Appendix B

MICROGRAVITY RESEARCH FACILITIES

Chapter 1 identifies the facilities presented in Table B.1 to showcase an important range of existing facilities to conduct microgravity research. This appendix presents an in-depth review of 3rd party ground based (second column) and space based (third column) facilities. This appendix also presents a review of the four major space stations which operated in the past, including their operations and the research conducted during the programs.

TABLE B.1 Sample of available facilities for μ-g research

In-house	3rd Party / Full μ-g	Space
Robot Helicopters	RGO (KC-135)	Free Flyer
6 DOF Robot Arms	Neutral Buoyancy Tank	ISS
Helium Balloons	Drop Towers	Shuttle Payload
Robot Cars		Shuttle Middeck
Flat Floor		
Air table		
Simulation		

B.1 3rd Party Ground-based Facilities

The available terrestrial facilities include: simulations, air tables, flat floors, robot cars, helium balloons, robot arms, robot helicopters, drop towers, neutral buoyancy, and reduced gravity airplanes (NASA's Reduced Gravity Office, as well as Russian and European facilities). Simulations, air tables, robot cars, helium balloons, robot arms, and helicopters, are all tools available to researchers at home. Their operations and capabilities depend on the design created by each researcher, and therefore it is not possible to identify their characteristics in general; further, these facilities only provide limited microgravity conditions, not necessarily creating a representative environment. Flat floors can be created by individual researchers, but some general use facilities do exist; and examples are presented below. Drop towers, neutral buoyancy tanks, reduced gravity airplanes, and the space shuttle require special attention, as they are facilities which usually involve a third party but which closely meet the need for a representative environment.

B.1.1 Flat Floors

Flat floors utilize an air cushion to float an experiment in such a way that frictionless motion is provided in a two dimensional environment. A basic flat floor setup provides simulated microgravity in two translational and one rotational dimension. While flat floors restrict the operations to 3DOF in most cases, they do present a viable intermediate step for technology maturation if their size is large enough to provide a representative environment. Further, the use of special carriages can allow limited 6DOF operations, as expected from the TPF experiments at JPL.

In the United States NASA operates a large flat floor facility at Marshall Space Flight Center and Boeing operates a privately owned facility. Both facilities are available for research by scientists at large. The facilities provide scientists with up to eight hours per day of operations, limited only by the operational nature of their experiments. While some limitations exist to ensure the safety of the flat floor, researchers can operate relatively freely in the facilities, maximizing the interaction with their experiments.

B.1.2 Drop Towers

Drop towers simulate microgravity by allowing the experimental item to free fall for a short period of time in a controlled environment. There is a large number of drop towers around the world which range in size from providing only fractions of a second to almost ten seconds of microgravity time. Important drop towers exist in the United States, Europe, and Japan. Two of them stand out in our discussion due to their openness for current research by a wide number of scientists and their relatively large size: the NASA Glenn 2.2 Second Drop Tower and the ESA's ZARM Drop Tower Bremen.

The NASA tower provides 2.2 seconds of microgravity, as its name implies. The drop takes place off a 100ft tower (the actual drop is 79'1"). A drag shield is used to minimize air drag. The tower allows up to 12 drops each day, with a clearly defined operational plan. The center provides a range of support facilities for assembly of the experiment and integration to the drag shell. The center also provides support hardware such as cameras, data acquisition equipment, and batteries. After integration the package is lifted to the top of the tower, at which point the investigator can perform any preparations necessary. The experiment is provided with electrical control signals which will indicate the exact time of the drop, such that experiments utilize as much as possible of the drop time and do not need to waste resources before the micro gravity time. The drop is initiated by cutting the cables that hold the experiment, achieving microgravity conditions within one-third of a second. The drop ends when the drag shield falls onto an airbag at the bottom of the tower; the impact peak values are 15 to 30g.

ZARM has a vertical drop of over 100m, providing 4.74s of free fall; the use of a catapult to allow a parabolic path of the payload gives up to 10s of free fall. A picture and diagram of ZARM are shown in Figure B.1 [ZARM, 2000]. But ZARM allows only a maximum of three drops in one day. Further, the ZARM operations are more complex, requiring the investigators to be on site at least ten days prior to the tests in order to prepare their payloads. Once the payload is integrated, researchers have remote access to the payload once it reaches the platform, but before the drop. The small number of drops is due to the fact that ZARM evacuates its drop tube to under 10Pa (the experiment is pressured), a process that takes two hours, but remote access to the experiment is available during this time. The experiment experiences up to 25g at impact. It takes approximately one hour to retrieve the experiment. A full set of experiments at ZARM usually consists of 8 to 24 drops, which takes approximately three to four weeks to complete.

