Section 3 - Shuttle Integration With *Mir*

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3.1 Introduction

This report presents a joint NASA-RSC Energia (RSC-E) summary of the significant activities and accomplishments of the Phase 1 Program Joint Systems Integration Working Group (SIWG). The managers of the Phase 1 Program (then known as the Shuttle-*Mir* Program) established the SIWG in November 1992. The SIWG was paired with the Flight Operations Working Group, to constitute Phase 1 Working Group 3 (WG-3) – Joint Flight Operations and Systems Integration. This report is divided into a number of stand-alone sections addressing the work and significant accomplishments in the various SIWG disciplines.

The Phase 1 Program SIWG was responsible for the physical interfaces and interactions between the Space Shuttle Orbiter and the *Mir* Orbital Station. NASA and RSC-E both have a long and successful legacy of human spacecraft design, development, and operations. Each organization had successfully performed complex engineering design and analysis tasks for many years on their respective spacecraft programs, addressing activities such as spacecraft rendezvous, docking, mated pressurized operations, and undocking. But the Phase 1 Program introduced new and unique engineering design and analysis challenges to both parties. Although the two organizations had previously cooperated in conducting the Apollo-Soyuz Test Project, the dramatic differences between the Apollo/Soyuz and the Shuttle/*Mir* spacecraft sets necessitated a fresh, comprehensive engineering assessment of all aspects of projected operations between the Shuttle and the *Mir*.

From the beginning of the systems integration joint work, the classical engineering project process was followed: requirements definition; design and analysis plan definition; data and information development and exchange; review of hardware designs and analysis results; and, finally, flight readiness recommendation and certification. Though the plan was simple, the work of integrating the efforts of two large, foreign engineering communities posed a number of administrative and technical challenges.

Developing a new, joint process for defining and documenting necessary engineering requirements was the first major step in our work. A series of 12 joint documents was eventually developed. Each document addressed a discrete engineering area, such as thermal control or structural mathematical models.

Many of the specific engineering tasks the parties performed were straightforward and similar, if not identical, to the standard tasks performed for Shuttle or *Mir* unilateral missions. But new and difficult spacecraft engineering issues were introduced to each party due to the complexities of the Shuttle and *Mir* spacecraft and the planned operations. The most challenging technical issues presented by the Phase 1 Program, requiring development of new analysis methodologies and/or new mathematical model development, were in the following areas:

- structural modeling and analysis
- docking dynamics
- rocket thruster plume impingement on large, flexible structures

- maneuvering and attitude control of large-scale mated vehicles
- habitable compartment atmosphere conditioning
- potable water treatment, transfer, and stowage
- Shuttle launch and orbital delivery/installation of a Russian space station module (*Mir* docking module, or DM)

A final area requiring joint development and agreement was formal certification for flight. Although each party had an existing flight certification process for their respective unilateral missions, these existing processes differed in a number of details. Therefore, the working group developed a plan whereby each party certified its individual spacecraft and equipment per their normal, unilateral flight certification processes, then signed a mutual statement that the two spacecraft were ready for the planned mission as defined in the joint engineering requirements.

Initially the Phase 1 program involved only one Shuttle-*Mir* docking mission. Within 18 months of inception however, the Program had expanded in scope to one rendezvous and 9 docking missions (all spaced approximately 4 months apart), including delivery of a Russian-built *Mir* DM for launch on the Shuttle and delivery to *Mir* on the second docking mission. Further, the relative docking/docked geometry of the Shuttle and *Mir* needed to be changed for the second docking mission (and then remained constant for the remaining missions) to accommodate periodic *Mir* resupply and expansion in parallel with routine Shuttle visits. This expansion of the Program scope significantly increased the scope and scale of work this working group had to accomplish before the first docking mission. The time and effort required to complete necessary bilingual documentation for these two very different mission scenarios imposed a large burden on the individual specialists over and above their analysis tasks, since no separate documentation staff was allotted.

In summary, the Phase 1 Program Joint SIWG developed and executed the NASA and RSC-E engineering activities necessary to successfully enable joint operations between the two largest orbital vehicles in existence. Engineering methods and solutions were jointly developed and applied to thoroughly assess the technical aspects of the Shuttle-*Mir* missions. Several of these methods and solutions advanced the state of the art in their respective fields and are being used today to design and plan International Space Station (ISS) missions, as well as in the design of ISS elements themselves. Also, as the individuals from each country worked together on problems and struggled with each other's language, they forged close personal and professional bonds. This spirit of personal and communal cooperation exhibited by all the individuals in the SIWG was critical to the success of our efforts. We hope that the cooperative personal and technical efforts of this joint Phase 1 Program working group will be useful and educational to engineers working on all future space programs.

3.2 Structure/Process/Organization Relationships

To conduct joint activities in preparation for Shuttle missions to *Mir*, WG-3 was established with co-chairmen designated from NASA and RSC-E. The co-chairmen directed the overall joint operations and engineering integration activities necessary for planning and conducting the joint Shuttle-*Mir* missions. The combination of the operations and integration specialists from NASA and RSC-E into the same working group was crucial to the success achieved during the joint program.

The systems integration component of WG-3 was divided into technical teams that encompassed the following basic areas of responsibilities on all missions:

- Spacecraft Physical Characteristics
- Active and Passive Thermal Control Systems
- Life Support Systems
- Avionics, Audio, and Video Systems
- Mated Flight Control Systems
- Approach, Docking, Mated, and Separation Loads (including Structural Modeling)
- Thruster Plume Definition

NASA and RSC-E engineering specialists were selected as co-leaders for the technical teams. The co-leaders were responsible for the preparation of joint documentation that defined the requirements, constraints, and limitations for the Shuttle and the *Mir*.

