involvement, especially after more political upheaval in Moscow in the preceding weeks. On 6 December representatives from 10 European countries, Japan, Canada and the US formally invited the Russians to take part in the space station project. Finally, on 16 December the Russians officially accepted the invitation during the second meeting of the Gore/Chernomyrdin commission in Moscow, completing almost nine months of lobbying. It took several more months of intense negotiations to work out the organisational and financial details of the joint undertaking. On 23 June 1994, in a ceremony timed to coincide with the third meeting of the Gore/Chernomyrdin commission in Washington, the heads of the US and Russian space agencies signed a $400 million contract under which NASA would pay $305 million to Russia for joint Shuttle/Mir operations and $95 million for Russian contributions to the International Space Station. On the organisational side, the Russian Space Agency would be responsible for co-ordinating work on the ISS Russian segment and carrying out negotiations with foreign partners, while RKK Energiya would act as prime contractor.

On 28 September 1994 NASA released a new assembly sequence, which aside from a slip in the FGB's launch from May to November 1997 showed some important changes in the Russian segment. Some of these resulted from a 10 August meeting where RKK Energiya general designer Yuriy Semyonov had signed the Draft Plan for the Russian segment. Most notable was the addition of the so-called Docking and Stowage Module (NASA acronym: DSM, Russian acronym: MSS), which was to provide extra storage room and had an aft docking port for receiving Russian ferry vehicles as well as the planned US lifeboat. The DSM was to be docked to the FGB nadir port, necessitating another relocation of the Life Support Module, which was now moved to one of the lateral docking ports of the Universal Docking Module.

The new schedule also reflected NASA's attempts to ease Russia out of the 'critical path' as much as possible. In the original assembly schedule there was a heavy reliance on the Russian Science Power Platform to provide energy for the US segment in the early stages of station construction. The huge US solar arrays could not be installed until after the deployment of the truss on the US Lab. In July 1994 NASA decided to push forward the launch date of one of its solar arrays from August 2000 to September 1998 by temporarily mounting it on on top of the US Node 1, mainly to satisfy the energy requirements of the US Lab. At that time a preliminary decision was made to delay the launch of the SPP to October 2000. However, in the September 1994 assembly schedule that date was moved *back* to late 1998/early 1999 in order to avoid the opposite situation, namely that the Russian segment would have to draw too much power from the US solar arrays [29].

Another pivotal Russian element in the early stages of station construction was the Docking Compartment, which was to play a crucial role in connecting the Russian and US segments. The plan was for the DC to link up with one of the FGB's longitudonal docking ports and subsequently receive the Shuttle on the Node-1 delivery mission. Once the Shuttle had arrived, the FGB was to undock, reposition itself so that one of its radial ports faced the DC/ Shuttle combination and then redock. Next the Shuttle's remote manipulator arm would lift Node-1 out of the cargo bay and attach it to the now vacant 'front' port of the FGB (Fig. 12). Apparently, NASA considered this procedure too risky and opted instead for a mission in which the Shuttle's arm would capture the FGB and then directly dock it to the Node-1 still sitting in the cargo bay. This obviated the need for an early launch of the DC and no longer required it to be attached to the FGB zenith port, which was deleted from the FGB design. Instead, the Docking Compartment was transferred to the UDM, which now had all its four radial docking ports occupied (DC, LSM, RM-1 and RM-2). This meant that the LSM had to be fitted with an aft docking port in order to receive the third and final Research Module.

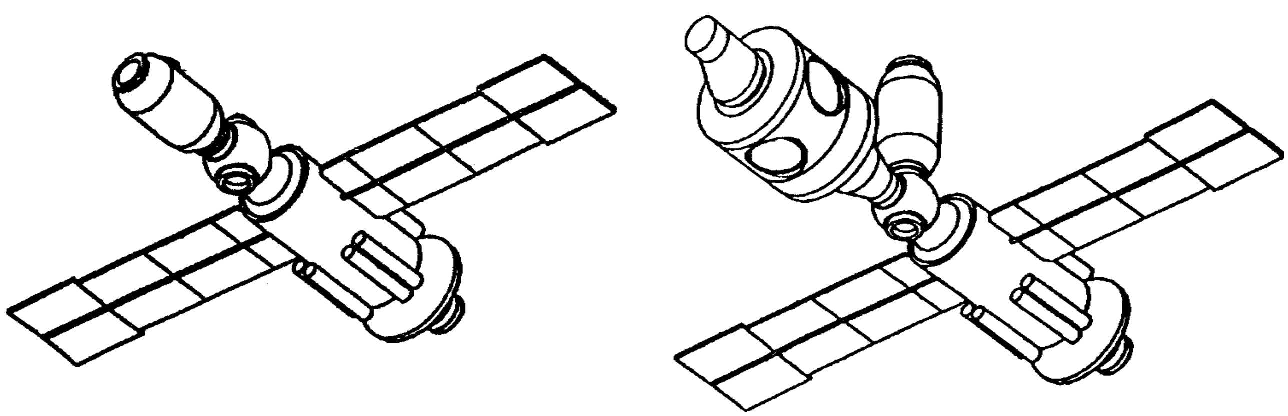


Fig. 12 Original location of the Docking Compartment to receive Node-1. (source: Novosti Kosmonavtiki)

It was also at this point that the Russians decided to have three types of docking ports on their segment rather than one. The original plans for the Russian segment had called for the use of a single type of docking unit, namely the so-called APAS-89 (Russian short for Androgynous Peripheral Docking System) [30] (Fig. 13). A modified version of the Apollo-Soyuz APAS-75 system, it had originally been built for use on Buran's docking adapter and two of them had also been installed on Mir's Kristall module to receive Buran orbiters, small scientific modules and eventually also the US Space Shuttle. Reportedly, the problem with APAS was its relatively high mass, which would make Soyuz too heavy to transport a three-man crew to the station [31]. Therefore, the only APAS left on the Russian segment was on the side of the FGB docked to Node-1. All the other docking ports would be either of the standard 'probe-drogue' type used on Mir, officially called the Internal Transfer Docking System (Russian abbreviation SSVP) (Fig. 14), or a hybrid of the APAS and the SSVP

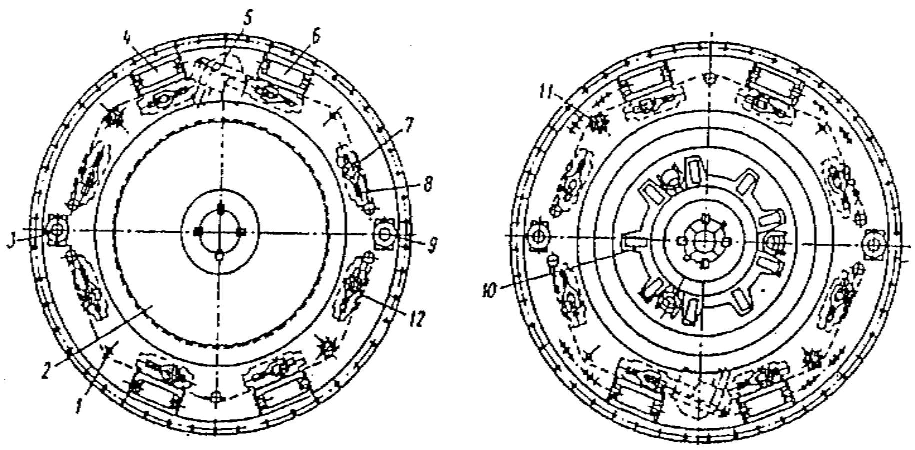


Fig. 13 Passive (left) and active APAS-89 docking port. (source: RKK Energiya)

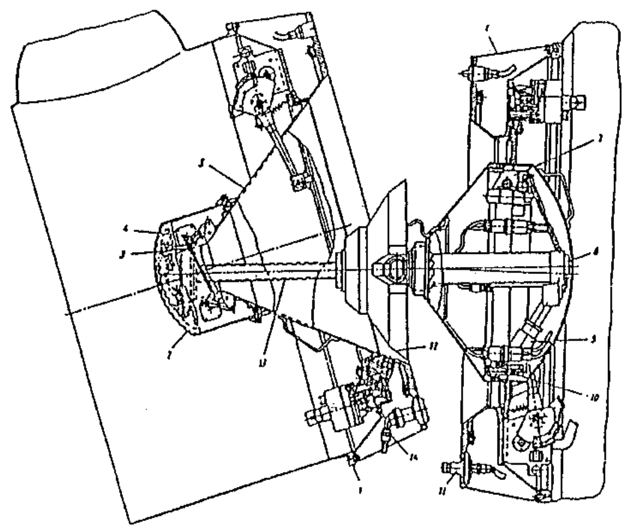


Fig. 14 SSVP "probe-drogue" docking mechanism. (source: RKK Energiya)

called SSVP-M (Fig. 15). Providing a firmer connection than the SSVP, the SSVP-M had the probe-drogue linking mechanism of the SSVP and the periphery of the APAS. Since the SSVP and the SSVP-M were incompatible, every module and ferry was now restricted to a certain number of docking ports. Further complicating the docking situation was that all modules headed for the Universal Docking Module first had to link-up with its aft axial port and then engage one of two sockets on the UDM to be transferred to one of the four lateral ports (as had been the case on Mir's spherical docking adapter) [32].

The Mir Option (December 1995)

As things stood in 1995, Russia was to abandon its Mir complex in 1997 after seven Shuttle-Mir flights and then dedicate all its manned spaceflight resources to the assembly of the ISS. However, as time went on, it became clear that Mir would be able to continue in orbit for several more years, the more so because its two last add-on modules wouldn't be launched until the mid-1990s. All this faced the Russians with a dilemma. With Russia shouldering much of the responsibility for the early stages of station construction, the country could barely afford to operate two space stations simultaneously. In June 1995, only weeks after the launch of Spektr, a deputy of Yuriy Koptev raised the possibility of transferring Spektr and Priroda to ISS during a meeting with NASA station director Wilbur Trafton at the Paris Air Show. This would have involved the use of either the Shuttle or some sort of propulsion module, although the Russians would have had to incur the costs of the transfer.

In August officials of NPO Energiya and the Khrunichev Centre jointly began working out plans for making maximum use of Mir's resources in the build-up of ISS. These focused either on assembling the ISS in the vicinity of Mir or, more radically, on using Mir as a starting point for the assembly of the ISS. During a meeting at the Russian Space Agency on 13 October 1995 it was decided to present the plans to the Americans. In mid-December a Russian delegation visiting Houston outlined two scenarios in which the initial elements of the ISS would be attached to Mir, after which Mir elements would be gradually discarded as they became too old to remain in orbit. Few details of the Russian proposal were made public. Apparently, the plan was to first dock the FGB and Node-1 in orbit and then link up the combination with Mir's front docking port. The Service Module

Fig. 15 Passive SSVP-M hybrid docking port on the Service Module. (source: NASA)

could then have been sent up to dock on the other side of Mir or could have stayed on the ground until the Mir core module had outserved its usefulness. Meanwhile, the US and the other partners would be free to build up their segment of the station on the Node-1 side. Under this plan the Russians would have been able to use the newly launched Mir modules to the maximum extent possible and could have scrapped the development of two of the three ISS Research Modules [33].

The plans, which had already drawn a lot of criticism from the US side in the weeks before the arrival of the Russian delegation, were rejected outright by the Americans. With the full backing of both Al Gore and Dan Goldin, two key House members in charge of NASA funding visited Moscow in early January to deliver the message that with such radical proposals the Russians were jeapordising Congressional support for the station and that, if necessary, the US and the other partners would go it alone. It was claimed that the Mir option would delay completion of the station by up to a year and would add billions of dollars to the station's price tag. For instance, it would force engineers to completely redesign electrical and mechanical connections between Mir and the Russian station components.

Later that month US and Russian negotiators hammered out a compromise plan that would allow Russia to keep Mir in orbit and still meet its space station obligations. The most important elements of the plan were approved at the 6th session of the Gore-Chernomyrdin commission in Moscow in late January 1996. In order to reduce the number of Progress resupply missions to Mir, NASA agreed to fly an additional two Shuttle missions to Mir in 1998 to deliver about 6,000 kg of supplies and scientific experiments and to study the possibility of adding additional flights in 1999. In addition to that, the bulk of the Russian Science Power Platform components were now to be put into orbit in late 1999 on a single Shuttle mission instead of three Zenit launches and several of the less critical Russian add-on modules would be allowed to slip in the assembly schedule. In return, Russia pledged to deliver the FGB and the Service Module on time to ensure that the initial stages of station construction remained on schedule. As later events would show, the Russians were not able to keep that promise.

The Backbone: Zarya and Zvezda

FGB/Zarya

Design Features

Being the first element of the ISS, the FGB was to provide electrical power, attitude control and computer commands to the embryonic station and also to keep it in the proper orbit. It was to play an active role in docking the Service Module to the station and after this operation would mainly serve as a fuel depot and storage facility.

FGB is the Russian acronym for Functional Cargo Block (*Funktsionalno-Gruzovoy Blok)*, although in NASA documentation it was referred to as the 'FGB Energy Block'. In June 1998 it was officially named Zarya ('Dawn'), symbolising the beginning of a new era in space exploration, although this was hardly a new name in the Russian space programme [34]. A proposal by the Russian Space Agency to name it Atlant had earlier been rejected by NASA.

Zarya is a descendant of the Transport Supply Ships (TKS – index 11F72) originally designed in the late 1960s at the Chelomey bureau to ferry crews and supplies to the military Almaz space stations. Built at Khrunichev, the TKS vehicles consisted of a Functional Cargo Block (index 11F77) designed by the Fili branch of the Chelomey bureau and a Return Apparatus (index 11F74) designed by the central office of the Chelomey bureau in Reutov. The FGB section had storage room, propellant tanks and engines and the Return Apparatus was to house cosmonauts during launch, docking and landing. Four TKS vehicles were eventually flown, one on a solo mission (Cosmos-929), one to Salyut-6 (Cosmos-1267) and two to Salyut-7 (Cosmos-1443 and 1686). A modified FGB section called PGO (for Instrument Cargo Compartment) later served as the front section of the Mir modules Kvant-2, Kristall, Spektr and Priroda (common index 77KS). Attached to the PGO were one or more additional compartments tailored to each module's specific needs.

The lineage of Zarya is reflected in its index 77KM (serial number 17501). The vehicle is divided into two main sections, the Instrument Cargo Compartment (PGO) and a spherical docking hub referred to by the Russians as the Hermetic Adapter (GA). The PGO is subdivided into three compartments: PGO-2 is the 'aft' conical compartment with an active SSVP-M docking port for the Service Module and PGO-1 and PGO-3 are the two cylindrical compartments that constitute the pressurised core of Zarya. PGO-3 is separated by a hatch from the GA, which has an axial APAS-89 docking port compatible with Node-1/Unity and an SSVP nadir docking port. The zenith port was dropped early in the module's design. Outwardly, Zarya most closely resembles Kristall, the major difference being that on Zarya the pressurised core has the same diameter throughout (Fig. 16).

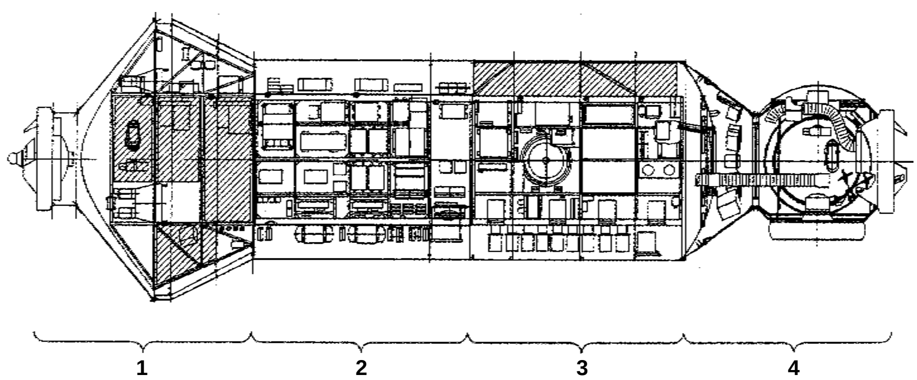


Fig. 16 The main compartments of Zarya. (source: Novosti Kosmonavtiki)

Key: 1. PGO-2; 2. PGO-1; 3. PGO-3; 4. GA.