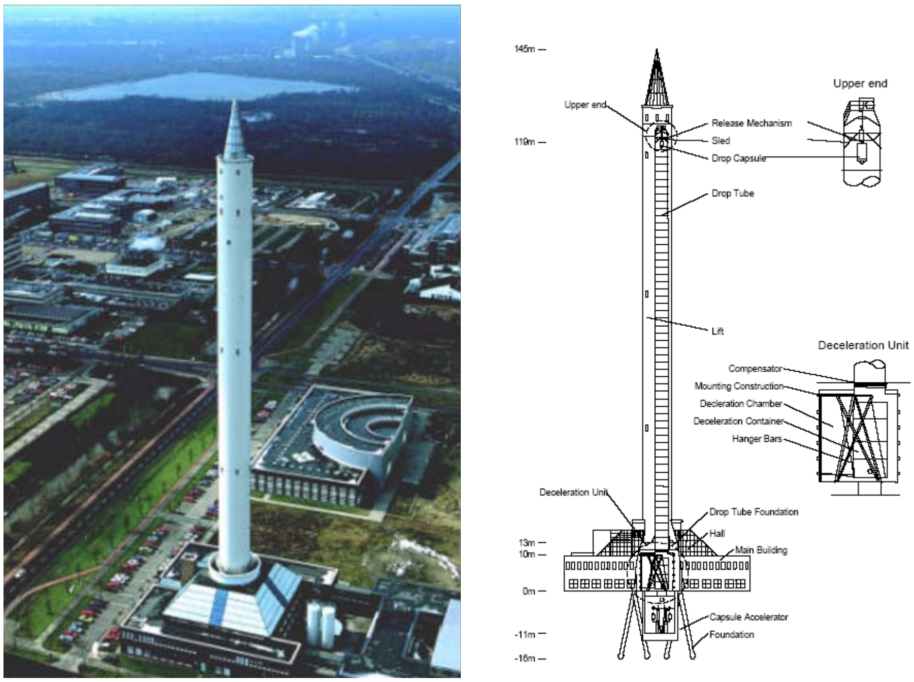

Figure B.1 ZARM drop tower

Drop towers present good opportunities for research in terms of the ability of investigators to work directly with their experiment both before and after the microgravity test. In general the size of the experiment is not restricted; the limitations are one to two meters in diameter and a mass of over 100kg. But:

> "...not all types of scientific inquiry are appropriate for the drop tower. For example, meaningful microgravity research of the life sciences, biotechnology, and materials sciences can seldom be conducted in drop facilities (living things and crystals grow too slowly). On the other hand, flames can spread very quickly, which explains why combustion experiments account for approximately 90% of the experiments conducted in the drop tower." [NASA, URL3]

The applicability of drop towers for space technology maturation is limited. Only those tests that can conclude well within five seconds will benefit from drop towers.

B.1.3 Neutral Buoyancy Tanks

Neutral buoyancy tanks are operated in multiple places around the world. The major tanks are operated by NASA, the Russian Space Agency, and the University of Maryland (UoM). NASA and the Russian Space agency manage major neutral buoyancy facilities. The UoM Space Systems Laboratory operates a neutral buoyancy facility for research purposes. All of the tanks are large enough to allow full-sized tests of major spacecraft. For example, the NASA Neutral buoyancy Laboratory at the Johnson Space Center can hold several full-sized mock-ups of modules of the International Space Station (Figure B.2 [NASA, URL6]).

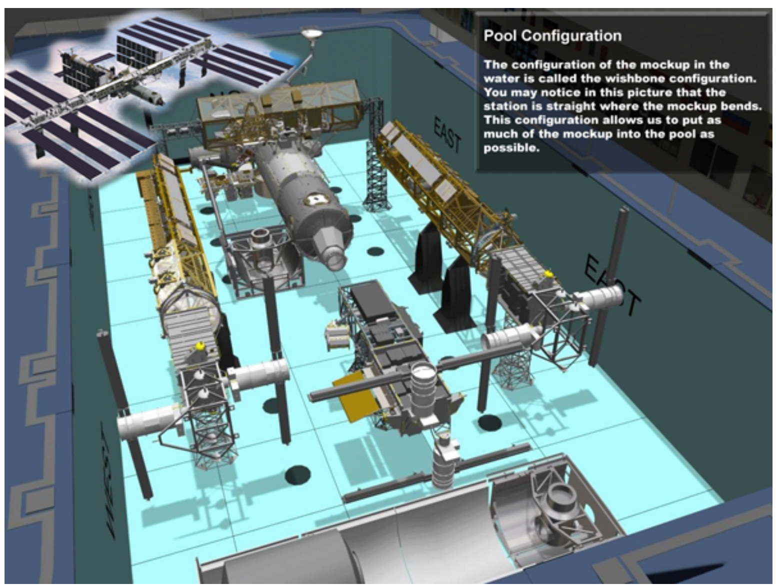

Figure B.2 NASA Neutral Buoyancy Laboratory

NASA manages facilities at JSC and at the Marshal Space Flight Center. The Russian Space Agency manages a tank at the Gagarin Cosmonauts' Training Center outside Moscow. The primary purpose of these facilities is to train astronauts for extra-vehicular activities (EVA). Full scale mock-ups of spacecraft that will require assembly in space are created; astronauts and cosmonauts use the same tools they will use in space for training. The only difference usually present is that the astronauts supply of breathable air and power for the EVA suits is provided by tethers, rather than through the backpacks of EVA suits.

The UoM SSL tank is the only neutral buoyancy facility dedicated to research. It supports experiments by undergraduates, graduates, and faculty of the university. The UoM SSL has also established a program by which external parties can conduct research at the tank. Research has concentrated on EVA operations and tools, the Ranger vehicle for telerobotics, and the SCAMP project for additional video during EVAs.

