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ANALYSIS OF DESIGNS OF SPACE LABORATORIES
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Space Laboratories

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Space Laboratories

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ABSTRACT

This paper presents a review of the development and evolution of space laboratories. Laboratories in space constitute the unique and necessary working environment in which researchers conduct scientific experiments, engineering tests, and technology development missions. The United States (US) and (former) Soviet Union pioneered space laboratories with the Skylab and Salyut series stations. In the Space Shuttle era, the European Space Agency's (ESA) SpaceLab, the commercial SpaceHab, and shuttle middeck lockers provided experiment accommodations for a broad range of disciplines. The MIR station provided a suite of laboratories and other facilities. The Space Station Alpha (SSA) will soon provide a multiplicity of laboratories, including the US Lab, the ESA Columbus Module, the "Kibo" Japan Experiment Module, and other facilities. Beyond the SSA, planetary exploration missions to the Moon and Mars will include Space Laboratories. The design of these laboratories is a critical ingredient of success for science. This paper generates *units of analysis* for evaluating the design of space laboratories.

INTRODUCTION

The original idea for this paper was to be a review article of space laboratory architecture, presenting essential precedents for science facilities in space, including design concepts and flight units. From this survey, the paper would extract knowledge about the principles of space laboratory design. However, in conducting this design research, it became apparent that this approach was somewhat backward. Most of the compelling data appears in the efforts of designers who were grappling with each of these challenges for the first time: struggling to define the problem; analyze its components and composition; and develop design solutions for it. The potential pitfall of the "post-occupancy" approach envisioned originally was that it would make all these precepts appear normalized and trivial as obvious "lessons learned" from accounts after the fact.

Thus, it appears more valuable to capture the design drivers that led to specific design considerations manifested in the design of specific space laboratory precedents. The approach this inquiry takes is unorthodox insofar as it does not seek out the latest result, or cite only the most recent articles as references. Rather, this approach is to find the design reports and concepts that illustrate how the designers engendered these laboratory architectures. Certainly, it is still necessary to present representations of these laboratories: drawings, models, mockups, and photographs. The method of this paper is not to provide a comprehensive catalog of each space laboratory and every design topic that applies to it, but rather to provide salient exemplars that illustrate the point or principle. What is more important, the process of discerning these points and principles led to the new construct of *units of analysis* within which to comprehend space laboratory design.

ESSENTIAL DISTINCTIONS—An essential distinction is the difference between a space laboratory as a scientific and engineering research facility and a space station. A space laboratory may be a part of a space station, or it may fly as part of the space shuttle, or some other space vehicle. What the definition of a space laboratory does not necessarily include are all those parts of the space station devoted to keeping the crew alive and safe, and to keeping the whole assembly on orbit in the correct trajectory. Although the life support, habitation and station-keeping functions certainly impinge on the laboratory, this approach seeks to appreciate the laboratory separately. However, it also seeks to correct a semantic error that emerged early in the US Space Station program—the distinction between the "habitability module" and the "laboratory module." In short, the laboratory must also be habitable to provide a safe, supportive and productive working environment for the scientific mission and payload specialists who work in it.

APPROACH—This paper evolved in two parts: an architectural overview and an analytical methodology: the *units of analysis*. The first part is an overview of salient highlights of space laboratory architecture. It is not intended to be an encyclopedic catalog of these precedents—nor a walk down memory lane—but rather an exposition of the characteristics that lead to the analytical section. It is intended as an expert overview, without the clutter of the thousand reference citations that would easily apply. The analytical section attempts to probe and extract the more outstanding issues and criteria, because of success and failure, both dramatic and catastrophic. However, the analytical section is not merely a compendium of canned "lessons learned"—if only it were that easy! On the contrary, the units of analysis present provocative issues for which the planners and designers must learn or relearn the lessons each time, as they apply them to the specific space laboratory architecture. Because of the methodological and theoretical aspects, as well as potential controversy, the analytical section contains the reference citations in the paper.