Zarya's engine system consists of two 417 kg thrust rendezvous and orbital manoeuvering engines, twenty-four 40 kg thrust approach and stabilisation engines and 16 Vernier engines with 1.36 kg of thrust each for attitude control. Exclusively used before the arrival of the Service Module, these engines drew their propellant from 16 tanks mounted in pairs on the exterior of the pressurised core (eight nitrogen tetroxide tanks and eight UDMH tanks). Ten of the tanks (five oxidizer, five fuel) hold propellant at high pressure for the small-thrust engines and the remaining tanks hold propellant at low pressure for the two high-thrust engines. After the arrival of the Service Module the propellant is stored for use by the Service Module's engines.

Electricity is provided by two solar arrays with a surface of 28 m² each (7 m in length and 4 m in diameter). Extending from the PGO-3 compartment, they have a combined capacity of 6 kWt. If needed, they can be folded up later in the station assembly process if they become shaded by other station elements. There are six nickel-cadmium batteries inside the PGO-1 compartment which store electricity for use during the nighttime portions of the station's orbit. Installed behind panels inside the PGO-1 and PGO-3 compartments are other FGB support systems as well as lockers for equipment storage, leaving only a relatively narrow passageway for crew members floating through the module. Zarya's command and control post is situated in the conical PGO-2 section and contains two US-built multiplex-demultiplex processors using Russian software [35].

The Road to the Launch Pad

NASA considered for a while to lease the FGB from the Russians, but given the critical nature of the vehicle in

station assembly eventually decided to procure the vehicle from Khrunichev. Under the $400 million contract signed between NASA and the Russian Space Agency on 23 June 1994, $25 million was earmarked for early work on the FGB. The contract to buy the FGB from Khrunichev was to be negotiated by Lockheed Missiles and Space Co., which had strong ties with Khrunichev through a joint venture called International Launch Services, responsible for marketing the Proton rocket. The money for the FGB was to flow from NASA to US station prime contractor Boeing to Lockheed to Khrunichev. It took several months to reach agreement on the total value of the contract and on the issue of who would pay for the launch. NASA found Khrunichev's selling price of $245 million unacceptable, with the Russians countering that the same piece of hardware built in the US would cost $1 billion. A final deal was not reached until early February 1995. NASA would pay an additional $190 million (beyond the $25 million approved in June) for the manufacture and testing of the FGB, while the Russian side would pay for the launch, in-orbit maintenance and flight control. Later that year Boeing became concerned about cost growth and management efficiency with Lockheed sandwiched between it and Khrunichev and therefore inherited the contract from Lockheed, with the signing ceremony taking place on 15 August 1995. Later NASA would pay an additional $35 million for modifications to the FGB, bringing the total value of the contract to about $250 million.

Construction of the FGB flight model got underway in December 1994. With launch set for November 1997, Khrunichev had only about 2.5 years to complete assembly and testing before shipment of the FGB by rail to Baykonur in May 1997. This would only be possible thanks to the vehicle's strong lineage with the TKS spacecraft and Mir modules. Perhaps one of the greatest challenges from Khrunichev's perspective was to take into account the 500 or so specific design requirements levied upon it by the US, some of which were related to Zarya's 15-year design lifetime (much higher than that of the Mir modules). For instance, NASA insisted on six times more meteoroid and space debris shielding on the vehicle's hull than the Russians had initially proposed.

Assembly of the FGB went very smoothly, with the hull being completed by the end of 1995. There was a setback in early December 1995, when the internal bulkhead and part of the pressurised section were damaged during a pressure test, but this caused no significant delays. In keeping with tradition, Khrunichev built various mock-ups and test articles of the FGB and even a self-financed back-up vehicle (FGB-2 or 77KM N°17502) that could be sent into orbit within a year should something go wrong with the launch of the primary FGB.

By the spring of 1997 the FGB was essentially ready to be shipped to Baykonur, but problems with the Russian-financed Service Module had delayed the start of station assembly from November 1997 to June 1998. The Service Module was not only to act as the living quarters for the crew, but was also supposed to take over station reboosting from the FGB once it arrived in December 1998. Any further delays in the SM launch might cause problems, because the FGB had limited fuel supplies on board and could only be refuelled by Progress vehicles *via* the Service Module. Therefore an alternative had to be found for station attitude control and reboosting in case the SM slipped further once the FGB was already in orbit. NASA proposed an Interim Control Module (ICM) based on a classified Naval Research Laboratory upper stage dispenser used to manoeuvre and deploy Navy ocean surveillance satellites and even drew up plans for a follow-on Propulsion Module should the SM be delayed even further. Khrunichev on the other hand suggested to launch the FGB-2 as a temporary replacement for the SM, but RKK Energiya and the Russian Space Agency felt that this would have a negative impact on the SM launch preparations. One reason why the FGB-2 idea was not found attractive may have been that the vehicle would have to be modified with American money and therefore be considered by many as yet another US element of the station. Eventually it was decided to solve the problem by modifying the FGB such that it could control the station for an extended period of time, while also keeping open the option of launching the ICM should the need arise. A protocol on the FGB modifications was signed between NASA and the Russian Space Agency on 22 February 1997.

The major change required to the FGB was to allow it to be directly refuelled by Progress vehicles, which necessitated some changes to its nadir docking port. This port was a 'hybrid' SSVP-M type, capable of receiving the Docking and Stowage Module, which in turn could receive a Soyuz-TM or US crew rescue vehicle. The nadir port was now changed into a standard probe-drogue SSVP type compatible with Progress and equipped with the necessary connections for refuelling operations. Further, the FGB would be capable of storing 6.1 tonnes rather than 5.7 tonnes of propellant, although it would be launched with no more than 3.8 tonnes of propellant. Changes were also made to the FGB's control system so that it could handle more ISS configurations and to its axial SSVP-M port to make it compatible with the ICM.

The modifications to the FGB were completed by the end of 1997 and in January 1998 the module was shipped to Baykonur, where it was placed in the former Buran assembly building. In May 1998 further problems with the Service Module forced the launch to be delayed from 30 June to 20 November 1998. After mating with its Proton rocket, Zarya was rolled out the launch pad on 16 November and launch took place as scheduled on 20 November at 06.40 UTC, marking the long-awaited beginning of ISS construction (Fig. 17). About a month before the launch the Russians had unexpectedly proposed to delay the launch until 15.20 UTC so that Zarya would wind up in the same plane as the Mir station, making it possible for Progress vehicles to transfer some 2.1 tonnes of scientific equipment from Mir to ISS. This proposal was made despite the fact that long before this US and Russian orbital mechanics experts had settled on a launch time that would place the FGB into an orbit as far *away* from Mir as possible so that passes over Russian ground stations would not overlap [36]. NASA rejected the new launch time, saying it would require too many changes to the timeline for the upcoming STS-88 Shuttle mission that would dock Node-1/Unity to Zarya. It may also have seen the Russian move as a veiled attempt to revive the 1995 joint Mir/ISS assembly plan should the Service Module fall victim to further delays.

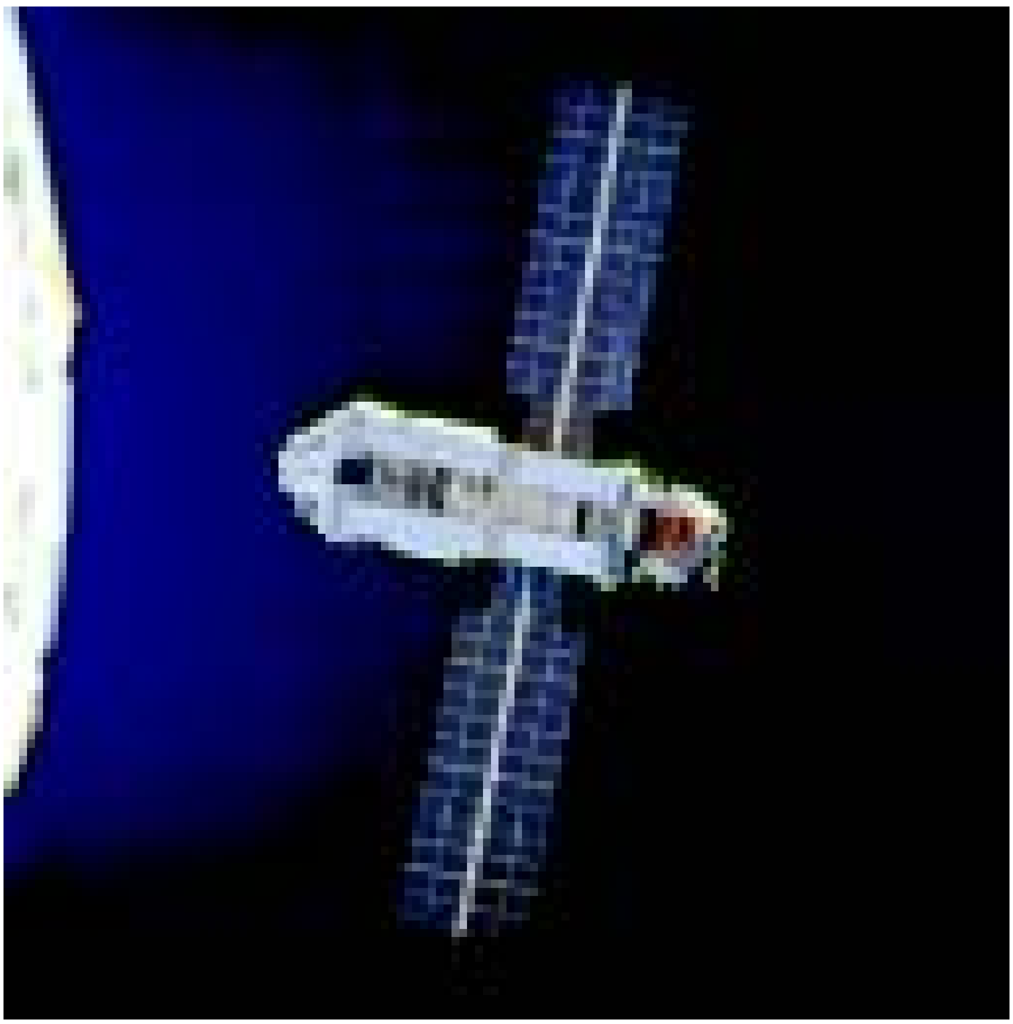


Fig. 17 Zarya in orbit as seen by the STS-88 crew. (source: NASA)

Service Module/Zvezda

Design Features

The second module of the Russian segment serves as the cornerstone for early habitation of the ISS and also provides important flight control and orbit maintenance functions. Originally known as the Mir-2 Base Block, it was renamed the Service Module, which was not the best of choices. The same term had been coined in the 1960s for the propulsion compartment of the Apollo spacecraft and was accordingly often used in Western literature for the analogous section of the Soyuz spacecraft. Moreover, it was identical to the name of one of Mir-2's add-on modules, which had also been part of the ISS in the original Russian proposal. In May 1999 the Service Module was officially called Zvezda ('Star'), a name which had been used for at least five cancelled Soviet space projects in the past [37].

Having been originally built as a back-up for Mir, the Service Module is very similar in layout to the Mir core module. It consists of four major compartments: the Transfer Compartment (PKhO), the Work Compartment (RO), the Transfer Chamber (PrK) and the Instrument Compartment (AO) (Fig. 18).

The spherical Transfer Compartment has three passive SSVP-M docking ports (axial, zenith and nadir) and can also serve as an airlock for EVAs until the arrival of the Docking Compartment. The Work Compartment is the main living and working zone for the crew and has two sections, one with a diameter of 2.9 m and the other with a diameter of 4.1 m. The first section among other things houses the central command post of the Service Module and provides room for installing the TORU remote-control docking system. The second section has two personal sleeping quarters, a personal hygiene facility, cooking facilities and a refrigerator-freezer, a table for securing meals while eating, equipment for physical exercises and a small airlock for disposing of garbage or ejecting small satellites.

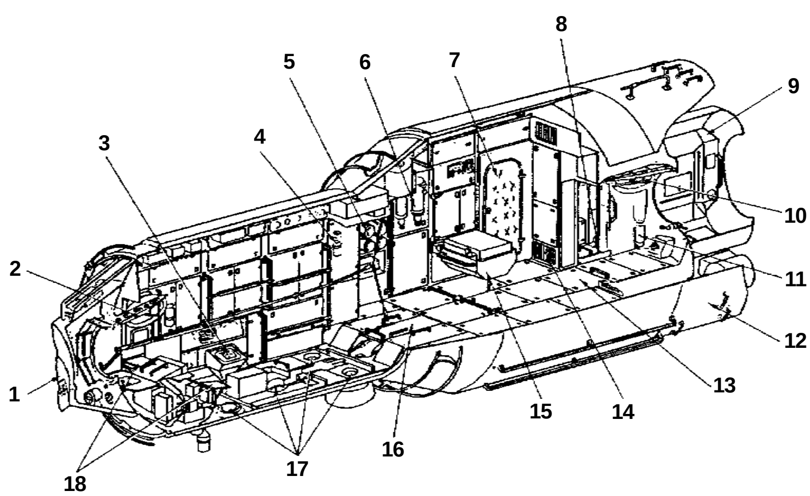
The Transfer Chamber is a small tunnel allowing cosmonauts to transfer from the Work Compartment to an attached Soyuz or Progress spacecraft. It is equipped with a standard passive SSVP docking port, identical to the ones used on Mir. Surrounding the Transfer Chamber is the unpressurised Instrument Compartment, which contains the engines and propellant tanks of the SM's Combined Engine Installation (ODU). The ODU comprises two main correction engines (each with a thrust of 315 kgs) and a total of 32 attitude control engines (each with a thrust of 13.3 kgs). The propellant tanks can be topped up by Progress ships docked to the Zvezda aft port or to the Zarya and Zvezda nadir ports (or via any modules docked to the nadir ports). Propellant can also flow from the SM's tanks to the FGB tanks (for storage), back to Progress for additional manoeuvres and to the attitude control engines of the Universal Docking Module. The ODU main engines can only be used when the SM's aft docking port is unoccupied, meaning that most ISS orbit corrections are carried out by Progress vehicles docked to the aft port. However, the SM thrusters can be fired for attitude control during such Progress burns. Attached to the Instrument Compartment is a high-gain antenna, which makes it possible to communicate with the ground via Altair geostationary relay satellites.

Fixed to the outside of the 2.9 m diameter section of the Work Compartment are two solar panels, each of them covered with 38 m² of solar cells. Their total capacity is 9.8 kWt and this can be increased to 13.8 kWt with the attachment of four small add-on panels. Inside the SM are eight storage batteries, five of which are launched with the SM and three delivered later. The SM is supposed to provide power to the entire Russian segment (except the FGB) until the arrival of the Science Power Platform. The SM's power system can also load the storage batteries of Soyuz and Progress vehicles attached to the ISS. In order to augment meteoroid and space debris protection cosmonauts will make several spacewalks to install 23 protective covers on Zvezda's hull as well as four shields on the solar arrays.

The Service Module's brain is the DMS-R (Data Management System of the Russian Service Module), a set of on-board computers, their avionics and software that provide overall control, mission and failure management for not just the SM, but for the entire Russian segment. It is also responsible for the exchange of data and commands with other parts of the ISS. The key hardware for the DMS-R was developed in Europe by an industrial consortium led by

Fig. 18 Cut-away drawing of Zvezda (docking adapter and engine compartment not shown). (source: Novosti Kosmonavtiki)

Key:
1. Transfer Compartment;
2. Hatch;
3. TORU remote-control docking equipment;
4. Gas mask;
5. Air cleansing units;
6. Solid-fuel oxygen generators;
7. Sleeping quarters;
8. Toilet;
9. Transfer chamber;
10. Hatch;
11. Fire extinguisher;
12. Instrument Compartment;
13. Treadmill attachment structure;
14. Dust collector;
15. Table;
16. Stationary bicycle attachment structure;
17. Portholes;
18. Central command post.



Astrium in Bremen, Germany. Actually, ESA had originally proposed the Data Management System as one of its contributions to the Mir-2 project in 1992. The ESA-provided on-board units are two Fault Tolerant Computers (a Control Computer and a Terminal Computer) and two control posts for command and control by the crew and for commanding experiments and the European Robotic Arm, which is to be installed on the Science Power Platform. The application software for the on-board computers was developed by RKK Energiya [38].