Conducting operations in the tanks requires certified SCUBA divers to either perform the activities and/or support the test subjects. In the case of astronaut training, the astronauts are supported by large teams of SCUBA divers who monitor their health and progress. In the case of research, certified divers must perform the experiments. This operational scenario introduces the need for a third party to sometimes perform the experiment, rather than the scientist always being directly at the controls, since not all research scientists will have the required certification. This trend will continue from this point forward as the operational environments get more complex. Given the nature of SCUBA diving, the facilities usually perform one major session a day. The test session can be several hours long, allowing a substantial amount of research to be conducted and minimizing the impact of setup times. The high level of support at the locations, such as SCUBA support, machine shops, and work areas, allow research to be conducted with low risk. Because they are based in ground facilities the research is not strictly limited to autonomous operation, and supplies can be replenished easily. Through the course of a few weeks, a scientist could get a substantial number of tests performed; the tanks are readily available for continued research.

The type of activities conducted in neutral buoyancy tanks gives a clear idea of their best use: human interactions and large spacecraft mock-ups. While neutral buoyancy allows full 6DOF maneuvers, the effects of drag in water prevent the dynamics from being equivalent to space. Therefore neutral buoyancy tanks are not practical for tests that will be affected by drag, such as propulsion tests or precision spacecraft control. Therefore, the applicability of neutral buoyancy tanks is best suited for that range of research which does not require precise representation of a microgravity environment, especially with respect to the dynamics of the system.

B.1.4 Reduced Gravity Airplanes

NASA and the Russian Space Agency operate the most commonly used reduced gravity airplanes, although other national space programs and private ventures also exist. NASA operates a program out of its Reduced Gravity Office at the Johnson Space Center. The Russian aircraft operates out of the Gagarin center outside Moscow. Both programs continuously support research by government, academic, and private agencies, as demonstrated by the NASA Reduced Gravity Program Mission Statement:

> "To provide a world-class, reduced gravity research platform that emphasizes user compatibility, quality reduced gravity levels, and a customer-oriented support organization."

Reduced gravity is achieved by following a parabolic curve with an amplitude of approximately 10,000 feet, providing approximately 20 seconds of microgravity. Each microgravity flight consists of 15 to 40 parabolas, for up to 400 seconds of micro gravity time in a day (Figure B.3, [NASA, 33899] [NASA, 33898]). This period more than doubles the available time from drop towers per drop, and is four times that per day; however, it is substantially less than that of neutral buoyancy tanks. The airplanes provide another important benefit over the drop towers: the scientists can directly interact with their experiments; it is also an improvement over neutral buoyancy tanks because they do not need SCUBA certification or equipment, allowing easier interaction with the equipment.

Like with drop towers, operations on a RGA are very structured and time critical. The following example is based on the NASA RGP. Usually experiments operate on the aircraft one week at a time, with one day for setup and then four days of operations (up to 160 parabolas), requiring scientists to travel to JSC for a minimum of three days and up to a week. The first day involves integration of the experiment to the aircraft, usually within

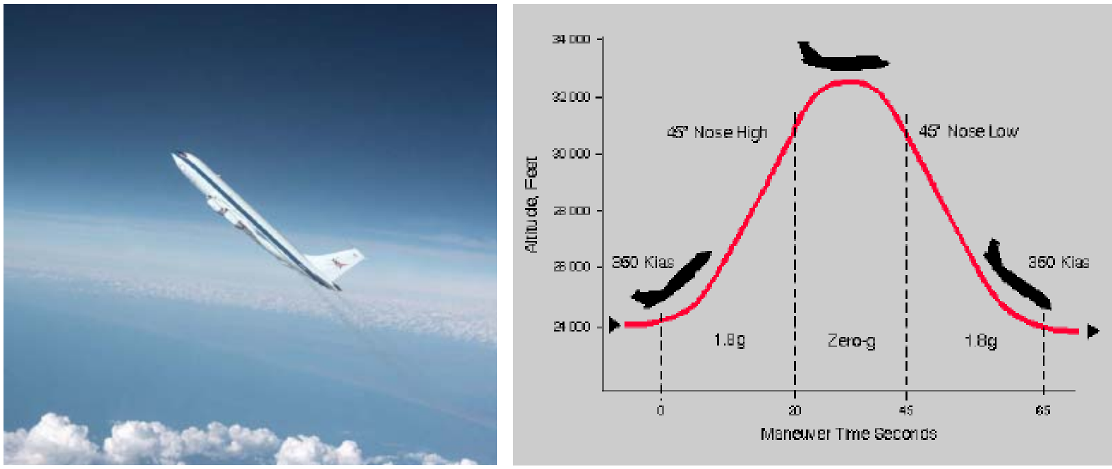

Figure B.3 NASA KC-135 airplane and flight path

three or four hours. The flight days are especially time critical; the experiments are accessible for about one hour before flight; after takeoff there is a period of about 15 minutes to start experiments; then parabolas start. The parabolas consist of approximately 40 seconds of "pull-up", times with 1.8g when the airplane flies towards the top of the parabola, and then 20 seconds of microgravity as the airplanes flies over the top; 10 parabolas are repeated consecutively. Five minute breaks are available after parabolas 10 and 30; a 10 minute break is available after parabola 20. While the scientists have full access to their experiments and can interact with them, this environment is not susceptible to substantial modifications or repairs without wasting valuable microgravity time. Therefore scientists must be prepared for successful operation and have backup plans in case of equipment failure or incorrect assumptions in their setups.