LABORATORY MODULE ARCHITECTURE

The design of space laboratories has historically been subject to infrastructural concerns of how to furnish a versatile facility, rather than by the individual needs of the experiments. This approach derives from the need to rationalize the support provisions and services that the laboratory module supplies to scientific and other payloads. However, the predominate infrastructure-driven approach can tend to obscure many of the architectural, perceptual, functional and operational issues.

The design of a space module to accommodate the working environment, especially laboratory equipment, imposes stringent design requirements. The unique character of space laboratories to date is the microgravity environment, which attracts the great majority of the scientific payloads. The working environment extends the living environment and so forms an ensemble with the overall space habitat architecture. The laboratory function also modifies the living environment to accept the specific payload equipment. In Skylab, this installation occurred somewhat haphazardly as engineers bolted equipment to virtually any available attachment surface. The Shuttle middeck lockers established a new norm of modularized packaging and support, accommodating a variety of payloads from materials processing to a "biomass production" chamber for plants. The accommodation for SpaceLab was the first to involve a payload rack system in which to install scientific equipment. This accommodation featured life science experiments -- including animal and plant habitats, materials science and other experiments. For Space Station Alpha (SSA), the rack system integrates a set of structural stand-offs, utility connections, primary rack structures, lighting and equipment installations. SSA will feature the Life Science Centrifuge as a major focus for research. FIGURE 1 shows a longitudinal view of the interior of the US Destiny Lab Module. TABLE 1 presents an overview of the space laboratory modules (and stations of which they comprise a part).

FIGURE 1. Interior View of the U.S. Destiny Laboratory Module on Space Station Alpha. Courtesy NASA-Johnson Space Center.

Planetary surface science laboratories (first on the Moon and then on Mars) will embody a further evolution of space laboratories that can take advantage of gravity to allow relatively normal experimental procedures. Planetary laboratories will support a different set of inquiries, particularly the search for life and an improved understanding of planetary origins and the evolution of the solar system. Planetary surface laboratories convey an advantage comparable to that of orbital life science laboratories: the ability to conduct in situ research on specimens, instead of waiting to return them to Earth, with the delay and complications that entails. The planetary surface lab will require a new generation of scientific equipment and capabilities to extend terrestrial investigations to Mars and to asteroids, moons, and planets beyond Mars.

The evolution of the several space laboratory architectures or typologies follows a path that appears neither linear nor direct, especially when comparing the relative progress between the US and Soviet/Russian programs. At the risk of oversimplification, it is possible to summarize the two programs as having evolved with almost opposite and complementary strengths and weaknesses, which their space laboratory accommodations reflect in the most fundamental ways.

FIGURE 2. Artist's cutaway view of the interior of the Saturn Orbital Workshop on Skylab. Courtesy of NASA-Marshall Spaceflight Center. The science experiment deck and living quarters appear on the lower deck, with a rather low ceiling above it, that served also as the floor of the much larger "dome area" above it. The upper port ring attached to the EVA Airlock, which in turn provided passage to the multiple docking adapter (MDA). The MDA accommodated the Apollo Telescope Mount console for operating the solar observatory.

Soviet/Russian Space Laboratories—The Soviets launched the first space station, Salyut-1 in 1971, with the goal of long duration space habitation, but they had an extremely checkered career in getting their stations to operate reliably and safely until Salyut-6, which was their first resounding success. Once the Soviets succeeded in keeping their station on orbit safely and reliably, they achieved an outstanding capability in terms of long duration; with missions lasting hundreds of days becoming routine. However, the Soviet/Russians tended to have a great many problems with the safe and successful operation of their experiments. In some cases the hardware or software design posed the problem, in other cases, the Salyut or Mir stations simply could not provide the power, cooling, data link or other resources necessary to operate the payload as designed and intended.