The Road to the Launch Pad

Although construction of the Service Module as part of the Mir-2 project had begun in the early 1980s, it would be responsible for the biggest delays in the start of ISS construction. This was mainly due to the fact that, unlike the FGB, it was to be funded entirely by the cash-strapped Russian government. The funding problems became evident by early 1996 and prompted repeated appeals from US officials to the Russians to honour their space station commitments or face the possibility of being elbowed out of the project. Despite Russian pledges to resume long-delayed payments to Khrunichev, RKK Energiya and their subcontractors, the Service Module was about 8 months behind schedule by the end of 1996. What had been obvious for many months became official in May 1997, when the Space Station Control Board decided to delay the start of station assembly from November 1997 to June 1998, with the Service Module slipping from April to December 1998. Exactly one year later further delays in funding and building the Service Module forced yet another postponement of its launch to April 1999, with the FGB moving to November 1998.

An important milestone was reached on 1 June 1998, when the Service Module was finally shipped from Khrunichev to RKK Energiya's ZEM factory for final outfitting and electrical tests. An option that had been considered to save time was to transport it directly from Khrunichev to Baykonur and finish all the necessary work there (as had been done with the Mir core module in 1985), but this was considered too risky. By early October ongoing funding problems, compounded by the financial crisis that hit Russia in August of that year, necessitated a postponement of the SM launch to July 1999, although the start of station construction in November 1998 remained on schedule. Work on the SM gained fresh impetus that same month with a $60 million cash infusion from NASA, in return for which the Russian Space Agency agreed to give NASA up to 75 % of its research crew time and extra stowage space aboard the SM during the assembly phase. This was supposed to be only the first payment under a $660 million bailout plan crafted by NASA to help the Russians complete crucial hardware for the ISS until 2002. It was to be followed by four annual payments of $150 million, mainly to help defray the cost of building Progress and Soyuz vehicles for resupply and reboost during assembly. However, NASA later decided against including the remaining $600 million in its budget request because it would take the pressure off the Russian government to contribute its share of money to ISS.

In May 1999 the Service Module was shipped to the Baykonur cosmodrome, where the final hardware was to be installed. Another slip in the SM launch date was announced in June, this time from July to 12 November 1999. In late September the space station partners agreed on a delay to sometime between 26 December and 16 January, mainly because the Space Shuttle fleet was temporarily grounded for wiring inspections after a potentially dangerous short-circuit during the launch of STS-93 in July. Zvezda's launch was to be followed by a Shuttle outfitting and resupply mission and managers wanted the interval between the two flights to be as short as possible. Other reasons for the delay were software integration problems between computers on the US segment of the station and the European Data Management System on the Service Module as well as delays in preparing Russian ground stations for the launch.

A major setback came on 27 October 1999, when Zvezda's launch vehicle, the Proton rocket, suffered a second-stage engine failure during the launch of an Express communications satellite from the Baykonur cosmodrome. It was the second Proton failure in just under four months, with an almost identical accident having taken place on 5 July during the launch of a Gorizont communications satellite. Although the Proton had made two successful flights in September, this latest failure under very similar circumstances required a thorough analysis, throwing the Proton launch schedule into complete disarray. In early January 2000 the investigation board concluded that just like the July accident the 27 October failure had been caused by contamination in one of the 2nd stage engines. Not coincidentially, the engines from both ill-fated flights were from a batch manufactured at the Voronezh Mechanical Plant back in 1992-93, when the facility had been in the midst of a production slump. The commission recommended to modify the 2nd and (nearly identical) 3rd stage engines by installing filters and using special nickel coating in the turbompumps to protect them from burn-throughs. On 11 February the Council of Chief Designers met to discuss the impact on the Zvezda launch and decided to reschedule it for 8-14 July on condition that it was preceded by two successful Proton launches with modified 2nd and 3rd stage engines. The latest delay was officially included in the space station assembly schedule in late March.

Two partially modified Protons (using only the filters) were successfully launched on 12 February and 17 April, but the first Proton with all the recommended modifications did not fly until 6 June. After two more launches of partially modified Protons on 24 and 30 June, Zvezda was transported to a Baykonur facility where its tanks were to be loaded with propellant. This critical and irreversible operation was not to begin until after the launch of the second completely modified Proton early on 5 July, which came on the brink of failure after experiencing a drop of pressure in its 2nd stage fuel tank. Considering this a random problem, the Russians gave the green light for fuelling Zvezda *before* informing the other space station partners about the mishap. With no way of turning back, Zvezda was mated with its Proton launch vehicle on 6 July and rolled out to the pad two days later. What was probably the most critical launch in the history of the ISS took place on 12 July at 04.56.36 UTC (Fig. 19). For Zvezda it was the end of an almost 25-year countdown that had begun with the approval of the DOS-7 and DOS-8 space stations way back in 1976. The Russians took every necessary precaution not only to make sure that the launch went off without a hitch, but also to ensure that Zvezda safely docked to Zarya/Unity. Just in case something went wrong, a two-man rescue crew (Padalka/ Budarin) was on stand-by to fly to Zvezda aboard a Soyuz spacecraft and dock Zarya to Zvezda using the TORU remote-control manual docking system. In the event the module successfully docked with Zarya/Unity on 26 July at 00.44.44 UTC, making it possible for ISS assembly to begin in earnest.

Fig. 19 Launch of Zvezda on 12 July 2000. (source: NASA)

The Add-On Elements

Since the whole ISS assembly sequence hinged on the availability of the FGB and Service Module, virtually all attention in the 1990s was focused on putting these cornerstones into orbit on schedule. With the Russians barely finding the necessary funds to build Zvezda, the development of the add-on elements was put on the backburner for many years. Since these were pretty much out of the 'critical path', there was much less pressure on the Russians to launch them on time, which probably explains why they were allowed to go through a myriad of design changes as the years went on. Even after the launch of Zarya and Zvezda, the future of the add-on elements remains uncertain and only one of them (the Pirs Docking Compartment) has been launched to date.

Original Plans

According to the ISS assembly plan agreed upon in September 1994 all the Russian elements to be attached to the FGB and the Service Module were to be both designed and built by RKK Energiya and delivered to the station by a propulsion compartment that would be detached after docking. The Docking Compartment would be orbited by the Soyuz rocket and ferried to the station by a standard Progress-M propulsion compartment, while all the other elements would go up on Zenit and use the Progress-M2 propulsion compartment as their space tug. After the jettisoning of their propulsion compartments, most of the modules would have an aft docking port available for receiving other vehicles.

The design of all these modules can easily be traced back to Mir-2. The Docking Compartment (which doubled as an airlock for EVAs) remained largely unchanged from its Mir-2 configuration, although it would now receive Soyuz and Progress ships rather than Buran. The Universal Docking Module, made up of three compartments and sporting six docking ports, was also virtually identical to its Mir-2 progenitor, although another option studied was to make it smaller and orbit it with a Soyuz rocket [39]. The Docking and Stowage Module, the Life Support Module and the three Research Modules outwardly looked pretty much the same as the other Mir-2 add-on modules, consisting of a single 6.5 m long compartment weighing about 8 tonnes.

Although the design of the DSM and LSM was inherited from the Mir-2 modules, both were introduced specifically for ISS. The DSM, essentially a storage facility for equipment ferried up by Progress resupply ships, was probably conceived after the negative experience with cluttering aboard Mir, where cosmonauts would often spend long hours searching for lost items. In addition to this, the DSM had an aft docking port for Soyuz-TM ships and later American crew rescue vehicles. The LSM was to have several life support systems similar to those used on Mir, such as an Elektron unit for oxygen production and a system to recycle water from urine. It was also to carry various personal hygiene facilities including a small sauna. Preliminary plans for the Research Modules called for a technological, a biotechnological and a remote sensing module. One option studied was to use the Euro-Russian Technological Complex (see Mir-2 section) as one of the Research Modules.

The Science Power Platform was a simplified version of the cross-beam originally intended for Mir-2, which in its 1992/1993 configuration had two solar parabolic concentrators and a set of four solar panels. In the original ISS plans the Russians had intended to install the concentrators on the SPP, but by late 1993 they were forced to use the four solar panels instead. In 1994 the number of panels was increased to six. According to the September 1994 assembly plan the SPP was to be built up in various stages using specialised Progress-M2 vehicles in which the payload would replace the 6.5 m long pressurised cargo compartment (the 'assembly version' of Progress-M2 described in the Mir-2 section). The first such mission was to carry up the SPP-1 section, consisting of the lower truss, a pressurised section for gyrodins and storage batteries and a radiator panel. After delivering these elements to the zenith port of the Service Module, the Progress-M2 propulsion compartment would separate, opening a docking port for the SPP-2 section, which was to be transported to the station in similar fashion. SPP-2 comprised the middle and upper truss, a solar array drive installation, a Portable Engine Unit (VDU – similar to the one carried on Mir's Sofora truss) and the European Robotic Arm (ERA) plus a rail structure allowing the arm to move along the SPP. Several spacewalks would be required to deploy the various elements and to extend the ERA rail all the way down to the Universal Docking Module. After that two or three more specialised Progress-M2 vehicles would dock with the UDM to deliver the solar panels and their attachment structures plus additional or replacement VDU thruster packages. These were to be transferred to the SPP using the ERA or a cargo crane mounted on the Service Module. The gyrodins for the SPP-1 section were to be sent up separately aboard several standard Progress-M or Progress-M2 cargo ships [40] (Fig. 20, 21).

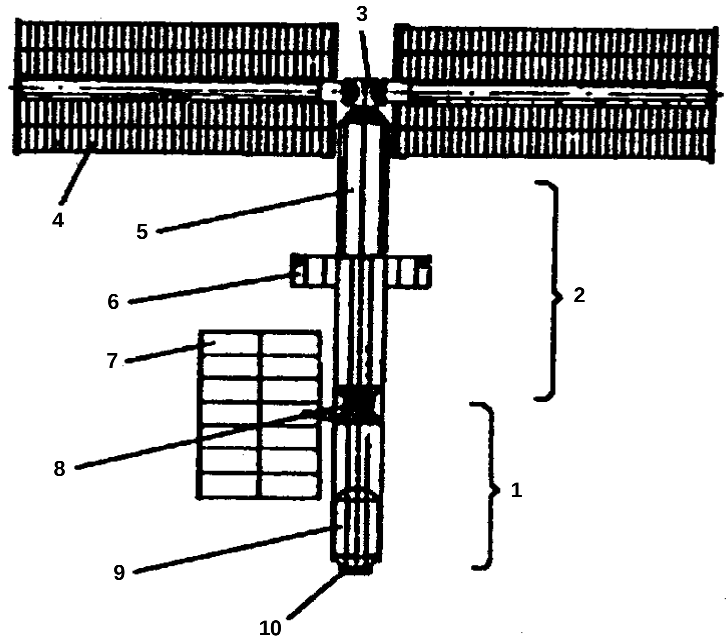


Fig. 20 An early version of the Science Power Platform with four solar panels. (source: Novosti Kosmonavtiki)

Key:
1. SPP-1 section;
2. SPP-2 section;
3. Solar array drive mechanism;
4. Solar panel;
5. Extendable part of SPP-2 section;
6. VDU thruster package;
7. Radiator;
8. SPP-1/SPP-2 interface;
9. Pressurised section with gyrodins;
10. SPP-1/Zvezda interface.

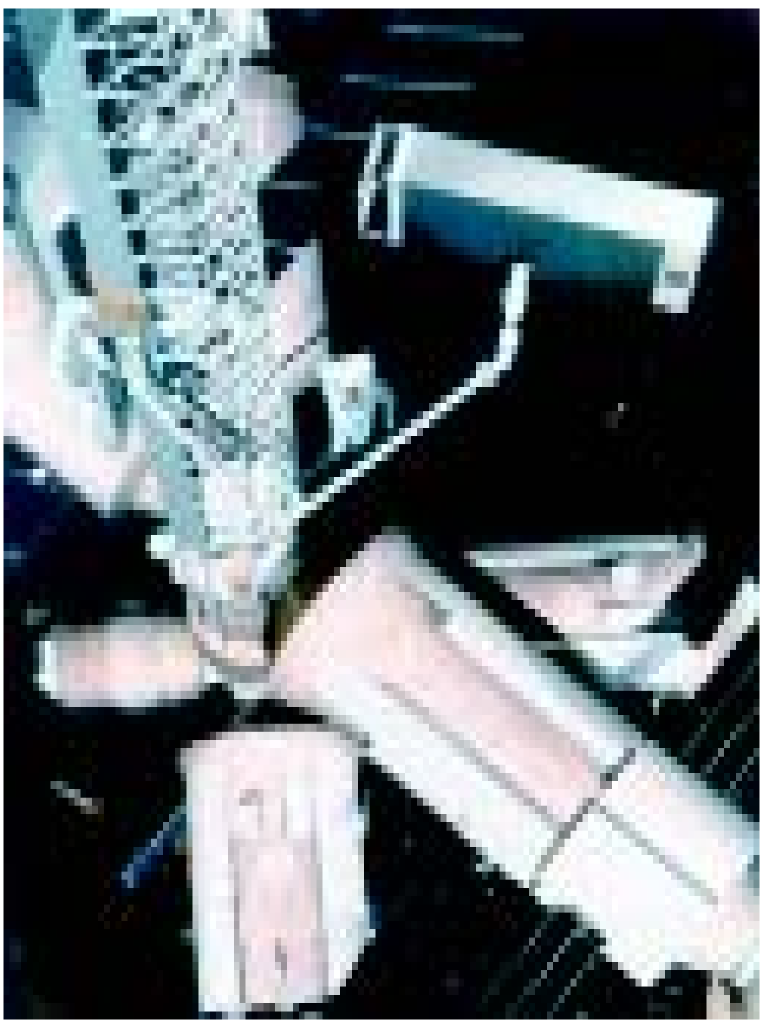


Fig. 21 Cosmonauts using the ERA to install a solar array. (source: Fokker Space)

Zenit Dropped

The configuration of the add-on elements remained unchanged until the 6th meeting of the Gore/Chernomyrdin commission in late January 1996, where it was decided that the Zenit rocket would not be used in station assembly until at least 2000. Several months later the Russians dropped the Zenit from the ISS assembly schedule altogether. The official reasons given by Yuriy Koptev after the Gore/Chernomyrdin meeting were the high risks associated with having only one Zenit launch pad at Baykonur (the other one had been destroyed in a pad explosion in October

1990) and the relatively high cost of the rocket. Another reason must have been that Russia wanted to avoid cash payments to Ukraine, where the Zenit was assembled [41].

All this automatically meant that the Progress-M2 based ISS modules scheduled to fly to ISS would have to be cancelled. The implications were reflected in Revision B of the ISS assembly schedule, released in September 1996. The Universal Docking Module would now be built on the basis of FGB-2, the Zarya back-up. The DSM and the LSM were each split into two modules (DSM-1, 2 and LSM 1, 2) to be docked in tandem to the FGB nadir port and one of the UDM radial ports respectively. Outwardly similar to the Mir Docking Module, each module would weigh about 3 tonnes after jettisoning its propulsion unit and launch would take place with either the Soyuz or the upgraded Soyuz-2. Only two Research Modules remained by this time, and consideration was given to building them on the basis of the FGB design. The SPP was to be delivered by two Shuttle missions (9A.1 and 14A) and would now have a total of eight solar panels with a capacity of 50 kWt. The first Shuttle mission was to carry the truss components, the pressurised section with gyrodins, four solar panels and the ERA arm and the second another set of four solar panels. In 1998 the delivery of the final four solar panels was split between two Shuttle missions (1J/A and 14A) to make room in the cargo bay for some of Zvezda's anti-debris shields. Transferring the SPP components from the cargo bay to the Zvezda zenith port required a complex operation in which the Shuttle's RMS robot arm would hand over the elements to the station's SSRMS manipulator arm.

Since it would take a certain amount of time to transform the FGB-2 into the UDM, its launch slipped considerably. This left the Russian segment without adequate EVA capability in the early stages of assembly, because the airlock-equipped Docking Compartment was to use the UDM as its berthing place. This is why it was decided to build two Docking Compartments. The first one would link up with Zvezda's nadir port and be deorbited by an attached Progress vehicle when the UDM was ready to take its place. Subsequently, a new DC would be launched to dock with the UDM. A more economical approach would have been to redock the first DC after the arrival of the UDM (using the same Progress vehicle), but this was not possible because of the use of several types of docking ports on the Russian segment. While the Zvezda nadir port had an SSVP-M port, the UDM's aft docking adapter only had SSVP ports, meaning the original DC could not be redocked to the UDM [42].