Research conducted at NASA's RGP covers a wide range of areas including human factors, medicine, space technology, astronaut training, and combustion. The range of science is substantially more than that of drop towers or neutral buoyancy tanks for two main reasons: human presence over a substantial period of time. Yet, the RGAs are not suitable for every type of science either. Like with drop towers, research on biological sciences, some human factors, and spacecraft control usually requires prolonged exposure to microgravity. Further, the effects of turbulence and the rotational motion as the airplane goes over the parabola prevent it from providing completely clean dynamics.

B.2 Space Shuttle

> "The United States developed the Space Shuttle system to improve its access to space. Since the first flight in April 1981, the Shuttle has carried more than 1.5 million pounds of cargo and over 600 major payloads into orbit. The Shuttle is the first and only reusable space vehicle, and is the world's safest, most reliable and versatile launch system. It is designed and operated to support a variety of space-based activities from the delivery of large payloads to orbit, the capability of spacecraft retrieval and servicing, to providing a versatile platform to conduct research and development experiments in a "shirt-sleeve" laboratory environment. The Shuttle also provides for experiment return and re-flights.
>
> "Among the Shuttle's greatest strengths, in addition to its amazing array of capabilities, is its ability to adapt and evolve to meet new mission requirements. Whether it means installing a spare part, or sending astronauts on a spacewalk to retrieve an errant satellite, the Shuttle is unrivaled in its ability to adapt real-time to get the job done....:
>
> - Payload Deployment and Retrieval
> - On-Orbit Assembly
> - On-Orbit Repair and Servicing
> - On-Orbit Research
> - Technology Testbed
> - Crew Transfer
> - Cargo Return " [NASA, URL4]

NASA's Space Shuttle Program (SSP) provides service to a wide range of payloads, from small experiments operated inside the crew compartment area (middeck) to the deployment of large satellites into orbit from the payload bay (Figure B.4 [NSTS, XIV]). Among the most unique features of the SSP is not only the availability of humans, but also the return of the vehicle, crew, equipment, and products to Earth in a short period of time. Further, the SSP supports two main operational areas: a payload bay for experiments fully exposed to the space environment, and the middeck area for experiments that require human interaction and/or a pressurized environment.

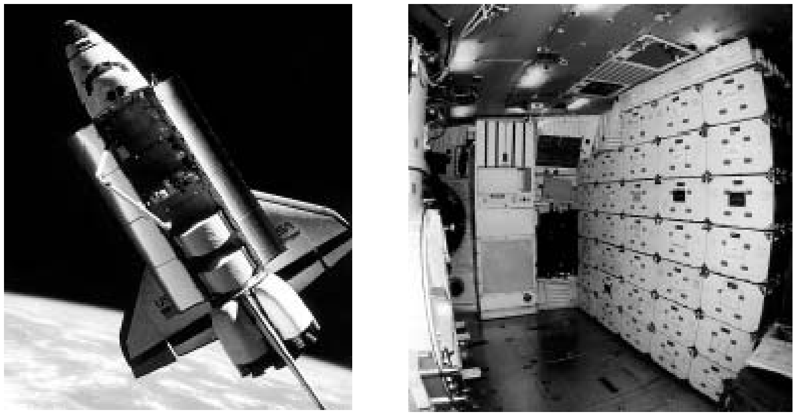

Figure B.4 Space Shuttle payload bay and middeck

A typical SSP program starts two years before flight by presenting the necessary documentation to NASA. During the first year scientists present safety and interface documentation to NASA while they develop their experiments/products. The year before flight involves the development of the flight hardware and at least six months of integration. During this time researchers must also train astronauts.[NASA, 2000a]

A typical Space Shuttle mission starts with launch at KSC. After launch the orbiter can reach altitudes of 100-600nm and inclinations of 28-51deg. Approximately 10 minutes after liftoff the shuttle performs its final main engine firings to reach the approximate orbit. Next the payload bays are opened to allow the space radiators to dissipate heat; the doors remain open for the duration of the mission. The base mission is seven days long, but a mission can be extended for up to 16 days. The orbiter returns to earth by firing its main engines to reduce its speed, after which it glides back to earth un-powered.

The standard operating procedure for experiments grows in complexity from previously presented facilities. While the RGA carry two pilots, three to five operations support personnel, and 15 to 20 scientists, the space shuttle carries at most seven astronauts that share research and operational duties throughout the mission. Therefore, conducting experiments begins with the training of astronauts; this training must be substantial enough that astronauts could conduct the research independently in case there is no real-time link between the shuttle and ground. Due to limited communications between the shuttle and ground the experiment must also be ready to operate without further assistance from the scientist once it gets integrated into the spacecraft, usually no less than four weeks prior to launch. While software updates are possible once in flight, the process must involve, as a minimum, the payload integration office and mission control, adding layers of complexity to the ability to change experiments while in flight. As a result, in general, experiments are fully designed months prior to being conducted in the shuttle.