United States Space Laboratories—In contrast to the /Russian program, the US space laboratory program has benefited from excellent hardware and software development. For this reason, Skylab, shown in FIGURE 2, although launched in 1973 — about two years after Salyut-1 — was the first truly functional and successful space laboratory. The US laboratory facilities have enjoyed excellent resource support both on Skylab and in the Spacelab modules. However, up until the Shuttle-Mir cooperative program, the US space laboratory assets always lacked one critical resource: time on orbit. Skylab crews made three flights of 28, 56 and 84 days to the US station, which paled by comparison to the year-long durations the Soviets began to achieve in 1977 with Salyut-6. Once the Space Shuttles began flying in 1981, the Spacelab program seemed to go in almost the opposite direction from long duration. Spacelab duration on orbit was constrained by the ability of the orbiter Columbia to stay on orbit, for typically a maximum of 15 days. The relative shortness of the Shuttle/Spacelab flights led to the design of short-term experiments, and in so doing, shaped the type of science Spacelab researchers could propose and conduct. However, despite the length of their missions both Skylab and Spacelab produced an abundance of successful and useful results.

Payload Accommodation—The accommodation of scientific and experimental payloads takes two basic formats: the "bolt it down anywhere" approach that typifies the earlier laboratories, including Skylab, Salyut and Mir, and the rack-based accommodation featured in Spacelab and Space Station Alpha (SSA) throughout its various incarnations. These choices of payload mounting lead to far-reaching architectural implications for character and quality of laboratory interiors. FIGURES 3 and 4 compare two longitudinal views of the two bolt-anywhere approach in Skylab and the rack accommodation approach in Spacelab.

Apollo Soyuz Test Project—FIGURES 5 and 6 show the Apollo Soyuz Test Project (ASTP), in which an Apollo CSM docked with a Soyuz in LEO. ASTP carried out an impressive array of science experiments, especially considering the tightness of the combined volume of the two spacecraft. ASTP experiments included possibly the first third-party international payload, the German

Biostack III experiment in HZE galactic cosmic ray particle effects on biological organisms.

Salyut—FIGURE 7 shows the Salyut-6 configuration, circa 1977, with a Soyuz vehicle docked to it. The cutaway view of the crew cabin reveals the three cross-sectional diameters of 2, 2.9 and 4.15 meters. These multiple diameters derived from the system of mounting the Salyut on top of a launcher. However, these varying diameters made equipment and payload accommodations more complex and difficult.

Mir—FIGURE 8 shows the Mir core being prepared for launch in 1986 at the Biakonur cosmodrome in the Soviet Union. This photograph gives a sense of visual scale to the Mir, which was built on the same "assembly line" as its seven Salyut predecessors, sharing their main dimensional features. This photo also reveals the detailed complexity of the Mir in a way that is not apparent from photographs taken on-orbit. One major difference between all the Soviet/Russian Space Stations and laboratory modules and the post-Skylab American/European/Japanese modules is that all the former flew to orbit under their own power, instead of the latter being trucked to orbit by the Space Shuttle. The Mir laboratory modules also maneuvered remotely and docked to Mir using their own propulsion, guidance, and navigation systems. The fact that the Soviet/Russian modules needed to carry their own engines, propulsion fuel tanks, moment control gyros, and other power and navigation equipment made them much heavier and complex per unit of pressurized volume than the Shuttle-launched lab modules. But this mass to orbit was not entirely wasted after attaching to *Mir*. For example, *Mir* came to rely upon the gyrodyne CMGs in the laboratory modules Kvant-1 and Kvant-2 for attitude control and stabilization of the entire station.

FIGURE 9 shows the complete ensemble of the *Mir* complex including a visiting US Space Shuttle with the shuttle-deployed docking tunnel connecting it to *Mi*r. It shows all the science components of *Mir*, including the *Mir Core, Kvant-1, Kvant-2, Kristall, Spektr*, and *Priroda* laboratory modules. It also shows the *Soyuz-T* transport vehicle docked to the *Mir* core node and a *Progress* freighter docked to the port on the *Kvant-1* Lab.