Each subgroup co-chair was responsible for certifying that his/her respective spacecraft was compatible with the joint requirements for a given mission, and each signed a certificate of flight readiness for each joint mission, for the appropriate technical area. Following subgroup flight certification, the WG-3 co-chairs signed and submitted to the program managers a group flight readiness certificate.

3.3 Joint Accomplishments

3.3.1 STS-63 Integration

The first Shuttle flight to rendezvous to close proximity with *Mir* successfully tested and demonstrated Shuttle piloting techniques, range sensor performance, docking target lighting, and *Mir* maneuver to docking attitude capabilities. A centerline TV camera was simulated in the Spacehab overhead window and provided excellent views of the docking target. The Shuttle Ku-band radar, the Handheld Laser and the Trajectory Control System (TCS) laser systems demonstrated the capability to track the *Mir* Station. The air-to-air VHF voice communications systems were also demonstrated.

3.3.2 STS-71 Integration

Planning for the first two joint missions, STS-71 and STS-74, presented some of the greatest challenges and accomplishments. Top-level agreements for operating Shuttle and *Mir* together set the stage for subsequent missions and were key to the success of the program. Piloting and docking the Shuttle to *Mir* involved considerations in jet thruster firing loads and contamination, and accuracy of piloting techniques, while studying approach relative position and velocities required to obtain capture. Positioning *Mir* for a Shuttle approach involved feathering and rotating *Mir* solar arrays to minimize impacts from jet plumes and shutting down systems to conserve power as a result. The control of the mated Shuttle/*Mir* vehicle became the primary responsibility of Shuttle, as a natural consequence of Shuttle's "renewable" propellant source on each flight. Lighting, communication, and thermal constraints influenced joint vehicle attitude decisions. The *Mir* environments shared by the crews in Shuttle and *Mir* were augmented by Shuttle's capabilities to produce oxygen (O2) and nitrogen (N2) and the design of transfer methods across hatches. Hardware designs and movement of equipment acceptable to both sides accomplished audio and visual crew communication to U.S. and Russian mission operation centers.

One of the early engineering challenges was to design the Shuttle/*Mir* docking interface that would allow safe mating of both vehicles. A location for the docking was chosen to maximize both Shuttle performance and cargo bay space for supporting modules/hardware and maximize clearance/minimize environmental impacts between vehicles. A design that tied together the external airlock with the Spacelab module was optimized using a series of tunnel sections and unique integration hardware (bridges, ducts, etc.). A number of existing program tunnel sections were utilized for Phase 1. Most, if not all, of this hardware will be used for the ISS Spacehab resupply missions.

3.3.3 STS-74 Integration

The Shuttle/*Mir* mated configuration for STS-74 was completely redefined. When RSC-E informed NASA that the Kristall module/docking port had to be repositioned from its temporary location on the X-axis to its permanent location along the Z-axis, the new Shuttle/*Mir* configuration had to be re-engineered. "Clocking studies" were performed to determine the best mix of physical clearances, thermal constraints, communication needs, loads, attitude control, contamination, plume impingement, piloting, and remote manipulator subsystem (RMS) operations. The success of the subsequent Phase 1 missions demonstrated that a key criteria considered for these early analyses was defining a mated configuration that would last throughout the Phase 1 program.

In between the STS-71 and STS-74 missions, RSC-E successfully returned the Kristall module to its permanent location using the mechanical arm. RSC-E designed the DM as an extension to the Kristall docking port to provide adequate clearances between the Shuttle and *Mir* solar arrays. There were major challenges involved for both NASA and RSC-E to accomplish integration of the DM into the Orbiter on an accelerated flight template including: joint data exchanges, manufacturing and testing in Moscow, delivery and testing at Kennedy Space Center (KSC), and satisfying NASA safety requirements with minimum analysis/design change. Joint cooperation was key to jointly determining and agreeing upon the optimum locations for NASA docking aid hardware on the DM (and docking system) that would serve Shuttle docking for both STS-74 and subsequent flights. These included lights, cameras, trajectory control sensor (TCS) retro-reflectors, primary and secondary targets, and the Shuttle vision system targets. STS-74 demonstrated the use of docking aids/cues for the remaining missions.

Berthing the DM to the Orbiter docking system with the RMS, and docking the combined vehicle was successful, demonstrating that joint data exchange was accomplished, and pre-mission engineering and planning were accurate. Power transfer between androgynous peripheral assembly system (APAS) systems was performed smoothly. Both APAS units and DM systems operated nominally. STS-74 proved to be nearly identical to the on-orbit berthing operations that would be required on the first ISS joint mission.

3.3.4 Docking Module Integration

Integration and operations planning for delivering the Russian DM aboard Shuttle to the *Mir* Space Station was accomplished successfully in a very short time. It is to RSC-E's credit that they designed, manufactured, tested, and delivered the DM to the U.S. in 18 months. There may be some education in hardware development for NASA, since few changes were made to the design as a result of analytical validations performed by NASA. It is to NASA's credit that the Shuttle launch and on-orbit integration requirements were clearly transmitted, Russian engineering processes were understood, and — with a compressed mission cycle — the right engineering information was extracted to perform an enormous amount of analytical work to deal with safety and verification issues in the Shuttle standard integration process. Dedicated individuals at JSC and KSC performed the right studies and analyses, sharing the results with RSC-E counterparts. NASA performed design thermal and loads analyses and non-linear studies on individual hardware elements, participated in DM testing both in Moscow and in the U.S., integrated NASA hardware inside and out, planned RMS operations, and developed crew procedures as well as other integration activities. KSC did an outstanding job of planning and executing ground operations, while managing to land a Russian plane on the Shuttle landing strip, house and transport Russian personnel, and smooth the entry and exit of various RSC-E test personnel.