Once actual operations start, astronauts follow established procedures for the experiments. These procedures guide the astronauts through the complete experiment, and usually the scientist is not involved in real-time. In the cases where a real-time link is available, the communications is handled through mission control; the scientists communicate with mission control, who forward the instructions from the scientists to the astronauts. The scientist does directly observe and/or hear what the astronaut is doing, but mission control must be involved in any communications to the astronauts.

After the experiment is performed the scientists will usually wait for the return of the shuttle to ground before accessing their data. Limited communications do exist to allow scientists access to the data prior to return of the shuttle, but the use of these systems will further add to the complexity of the integration process (a trade-off which scientists must consider).

Each space shuttle mission carries three types of payloads: primary, secondary, and middeck. The primary payloads are those that justify the flight; each flight can have one or multiple primary payloads. Secondary payloads, in general, do not define the critical path of the integration process, but use a significant amount of SSP resources. It is possible for a number of secondary payloads to together justify a flight as a primary payload. A middeck payload does not define the critical path of the integration process, but still requires significant SSP resources. [NSTS, XIV]

In general SSP missions conduct dozens of experiments. The astronaut time must be carefully divided throughout the one to two weeks of operations. To accomplish this the SSP has a clearly defined integration process which dictates how payloads are added to the program and their priority. Therefore, even though each mission has hundreds of man-hours available, the operations in the shuttle are even more structured than those in RGAs. Once a research session is scheduled on the shuttle, scientists must ensure that they will fully utilize their assigned time. Scientists have to consider the time to set up their experiment, the amount of interaction with astronauts while the experiments run, and the time to take it apart. Still, each experiment can take on the order of hours (attended), and even days or weeks (unattended) to complete, rather than a few seconds.

The space shuttle exposes payloads to full microgravity conditions, with almost perfect dynamics for spacecraft. External payloads are further exposed to space conditions. The shuttle does orbit the earth in LEO, which means that the orbital dynamics to which experiments are exposed are not necessarily identical to that of final missions (for example, some experiments may be precursors of earth-trailing satellites). Further, the shuttle does have orbit correction maneuvers during its mission, at which point experiments are exposed to non-realistic forces from thrusters. Still, the SSP provides one of the cleanest microgravity conditions available for research.

The large number of experiments conducted so far in the SSP demonstrates its success in conducting microgravity research. Projects have covered almost every area of space research, including astronomy, biological experiments, material science, space technology development, human factors, and space propulsion; the shuttle has also been used for deployment and capture of a wide range of spacecraft which have conducted their own science.

The major challenges in conducting research aboard the space shuttle lie in the integration process. Because the SSP is a precious facility with limited operations, the integration process is not only time-consuming, but also requires substantial investments by the scientists in both work hours and money. A decision to use the SSP as a research environment means the scientists are wiling to compromise between obtaining almost ideal microgravity conditions in exchange for a substantial jump in operational complexity. The SSP requires scientists to go through substantial safety approvals and astronaut training. Further, it requires that a third party always be involved in operations, since the researcher cannot communicate directly with the astronauts conducting the experiments.

B.3 The International Space Station

> "The purpose of the ISS is to provide an “Earth orbiting facility that houses experiment payloads, distributes resource utilities, and supports permanent human habitation for conducting research and science experiments in a microgravity environment.” (ISSA IDR no. 1, Reference Guide, March 29, 1995)
>
> "This overall purpose leads directly into the following specific objectives of the ISS program:
>
> - Develop a world-class orbiting laboratory for conducting high-value scientific research
> - Provide access to microgravity resources as early as possible in the assembly sequence
> - Develop ability to live and work in space for extended periods
> - Develop effective international cooperation
> - Provide a testbed for developing 21st Century technology."
>
> [NASA, 1998]

The ISS is the only existing facility which provides a true microgravity environment whose goal is specifically to support scientific research. While its configuration and specific research goals have changed over time, the basic concept remains the same: to provide a manned microgravity environment for scientific research and technology development.

The idea of a permanent space station began in 1984 when President Ronald Reagan invited Canada, Europe and Japan; Russia joined the program in 1993. ISS development has been split into three phases. ISS Phase I took place before assembly and consisted of a series of cooperative research flights between the United States and the ISS partners. Most notably, this involved a series of rendezvous flights between the Space Shuttle and the Russian space station MIR, cosmonaut flights on the Space Shuttle, and U.S. astronaut stays on MIR; research on MIR was expanded to US and other international partners. In ISS Phase II, the knowledge gained from Phase I operations is being applied to the on-orbit assembly of the ISS. ISS Phase II will conclude with the successful assembly of the U.S. and Russian components of the ISS that are necessary to begin Station research. ISS Phase III development consists of the final research outfitting of the ISS, as the European, Japanese, and Canadian elements are transported to orbit and the Station becomes fully operational. [IMBOSS, URL]

Assembly of the ISS began in 1998 and will reach "US Core Complete" after mission 10A (predicted for the end of 2006), marking the end of Phase II. Figure B.5 ([NASA, ULR8]) shows a picture of the ISS on October 2002. At that point the ISS habitable modules will consist of the Zarya control module, two nodes, three docking modules, the US Destiny Laboratory, the ESA Columbus laboratory, the Japanese Experiment Module (including an exposed facility), a centrifuge module, and two airlocks. The exposed elements will include solar arrays to provide up to 30kW of power for research, multiple express pallet mounting points, a science power platform, and the CSA robotic arm. At core complete, the ISS will be permanently inhabited by three people.