FIGURE 10 is a detailed drawing of the Kvant-1 laboratory module, the first pressurized addition to the original Mir core. The drawing shows a Cosmonaut seated in a chair making observations, however, he appears to be drawn too small -- deceptively out of scale -- making the 4.15m diameter *Kvant-1* appear larger than it really was. The drawing conveys the jumbled-together format of "bolt-anywhere" equipment accommodations. Insofar as this drawing is a design document rather than a post-facto illustration, it shows that the equipment accommodation was highly subjective even in the design stage. Each of the panel fronts shown on the surface behind the cosmonaut are removable, and became a favorite place for the cosmonauts to store equipment "out of sight—out of mind." Unfortunately, this practice made it virtually impossible to track and inventory all these pieces, and often the ground controllers had no information to give a new crew where to find an item that a previous crew had stored behind one of these many unlabelled panel fronts.

FIGURE 11 is a photograph of the interior of the *Kvant-2* module, taken by a NASA astronaut. The interior is cluttered to such a degree that it is difficult to imagine this environment as a science laboratory, let alone a working environment. This photo reveals the stowage problems the cosmonauts and astronauts encountered on *Mir*. Unfortunately, the new Space Station Alpha is experiencing similar stowage shortfalls, with the same solution of "letting it all hang out" in fabric bags in the free volume of the living and working environments.

FIGURE 12 shows a somewhat more plausible working environment. Astronaut Shannon Lucid appears before the NASA Langley Research Center's Microgravity Science glovebox, apparently installed in the Priroda laboratory module. In this photo, it is possible to see how the ubiquitous closeout panels throughout the Mir complex serve as a kind of custom rack-mounting system. Although the panels and equipment do not separate from the laboratory walls for mounting and dismounting as complete units like the Spacelab or Space Station racks, they do allow a rather more flexible attachment system than on Skylab or the earlier Salyuts. The photo also reveals an integrated system of handholds attached to either the front face of the panels or the equipment accommodated within the panels. Priroda was the most Spacelab/SSA type module on Mir, with its interior being specifically designed and built to accommodate payloads such as the NASA microgravity science glovebox. Despite the presence of this glovebox, Priroda's primary purpose was Earth remote sensing. Apparently, most or perhaps even all of the payloads came from international partners of the Russians. In this sense, Priroda may have been the first effort by a governmental space agency to create a module exclusively for "leasing" by other parties.

Spacelab—Although Spacelab first flew in 1983, three years before Mir, in terms of laboratory design development, it is a generation beyond Mir. Only in the Priroda Laboratory module launched last among the Mir components in 1997, do any "lessons from Spacelab" show a hint of appearing. FIGURE 13 shows a model for the full Spacelab ensemble, as it would be configured for flight, with the external experiment carrier pallet in the Shuttle Columbia cargo bay. The European Space Agency built the Spacelab system, and its constituent national space agencies stand out among its principal customers. Spacelab also flew many Japanese payloads, including the dedicated Spacelab-J. Spacelab supported many Life Science payloads, culminating in Neurolab as a dedicated Life Science mission, and one of the most successful. The cutaway section on the left half of the pressurized Spacelab module shows how the payload accommodation racks are installed inside. The personnel access tunnel runs from the center of the Spacelab left frusto-conical endcap to Columbia's airlock hatch. The Spacelab pressurized module and external pallet marked the first use of modularized system for both internal and external payloads. FIGURE 14 shows the Spacelab D-1 Mission crew working in the pressurized lab. A small materials handling type glovebox appears in the rack on the right. The Spacelab racks were based on the standard US .475m (19 inch) electrical equipment rack module, such that a Spacelab "double rack" was .95m (38 inches) wide. Note that astronaut Gluion Bluford is holding onto the handrail and a notebook or manual with his left hand while performing a task with his right hand.