There was great cooperation at the project engineering level. RSC-E appointed a Chief Designer to head the project at RSC-E, emphasizing the significance and importance of the program. Mr. I. Efremov’s effective managerial and technical abilities ensured success in this monumental task of building a new *Mir* module and designing it to be compatible with a foreign transportation vehicle in a very compressed time frame. NASA appointed a dedicated Shuttle lead to oversee all areas of mission integration. The efforts of RSC-E and NASA project personnel, test engineers, operations planners, and analysts were outstanding, given the cultural barriers and ambitious schedule for delivering and integrating the DM with the Shuttle.

NASA and RSC-E engineers jointly accomplished the task of installing U.S. hardware inside the DM for later crew removal. Defining Russian hardware that the crew would interface with under both nominal and contingency situations took patience and fortitude. SVS targets were added after the DM design was complete. These targets allowed early ISS Program (ISSP) testing of a new berthing tool that will be used to construct the ISS.

The DM, which was carried up and berthed to the *Mir* on STS-74, was powered, commanded, and monitored via Shuttle systems while it was in the Shuttle cargo bay as well as when it was berthed to the Orbiter docking system (ODS). For STS-74, joint document 3411 was the program agreement for delivering DM to *Mir*. This document defined all technical requirements for interfacing the DM with the Shuttle, as well as the Shuttle environments (thermal, loads, etc.) which the DM would be subject to during ascent and an orbit. The DM was transitioned to *Mir* power and control while docked, and remained on the *Mir* as the new docking interface for Shuttle.

3.3.5 Vehicle Attitude Control

3.3.5.1 Shuttle

A significant challenge during the Shuttle/*Mir* program was the successful docking of the Shuttle and *Mir*. The Shuttle crews performed the relative translational control manually, but the Shuttle and *Mir* autopilots were required to maintain precise rotational orientations. Previous experience had demonstrated the effects of the Shuttle control on Shuttle proximity piloting, but the effects of the *Mir* control system on this operation were unknown.

Models of the *Mir* control system were developed and implemented in Shuttle piloting simulations to analyze the effects on piloting and plume. These models became invaluable in understanding the effects of various activities that occurred on *Mir*, including a brief period of dual control on STS-81.

Shuttle/*Mir* proximity operations were complicated by the fact that the Russian docking mechanism required high closing velocities to ensure capture. These high closing velocities would make precise control of the docking difficult for the crew and would result in unacceptably high docking loads. Procedures and software were designed to allow a slower, more precise approach to be flown with low contact velocities. This was achieved by developing software that performed an automatic series of firings that were initiated by the crew at vehicle contact to drive the docking mechanisms into a latched state. This software upgrade was implemented on a fast track schedule to be available for the first Shuttle/*Mir* docking flight.

The successful Shuttle attitude control of the mated Shuttle/*Mir* stack represented a significant milestone in the Shuttle program. The mated vehicle was the largest spacecraft ever orbited in space (~500K lb). STS-71 was the first flight of a large space structure (the Shuttle/*Mir* stack) with the potential for significant control-structures interaction. The vehicle was flexible, with dominant structural modes near the Shuttle control bandwidth. The Phase 1 program demonstrated that a series of Orbiter control system upgrades, developed to provide control of large, flexible, space structures, worked successfully and could be relied upon to provide control during the critical early assembly flights of the ISS. The Shuttle also demonstrated that it could control a variety of mated configurations with widely varying mass properties and structural flex characteristics. The control system had to meet stringent loading constraints, while providing robustness to uncertainties in the modeling of the rigid body mass properties and flexible dynamics.

3.3.5.2 *Mir*

The basic tasks performed by the *Mir* motion control system in joint flights were as follows:

- development of the attitude control timeline and preparatory operations before docking with the Shuttle;
- support of motion control system passive mode in controlling stack attitude from the Shuttle;
- verification of capability and support of stack attitude control;

- Performance of tests and technical experiments.

To support Shuttle approach and docking in all joint flights, the *Mir* motion control system supported the following operations:

- Inertial coordinate system correction using Kvant module star sensors with an inertial system setting precision no worse than 10 angular minutes;
- Maneuver of the *Mir* from the inertial coordinate system to baseline attitude for docking (such as the orbital coordinate system);
- Maintenance of orbital coordinate system attitude until mechanical capture;
- Movement of solar array panels to position required for docking;
- Forced desaturation of gyrodyne total kinetic moment to zero value;
- Transition to passive mode until mechanical capture is achieved.

All of the above operations were carried out nominally in all joint flights with automatic motion control, system control and with crew assistance.

During stack attitude control using the Shuttle vernier reaction control system, the *Mir* motion control system was in passive (indicator) mode. During passive mode, attitude control jets were blocked from firing both by the software and by an electrical interlock, and a gyrodyne kinetic moment value in a sphere with radius of 500 nms was provided.

The attitude of the *Mir*-Shuttle stack during various joint flights was controlled for the purpose of demonstrating the *Mir* motion control system capability to execute stack attitude control maneuvers using the attitude control jets and to maintain stack attitude using the gyrodynes. During an off-nominal situation for the Shuttle control system on STS-89, the *Mir* motion control system took over attitude control at MCC-H request.

During stack control there were from 9 to 11 gyrodynes in the control loop. Various jet configurations for control were used.

3.3.6 Vehicle Dynamics and Structures

Developing methods to dock and undock the vehicles and developing acceptable structural loading and strength for all operations was a key challenge with the influences of both vehicles. Shuttle pilot control of approach relative position and velocities, minimum jet firings, and docking contact accuracy was excellent. Docking capture was successful on the first try on each mission, with contact misalignments approximately one-third of their allowable limits. Shuttle plume loads on *Mir* were negligible. Attitude control of the joined vehicles used the very low load Shuttle vernier jets or the *Mir* gyrodyne systems. Only several hours of high load Shuttle primary jet control were performed to demonstrate its backup capability, since the vernier jets demonstrated good reliability by controlling attitude nearly the entire mission duration.