Like the space shuttle, the ISS offers extremely clean microgravity conditions in both its pressurized and exposed modules. The only limits of the ISS lie in the need for orbit correction maneuvers, which introduce artificial forces on the experiments, and the orbit location in LEO. As compared to the space shuttle, though, the ISS long-term deployment allows experiments to be exposed to microgravity conditions even for years at a time. The constant number of servicing flights to the ISS allow experiments to be returned to earth within a reasonable time. The expanded number of flights, beyond the space shuttle, allow the hardware of experiments to be upgraded in shorter time periods than possible with SSP.

Figure B.5 The ISS on October 2002

As with the space shuttle, ISS operations are highly structured, time-critical, and require the presence of third parties throughout a substantial part of the program. Even with three humans permanently present in the ISS, their time is extremely precious. NASA and its partners spend incredible amounts of time organizing the schedules of astronauts. Even when an astronaut completes their duties early, a number of activities are always ready to be performed. Therefore, many scientific experiments are likely to be performed at random times, preventing the scientists to interact in real-time with the astronauts. As such, like before, all experiments must go through enough training and integration that they can be conducted independently by the astronauts. As with the SSP, when real-time communications are possible, the scientist must interface with mission control and the payload integration office, rather than directly with the astronaut. The ISS does provide a substantial improvement on communications, such that when properly planned, real-time audio, video, and data transfer (both downlink and uplink) are possible. Even though the operations of the ISS are clearly more complex than a scientist conducting research in their own facility, the trade-off between operational complexity and availability of microgravity is not as important because of the availability of substantial astronaut time, real-time interaction, and ability to upgrade both hardware and software in a reasonable amount of time.

B.4 Past Space-based Laboratories

The ISS had both US and Russian predecessors: the US Skylab, Space Lab, and the Russian Sályut and MIR Space Stations. This section presents a quick historical review of these four different facilities, as well as their contributions to scientific research in space and the development of the ISS.

B.4.1 Sályut

Multiple Sályut space stations were built through the 1970's and into the 1980's. The first station was launched in May 1971. Its first crew worked on the station for 21 days; unfortunately the crew died after a de-pressurization accident upon reentry. The second mission was destroyed in an explosion of the launch vehicle. The third attempt reached orbit in 1973, but contact was lost before a crew could reach the station. The fourth version flew successfully in 1974. The sixth and seventh missions flew in 1977 and 1982, respectively. The sixth mission was the most successful, recording 27,785 orbits of Earth and five manned expeditions over four years and ten months of operations. The longest crew duration was 185 days. The seventh mission was aloft for four years and two months; two to six crew members were aboard at any one time through six main expeditions and four secondary flights (including French and Italian cosmonauts). Mission durations of up to 237 days were achieved. The seventh and last Sályut mission ended in June 1986; the spacecraft burned up in the Earth's atmosphere in 1991.

The Sályut program featured important capabilities seen in the ISS. The stations performed docking of both manned and unmanned spacecraft for crew rotation and resupply missions. For this purpose, the stations had two separate docking ports. The stations had an airlock, which allowed dozens of EVA's to take place. Of special importance to the ISS program is that a number of international cosmonauts flew to the Sályut stations over the years, the first time that international cooperation would occur in a space station. Lastly, the objective of the Sályut program was directly in line with that of the ISS:

> "Objectives: Continuation of scientific research on board manned space complexes in the interests of science and the Soviet national economy; testing of advanced systems and apparatus for orbital stations. Continuation of the scientific research in progress on board manned space complexes in the interests of science and the national economy; testing of advanced systems and apparatus for orbital stations." [Astronautix]

The sixth mission completed many of its objectives with a wide range of scientific equipment: multi spectral camera system, high resolution topographical camera system, 10 m diameter radio telescope, alloying/materials processing furnace, containerless processor for semiconductor materials, 1.5 m diameter cryogenic submillimeter/ultraviolet/infrared telescope, Refraktion and Zarya spectrometers for sun/moon views through Earth's limb, experiment for coating of plates with materials, gamma ray telescope, plant growth unit, and cardiovascular monitoring system. The seventh mission was dominated by military research after cutbacks in other military programs forced the use of the Sályut for this purpose.

B.4.2 US Skylab [Belew, 1977]

Skylab was the United States' first space station. It was more than the actual space station, it was a comprehensive scientific program. The program consisted of four launches: one unmanned delivery of the space station and three separate manned missions. The station was launched in May 1973 and remained in operation through its third man mission which ended in February 1974. Through these months in space Skylab completed more than 100 experiments in a wide range of topics.

The Skylab station consisted of five major elements (Figure B.6, [Belew, 1977]): command and service module (CSM), orbital workshop, airlock module, docking adapter, and the Apollo Telescope Mount for solar observations. The unmanned launch put into orbit all the modules except the command and service module; the CSM, a standard Apollo command module, carried the crew to the station and returned them to Earth at the end of their mission. The majority of the activities occurred in the orbital workshop, which included the living and working quarters.