More Changes

In 1997 the Khrunichev Centre and RKK Energiya began design work on the FGB-2 based UDM. Although most of the work on the module would be done at Khrunichev, RKK Energiya remained the prime contractor. As in the earlier Progress-M2 design, the primary function of the module was to receive add-on modules at its aft axial port and then transfer them to one of the four radial ports. The aft port would also be able to receive Soyuz and Progress vehicles, with the latter being able to refuel the Zarya and Zvezda propellant tanks via the UDM. Aside from housing scientific equipment and a computer for controlling the Russian segment, the UDM would also carry the gyrodins originally intended to be installed on the SPP and use its engines to provide roll control. The propellant for that would be fed from the Zvezda fuel tanks (Fig. 22).

Instead of constructing the UDM on the basis of FGB-2, it was soon decided to build it from scratch, because FGB-2 would have required too many modifications. For instance, the UDM's docking adapter needed five docking ports, while FGB-2 had only two, and it also had to be capable of acting as back-up airlock in case cosmonauts wouldn't be able to seal the DC-2 hatch after an EVA. Unlike FGB-2, the UDM was not supposed to perform the role of fuel depot and power facility, requiring only four fuel tanks (compared to sixteen on FGB-2)

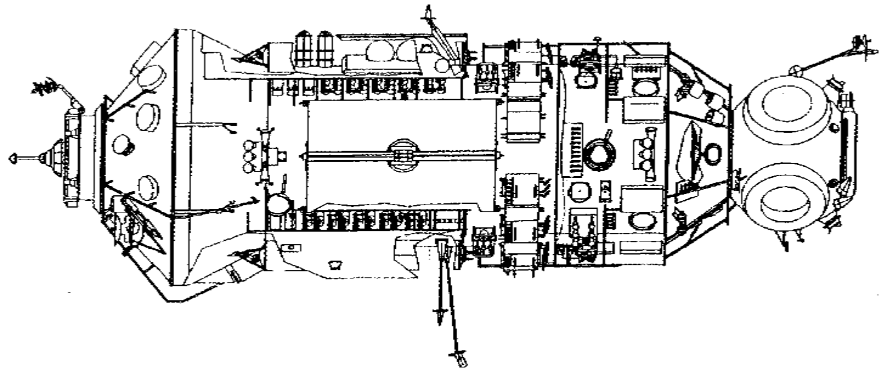


Fig. 22 The Universal Docking Module based on the FGB design.
(source: Novosti Kosmonavtiki)

and small non-rotatable solar panels that would be folded after the module's arrival at the ISS (meaning that the bays for the solar array drive mechanisms in FGB-2's hull had to be removed). The installation of the gyrodins would also have required major changes to the FGB-2's interior.

The first half of 1998 saw several more significant changes to the UDM design. The multiple docking adapter was to be turned 45° clockwise and the nickel-cadmium storage batteries were to be replaced by nickel-hydrogen batteries that would be mounted outside rather than inside the module, freeing up 2.5 m^3 of internal volume. Other changes resulted from a decision made by the Council of Chief Designers on 28 April 1998 to scrap both Life Support Modules and return to a single large Docking and Stowage Module which would now be built on the basis of FGB-2. The UDM's six gyrodins were transferred to the Docking and Stowage Module and the additional room that became available inside the UDM could now be used to install some of the equipment originally intended for the LSMs (including a system to recycle water from urine, the Elektron oxygen generator, a small washing facility and a mini-sauna). These latest changes to the Russian segment were reflected in Revision D of the ISS assembly schedule, released in May 1998. Design work on the UDM was temporarily halted in July-August 1998 because of a lack of financing and also because RKK Energiya and Khrunichev could not agree on the exact division of work. A final agreement between the two was not signed until October 1998.

The new FGB-based DSM retained its original function of equipment storage facility, but was now also to play an important role in the station's attitude control. Not only did it now carry the six gyrodins, its engines were also to take part in attitude control, drawing propellant from Zvezda and Zarya. In addition to that, special propellant lines were to be routed through the DSM to allow Progress vehicles docked to the DSM's aft port to refuel Zarya. Two radial docking ports would be available on the aft docking adapter, although the purpose of those was not announced.

Meanwhile, plans for the two Research Modules remained as uncertain as ever. An important development came on 31 May 1997, when Russian and Ukrainian presidents Boris Yeltsin and Leonid Kuchma signed an agreement on space co-operation, one aspect of which was the inclusion of a Ukrainian research module in the Russian segment. This meant that there would now be one Russian and one Ukrainian Research Module. However, with Ukraine having no experience in building space station modules, the contract for the Ukrainian module would have to go to either RKK Energiya or Khrunichev.

At the meeting of the Council of Chief Designers in April 1998 RKK Energiya and Khrunichev presented competing proposals for the Russian Research Module, although both probably were eying the Ukrainian contract as well. Despite the 1996 decision to refrain from the use of the Zenit in ISS assembly, RKK Energiya once again came up with a Zenit-launched Progress-M2 look-alike vehicle weighing 9 tonnes (minus the tug) which could later be outfitted with 3 additional tonnes of scientific equipment. Khrunichev presented a DOS-based vehicle weighing 20 tonnes at launch and 24 tonnes after being outfitted in orbit. However, it reportedly also proposed a stripped-down FGB-based vehicle that was compatible with Zenit, making it more attractive to the Ukrainian side. In both proposals the modules had standard scientific racks, making it easier for the international partners to gain access to them. The Ukrainian space agency was expected to pick one of the proposals in early 1999, but no such decision followed, probably because Ukraine could not afford the $100 to 150 million price tag associated with building the module.

Later TsNIIMash, Russia's main civilian space R&D insitute, released its long-awaited specifications for the Russian module's scientific equipment, which would require a module weighing 16 tonnes. Responding to this announcement, Khrunichev donwsized its module to a 16-tonne vehicle that would be towed to the station by a 4 tonne, 2.9 metre diameter detachable space tug using FGB hardware. This was somewhat reminiscent of the configuration of Kvant, although the mass distribution between module and tug on that vehicle had been significantly different (11 tonnes for the module and 9 tonnes for the tug). The module proper would consist of a conical section derived from the FGB design and a 4.1 m diameter cylindrical section inherited from the DOS space stations. Other configurations were proposed as well, including smaller modules with externally mounted scientific platforms. Since RKK Energiya had an entire department responsible for scientific equipment aboard space stations, Khrunichev proposed that it would solely be responsible for building the module and tug and then hand over the module to Energiya after it reached ISS.

However, Energiya continued to pursue the idea of building its own modules and in May 1999 presented a plan to the Russian Space Agency for a unified series of Zenit-launched vehicles with identical propulsion compartments. This basically marked a return to the Progress-M2 concept for Mir-2 and the initial version of the ISS Russian segment. Although the May 1999 plan centred on a NASA-funded replacement for the Docking and Stowage Module, Energiya suggested to use the same design for the Russian and Ukrainian Research Modules and later also for a heavy cargo ship. An alternative considered for the Zenit rocket was the all-Russian Yamal, an uprated Soyuz rocket for which RKK Energiya was the lead design bureau. Using improved engines in the first and third stages and an NK-33 engine in its core stage, Yamal had a payload capacity only slightly less than that of the Zenit. Reviewing the proposals for the Research Modules on 1 July 1999, the Russian Space Agency decided that both the RKK Energiya concept (using either Zenit or Yamal) and Khrunichev's FGB/DOS-based module/tug combination (using the Proton-M) required further study. A follow-up meeting to decide on a final design never took place, leaving the future of the modules up in the air [43] (Fig. 23).

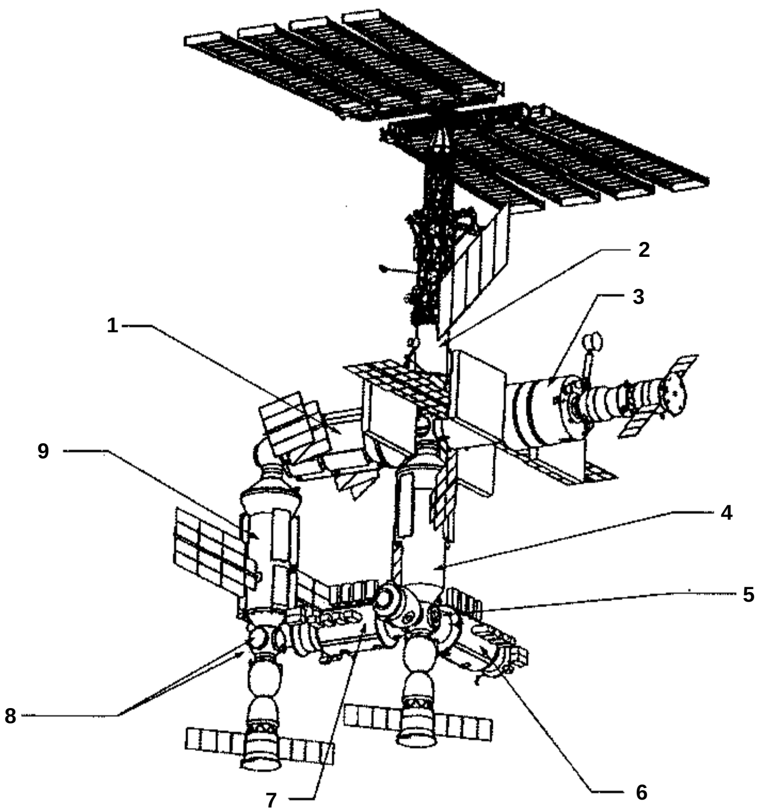


Fig. 23 The Russian segment as planned in late 1998. (source: Novosti Kosmonavtiki)

Key:
1. FGB;
2. Science Power Platform;
3. Service Module with anti-debris shields on the solar panels;
4. Universal Docking Module;
5. Free docking port;
6. Research Module 1;
7. Research Module 2;
8. Two free docking ports;
9. Docking and Stowage Module.

Going Commercial: Enterprise and the CSM

As 1998 drew to a close, the only add-on module that looked like it had a chance of flying anytime soon was the nearly completed FGB-2, but the prospects of turning it into the Docking and Stowage Module looked dim with the scarce government funds available. Khrunichev had already spent a large amount of its own resources on the vehicle and clearly wanted to gain some commercial benefits from it. There were ideas to use it as a Logistics Transfer Vehicle and even as a free-flying remote sensing module in the framework of a proposed European Global Environmental Service. Part of the problem with deciding the fate of FGB-2 was that no commitments could be made until after Zarya was safely launched into orbit. On 21 November 1998, the day after the Zarya launch, Khrunichev and Boeing signed a memorandum on the possibility of using the FGB-2 in a different role than Zarya back-up.

Khrunichev's first proposal was to turn FGB-2 into what it called a Multipurpose Module (Russian abbreviation MTsM). Intended as a replacement for the Docking and Stowage Module, it could house American scientific equipment originally supposed to be installed in the US Laboratory Module Destiny and the US/Japanese Centrifuge Accommodation Module. Because of delays in the launches of these modules, NASA had already bought space and crew time aboard Zvezda to run some of the US experiments earlier, but the proposed Khrunichev module would offer much more room to carry out the experiments. Negotiations on adapting the FGB-2 for that role began in February-March 1999 and in May 1999 Khrunichev and Boeing officials held two weeks of talks in the US which were expected to end with the signing of a contract under which NASA would buy the module in an arrangement similar to the purchase of Zarya (with Boeing acting as an intermediary). However, just two days before the end of the talks, Boeing received a letter from RKK

Energiya with a suggestion to build the MTsM on the basis of its newly proposed series of unified vehicles and launch it with a two-stage version of the Sea Launch Zenit (Zenit-2SL) from Baykonur. Boeing officials had already been informed about this option by RKK Energiya at a meeting of the Sea Launch partners on the Cayman Islands on 29-30 April. Since Boeing was the leading partner in the Sea Launch venture, it found RKK Energiya's offer attractive and asked for two months to study the proposals of both Khrunichev and Energiya. In a letter to Yuriy Koptev on 13 May 1999 Yuriy Semyonov outlined some of the advantages of RKK Energiya's vehicle over the FGB-2, claiming it could better perform the tasks originally set aside for the Docking and Stowage Module and underlining that the same design could be used for the Russian and Ukrainian Research Modules. A Russian Space Agency meeting the following day concluded that both proposals deserved further study, but in early July Boeing informed its Russian partners that NASA had abandoned the idea of building the MTsM for financial reasons [44].

With little hope in sight of securing any significant Russian government funding for the expansion of the Russian segment, both RKK Energiya and Khrunichev continued to pursue the idea of selling their module concepts to Western customers. After negotiations held in July and October 1999, RKK Energiya signed a contract with Washington-based Spacehab Inc. on 8 December 1999 to jointly develop a commercial ISS module. In the contract the vehicle was referred to as the Commercial Docking and Stowage Module (Russian abbreviation KMSS), but two days later it was announced to the press as Enterprise. The Russians also continued to call it the Multipurpose Module, since it was essentially the same vehicle offered to NASA/Boeing earlier in the year, although now it would have accommodations for microgravity experiments like the ones Spacehab had been flying for paying customers on the Space Shuttle for many years. Enterprise would also be equipped with a tiny broadcast studio to produce educational and entertainment programming that would be distributed on a commercial basis via television and the Internet. The costs for Enterprise's development were expected to be split in half between Energiya and Spacehab, with each partner providing $50 million, although other Western companies such as DASA and Mitsubishi were expected to join later. On 11 April 2000 Spacehab announced that it had formed a new subsidiary called Space Media Inc. that would have exclusive rights to selling the information beamed down from Enterprise. The original idea was to launch Enterprise with the Yamal rocket, but in April 2000 RKK Energiya decided to substitute it for the Zenit, hoping that this would lead to some kind of deal with the Ukraine on the construction of that country's Research Module. Since the Zenit had a longer payload fairing than Yamal (17.65 m as compared to 14.80 m), it also became possible to lengthen both the module and the tug. As a result the tug could carry more propellant and the pressurised volume of the module grew from about 35 m^3 to 45 m^3, 25 m^3 of which was available for installing cargo [45].

Meanwhile, Khrunichev was still setting its sights on Boeing to join in the development of its own commercial ISS module, now aiming for a direct contract with Boeing without NASA involvement. The two companies reached an agreement in early May 2000 and an official announcement was made at the Farnborough air show on 27 July. Called the Commercial Space Module (CSM), the vehicle would be built on the basis of FGB-2. It would first deliver up to 3 tonnes of fuel and cargo to ISS as a prototype of the Logistics Transfer Vehicles and then offer about 20 m^3 of internal volume for installing scientific and communications equipment [46].

Although it was clear that both Enterprise and the CSM were supposed to become part of the Russian segment, there was confusion as to where exactly the modules would dock. First, the Zarya and Zvezda nadir ports were officially still occupied by Russian government modules (the DSM and UDM resp.) and second, the information provided by Energiya/Spacehab and Khrunichev/Boeing indicated that *both* wanted to have their modules attached to the Zarya nadir port. Things became somewhat more transparent with a joint press release from Energiya and Spacehab on 8 August 2000, stating that Energiya president Yuriy Semyonov and Russian Space Agency director Yuriy Koptev had signed a preliminary agreement on 17 May 2000 on the replacement of the DSM by Enterprise. Although NASA had been informed about this decision at the time, the news was not made public until several days after the CSM announcement and was undoubtedly timed to serve as a reminder to Boeing/Khrunichev that the Zarya nadir port was not up for grabs. If it were to come down to a race between the two modules, the CSM was certainly at an advantage, because FGB-2 was already 70 % ready and was expected to be launched by mid-2002. Enterprise, on the other hand, existed only on paper and was not scheduled for launch until early 2003. The 17 May agreement also stipulated that the Russian Space Agency would pay for the Zenit launch and that RKK Energiya and Spacehab would compensate for this by using some of the revenues earned with Enterprise to 'improve the characteristics of the Russian segment, such as energy, communications and other resources'. This would have included the installation of additional solar panels on the Service Module and the deployment of a geostationary communications satellite called Passat to relay data to and from Enterprise and the remainder of the Russian segment [47].