<u>Space Station Alpha</u>— The Space Station went through so many names and redesigns generally corresponding to the changes in names, that it is an encyclopedic topic by itself. The most familiar names are Space Station Freedom, dating from the Reagan presidency; the International Space Station, from the early Clinton presidency; and Space Station Alpha, from late in the Clinton Presidency. For the purpose of this discussion, this paper will use SSA to refer to all design, redesign, and developmental phases of the Space Station.

The SSA rack design built on the lessons of the Spacelab rack. Rod Jones, Space Architect at NASA Johnson Space Center was instrumental in developing the axially symmetric four standoff system. Each rack hinges at one end to allow it to swing away from the module pressure vessel wall for installation, servicing, and repair. To mitigate the extremely tight equipment fits that occurred in Spacelab racks, the SSA rack is 1.05m (42 inches) wide, and a "half rack" is .525m (21 inches) wide. Initially, its façade or front panel was conceived as a perfect double square, 1.05m wide and 2.10m (84 inches) high. This modularity hearkens back to the ad quadratum "square schmaticism" of early Renaissance architecture. However, practical considerations such as the required size of the structural stand-offs and the size of the utilities they needed to accommodate, such as lighting and ventilation, increased the size of the standoff and decreased the size of the rack façade. The flight racks shrank to 1.86m (73 inches) in height.

FIGURE 15 shows a cut-away isometric line drawing of the US Destiny Lab Module. The system of four racks, hinged from four stand-offs, and forming the central workspace of the lab module appears clearly. At the right (rear) end of the module, the infrastructural utilities such as ventilation ducts appear running around the cross-section of the module.

FIGURE 16 shows the Destiny laboratory module attached to Space Station Alpha, above the Space Shuttle cargo bay. A shuttle-docking adapter is attached to the forward port of the Destiny Lab Module, which in turn is berthed to a node. In this view, the shuttle appears to be docked to a docking adapter that projects downward from the node's nadir port. This image illustrates the difference between berthing and docking. ***Docking*** is a short-term mating of a propulsive vehicle and the station at a docking adapter. It is easy to remove and relocate a shuttle-docking adapter to a different port on a node or a module. ***Berthing*** involves the long-term or permanent attachment of a module or a node, with utility and infrastructure connections such as power, life support, and ventilation. Unlike the Russian Mir-type port or hatch, the utility connections run through the berthing ring that frames the hatch, not through the open hatch itself. The square hatch is 1.25m square, with 30cm radius corners.

FIGURE 17 provides a detailed view of Japan's Experiment Module (JEM), recently renamed the Kibo (Hope) Laboratory Module. Kibo is in many ways the most self-sufficient and "full-service" of the SSA laboratory modules. In addition to the pressurized cabin, it includes a pressurized logistics module that is dedicated essentially to carrying scientific supplies for the experiments in Kibo, although it may also be called into service to transport habitation supplies for the crew. In addition to the pressurized volume, Kibo incorporates several external components; af space environment exposure facility and an unpressurized exposed logistics carrier unit. Kibo includes its own point-mounted remote manipulator arm to handle all the external equipment and materials on the exposure facility and the exposed logistics carrier. In the end-dome of Kibo facing the exposure facility, below and slightly to the right of the remote manipulator arm is a square hatch. This hatch opens into the Kibo scientific airlock, which communicates between the pressurized laboratory cabin and the vacuum of space. This airlock includes a "slide table," on which researchers can place a sample, slide it into the airlock, seal the inner hatch, bleed off the atmosphere, then open the outer square hatch and slide the sample out into the vacuum of space. Once outside the airlock hatch, the remote manipulator arm can pick up the sample and move it to a location on the exposure facility or exposed logistics carrier.