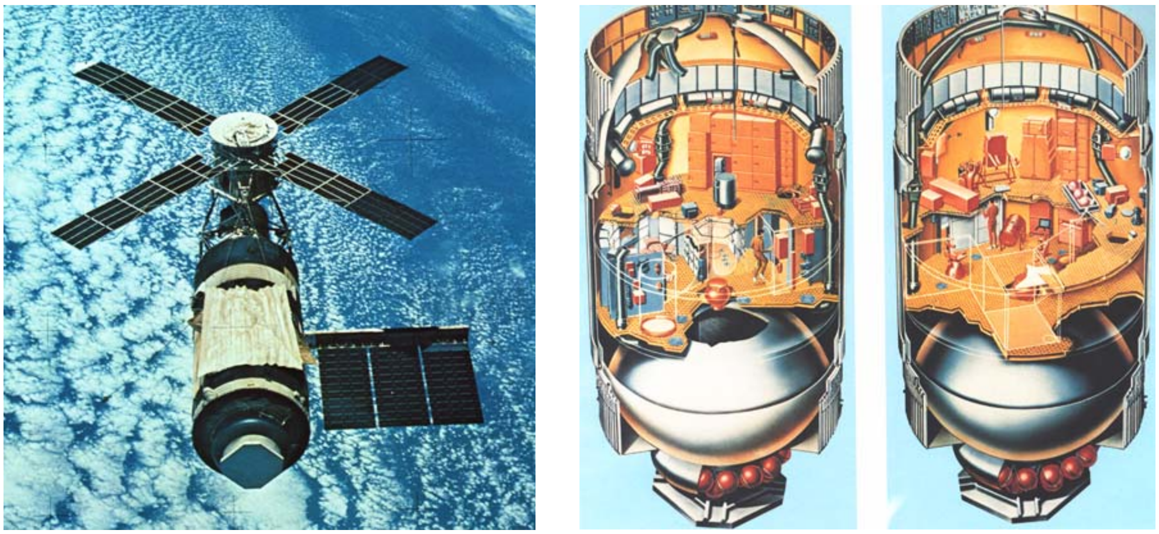

Figure B.6 US Skylab

The Skylab science covered multiple disciplines. The Apollo Telescope provided unprecedented observations of the sun. The location of Skylab outside the atmosphere also allowed studies of stellar astronomy, including the study of comet Kohoutek. Man's adaptability to long-duration space-flights was studied; this included both physiological and behavioral research. Observation of the Earth provided more than 40,000 pictures for scientists to study agriculture and forestry, geological applications, the oceans, coastal zones, water resources, atmospheric phenomena, regional planing and development, and remote sensing technologies. Substantial research was also conducted in the area of materials science, including crystal formation, homogeneity in semiconductors, diffusion in liquid metals, and solidification of metals. Lastly, Skylab also served as an educational environment; a large number of student projects were completed by the astronauts.

As a predecessor to the ISS, Skylab started the goal to develop space facilities dedicated to scientific research. While the scientific goals of Skylab were strictly defined to understand the human physiological responses to long-term microgravity conditions, with a pre-defined set of additional experiments, the major goals were always to support science.

B.4.3 Space Lab [Emond, 2000]

While not a true space station, the Spacelab program helped pave the way for the ISS in many ways. Spacelab was not a spacecraft launched to space for long-term microgravity research; rather, the Spacelab program was a successful attempt to open the use of the space shuttle to a broad range of research by the international community. Through a system of modules, Spacelab provided both pressurized and un-pressurized platforms. NASA operated the program, including providing the space shuttle to carry the modules. The ESA designed the modules and supported the operations of the laboratory's payloads.

The program lasted 17 years, from 1981 to 1998. Spacelab modules flew on 36 space shuttle missions; 16 missions were with pressurized modules, the rest with exposed pallets. A total of 375 days of flight were logged. Throughout its time it supported over 800 distinct experiments, leading to thousands of research articles and hundreds of graduate theses. Four principle components formed the core hardware of the Spacelab program. The Spacelab Module provided a pressurized environment. The Spacelab Pallet allowed large instruments to be in direct exposure to the space environment and broad fields of view. The Instrument Pointing System provided a high-accuracy mount for space telescopes. The Mission-Specific Experiment Support Structure supported up to 3000 pounds of payload.

Spacelab was a milestone towards the ISS in two important respects. It began unprecedented international space collaboration. Due to the size of the program, researchers, engineers, scientists, and peacemakers had to learn how to properly use the facilities that Spacelab provided. As a special part of the Spacelab program, the Spacelab 1 mission docked a Spacelab Module to the Russian MIR space station, providing a true laboratory environment for MIR, and creating, albeit for a short time, the first truly international space station for research.

By developing complex systems, which were different with each mission, many lessons were learned on how to use the facilities; sometimes what was learned was that you have to fly it to learn how to use it. Spacelab provided experience on integrating a wide range of experiments from multiple disciplines and countries. It also provided an environment where the scientist was directly involved in the actual process of conducting the science; scientists knew when execution would take place and had input on what would happen. Spacelab provided a clear perspective on what to expect from the operations of the ISS.

Spacelab fostered a broad range of research activities spanning widely separate fields of study. While research on the Sályut and Skylab missions was pre-defined and strictly scheduled, Spacelab opened the doors for a much broader range of science to be conducted. No longer was the science for the full program pre-defined, but rather unsolicited research could be conducted. Spacelab provided both the hardware and operational support needed to broaden the research spectrum. The program welcomed experiments exposed to space and pressurized in the module. The timeline allowed development of new experiments over time. New technologies that appeared after the program was launched could be integrated to enable new science.