Structural modeling proved very accurate as demonstrated by the measured *Mir* response to Shuttle docking and structural dynamic excitation tests of the joined vehicles. Modeling updates were made to the Shuttle model based on on-orbit test data, while no updates to the *Mir* model were necessary. Shuttle plume loads on *Mir* were not verified by flight experience since they were so infrequent, low level, and sparsely recorded.

Crew exercise loads were significant, since the pace of ergometer and treadmill exercise excites natural frequencies of the structure. This exercise also uses significant structural life because of the extended duration required for crew health maintenance. To reduce a loss of resources, limits were placed on the amount of time the cosmonauts ran on the treadmill. Shuttle docking produced the highest loads on the module structure; this was deliberate to maintain a high capture probability. Structural life usage from docking was not significant, since the number of cycles was very low.

Mir structural life was a significant consideration since the *Mir* use had been extended beyond original design intent. A Progress vehicle collision with *Mir* between Shuttle flights damaged one *Mir* module and loaded other primary structures in a severe manner, giving additional incentive to reduce *Mir* structural life usage. Lack of detailed structural health inspection techniques for long-duration spacecraft remains a technical and management challenge.

Significant tools were developed to examine the structural reactions of two mated vehicles. Individual tools were developed to determine loads due to crew exercise, crew extravehicular activity (EVA) and intravehicular activity (IVA), and Shuttle-induced plume loading on *Mir* solar panels due to Shuttle venting. Loads spectra analysis tools that use Shuttle postflight jet firing histories allowed us to report *Mir* life usage after each mission. Crew exercise forcing functions were developed based on test data. (All these have applications for the ISSP.)

3.3.7 Shuttle Jet Plume Impingement

Minimizing the loading and a contamination effect from Shuttle jet plumes during docking and mated operations was a prime consideration with *Mir* large surface solar arrays in the vicinity. The knowledge of Shuttle jet plume effects while approaching and docking with vehicles was limited before Phase 1 and became crucial to the integration of both vehicles.

Extensive effort to develop plume models for Orbiter reaction control subsystem (RCS) environment was accomplished through the use of chamber tests, on-orbit tests, and analysis. In particular, the Shuttle Plume Impingement Flight Experiment provided the plume environment data needed to develop a math model which accounted for the effects of scarfed nozzles and plumes from the simultaneous firing of two close-proximity thrusters. Significant tool development was performed, which greatly increased our analytical capability for modeling plumes and their impingement upon orbiting vehicles.

3.3.8 STS-76 Through STS-91 Real-Time Changes

Vehicle physical and environmental changes became a continual challenge in the *Mir* program. Continual changes to *Mir* configuration — such as Spektr/no Spektr, Priroda/no Priroda, Progress/no Progress, solar array orientations, thermal constraints, and newly identified (or delivered) hardware — gave NASA a constant challenge in mission planning and verification. RSC-E had to deal with Shuttle configuration/mass differences due to mission payload changes from Spacelab to DM to Spacehab. NASA added new airlock venting plumes and possible RCS jet leakage events to RSC-E's environments to consider. All these engineering challenges were successfully met.

The successful flexibility of the two programs in dealing with changes to each succeeding mission cannot be overemphasized. Sometimes events aboard *Mir* during the months before or during a flight required significant data exchange, negotiation, and replanning on both sides. Engineering studies and operating agreements to accommodate large anomalies, such as the Progress/Spektr collision, and small anomalies, such as the period of joint attitude control, were performed with no impact to the ongoing program. All Shuttle and *Mir* systems generally performed extremely well throughout each mission with few anomalies that affected joint operations. The flexibility exhibited by both programs before and during each mission is a good example of the maturity of the joint Shuttle/*Mir* program.

3.3.9 Active and Passive Thermal Control

Thermal control issues were prominent points of negotiation in arriving at joint mission plans acceptable to both sides. Differing thermal constraints for each vehicle challenged us to come to common agreements on attitudes; providing joint humidity control became a task in system operations management while maximizing water production capability.

Preflight negotiation of a mated stack attitude timeline was a major joint activity throughout the joint program. For each mission, the objective was to find an attitude sequence that was thermally acceptable to both the Shuttle and the *Mir*. In addition, the *Mir* solar array power production had to be considered in the negotiations. The priority was to find an attitude that met the needs of the *Mir* power and thermal requirements and the Shuttle passive thermal requirements. The Shuttle active thermal requirements were only considered if the total net water production was negative. Therefore, water transfer to the *Mir* was not the highest priority, since it was always difficult to meet the other three requirements. The discussion became unique for each mission because of the changes in vehicle configurations and the beta angle profile associated with each mission. In general, *Mir* thermal specialists preferred a solar vector parallel to the *Mir* X-axis (the base block long axis) in order to minimize the *Mir* cross-sectional area presented to the Sun. This would result in less solar energy absorbed by the *Mir* stack and less of a heat load to be rejected by the *Mir* active TCS. The importance of this "rule" was greater for missions at higher beta angles and greater if any element of the *Mir* TCS were out of operation (e.g., coolant loop down as a result of leakage). Shuttle passive thermal constraints prominent in the discussions included main landing gear tire minimum temperature limits, vernier RCS thruster minimum leak detection limit, external airlock extravehicular mobility unit water service line minimum and maximum temperatures, and the orbital maneuvering subsystem (OMS) oxidizer high-point bleed line minimum temperature limit. On the last two joint missions using Orbiters OV-105 and OV-103, respectively, the OMS oxidizer high-point bleed line issue disappeared with the removal of that hardware from those vehicles in preparation for ISS missions. In summary, all *Mir* and Shuttle passive thermal constraints were successfully protected throughout docked missions. Attitude timeline negotiations typically continued up to and after Shuttle launch for each mission, and some attitude adjustments were even negotiated after docking based on real-time data. Negotiations proved to be routine and successful.