In September 2000 the design of the Zenit-launched Enterprise was finalised, but in early October it became known that the price charged by the Ukrainian Yuzhnoye design bureau for the Zenit launch would be the same as that in the Sea Launch programme, forcing RKK Energiya to look at other launch options. By the end of October the choice fell on the more powerful Proton rocket and two months later the design of Enterprise was adapted accordingly. Although the overall dimensions of Enterprise and its tug changed little, the module would now be able to carry up to 3.2 tonnes of internally mounted equipment into orbit as compared to 500 kg when launched by Zenit. This would significantly reduce the number of supply missions to Enterprise, which was supposed to have 4.85 tonnes of internally mounted equipment when fully outfitted. The module (minus tug) was now 2.9 m in diameter, 8.87 m long and provided 48 m³ of pressurised volume. As before, it internally consisted of two sections, one for storage and scientific experiments and the other an in-orbit television studio for live broadcasts. There was also room for up to 1.5 tonnes of externally mounted experiments. An aft docking port was available for Soyuz and Progress vehicles and provisions were made for installing gyrodins and refuelling Zarya and Zvezda via Enterprise. In this way, Enterprise retained the major functions of the cancelled Docking and Stowage Module, as had been the intention from the outset [48]. A major milestone was reached on 5 March 2001, when Energiya and Spacehab announced that they had reached a final agreement with the Russian Space Agency on 16 February to include Enterprise in the Russian segment and dock it to the Zarya nadir port. In late February the Russian Space Agency had sent an official request to NASA to adapt the ISS assembly schedule accordingly [49].

With the Zarya nadir port now firmly booked, the Enterprise deal seemed to sound the death knell for the CSM. However, on 13 April 2001 Boeing and the Russian Space Agency signed a wide-ranging agreement on co-operation in space and aviation, one aspect of which was to study the commercial use of the FGB-2 module. Although this seemed to contradict the Enterprise deal, Yuriy Koptev said that a way would be found of including both modules in the Russian segment. For the moment though, the future of the CSM hung in the balance [50].

Pirs Joins the Russian Segment

Meanwhile, preparations were in full swing for the launch of the Docking Compartment, the first add-on element of the Russian segment. The DC has its roots in a docking adapter built in the late 1980s for Buran (Fig. 24). Similar in concept to the later Orbiter Docking System of the US Space Shuttle, the docking adapter was to allow Buran to perform dockings with other spacecraft and act as an airlock for EVAs during docking missions. It consisted of a spherical section (2.55 m in diameter) topped by a cylindrical tunnel (2.200 m in diameter) with an APAS-89 docking port. The spherical section, bolted to the floor of the cargo bay, had two side hatches, one to connect it with Buran's middeck and the other to provide access to a Spacelab-type module or allow cosmonauts to perform EVAs. The tunnel provided the actual interface between the docking adapter and the target vehicle and would be extended to its full length after the opening of the payload bay doors. With the tunnel fully extended, the adapter was 5.7 m high. At least one flightworthy version was built for a planned docking flight of the Buran-2 orbiter with a Soyuz-TM spacecraft and the Mir space station.

An adapted version of Buran's docking adapter was included in the Mir-2 and later in the ISS design to receive spacecraft (Soyuz, Progress and originally also Buran) and to serve as an airlock. It would be towed to the station by a detachable Progress-M propulsion compartment. The central part of the spherical section (2.55 m in diameter) was retained. Mounted to its aft end was a small section of the Buran airlock's cylindrical tunnel (without the extendable part) and attached to the front end was the forward part of a Soyuz-TM/Progress-M orbital module (Fig. 25). The design was more complex than that of the Docking Module of Mir (316 GK), which did not have to be used as an airlock and was merely an extension to the Kristall module to facilitate Shuttle dockings [51].

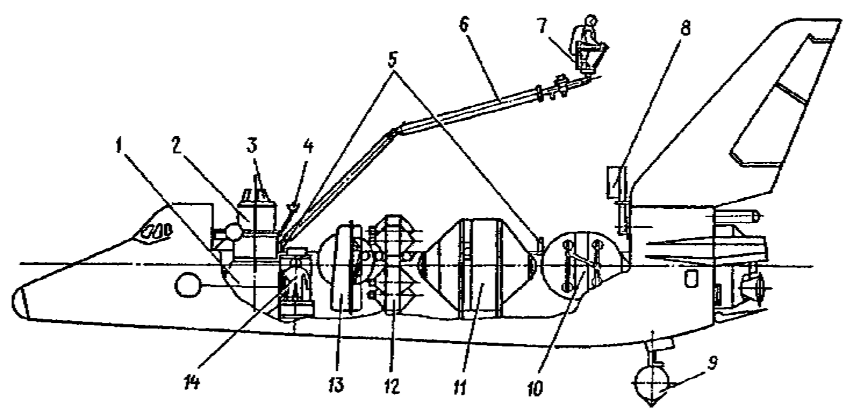


Fig. 24 : The Buran docking adapter (position 3), the progenitor of Pirs.
(source : RKK Energiya)

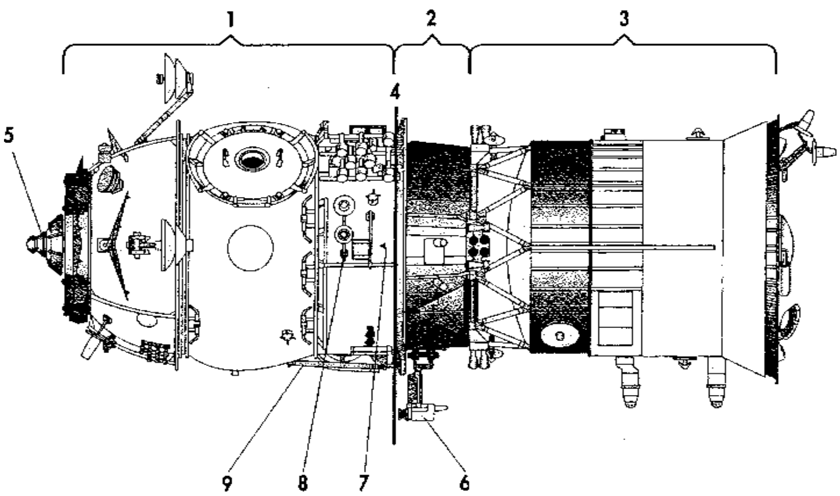


Fig. 25 : Drawing of Progress M-SO1. (source: Novosti Kosmonavtiki)

Key:
1. Pirs Docking Compartment;
2. Intermediate section;
3. Propulsion compartment;
4. Interface between Pirs and intermediate section;
5. SSVP-M docking port;
6. Television camera;

7-9. Antennas.

In the final ISS design the front docking port is an active SSVP-M (compatible with Zvezda's nadir port) and the aft port a passive SSVP (compatible with Soyuz and Progress). Progress vehicles can refuel Zvezda via the DC. There is a 1-metre diameter EVA exit hatch on either side of the spherical section, each having a small porthole in the centre. The two exit hatches date back to the Mir-2 design, where they would have enabled cosmonauts to assemble parts of the Science Power Platform inside the module with pieces sticking out from both sides. The choice of the hatches is now determined by which of the two provides the easiest access to the work area for a particular EVA. Both hatches are inward opening. Although this reduces the working volume inside the airlock, it precludes an eventuality where the hatch is violently swung open if there is any residual pressure inside the airlock. Such a situation caused permanent damage to the outward opening hatch of Mir's Kvant-2 module during a spacewalk in July 1990.

The DC is connected to its propulsion compartment via a short intermediate section, which is pyrotechnically separated from the module along with the propulsion compartment after arrival at the ISS. The propulsion compartment itself is almost identical to that of the Progress-M spacecraft, containing an engine unit, propellant tanks, solar panels and housekeeping systems needed during the vehicle's autonomous flight.

Construction of the module began at RKK Energiya in 1998 and was finished in late 2000. Joint electrical tests with the Progress-M based propulsion compartment got underway in late January 2001 and were finished in late June 2001 (Fig. 26). On 16 July the vehicle was delivered to the Baykonur cosmodrome, where it underwent final preparations in the former Buran assembly building. By this time the Docking Compartment had been dubbed 'Pirs' ('pier'). Even this was not a new name in the Russian space programme, having been used earlier for a cancelled ocean reconnaissance satellite system [52]. Among the designers the compartment was known as 240GK or SO-1 (for *Stykovochnyy Otsek* or Docking Compartment). The combination of the Docking Compartment and its Progress-M propulsion compartment was called Progress M-SO1, which is how the vehicle was officially registered after its launch with a Soyuz-U rocket on 14 September 2001 at 23.34.55 UTC (15 September local time) [53]. After a standard two-day Progress rendezvous profile, the spacecraft docked with Zvezda's nadir port on 17 September at 01.05.14 UTC. The propulsion compartment was jettisoned on 26 September at 15.36 UTC and was de-orbited on 27 September at 23.30 UTC.

Among the approximately 800 kg of cargo installed in Pirs was an extra Orlan-M spacesuit and a 'Strela' cargo crane (GStM-2) to facilitate cosmonauts' movements on the exterior of the complex. Another 'Strela' (GStM-1) had already been carried up on two Shuttle missions and temporarily mounted on one of the American Pressurised Mating Adapters by spacewalking astronauts. Both Strela booms were installed on opposite sides of Pirs during spacewalks in October 2001 and January 2002 [54].

The Currently Planned Configuration

By the time Pirs was launched, there was some more clarity about the future of the Russian segment, notably about the commercial modules. Negotiations on another reconfiguration of the Russian segment had been held in June-July 2001 and resulted in the signing of a joint document on 8 August by Koptev, Semyonov, TsNIIMash director N. Anfimov and Khrunichev's new director A. Medvedev. The proposed changes were approved by the Council of

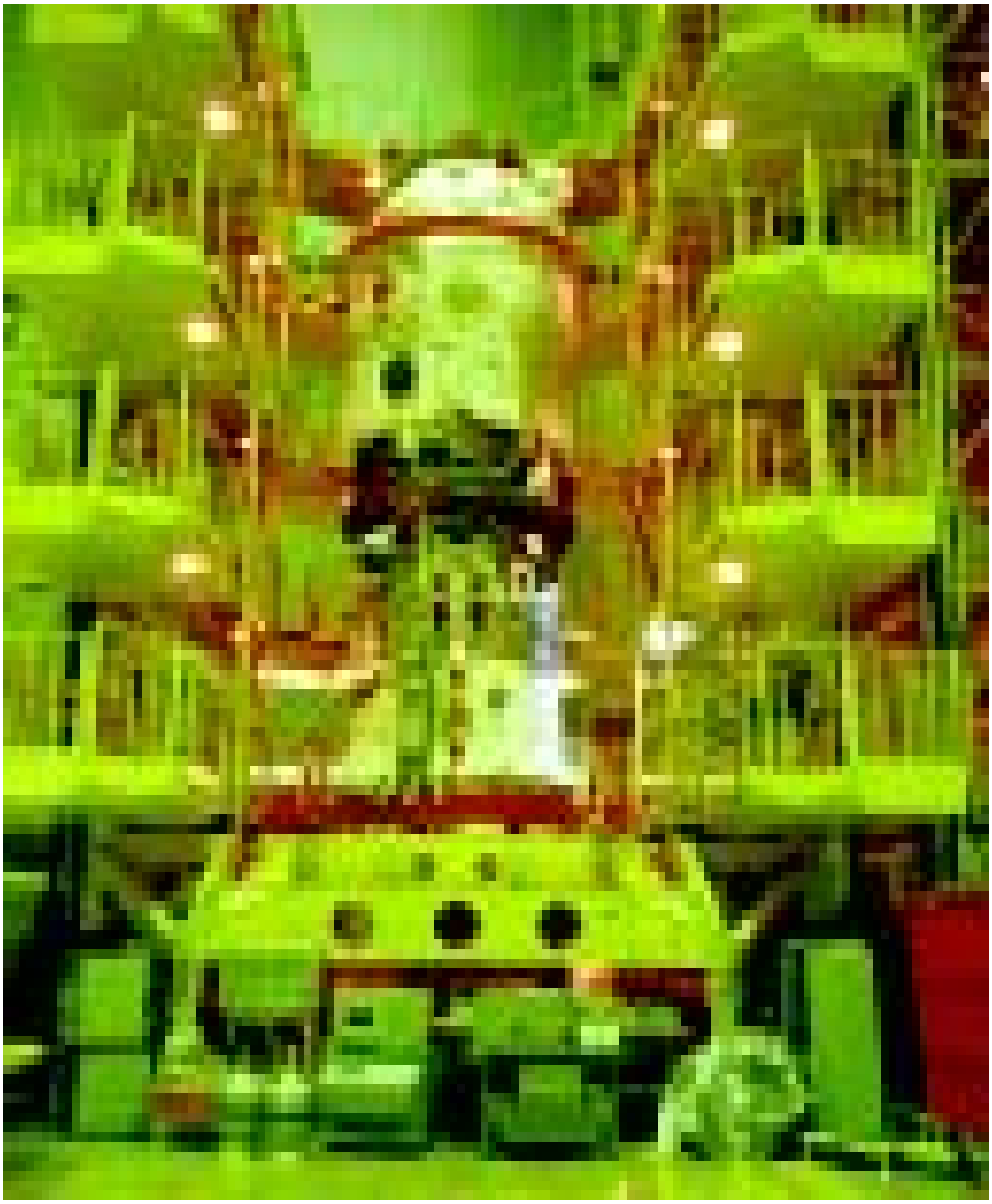


Fig. 26 Progress M-SO1 ready for shipment to Baykonur. (source: RKK Energiya)

Chief Designers on 28 August. After Pirs the following elements were to be added to the Russian segment: the Commercial Space Module on the basis of FGB-2, the Enterprise Multipurpose Module, a simplified Science Power Platform and two Research Modules (Fig. 27). The plans were slightly adjusted the following months and this is the planned assembly sequence for the remainder of the Russian segment as of mid-2002.

The next element to join the Russian segment should be the Boeing/Khrunichev Commercial Space Module, expected to be launched in early 2004. It will occupy the Zvezda nadir port instead of the Universal Docking Module. Actually, it will take over many of the functions of the UDM and is therefore also referred to by the Russians as the Simplified UDM. Under a contract signed between Khrunichev and Boeing on 27 December 2001, Boeing will pay the $50 million needed to adapt the FGB-2 for its new role. Khrunichev had earlier spent $53 million from its own resources to build FGB-2 as a back-up for Zarya. The European Astrium consortium may also join the deal. Some matters still have to be resolved with the Russian Space Agency before the work can go ahead, such as the thorny issue if the agency will finance the Proton launch. The CSM will have four docking ports, a front axial SSVP-M port to dock with Zvezda, an aft axial SSVP port to receive Soyuz and Progress vehicles and two radial SSVP ports on the aft docking adapter to receive the two Research Modules. Eight of FGB-2's sixteen fuel tanks will be removed from the outer hull, making room for some equipment that was originally supposed to be installed on the SPP. This includes batteries for converting and distributing the electricity produced by the SPP's solar panels and a part of the SPP's radiator panel to dissipate the heat produced by the batteries. Boeing and Khrunichev expect to gain revenue by providing room for experiments to paying customers. For this purpose a set of scientific racks will be installed inside the module with standard interfaces also used on the Destiny module.