Spacelab created a cultural change in the ways to perform microgravity research. The space stations by both the US and Russia demonstrated the ability of humans to reside in space for long periods of time. Spacelab demonstrated the ability to create an international program which welcomed a wide range of science.

B.4.4 MIR

MIR was constructed from 1986 to 1996. The MIR Core Module was launched in 1986 and provided living accommodations and station control. Two scientific modules, Kvant I and II, were launched in 1987 and 1989, respectively. A third module, Kristall, was added in 1990. The Spektr module, added in 1995, added space for a US astronaut to live in MIR. In 1996 the Docking module was added to provide a connection port to the US space shuttle. Figure B.7 ([NASA, URL5]) shows a picture of MIR taken from the Space Shuttle. MIR was burned in the Earth's atmosphere in March 2001. Through its lifetime, MIR was serviced by Soyus (manned) and Progress (supplies) vehicles.

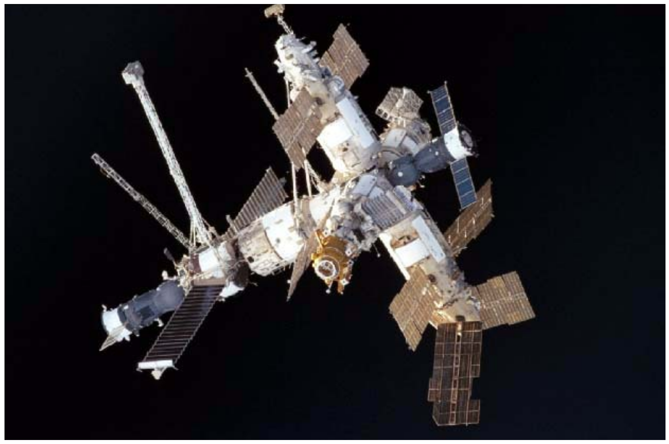

Figure B.7 The MIR Space Station

As a whole the MIR program surpassed all of its expectations. Originally scheduled for five years of operations, it was operational for almost 15 years. Even after the original Russian plans were complete, the station continued to grow to welcome US astronauts and the space shuttle. By the end of its life, when docked with the Space Shuttle, the joined MIR station and space shuttle formed history's largest spacecraft.

But MIR was not without problems. Through its history MIR had to be serviced continously. Assembly of the station required several unexpected EVAs after failed automatic dockings. The station suffered from fires, broken computers, oxygen emergencies, and a collision with a Progress vehicle in 1997. Unfortunately for the research community these problems meant that a high percentage of cosmonaut time was spent in maintaining MIR. The time spent on research in MIR was greatly affected by its history of problems. Yet, all of these experiences have served as lessons for the ISS.

Research on MIR was conducted in a broad number of areas. During the Shuttle-MIR program time, research took place on: advanced technologies, earth sciences, fundamental biology, human life sciences, ISS risk mitigation, life support risk mitigation, microgravity, and space sciences. Advanced technologies included materials science and the characterization of the micro-accelerations in MIR, which would help in the development of science facilities in the ISS. Combustion experiments also took place. Earth sciences concentrated on remote sensing and space photography to make detailed assessments of the Earth. Both the biosphere and the atmosphere were studied. Biology research concentrated on studying the effects of microgravity on the development of plants and animals; research on radiation effects was also performed. Extensive human life sciences studies took place, among the main research areas were: the cardiovascular system, endocrinology, hematology, human factors, immunology, microbiology, muscle and bone, neuroscience, pharmacology, and radiation studies. Space science experiments collected cosmic dust over extended periods for analysis on Earth.

MIR played a critical role in the development of the ISS. Phase I of the ISS involved the interactions of NASA and the RSA in using MIR and the Space Shuttle as a test bed for the future development of the ISS. Multiple shuttle flights took place to demonstrate assembly of the ISS by assembling new parts to MIR. EVAs which utilized both the Russian and the US hardware took place. The living environment of MIR was fully analyzed to develop standards for the new station, including air quality, noise levels, and water quality. The effects of crew motions on the structure were measured to help the design of ISS experiment support systems. The external environment of MIR provided valuable information on the external design of the ISS.

Quite possibly the most important benefit from Phase I was to force the internal partners, including the astronauts and cosmonauts, to work in a long-term relationship in a permanently manned space station. While Sályut had international astronauts visit the stations and Spacelab established a long-term relationship between international partners, neither required two separate organizations to work together to support life in space for a long period of time. The ISS Phase I program, using MIR, forced NASA and RSA to solve critical problems together; that required understanding each other.

Phase I drove significant designs of the ISS, including improvements to the rendezvous and docking instruments, "quick-disconnect" cables that come apart in seconds in the case of emergencies, and prevention of moisture buildup. It also provided important lessons for the administration of the ISS. NASA would work on more flexible schedules for astronauts. NASA surgeons learned how to perform medicine on a space station. And, perhaps the most important lesson learned from Phase I was humility; learning that, as with Spacelab, there is a lot to learn after launch. NASA learned how different operating a space station is from the shuttle. [Burrough, 1998]