A major accomplishment of the joint thermal activities was the successful integration of the Russian DM as Shuttle cargo. As a result of Joint Working Group discussions, DM system information was gathered that allowed the building of DM geometric and thermal math models. These models were used to perform DM design verification analyses as well as later mission verification analyses. The results were discussed with the Russian thermal specialists, to optimize the final design. The Shuttle provided electrical power to the DM during transport to *Mir* to maintain thermal control (circulates the ethylene glycol in the thermal control loops and add heater energy to these loops). The pre-mission thermal analyses predicted, and the STS-74 mission proved, that the DM could be successfully transported to and installed on *Mir* while protecting all DM thermal limits. The experience of integrating, analyzing, and transporting Russian cargo in the payload bay is felt by both sides to have laid important groundwork for upcoming ISS launch and assembly missions.

On each mission the Shuttle provided conditioned air to *Mir* through an air interchange duct (70 to 100 cfm). A booster fan and special bypass ducting was installed in the ODS maintaining the required airflow to other habitable volumes (Spacelab and Spacehab), while providing the agreed-to air flow to *Mir*. During STS-74, when the DM was installed on the ODS and the hatches opened for crew ingress prior to docking with *Mir*, the ODS ducting was used to establish and maintain a habitable environment in the DM in support of manned activities. Throughout all joint operations, thermal and humidity control of the exchanged air was accomplished by nominal stowed radiator control, deployed radiator control, and/or flash evaporator system (FES) activation. On STS-74, the FES was turned off (to save water) when the radiators were not controlling. After this mission, the Russians compared temperature and humidity data between STS-71 and STS-74, asked that the FES remain on for subsequent flights, for temperature and humidity control, and accepted the impact to water transfer.

On all Phase 1 missions, planning for water transfer required balancing attitude constraints for orbital debris protection, orbital heat rejection via the radiators, and orbiter passive thermal control. On earlier missions, special measures were taken thermally to boost the accumulation of water for transfer. In some cases, radiators were deployed during both predocked flight and docked flight to minimize the loss of water via the FES. For most of the missions, radiators were not deployed because of the increased risk of orbital debris penetration. When possible, predocked attitudes were selected to ensure thermal control by the radiators without the consumption of water by the FES. In general, on missions with higher Beta angles, the radiators were less effective in the ‘debris-friendly’ orbiter attitudes, and more water was required for FES cooling, and therefore less water was available for transfer. Leaving the FES on for air humidity and thermal control was given higher priority than water accumulation for transfer (with the exception of STS-74).

A final area of thermal activity was the verification of the various cargoes flown in the payload bay during these missions. In general, the primary payload bay occupants (like Spacelab, the DM, the ODS, and the Spacehab Single and Double Modules) were robust payloads using Shuttle services that were easily compatible with the joint missions. One modification did need to be made to the Spacelab water coolant lines to support the docked phase of STS-71: heaters were added to the lines to prevent freezing in case water flow was lost while docked with *Mir*. Normally, attitude control is used to prevent freezing in such a situation; however, while docked with *Mir*, attitude adjustment would not have been available to prevent coolant line freezing. Secondary payload bay occupants, including the Russian APAS, the TCS, and the European Space Agency proximity operations sensor, also had thermal limits of concern. Either attitude selection and/or real-time operational intervention avoided all thermal limit violations.

3.3.10 *Mir* Lithium Hydroxide (LiOH) Hardware

The regenerable carbon dioxide (CO2) system in the Kvant 1 module was unable to operate to its full capacity due to an ethylene glycol leakage in the cooling system. Hardware to assist in the removal — to maintain safe levels of CO2 in the Kvant 1 module — was developed and delivered on STS-74. The hardware had to be constructed such that air flow through the charcoal bed of the LiOH canister would occur first, since the LiOH might degrade some of the compounds to toxic products if they were not initially removed by the charcoal. Special adapters were constructed to attach the LiOH cartridges to a fan on board the *Mir*, accomplishing the pushing of the airflow through the center of the cartridge radially outward through the charcoal bed and migrating to the LiOH bed. Written procedures accompanied the hardware instructing the crewmen on proper LiOH canister installation and replacement of the spent cartridge. Supplemental fresh LiOH cartridges were manifested on successive flights to assist in maintaining onboard CO2 levels.

3.3.11 Water Transfer From Shuttle to *Mir*

A significant engineering challenge was meeting the agreement to deliver 4600 kg of water to *Mir*, both potable and technical (hygiene, electrolysis, waste system flush). When carrying water as part of Shuttle’s cargo didn’t make sense from maximizing vehicle performance capability, a ‘system’ was devised to collect fuel cell by-product, and treat and transfer it to *Mir*. The water requirements could not be met by standard production of fuel-cell-generated water, either in quantity or quality.

For STS-71, a joint agreement with the Russians was established to transfer iodinated water from the Shuttle to *Mir* for use as technical water. NASA created hoses and adapters to allow for water transfer from the Shuttle galley auxiliary port to the CWC or to the EDVs. Two other types of hoses with quick disconnects on only one end were shipped to Russia. In Russia, hydroconnectors were added to the other end of the hoses. These hoses, one with a male hydroconnector and one with a female hydroconnector, were flown on a Progress flight to *Mir*. The hoses allowed the CWC to be emptied on *Mir* into the Russian water system and also allowed the Russian water tank on the Shuttle to be filled.

The water transferred to *Mir* during STS-71 was used for technical purposes only, because it contained iodine, which is used in the Shuttle water system as a disinfectant. The *Mir* potable water system uses silver for bacteria control and adds minerals for taste enhancement. When iodine and silver are combined in water, they form a precipitate; therefore, Shuttle water and *Mir* drinking water are not compatible.