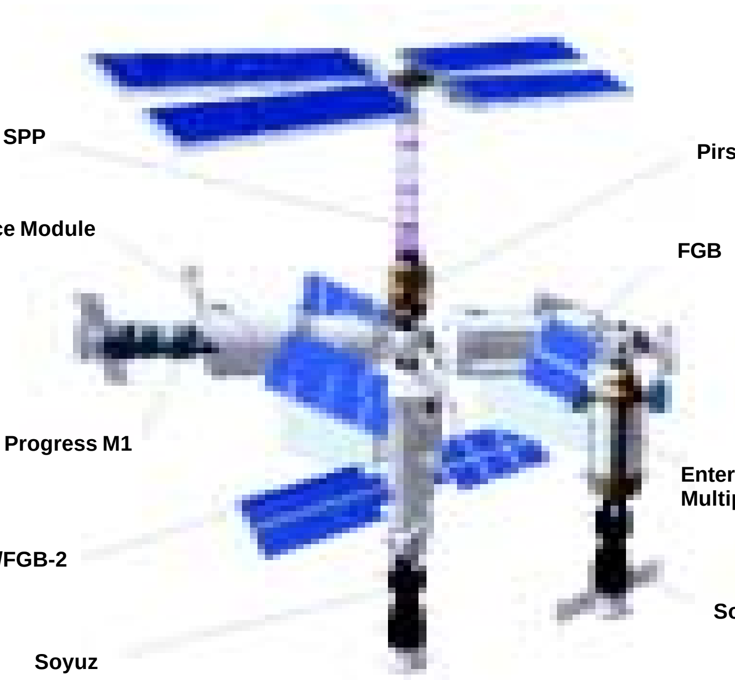


Fig. 27 The currently planned configuration of the Russian segment. **(source: Spacehab)**

TABLE 1: *Evolution of launch dates for elements of the ISS Russian segment. The November 1993 schedule is the baseline schedule, followed by several revisions made over the years. The final column lists the expected launch dates at the time of writing, which are subject to change.*

	Nov 1993	Sep 1994 (Rev. A)	Sep 1996 (Rev. B)	Sep 1997 (Rev. C)	May 1998 (Rev. D)	Jun 1999 (Rev. E)	Aug 2000 (Rev. F)	Jul 2002 (unofficial)
FGB	5/97	11/97	11/97	6/98	11/98	launched 11/98	launched 11/98	launched 11/98
SM	7/97	4/98	4/98	12/98	4/99	11/99	launched 7/00	launched 7/00
DC (1)	6/97	7/98	5/99	12/99	3/00	9/00	3/01	launched 9/01
DC 2	-	-	5/00	12/00	5/01	7/02	8/03	-
UDM	8/97	6/98	4/00	12/00	4/01	6/02	8/03	-
SPP-1*	9/97 (A)	11/98 (R)	11/99 (A)	7/00 (A)	1/01 (A)	11/01 (A)	10/02 (A)	7/04 (A)
SPP-2*	10/97 (R)	2/99 (R)	6/01 (A)	5/02 (A)	10/01 (A)	10/02 (A)	2/04 (A)	10/04 (A)
SPP-3*	-	5/99 (R)	-	-	8/02 (A)	8/03 (A)	5/05 (A)	1/06 (A)
DSM (1)	-	1/00	3/01	2/02	3/02	7/03	no date	-
DSM 2	-	-	no date	5/02	-	-	-	-
LSM (1)	6/99	10/00	2/02	1/03	-	-	-	-
LSM 2	-	-	3/02	3/03	-	-	-	-
RM 1	2/01	9/99	5/01	8/02	8/02	3/04	8/05	8/05
RM 2	8/01	6/00	12/01	11/02	11/02	8/04	3/06	4/06
RM 3	9/01	5/01	-	-	-	-	-	-
CSM	-	-	-	-	-	-	-	?/04
Enterprise	-	-	-	-	-	-	-	7/04 (A)

Notes: *Elements of the Science Power Platform have been scheduled for launch by both Russian (R) and American (A) launch vehicles. SPP-1, SPP-2 and SPP-3 refer to different components of the SPP at different times. Note that the September 1994 plan actually required a total of five Russian launches.

Shortly before the arrival of the CSM, the station's SSRMS robot arm will be used to transfer the Pirs Docking Compartment from the Zvezda nadir port to the Zvezda zenith port, which will become its permanent location on the ISS. Prior to this transfer an EVA will have to be conducted to install an SSRMS grapple fixture on the exterior of

Pirs. Moving Pirs to the Zvezda zenith port will no longer make it necessary to discard Pirs and launch a new Docking Compartment, as envisaged earlier. Pirs' aft docking port will now serve as the berthing place of the SPP, which has been significantly simplified. It will consist of a single extendable frame with four instead of eight solar panels (capacity 25 kWt instead of 50 kWt) and the European Robotic Arm with its rail structure. The radiator panel, the pressurised section for the storage batteries and the thrusters have been removed.

The resulting reduction in size and mass of the SPP left a lot of extra room on the Shuttle mission that was supposed to deliver most of its components to the ISS. Therefore Spacehab and RKK Energiya came up with a plan in October 2001 to launch the SPP *together* with the Enterprise module on a single Shuttle mission. Until then Enterprise had been slated for launch on a Proton, but since the module is a competitor for the CSM, Khrunichev was not expected to sell a Proton to Energiya/Spacehab at the going Russian domestic rates. If launched on the Shuttle, Enterprise would also no longer require a space tug to tow it to the ISS. Still awaiting approval, the current plan is to launch the entire SPP (the truss, four solar panels and the ERA) together with Enterprise on Shuttle assembly mission 9A.1 in July/August 2004. Four additional SPP solar panels currently remain manifested for missions 1J/A and 2J/A in 2004 and 2006 (two panels per mission) and may therefore be installed after all. Using both the Shuttle's own manipulator arm and the station's SSRMS arm, the SPP elements will be mounted on top of the Pirs module and Enterprise will be attached to the Zarya nadir port.

Enterprise may become the key to expanding the station's resident crew from three to six. Faced with massive budget overruns on ISS, NASA was forced in 2001 to indefinitely delay the Habitation Module and the Crew Rescue Vehicle (CRV), which effectively reduced the station's permanent crew to three and thereby severely limited the station's science capabilities. At the end of the year an independent task force headed by former Martin Marietta president Thomas Young recommended three ways of giving the station the needed life support capacity to house six crew members on a permanent basis. One was to build a habitat module on the basis of the Multipurpose Pressurised Logistics Modules (MPLM), a second to equip Node-3 with US life support systems and a third to outfit Enterprise with Russian life support systems. The first option foresaw the use of the CRV with a considerable financial contribution from ESA, while the second and third options involved the purchase of Russian Soyuz rescue craft. RKK Energiya and Spacehab had already begun exploring the possibility of turning Enterprise into a habitat module in February 2001 and the negotiations to launch the module on the Shuttle were apparently part of this effort. The exact financial details of any possible deal are still unclear. RKK Energiya and Spacehab have indicated that they intend to rent Enterprise to the space station partners "in a package" with the Soyuz spacecraft, which would serve as a lifeboat for the additional crew members working on board Enterprise.

Some significant changes have been made to the module to adapt it for its possible new role. In the latest design Enterprise is 2.9 m in diameter and 9.2 m long with a pressurised volume of 50 m^3. Although the ability to produce television programmes will remain, the dedicated broadcast studio has been replaced by three individual crew cabins and a toilet. The module will also house some of the life support systems originally intended for the Russian Life Support Module, such as an Elektron oxygen generator, a Vozdukh carbon dioxide scrubber and a system to recycle water from urine. There will still be room for scientific equipment (in both Shuttle type lockers and Destiny type racks), but far less than in the original plans. Installed on the exterior will be standard interfaces for Spacehab's Integrated Cargo Carrier (ICC) platforms, another part of the SPP's radiator panel as well as several body-mounted radiators and a set of gyrodins to take part in station attitude control. The gyrodins, originally supposed to be mounted on the SPP, then on the UDM and later on the DSM, will be delivered by Progress cargo ships and installed during spacewalks. Enterprise will retain its two SSVP docking ports, a front port for linking up with Zarya's nadir port and an aft port for receiving Soyuz and Progress vehicles (Fig. 28).

The assembly of the Russian segment should be rounded out with the addition of the two Research Modules in August 2005 and April 2006. Plans for a Ukrainian-funded module have apparently been given up, although the Russian and Ukrainian space agencies did agree in February 2002 on a series of 48 Ukrainian experiments to be conducted on the Russian segment in the coming years. No decision has been made yet on the configuration of the two modules and if no funding turns up they may never be launched at all [55].

Free-Flyers

Russia has also announced plans for free-flying spacecraft that would orbit in the vicinity of the ISS and periodically dock with it. The rationale behind this is that many experiments are much easier to perform from a free-flying

Fig. 28 The currently planned configuration of Enterprise (source : Spacehab)

platform than from a multimodular space station. This is especially the case for sensitive materials processing experiments, which require a vibration-free environment, and astronomical observations, which demand accurate pointing of telescopes. The idea is that such spacecraft regularly dock with the station for maintenance, refuelling, upgrading and both loading and unloading of scientific equipment. Plans for such free-flyers have been around for a long time. For instance, back in the early 1970s there were plans in the Soviet Union for a giant N-1 launched space station called MKBS which would have been joined by several such co-orbiting free flyers. An outgrowth of these was the Progress-based Gamma astrophysics module, launched in 1990.

The first proposal for a free-flyer was put forward by TsNIIMash as early as 1996 and is called MAKOS-T (for Reusable Automatic Space Orbital System - Technological) (Fig. 29). This is a spacecraft for materials processing experiments which exclusively uses proven technology. It consists of three sections: an engine unit and equipment bay (with housekeeping systems) both derived from the Phobos/Mars-96 space probes (developed by NPO Lavochkin) and a cargo module identical to that of the Progress resupply ships (developed by RKK Energiya). MAKOS-T is designed to remain in orbit without refuelling for three years and is supposed to dock with the ISS Russian segment twice a year, making it possible to run six cycles of technological experiments. Adapted versions of this spacecraft could also be used for astronomical observations, remote sensing of the Earth and particles and fields studies. In 1999 the Russian Space Agency was seeking partners interested in financing MAKOS, but the current status of the project is not clear.

Between 1997 and 2000 RKK Energiya worked on a free-flyer called AKA-T (for Automatic Space Apparatus – Technological). Weighing 7.8 tonnes, it had the same overall dimensions as Soyuz/Progress and aside from a pressurised cargo compartment had an airlock chamber to expose materials to the vacuum of space. It was able to carry up to 800 kg of materials processing equipment and was supposed to visit ISS two to three times a year. One of the payloads would have been a multifunctional furnace called Karat-T to manufacture various types of crystals using a wide range of production methods. One version of AKA-T had a boom with a shield extending from its aft compartment. The shield, which created a near-perfect vacuum in its wake, was to employ a technique called molecular beam epitaxy to produce ultrathin layers of semi-conductor materials for the microelectronics industry. Developed as part of a programme known as Ekran, this experiment was similar to those performed with the US Wake Shield Facility, a free-flyer flown on three Space Shuttle missions between 1994 and 1996.

A more recent proposal for a free-flyer was made jointly by RKK Energiya and the Astro-Space Centre of the Physical Institute of the Academy of Sciences and calls for the development of an astrophysics platform called SLK (Free-Flying Spacecraft) (Fig. 30). The SLK has a Progress-type pressurised module and aft propulsion compartment, but the usual propellant compartment is replaced by an unpressurised section with an infrared telescope called Submillimetron. A similar Progress-based infrared observatory (Aelita) was proposed by NPO

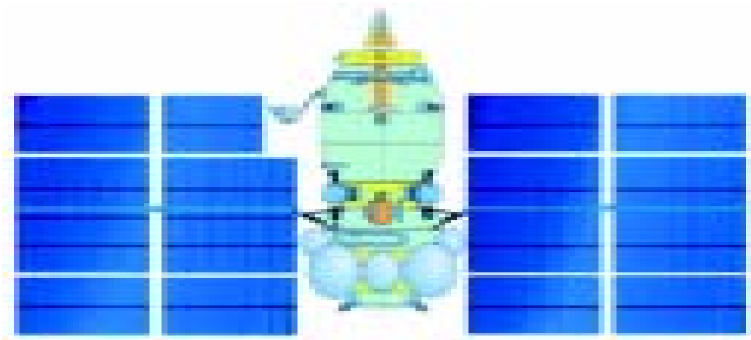


Fig. 29 MAKOS-T. (source: Novosti Kosmonavtiki)

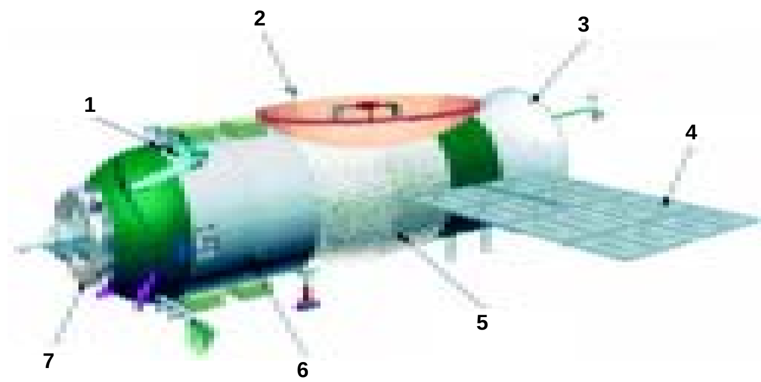


Fig. 30 The SLK. **(source: Novosti Kosmonavtiki)**

Key:
1. Docking system antennas;
2. Telescope mirror;
3. Propulsion compartment;
4. Solar panel;
5. Unpressurised equipment compartment;
6. Pressurised compartment;
7. Docking port.

Energiya in the 1980s. The Submillimetron telescope could be used to make a complete infrared survey of the sky and would focus among other things on galaxies and quasars, galactic sources of star formation, interstellar and interplanetary dust. It could also study minor fluctuations in the cosmic background radiation and spot potentially dangerous near-Earth asteroids. The SLK could remain in orbit for as long as ten years and would periodically dock with ISS, among other things to replenish the liquid helium used to cool the telescope. However, as in the case of MAKOS, private funding will have to be found to turn this idea into reality [56].

The Ferries

Soyuz

Soyuz as Part of Freedom

In the wake of the Challenger accident NASA issued a request of proposals in 1987 for what it called an Assured Crew Return Vehicle (ACRV) for space station Freedom. Since the Space Shuttle could only temporarily remain docked to the station, another means had to be found to bring astronauts back to Earth in case of an emergency inbetween Shuttle visits. The tasks formulated for the ACRV were to return an ill or injured astronaut or to bring back an entire crew if the station were to become uninhabitable or if the Space Shuttle was grounded indefinitely. Freedom could not be permanently manned until such a lifeboat became available. Both Lockheed and Rockwell studied a number of options (including lifting bodies and Gemini and Apollo-based vehicles), but all of those were expected to cost between $1 and 2 billion and would take several years to develop.

With the collapse of the USSR imminent and a new international political climate taking shape, NPO Energiya managers saw an opportunity to come to NASA's rescue. In October 1991 Energiya's general designer Yuriy Semyonov met with Boeing vice president R. Grant at the Congress of the International Astronautical Federation in Montreal, Canada to discuss among other things the possibility of using a Soyuz type vehicle as Freedom's ACRV. Semyonov repeated this offer while appearing at a Senate subcommittee hearing on 21 February 1992 and during the same week also continued his talks with Grant. This eventually led to a NASA delegation visiting Moscow in March to hold exploratory talks on the concept of using Soyuz as an ACRV. Besides Soyuz-TM, the Russians also proposed a vehicle derived from the cancelled 14F70/Zarya earlier envisaged for the giant Mir-2. This could house five to six astronauts and be orbited either by a Zenit rocket or in the cargo bay of the Shuttle.

On 18 June 1992, one day after the Bush/Yeltsin summit in Washington that paved the way for future US/ Russian space co-operation, NASA and NPO Energiya signed a $1 million contract under which the two organisations among other things would jointly study the use of Soyuz-TM as an interim lifeboat for Freedom until the American ACRV became available to replace it. One of the problems to be tackled was how to put Soyuz into the 28° inclination orbit where Freedom was supposed to operate, something which was not achievable with the Soyuz launcher from Baykonur. The Russians proposed alternative launch schemes using Zenit or Proton launch vehicles, but these were rather complicated. The Proton would have to place Soyuz into a 51.6° parking orbit and then use a Blok-D upper stage to transfer it to the required inclination. Even then, the mass of Soyuz had to be significantly reduced, which is why the Russians asked NASA to increase Freedom's inclination to 33.5°. This in turn implied that the Shuttle's payload capacity to Freedom's orbit would decrease, which was unacceptable to NASA.

Other boosters considered were the Titan or Atlas from Cape Canaveral or even Ariane from Kourou. In the end though specialists settled for placing Soyuz in the cargo bay of the Space Shuttle. This required only a few modifications to the Soyuz, such as removing equipment needed for rendezvous operations and developing systems to firmly secure it in the Shuttle's payload bay. After the Shuttle's arrival at the station, the Soyuz could be transferred to the required docking port with the remote manipulator arm of the Shuttle or the station itself. The 28° inclination of Freedom also meant that Soyuz could not land in the traditional landing zone in Kazakhstan. Several alternatives were evaluated, the most promising of which was found to be Australia. In November 1992 a team of American and Russian specialists went to Australia and explored four different landing areas, three of which were considered to be acceptable.