For STS-74, a method for removing iodine and adding silver and minerals was developed to allow the delivery of potable water to *Mir*. IRMIS (iodine removal and mineral injection system) was created for that end, allowing the final concentration of silver and minerals in the CWC water to meet Russian water requirements. After postflight water analysis was completed, iodide presence in the water necessitated upgrading to the IRMIS system. IRMIS worked successfully from that point on.

The total amount of water transferred to *Mir* exceeded the goal of the contract. The transfer of water from Shuttle to *Mir* was a learning opportunity in terms of water management. One of the significant lessons learned was how much water can be made available if water transfer goals are incorporated into on-orbit attitude planning. Attitudes before and after docking can have a significant impact on the amount of water available for transfer. It is not just the docked attitudes that determine the amount of water available. The timeline for filling water bags can affect how much can be transferred; that is, allow ample time to fill as many as possible. If additional stowage locations can be found to store more than four bags before docking, additional water can be transferred if the pre-docked attitudes are good radiator performance attitudes.

A practice learned from Energia was the removal of iodine from the water and the addition of alternative bio-control substances and minerals to the water. The removal of iodine has proven to be very timely as the Medical Office had raised an issue about iodine exposure to the crew during normal missions. The addition of minerals to the water is a technique the Russians use to insure their crew members do not become depleted in inorganic minerals during spaceflight.

Summary of Supply Water Transferred to *Mir*

Table 3.1

Flight	Summary	lb	Sample Results	Comments
71	3 CWC, 16 EDV	1067.4	Contained iodine	Re-processed on *Mir*
74	10 CWC	993.0	Failed iodide	Re-processed on *Mir*
76	15 CWC	1506.6	Passed	
79	20 CWC	2025.3	Passed	Reused 5 CWCs
81	16 CWC	1608.1	Passed	Reused 1 CWC
84	11 CWC	1038.0	Passed	1 half-filled CWC
86	17 CWC	1717.2	Passed	Reused 2 CWCs (81,84)
89	16 CWC	1614.9	Passed	Reused 1 CWC
91	13 CWC	1219.5	Passed	1 half-filled CWC
	Total:	12790.0 (5800.4 kg)		

3.3.12 Life Support Resources/Consumables Transfer

Mir Space Station O2 and N2 generation systems and CO2 removal systems were designed to normally support a crew of three. When docking missions were planned with crew work activities planned throughout Shuttle and *Mir*, mated air interchange and consumables planning became critical to the success of up to 10 crew members working and breathing in both vehicles. Shuttle capabilities were maximized to provide/boost the common atmosphere in both vehicles. Other factors contributed to the life support equation:

In the process of maneuvering to jointly acceptable docking attitudes and to minimize Shuttle jet plume impacts, the *Mir* solar arrays were often rotated and feathered in angles unfavorable to power production. *Mir* systems were turned off to conserve power use. The Vozdukh CO2 absorption system and the Electron O2 supply system were often not in operating mode during docking and sometimes during the joint mission. Joint planning and cooperation in life support were critical to providing a working environment. The Shuttle facilities were utilized to augment/maintain atmospheric pressure, humidity, and O2 and CO2 levels within tolerances for both vehicles.

NASA developed an integrated air exchange model as a tool to evaluate the integrated air interchange system capabilities, limitations, interface requirements, and operating constraints for each joint mission. Pre-mission analysis evaluated the N2, O2, CO2, and humidity conditions and allowed us to plan system usage and construct hardware required for transfer of consumables. After each mission, pressure and humidity conditions were measured. Preflight analyses results and postflight data comparison concluded that our tools were accurate and each mission was successfully planned and executed.

After docking Shuttle and *Mir*, the ODS vestibule was pressurized using *Mir* consumables, and leak checked. Pressurization from the lower pressure vehicle, the *Mir*, was necessary to prevent ‘burping’ of the *Mir* hatch. Opening the upper hatch valves of the Orbiter airlock then equalized the *Mir* and Shuttle volumes. The combined vehicle was pressurized by the Shuttle pressure control system and maintained at 14.7 psia until undocking. Careful management of N2 resources allowed Shuttle to provide the desired pressures.

Before undocking and before hatch closure, Shuttle resources were used to pressurize the combined volume. Nitrogen was used for *Mir* pressurization and O2 was used for the additional crew metabolic consumption during the docked phase and for raising the total partial pressure of *Mir*. We achieved the desired agreement of raising the *Mir* total pressure to 15.5 psia and partial pressure of O2 concentration to 25%.

***Mir* Pressurization Data**

Table 3.2

Flight (STS)	*Mir* Docking Pressure (mmHg/psia)	*Mir* – Undock Pressure (mmHg/psia)	*Mir* – Undock PPO2 (mmHg/psia)	GN2 Transferred (lb)	GO2 Transferred (lb)
71		780.9/15.1		87.4	48.3
74	710/13.73	796.4/15.40	199.1/3.85	44.2	59.0
76	737/14.25	801/15.49	193.4/3.74	42.2	61.6
79	729/14.10	802/15.51	187.96/3.63	43.2	69.2
81	739/14.29	790/15.28	190.7/3.69	42.1	57.7
84	734/14.19	785/15.18	200.6/3.89	20.9	81.5
86	620/11.99	780/15.1	189.3/3.66	130.7	75.7
89	643/12.43	798.5/15.44	189.1/3.66	133.4	56.4
91	623/12.05	788.5/15.25	185.7/3.59	149.4	46.6
Total N2/O2 Transferred to *Mir*				693.5	556.0

3.3.13 Communication Systems

Air-to-air communications between vehicles for proximity operations were highly successful, providing voice communications at ranges significantly greater than required. Air-to-air communications between vehicles was provided by the use of existing VHF radios and antennas on the *Mir*. The Shuttle used a commercial transceiver which was tunable to *Mir* frequencies, a new audio-radio interference unit for integration into the Shuttle audio system, and a window-mounted antenna which was stowed during launch and landing. Air-to-ground tests were successfully conducted with *Mir* before the first flight use on STS-63.