Lockheed and Rockwell, the two companies vying to build the American lifeboat, were hoping to win the contract that NASA was expected to award for work on the interim Soyuz ACRV. In September 1992 both companies signed separate agreements with NPO Energiya to study Soyuz hardware. After two weeks of talks in Houston in December 1992 NASA and Energiya officials concluded that there were no major show-stoppers to adapting Soyuz-TM as a station lifeboat. In March 1993 NASA and NPO Energiya signed a new contract under which the Soyuz/Shuttle plan would be examined in more detail. The main focus would be on finding ways of extending Soyuz' on-orbit lifetime to 1-3 years, much more than the 6 months it was designed to stay in orbit. NASA officials were invited to witness the landing of the Soyuz TM-16 spacecraft in July 1993 to get acquainted with the recovery techniques. In December 1993 another round of talks was held in Houston to evaluate the results of the studies. Although the prospects of using Soyuz-TM as a Freedom lifeboat were good, NASA cancelled the contract with NPO Energiya that same month after the final decision to build the international space station jointly with the Russians. A competing proposal for Freedom's interim ACRV is said to have come from NPO Mashinostroyeniya, the former Chelomey design bureau. It involved the use of the three-man return capsule (VA) of the TKS vehicles. The bureau had reportedly even designed 6 and 8-man versions of the VA, but none of the proposals were found to be acceptable [57].

Soyuz as Part of the ISS

After the Russians joined Alpha in late 1993, there was no need to develop a specialised ACRV for the initial assembly phase. As long as the station was staffed by just three crew members, the Soyuz-TM could serve both as a crew delivery and rescue vehicle as it did in the Mir programme. With Alpha using the 'Russian' inclination of 51.6°, Soyuz-TM needed no modifications and could be orbited as usual by the Soyuz rocket. The station's resident crew was not scheduled to be expanded to six until after the arrival of the US Hab module in 2002. From that point on two Soyuz-TM vehicles needed to be permanently parked at the station, but given the restrictions of Soyuz and the high cost of regularly changing them out, NASA wanted to develop a larger and more capable vehicle that could evacuate the *entire* crew and remain docked at the station for several years.

Responding to these requirements, RKK Energiya and Rockwell (later joined by Khrunichev) drew up plans in 1995 for a rescue craft that looked like an enlarged Soyuz descent capsule with a small engine compartment at the back. It drew heavily on the 14F70/Zarya design of the late 1980s and on a concept that the Russians had already proposed for the Freedom ACRV in early 1992. The 8-tonne descent capsule had a maximum diameter of 3.7 metres and could house a maximum of eight crew members. With a total mass of 12 tonnes and a length of 7.2 metres, the vehicle could be delivered to ISS by the Shuttle and remain on stand-by for five years [58] (Fig. 31). However, the Russian proposal was not the only one. Europe also showed considerable interest in developing a crew return vehicle and in 1995 NASA started its own studies of a lifting-body type vehicle that could fulfil the role of ACRV. Eventually, NASA and ESA decided to join forces to build the lifting body, which became known as the X-38.

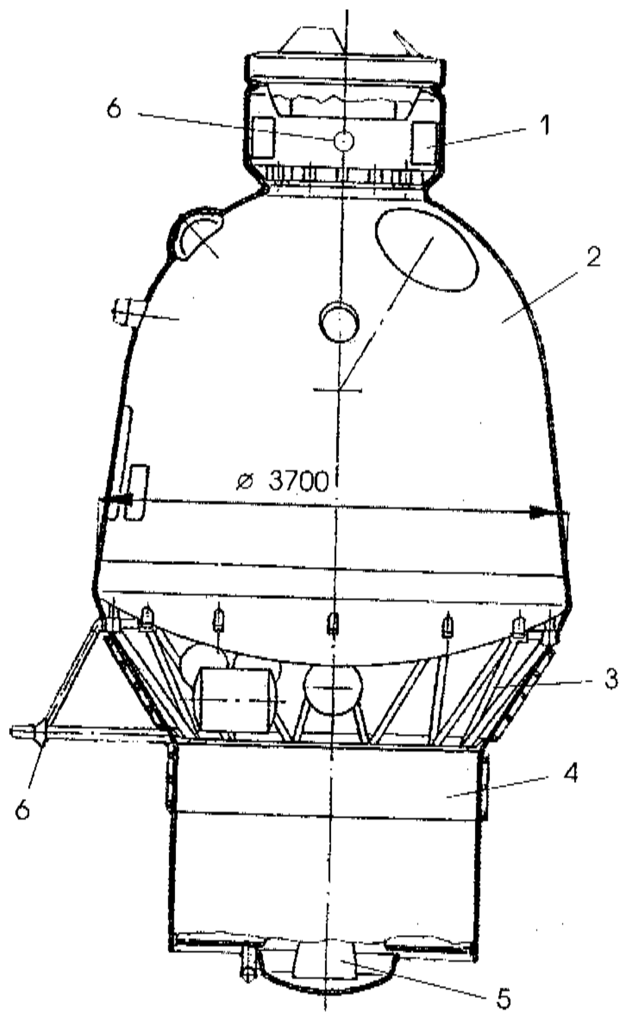


Fig. 31 "Big Soyuz" ACRV concept. **(source: RKK Energiya)**

Key:
1. Front compartment with docking port;
2. Descent compartment;
3. Intermediate compartment;
4. Instrument and propulsion compartment;
5. Main engine (with protective cover);
6. Shuttle payload bay attachment structures.

At any rate, until the US lifeboat became available, Soyuz-TM would be the only means of escape for an ISS resident crew in case of an emergency. An issue that needed to be resolved were the very stringent requirements that the Russians had for a cosmonaut's body length to fit inside the cramped Soyuz descent capsule. The problem came to a head in late 1995 when two American astronauts, Scott Parazynski and Wendy Lawrence, had to be bumped from Mir training for being too tall and too short respectively. According to NASA figures published at the time 45 percent of the American astronaut corps could not fit within the Soyuz. Actually, NASA had been aware of the body length restrictions since the Soyuz lifeboat studies for Freedom. In order to slightly ease these restrictions Energiya engineers had proposed that the astronauts would not wear pressure suits in case of an emergency return aboard Soyuz. The risk was considered acceptable given the low probability of a crew evacuation and the fact that Soyuz would be delivered to Freedom by the Shuttle and only be manned during the return to Earth.

Around mid-1995 NASA asked RKK Energiya to re-evaluate the problem of using Soyuz as an emergency lifeboat for resident crews launched to ISS aboard the Shuttle. RKK Energiya again put forward a plan to return the crew without pressure suits, although a 'leak compensation system' would now be developed to allow the astronauts to survive a depressurisation of the descent capsule during an emergency return. Launch of the Soyuz to ISS would be unmanned. NASA, however, preferred to slightly modify the Soyuz so that it could accommodate more US astronauts *with* pressure suits, not only for safety, but also to avoid a situation where there would be dedicated 'rescue' and 'transport' versions of Soyuz. Preliminary agreement on such modifications was reached at the 6th session of the Gore-Chernomyrdin commission in late January 1996. The expectation was that the modifications would be made under a separate contract between NASA and RKK Energiya, but eventually it was decided to make an amendment to the existing June 1994 contract between NASA and the Russian Space Agency. By early July it was agreed that NASA would pay $39 million for the modifications and on 19 September 1996 the amendment to the contract was officially signed. A Draft Plan for the modified Soyuz was approved by Yuriy Semyonov on 24 December 1996. The vehicle was called Soyuz-TMA, the A standing for 'anthropometric'.

The major change in Soyuz-TMA is that the seat frameworks (in which the individually tailored seatliners are installed) have been enlarged. This will allow the vehicle to carry astronauts with a standing height of between 150-190 cm and a sitting height of between 80-99 cm (compared to 164-182 and 80-94 cm resp. for Soyuz-TM). In order to install the larger seats, small changes had to be made to the hull to accommodate the feet of the crew members sitting in the left and right seats. It was also necessary to redesign the control panel (which has new computer displays) and to relocate some equipment under the seats (Fig. 32). By installing new shock absorbers in the seats, the weight limits for the crew members have been expanded from 56-85 kg on Soyuz-TM to 50-95 kg on Soyuz-TMA. The difference in weight between the left and right crew member can be as large as 45 kg. The automatic landing system has been adapted to handle the resulting changes in the ship's centre of gravity. In another change, two of the six soft-landing engines have been redesigned so that they can be operated at two different thrust levels depending on the exact landing mass of the descent capsule (ranging from about 2,980 kg to 3,100 kg). Soyuz-TMA will have a maximum mass of 7,200 kg (about 200 kg more than Soyuz-TM) and will therefore be launched by a slightly uprated Soyuz rocket with improved first and second stage fuel injectors. Called Soyuz-FG, the new rocket made its debut with the launch of Progress M1-6 in May 2001 and is now considered man-rated [59]. Later on Soyuz-TMA is expected to be launched with a further uprated rocket called Soyuz-2. Soyuz-TMA went through an extensive test programme, which included four drop tests of mock descent capsules from an Ilyushin-76 plane at an Air Force base near Akhtyubinsk between December 1998 and December 1999. The first flight of Soyuz-TMA (serial number 211) is currently planned for the autumn of 2002 and it will mark the first time in Soyuz history that a new modification makes its maiden flight with a crew on board. Four more Soyuz-TMA vehicles (nrs. 212-215) are now in various stages of assembly at RKK Energiya for flights in 2003 and 2004 [60].

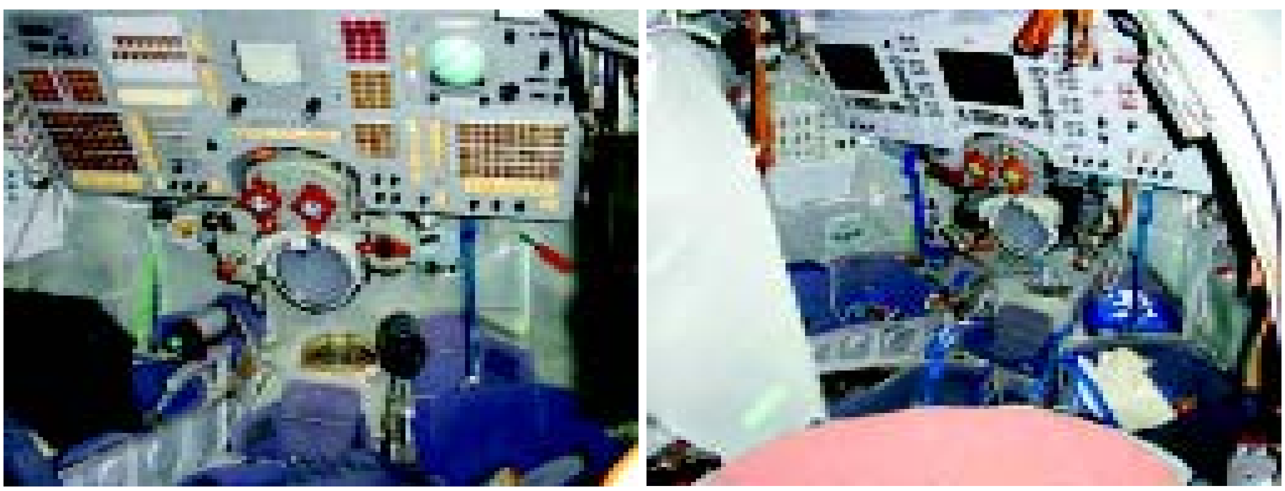


Fig. 32 Comparative views of Soyuz-TM (left) and Soyuz-TMA (right) cockpits.
(source: Mark Shuttleworth website at www.africaninspace.com)

RKK Energiya is already looking beyond Soyuz TMA and planning models that incorporate some more basic changes. RKK Energiya president Yuriy Semyonov had already issued an order to start work on improved Soyuz and Progress vehicles as early as November 1995. The goal would be to switch to modernised and lighter on-board systems manufactured solely in the Russian Federation (because companies situated in the former Soviet republics charged excessive prices), to enable various systems in the descent module to be reused and to increase the maximum flight duration to about one year. There was no room for such work under the Soyuz-TMA contract with NASA, which only covered the changes needed to accommodate taller astronauts. An offer by the Russians to include the work needed to increase the vehicle's lifetime had been turned down by the US space agency. It was not until June 1997 that Energiya signed a contract with the Russian Space Agency to start further modification work in earnest, with a Draft Plan for an improved model called Soyuz-TMM being approved in August 1998. The major modifications planned for Soyuz-TMM were:

- a single computer, installed in the descent module (as opposed to one in the descent module and one in the propulsion compartment on Soyuz-TM)
- an improved telemetry system
- two additional braking engines in the Approach and Docking engine system for safer dockings (probably a result of the collisions and near-collisions in the Mir programme)
- a satellite data relay system called Regul

- an autonomous satellite navigation system and an improved Kurs-MM rendezvous system
- deployment of the parachutes at a lower altitude and modifications to the automatic landing control system in order to increase landing accuracy
- increase of the maximum flight duration to 380 days. This will be achieved among other things by installing a thermoelectric cooling system for the tanks of the hydrogen peroxide thrusters on the descent module, improving the ship's batteries and making the oxidizer tanks in the propulsion compartment out of steel rather than an aluminium alloy.

It soon turned out that incorporating all these changes simultaneously would be too costly and by the summer of 1999 plans were approved for an intermediate version called Soyuz-TMS. This will only have the two extra braking engines, the improvements needed for more accurate landings (the eventual goal being to shift landings from Kazakh to Russian territory) and the cooling system for the hydrogen peroxide thrusters, although maximum flight duration will remain limited to 180-210 days. Soyuz-TMS will retain the separate computers in the descent module and propulsion compartment. The ship will also have an updated flight control system that among other things will increase docking safety and make the ship more attractive to NASA as a crew rescue vehicle. It will also have all the changes introduced by Soyuz-TMA. Semyonov approved the Draft Plan for Soyuz-TMS in December 1999 and if the necessary funds are made available, the vehicle could make its maiden flight in 2006 or 2007. The launch vehicle will be the Soyuz-2. Soyuz-TMM right now remains no more than a distant dream [61].

So far only the first ISS resident crew has used Soyuz to actually fly to the station. All subsequent resident crews went up and returned aboard the Shuttle. This means that the exchange of Soyuz vehicles has to be carried out by short-stay visiting crews on what have been called 'taxi missions'. These are now performed roughly every six months, whenever the maximum on-orbit lifetime of a Soyuz expires.

Due to serious cost overruns in the ISS programme it looks unlikely that the US-built Crew Rescue Vehicle (CRV) will ever fly. If the resident crew is increased to six, NASA will likely be forced to purchase extra Soyuz rescue craft, which was recommended in two of the three options for crew expansion presented by the Thomas Young commission in late 2001. In October 2001 the Russian Space Agency stepped up the pressure on NASA to opt for this solution by warning that foreign astronauts might soon lose long-term access to the ISS. The agency cited an 11 June 1996 agreement between the ISS partners under which Russia is obliged to deliver a Soyuz to the station only during the first 50 months of crewed operations. After that, the agency said, Soyuz would only be accessible to Russian cosmonauts unless the partners buy additional Soyuz lifeboats to provide emergency escape for non-Russian crew members [62]. Whatever the outcome of this debate, it looks like Soyuz will remain a key transportation system for the ISS for the foreseeable future.

Progress and the Logistics Transfer Vehicles

In the original station plans the ISS was to be resupplied and refuelled both by the Progress-M and Progress-M2 freighters. The Soyuz-launched Progress-M had been flying regular missions to the Mir station since 1989 and needed no modifications for its ISS role. The much more capable Zenit-launched Progress-M2 (see Mir-2 section) was originally conceived for Mir-2 and aside from serving as a cargo ship could also be adapted as a specialised tanker or as a tug for station modules or large structures to be used in station assembly. The cargo version was capable of delivering up to 5.7 tonnes of cargo and 800 kg of propellant to ISS and the tanker version up to 5 tonnes of propellant. Therefore, Progress-M2 was expected to allow the number of Progress-M missions to be significantly reduced in the course of station assembly.

All this changed with the decision made in early 1996 to drop the Zenit rocket (and consequently the Progress-M2 vehicles) from ISS assembly. After the 6th meeting of the Gore-Chernomyrdin commission in January 1996 it was announced that the indefinite delay of Progress-M2 was to be compensated by the development of several heavy cargo vehicles based on the FGB. Jointly financed by the US and Russia, the FGB-based freighters would be able to deliver about 10 tonnes of cargo, about as much as three Progress-M vehicles. NASA referred to these as Logistics Transfer Vehicles (LTV) and the Russians called them GTK-FGB (GTK standing for Cargo Transport Ship). Several of them were included in the ISS assembly schedules compiled later in 1996. However, in 1997 NASA decided not to fund the LTVs and instead carry up additional supplies on the Shuttle. Subsequently, Khrunichev proposed that the LTVs be funded by Russia alone to resupply only the Russian segment, but this drew heavy criticism from RKK Energiya, which did not want to see Russian money earmarked for its Progress craft to be transferred to the Khrunichev vehicles. Another argument used by RKK Energiya against the LTV were the relatively serious consequences of a launch or docking failure compared to the loss of a single Progress.