The Ku-band system was used in radar mode for rendezvous and separation activities within previously agreed-to distances. It was reconfigured to communication mode for transmission and reception of voice, data, and TV. An obscuration mask was used during all docked operations to preclude irradiating the *Mir*. The Ku-band system operated nominally.

ODS centerline and truss-mounted closed circuit television cameras were used as the principle visual cues for docking and undocking with *Mir*. After docking, the Shuttle external airlock centerline TV connections were used to hook up a drag-through camcorder/speaker microphone system which contained multiple quick-disconnects on the cable to allow use of this system in any of the *Mir* modules. Performance of all of the TV systems was very satisfactory.

3.3.14 Spacecraft Physical Characteristics

The joint vehicle drawings, known as document 3402, were developed during STS-63 to identify the configuration and properties of each vehicle. The content was expanded at STS-71 to include mated Shuttle/*Mir* configuration and properties. Vehicle descriptions expanded to include mass properties, antenna & jet locations, docking target and camera locations, vents, lights and windows, and alternate configuration. All these critical physical attributes pertaining to both vehicles were required to perform mission planning and analysis. The 3402 document was used across the program by the Safety and EVA groups, and for crew familiarization. This document has been carried over to the ISSP.

3.4 Docking System

The docking system utilized during NASA-*Mir* joint flights provided reliable attachment and subsequent mechanical and electrical connections between the Shuttle and the *Mir* during Shuttle docking in manual mode. Following docking and hatch opening, it provided a pressurized pathway between vehicles.

The docking system for the Space Shuttle was developed on the basis of the АПАС-89 androgynous peripheral docking assembly (APDA), which had been developed for the Buran Orbiter. Two APDAs, installed on the Kristall module, have been on the *Mir* since 1990. Near the start of the Shuttle/*Mir* program preparatory period, the Soyuz TM-16, also equipped with an androgynous docking system, was mated with the Kristall module АПАС-89.

Nine Shuttle dockings with the *Mir* were carried out from 1995 through 1998 (STS-71, -74, -76, -79, -81, -84, -86, -89, -91). From 1993-1995, in preparation for STS-71, the RSC Energia designed, developed and flight-certified a docking system for the *Atlantis* Orbiter (OV-104). The Rockwell Company (now BNA) installed an APDA on the newly developed exterior airlock and integrated the system as a whole with other Orbiter systems (electric power, control, monitoring, and telemetry). The combined APDA and Orbiter systems were commonly referred to as the ODS. The APDAs, instruments, control console, and other hardware, as well as docking dynamics and strength, were developed and certified at RSC-E. The docking system components were integrated with the Orbiter components and were tested on an electrical mockup ("brassboard") of the Rockwell Company. Working jointly, NASA, Rockwell and RSC-E experts tested the docking system at Rockwell, performed preflight preparation at KSC, and provided for spaceflight mission support.

The Shuttle/*Mir* docking process for the *Mir* missions had seven phases of operation: deployment, capture, attenuation, extension, retraction, structural lockup and separation. The deployment phase begins when the docking mechanism guide ring is driven from its stowed position to its ready-to-dock position. In the ready-to-dock position, the mechanism capture latches are disengaged. The capture phase begins when the astronauts/cosmonauts maneuver the docking port of the Orbiter into contact with the *Mir* port. The orbiter interface is forced onto the *Mir* interface by the relative velocity between the vehicles and by an orbiter primary reaction control system (PRCS) jet-assisted maneuver. The thrusting maneuver is initiated manually by the orbiter crew once initial contact at the interface is detected by contact sensors (or when visual queues indicate that thrusting is safe). The immediate response of the orbiter, caused by the PRCS thrusting, forces the three guide ring petals on each APDA into alignment. The capture latches then engage, once the interfaces have been fully seated. Each of the three petals on the active interface is equipped with a latch assembly consisting of two capture latches. The three capture-latch assemblies are passively engaged. Each engages to a body mount on the passive mechanism and functions independently of the other two. The latches are designed so that the vehicles can safely separate in the event that only one or two latch assemblies engage. Once all three latch assemblies engage, all possible axes of rotation between the interfaces are removed and “soft-docking” has occurred. This completes the capture phase. The docking process switches to an automatic mode once capture has been sensed. Five seconds after capture latching, the hardware switches to a high-damp mode, which is intended to attenuate the relative vehicle motion in a deliberate manner. Prior to the high-damp mode, a load-limiting device prevents either vehicle from being overloaded during compression of the mechanism. After the high-damp mode has been initiated, the load-limiting device is no longer effective in limiting the loads.

After the relative vehicle motion has been arrested, the mechanism is slowly driven to a fully extended position. As the mechanism moves into its forward position, the relative vehicle misalignments, originally absorbed by the APAS, are driven out of the system. In the forward position, there is an operational delay as alignment indications are detected. Once the alignment indication is received, the retraction phase begins. Retraction starts as the mechanism locking devices are engaged. The locking devices keep the mechanism rigid and prevent relative vehicle misalignments from accumulating during retraction. As the retraction phase progresses, the vehicle structural interfaces are brought together and, once the final position has been detected, the structural lockup phase is initiated. As the passive and active structural hooks engage, the interface seals and separation devices are preloaded. For structural latching, there are two gangs of six structural hooks on each vehicle at the structural interface. Each gang of latches consists of a passive hook and active latch. Each active latch engages with the opposing passive hook. Once the latches fully engage, the structural interfaces are preloaded at the required level, and “hard-docking” has occurred. At the end of the mission, the tunnel is depressurized for undocking. The structural latches are disengaged, and the preloaded separation devices provide the impulse necessary to push the vehicles apart. Once the vehicles are a safe distance apart, the orbiter initiates a separation burn, completing the undocking operation.

STS-74 differed fundamentally from STS-71 in that it was necessary to dock with the Kristall module, which was at a *Mir* lateral berth. To do this, an additional docking module was created with two APDAs. The Orbiter APDA was a redesigned version with electrical interface connections to control two APDAs successively: first the APDA on the ODS and then the APDA on the docking module (through the interface connectors). The APDA with interface electrical connectors and a special switching device for switching control circuits was in the Orbiter for this mission. The entire configuration was successively developed and tested on the ground.

The docking procedures for STS-74 were more extensive than the other missions. The docking module aft APDA was berthed to the ODS APDA using the Orbiter remote manipulator arm. Subsequently, the docking module active APDA was controlled from the Orbiter through the APDA electrical connectors and was docked to Kristall. After undocking in flight STS-74, the docking module assembly remained as part of the *Mir*. All subsequent dockings were with the docking module APDA.

Missions STS 71 through STS-86 were carried out on the Orbiter *Atlantis*. The Orbiter *Endeavour* (OV-105) was prepared for mission STS-89 after the ODS was configured similarly to that of flight STS-74, with the control circuit switch. The APDA remaining from STS-71, modified with respect to interface electrical connectors, was used for this purpose. This configuration was developed in preparation for the first Orbiter flight in the ISS program (STS-88, flight 2A).

The Orbiter *Discovery* (OV-103) was prepared for the mission STS-91, with a modernized docking system designed for long-term use in the ISSP. This system uses the so-called “soft” APDA, with the new adaptive shock-absorbing system, ensuring substantially lower loads during docking. The control system of this assembly was altered accordingly, and the piloting procedure revised.

All 9 dockings and subsequent undockings were implemented completely and virtually without problems, in nominal modes. As a result, during Phase 1 the rightness of the designs, joint operations organization methods, approach to certification, hardware preparation, and piloting procedures, as well as crew and ground personnel training, were completely confirmed.

3.5 Lessons Learned/Applicability to ISS

3.5.1 Structure and Process

The organizational structure in which the operations and engineering integration specialists from NASA and RSC-E were combined into the same working group was crucial to the success achieved during the program. It was extremely valuable that NASA and RSC-E specialists responsible for the various technical disciplines worked directly with each other. A similar structure should be considered for ISS application.

The first rendezvous mission (STS-63), the first docking mission (STS-71), and the first assembly mission (integration, transportation, and on-orbit assembly of the DM on STS-74) exercised many of the engineering integration and operations that will be required for ISS launch and assembly missions. The remaining Shuttle missions to *Mir* further developed and refined these methods. The experience obtained by both NASA and RSC-E managers and engineering specialists in preparation for and during these missions will be invaluable as they apply their experience to the upcoming ISS missions.

3.5.2 Vehicle Dynamics, Structures and Attitude Control

The Shuttle readiness to support ISS for on-orbit operations in the vehicle dynamics, structures and control integration technical area is complete. Performance of essentially all functions (rendezvous and proximity operations, docking, mated vehicle attitude control and loads) has been successfully demonstrated. The Shuttle/*Mir* missions utilized the docking system hardware and on-orbit operations that will be required on ISS missions. Also, the Orbiter control system upgrades, developed to provide control of large, flexible space structures, worked successfully and can be relied upon to provide control during the critical early assembly flights of the ISS.

Just as with the Shuttle control system, the *Mir* motion control and navigation system performed the task of controlling the attitude of a stack with a mass close to 250 tons. The problems of control caused by the lack of rigidity of such a design were successfully solved. Control was provided both by vernier thrusters and gyrodynes. The simultaneous setting of the inertial coordinate system which was performed during several experiments on the Shuttle and *Mir* enabled a procedure to be developed for tying in the coordinate systems of the modules comprising the station. A procedure was developed for the correction of the inertial coordinate system of the *Mir* using data concerning the status vector received from the Shuttle. The experience accumulated during the performance of the tasks listed above will be used to solve analogous tasks facing the ISS.

3.5.3 Life Support and Thermal Control

During Shuttle-*Mir* program flights, the rightness of decisions made regarding integration of the life support and thermal mode control systems was confirmed. The Shuttle environment control systems, with nominal ventilation between the *Mir* and the Shuttle, had no trouble maintaining atmospheric parameters in the combined volume within acceptable limits.

Experience gained may be used in ISS operations. This applies first of all to joint flights of the ISS with the Shuttle, but this experience will also be helpful also in integrating the American and Russian ISS segment systems.

The hardware and operational techniques developed for water transfers to *Mir* are directly applicable to Shuttle/ISS water transfer. For the first five years of ISS assembly/operations, the techniques developed during Phase 1 for water transfer will be used for ISS.

3.5.4 Communications

The developed diagrams and documentation on the organization of communications during work in joint flights from STS-63 to STS-91 may be used in the future, and were the foundation for development of documents and operations on the ISS.

3.5.5 Tools and Operating Techniques

Engineering tool development and operating techniques were constantly improved during the program by both NASA and RSC-E in all technical areas. Obvious shortfalls were detected at the start of the program and better efficiencies were necessary as the time to prepare for each mission grew shorter. The Shuttle/*Mir* program challenged the efficiency of some existing engineering tools and created a demand for new tools to address mated vehicle operations. Many of these tools have applications for the ISSP.

STS-86 and STS-91 astronaut Wendy Lawrence performs transfer operations