Little has been revealed about the exact modifications that would be required to the FGB to turn it into an LTV. One idea was to mount 22 propellant tanks on the outside of the pressurised hull and replace the aft docking adapter by a small undetachable space tug, similar to the one proposed at one point for the Research Modules. This space tug also featured in a proposed ‘assembly version’ of the LTV, where the pressurised module would be replaced by a cross-shaped platform outfitted with various types of equipment to be mounted on the exterior of ISS [63]. On several occasions Khrunichev proposed to turn FGB-2, the Zarya back-up, into an LTV demonstrator. If FGB-2 eventually flies as the Commercial Space Module, it will actually perform that task, supplying large amounts of cargo and propellant to ISS before being used for other purposes. If this will be followed by any dedicated LTV flights remains to be seen.

Another measure announced after the January 1996 Gore-Chernomyrdin meeting to offset the loss of Progress-M2 was to increase the cargo capacity of the Progress spacecraft by 200 kg. This appears to have been part of an effort to gradually upgrade Progress by using ever more powerful versions of the Soyuz rocket under the Rus programme (some publications actually referred to the vehicle as Progress/Rus). It is known that in 1997-1998 RKK Energiya worked on an improved vehicle called Progress-MM that featured some of the same modifications as Soyuz-TMM. In 1999, simultaneously with the switch from Soyuz-TMM to TMS, those plans were abandoned in favour of a more modest modification named Progress-MS. The Draft Plan for this vehicle was approved by Semyonov in January 2000 and it is expected to make one or two flights *before* the first Soyuz-TMS to test the improved flight control system.

In early 1999 RKK Energiya also began studying an 11-12 tonne resupply ship to be orbited by the Yamal booster and sharing many design features with the ISS modules put forward by Energiya that same year. By the end of the year designers settled on a vehicle reminiscent of Progress-M2, but about 2 m shorter because Yamal had a smaller payload fairing than Zenit. Called Progress-M3, it had a total mass of about 11.5 tonnes and could deliver about 5.5 tonnes of cargo and propellant to ISS (Fig. 33). However, as Progress-M3 appeared on the drawing board, the focus shifted to a commercial version of Yamal ('Avrora') to be launched from Christmas Island and to the Enterprise module built jointly with Spacehab. Plans to launch Avrora from Baykonur’s UKSS launch pad (used for the first Energiya launch in May 1987) have been abandoned, making it unlikely that Progress-M3 will ever be built [64].

A new iteration of Progress that *did* appear after the start of ISS assembly is Progress-M1. Remaining within the payload capacity of the standard Soyuz rocket, it carries more propellant to refuel ISS than Progress-M. Although the order to develop this vehicle was signed by RKK Energiya president Yuriy Semyonov on 15 February 1996, a Progress with an increased propellant supply was already mentioned in Russia’s original ISS plans and it may have been developed independently from the Progress/Rus effort [65]. The increased propellant load is achieved by replacing the ‘Rodnik’ water tanks in the mid-section with four additional propellant tanks, giving a total of eight propellant tanks with a maximum of 1,700 kg of propellant (compared to 850 kg on Progress-M). Water (100 kg less than on Progress-M) is now stored in the cargo section. Twelve nitrogen and oxygen tanks were placed on the exterior of the craft around the intersection between the cargo and propellant compartments. Progress-M1 also has an improved computer (replacing the Argon-16), an autonomous navigation system using GPS and Glonass and an improved Kurs-MM rendezvous system, although the latter doesn't seem to have been used so far [66] (Fig. 34). The first two Progress-M1 cargo ships were launched to Mir in February and April 2000 and the first launch to ISS took place in August 2000.

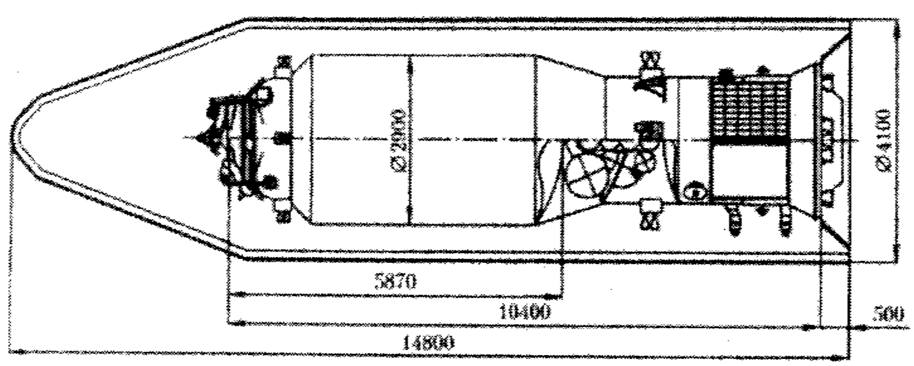


Fig. 33 Progress-M3.
(source: RKK Energiya)

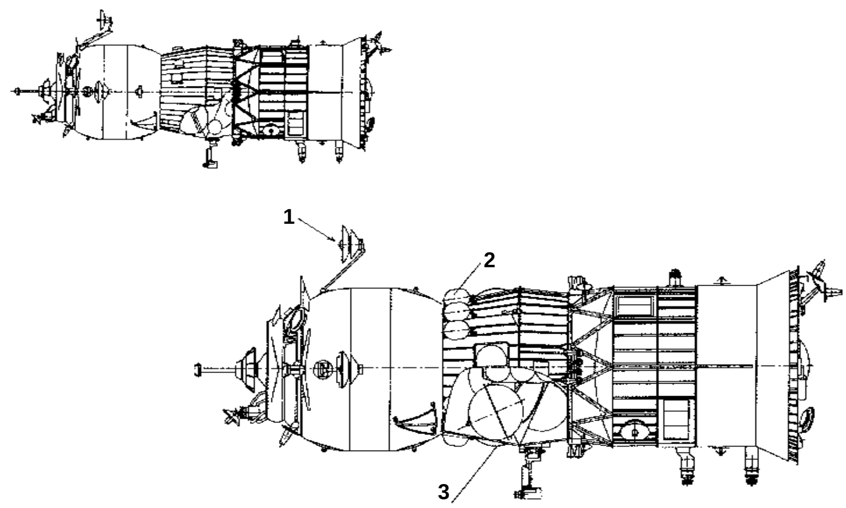


Fig. 34 Comparative views of Progr- ess-M (above) and Progress-M1.
(source : Novosti Kosmonavtiki)

Key:
1. Kurs-MM antenna;
2. Oxygen and oxygen-nitrogen tanks;
3. Propellant compartment with 8 propellant tanks.

Conclusion

Almost ten years after the International Space Station was conceived, the Russian segment is still a long way from reaching its final configuration. Russia's inability to complete its part of the station without Western financial support demonstrates that its domestic manned space programme would probably have been scaled back substantially or even cancelled without the space partnership it entered with the West in 1993. On the other hand, without critical Russian contributions such as the Service Module and the venerable Soyuz and Progress ferries, the ISS might never have been permanently manned as early as it did. Although largely built with Western money, it will probably also be Russian hardware that eventually will enable the station to be manned by the number of astronauts required to fully exploit its scientific potential.

Acknowledgments

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22. The text of the pact is published in: "Joint Russian-American Commission on Energy and Space: Joint Statement on the Development of Co-operation in the Area of Space" (in Russian), *Novosti Kosmonavtiki*, 18/1993, pp.5-7; also see: P. Mann, "US, Russia Draft Historic Space Pact", *Aviation Week & Space Technology*, 6 September 1993, pp.22-23.
23. J. Asker, "NASA Details New Station Plans", *Aviation Week & Space Technology*, 13 September 1993, pp.20-21.
24. K. Lantratov, "Russia-USA. Into Space Together" (in Russian), *Novosti Kosmonavtiki*, 26/1993, pp.13-16.
25. Yu. Zhuravin, "What Is The FGB?" (in Russian), *Novosti Kosmonavtiki*, 1/1999, pp.2-3. According to this source the Russian Space Agency initially refused to include the FGB as an element of the Russian segment because of objections raised by RKK Energiya. It was not until NASA expressed its readiness to purchase the FGB, that the Russian Space Agency went along.
26. K. Lantratov, "Russia-US. Into Space Together", op. cit., p.17.
27. K. Lantratov, "Russia-US. Into Space Together", op. cit., p.18 ; L. Tucci, "Partnership Yields Sketchy Details On Savings", *Space News*, 29 November-5 December 1993, p.3.
28. K. Lantratov, "Russia-USA. New ISS Assembly Schedule" (in Russian), *Novosti Kosmonavtiki*, 3/1994, pp.32-37.
29. "ISS Assembly Sequence Changed" (in Russian), *Novosti Kosmonavtiki*, 14/1994, pp.47-48; I. Lisov, "ISS Assembly Schedule Changed" (in Russian), *Novosti Kosmonavtiki*, 20/1994, p.44.
30. NASA initially referred to it with the English acronym APDS, but later adapted the name to fit the Russian acronym, calling the system Androgynous Peripheral Assembly System.
31. Private correspondence with Konstantin Lantratov, 7 June 2002.
32. K. Lantratov, "International Space Station Alpha" (in Russian), supplement to *Novosti Kosmonavtiki*, June 1995, p.7, 18, 21-24; K. Lantratov, "New Russian Element of ISS Launched" (in Russian), *Novosti Kosmonavtiki*, 11/2001, p.7.
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34. Zarya was the name first proposed for the civilian DOS space stations. Just a few days before the launch of the first DOS, it was decided to name the station Salyut instead. However, it was launched with the name "Zarya" painted on the hull and on the nose fairing of the Proton rocket. Zarya was also the name of the Zenit-launched "Big Soyuz" (14F70) designed by NPO Energiya in the 1980s. Finally, Zarya was an unofficial name for the Baykonur cosmodrome in the late 1950s and early 1960s and it was also used as the call-sign of capcoms talking to orbiting cosmonauts in the early years of the Soviet manned space programme.
35. Main sources used for Zarya section: K. Lantratov, "The FGB Energy Block" (in Russian), *Novosti Kosmonavtiki*, 4/1994, pp.25-27; C. Covault, "Russian FGB 'Space Tug' Leads Station Alpha", *Aviation Week and Space Technology*, 4 September 1995, pp.48-51; V. Sorokin, "The FGB Will Be Modified" (in Russian), *Novosti Kosmonavtiki*, 7/1997, pp.48-50; Yu. Zhuravin, "What Is The FGB?" (in Russian), *Novosti Kosmonavtiki*, 1/1999, pp.2-7.
36. For more background on this see: J. Oberg, *Star-Crossed Orbits: Inside the US-Russian Space Alliance*, McGraw Hill, New York, pp.231-247, 2002.
37. The name Zvezda first emerged in the early 1960s for a space station designed by Korolyov's OKB-1 design bureau. Korolyov's engineers were reportedly inspired by the Russian SF novel *Zvezda KETs* written by Aleksandr Belyayev (KETs standing for "Konstantin Eduardovich Tsiolkovskiy"). This was the name of a space station described in the novel. Later the name was used for the following projects: a spaceplane proposed by the Tupolev bureau in the early 1960s; a manned military vehicle designed by Branch Nr. 3 of OKB-1 in 1965-1967, also known as 7K- VI and 11F72 ; an Almaz military space station with multiple docking ports designed by the Chelomey design bureau in the 1970s ; a lunar base proposed by NPO Energiya in the mid-1970s. For the origins of the name Zvezda see: T. Varfolomeyev, "Soviet Rocketry That Conquered Space: Early Space Station Projects by OKB-1, 1954-1965", *Spaceflight*, **42**, pp.384-385, 2000.
38. This section based on: K. Lantratov, "The Zvezda Service Module" (in Russian), *Novosti Kosmonavtiki*, 9/2000, pp.7-14.
39. V. Voronin, "The Universal Docking Module" (in Russian), *Novosti Kosmonavtiki*, 10/1998, p. 36.
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43. This section based on: "Statement on Russian-Ukrainian Co-operation" (in Russian), *Novosti Kosmonavtiki*, 11/1997, p.33; V. Voronin, "The Universal Docking Module" (in Russian), *Novosti Kosmonavtiki*, 10/1998, pp.36-37; V. Kirillov, "More Changes in the Russian Segment" (in Russian), *Novosti Kosmonavtiki*, 10/1998, pp.38-39; Yu. Zhuravin, "Ukrainian Module for ISS"/"News from the Russian Segment" (in Russian), *Novosti Kosmonavtiki*, 1/1999, p.26, 28; Yu. Zhuravin,

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47. **V. Mokhov, "The Russian Segment of ISS Is Becoming Ever More Commercial" (in Russian),** *Novosti Kosmonavtiki*, **10/ 2000, p.18; Yu. Semyonov,** *RKK Energiya...1996-2001*, **op. cit. pp.508-509, 512, 514.**
48. **Yu. Semyonov,** *RKK Energiya...1996-2001*, **op. cit., pp.511-514, 634.**
49. **V. Mokhov, "Enterprise Legalised" (in Russian),** *Novosti Kosmonavtiki*, **5/2001, p.30.**
50. **I. Afanasyev, "Agreement Between Boeing and Rosaviakosmos" (in Russian),** *Novosti Kosmonavtiki*, **6/2001, pp.70-71; V. Mokhov, "Boeing and Khrunichev Will Build A Commercial Module After All" (in Russian),** *Novosti Kosmonavtiki*, **7/2001, p.12.**
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52. **V.V. Favorskiy and I.V. Meshcheryakov,** *Voenno-kosmicheskiye sily: kniga 2*, **Izdatelstvo Sankt-Peterburgskoy tipografii, Moscow, p.131, 1998.**
53. **Some Western reports took over the Cyrillic spelling CO. Progress M-SO1 had a serial number in the Progress-M series (11F615A55 N° 301). No international designator was applied to Pirs itself, only to the combination of Pirs and the propulsion compartment (2001-041A). The propulsion compartment retained that designator after being separated from Pirs.**
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58. **Yu. Semyonov,** *RKK Energiya…1946-1996*, **op. cit., p.521.**
59. **FG stands for "forsunochnaya golovka", the Russian word for fuel injector. The first and second stage engines have been redesignated: the engines of the four strap-on boosters are called RD-107A or 14D22 (as compared to RD-107/11D512 on the 'old' Soyuz) and the core stage engine is named RD-108A or 14D21 (as compared to RD-108/ 11D511). The improved fuel injectors are one of the modifications under the so-called "Rus" programme that will eventually lead to the development of the Soyuz-2 rocket. See: I. Afanasyev, "Progress M1-6 Launched" (in Russian),** *Novosti Kosmonavtiki*, **7/2001, p.9.**
60. **K. Rusakov, "Soyuz TMA – Ship for ISS" (in Russian),** *Novosti Kosmonavtiki*, **15-16/1998, pp.54-56; S. Shamsutdinov, "The Soyuz TMA Ship" (in Russian),** *Novosti Kosmonavtiki*, **17-18/ 1998, p.53; Yu. Semyonov,** *RKK Energiya...1996-2001*, **op. cit., pp.356, 600-628.**
61. **Details of Soyuz-TMS and TMM are from: Yu. Semyonov,** *RKK Energiya...1996-2001*, **op. cit., pp.628-631.**
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64. **Details of Progress-MM, MS and M-3 are from: Yu. Semyonov,** *RKK Energiya...1996-2001*, **op. cit., pp.631-634, 730-731; O. Urusov, "Avrora Will Not Fly From Baykonur" (in Russian),** *Novosti Kosmonavtiki*, **1/2002, p.48.**
65. **A "tanker" version of the standard Progress-M is mentioned in: K. Lantratov, "Ships for ISS" (in Russian),** *Novosti Kosmonavtiki*, **7/1994, p.23.**
66. **K. Rusakov, "The Transport Cargo Ship Progress M1" (in Russian),** *Novosti Kosmonavtiki*, **4/2000, p.16; Yu. Semyonov,** *RKK Energiya...1996-2001*, **op. cit., p.579.**

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