FIGURE 18 shows the Kibo attached to the Space Station at a node through a berthing port at the distal end from the external exposure facility. In this arrangement, its longitudinal axis runs parallel to the large truss that supports the solar photovoltaic arrays. The Kibo pressurized logistics module projects upward, parallel to the US/Italian logistics module, suggesting a commonality of operations between the Space Shuttle cargo bay and the installation and removal of these two pressurized logistics units.

FIGURE 19 shows the ESA Columbus Laboratory Module, attached to a node at the berthing port opposite the Kibo. The Columbus appears to be the simplest of the three major laboratory modules. One interesting feature is the yellow handrails that run prominently around the Columbus to provide handholds and restraint anchorage for EVA astronauts.

FIGURE 20 shows a detailed cutaway view of the Columbus Laboratory Module. It uses the same four rack and standoff system as Destiny and Kibo. This rendering is valuable for revealing the truss-like structures that form the sides of the swing-away equipment racks, and the triangular truss cross-sections that form the longitudinal stand-offs to which the rack hinges attach. This illustration shows a variety of externally mounted instrumentation for space science experiments and perhaps Earth observations to be conducted from within the Columbus. The ubiquitous yellow handrails appear externally for EVA use and internally on each of the racks for IVA use.

FIGURE 21 shows a detailed view of the ESA Fluid Science Laboratory (FSL) rack for the Columbus module. Note the foot restraints on the bar extended in front, and the laptop computer that serves as a general workstation and data interface. The FSL is a multi-user facility for conducting fluid physics research in microgravity conditions. It can be operated in fully- or in semi-automatic mode and can be controlled on-board by the SSA astronauts, or from the ground in the so-called telescience mode.

DISCUSSION OF SPACE LABORATORY DESIGNS—The historic development of space laboratories show a steady trend toward greater specialization. The rack-based payload packaging system is a key to this progress. The rationalization of space laboratory equipment payloads into these discrete, rack-based payloads has advanced to the level where developing them can occur on a normal industrial basis. If the proper utility connections are in place, these racks can be moved around almost interchangeably on board the space station, from one place in a lab module to another, and between laboratory modules. The allocation of crew time to serve all these tasks is a major scheduling challenge. It involves a detailed assessment of what functions that crew can best perform, what computers or automation on board the station can best perform and what teleoperators on the ground can best perform.

Yet, this rationalization of payloads and packaging comes only with certain costs and trade-offs. The now ubiquitous Space Station laboratory rack can prove highly constraining of payload accommodations. It forces the payload into a somewhat arbitrary volume, structure and mass envelope. This constraint compares in a revealing way to the “bolt anywhere” approach of earlier space laboratories that did not impose such a discipline. The rack system defines a well-defined set of ground-rules and guidelines for packaging space payloads at the expense of odd shapes and sizes.

Although few scientific or other experiment payloads are so large as to exceed the limits a lab rack, those that do must find another way to go or be excluded from the Space Station. This scenario is exactly what happened with the Life Science Centrifuge (SSLSC). Initially, the proposal was to build a nominal 2m centrifuge in a quadruple rack that initially offered 2.10m square front elevation. When the rack height shrank to 1.86m, it was too short to accommodate a centrifuge of productive and reasonable size. The outcome was to develop a separate concept for a 2.5m centrifuge, mounted within its own envelope to the end dome of the Centrifuge Accommodation Module (CAM). The CAM will consist of a relatively short (perhaps 6m to 8m long) module that the NASDA, the Japanese space agency will build for the Ames Research Center as a reciprocal barter. The CAM will house the majority of the SSBRP, which includes the Centrifuge.

TABLE 1. Space Laboratory Modules Launched to Low Earth Orbit. This table describes the architectural laboratory modules rather than the multiple missions to each laboratory. Compiled and converted from many sources, including measurements taken at the National Air and Space Museum, Washington DC.

Laboratory Name	Origin	Date	Length m	Dia. m	Mass Kg.	Pressurized Volume m^3	Key Payloads	Remarks
Skylab Overall Cluster	USA	1973	36.1 with CSM	6.5	90,795 with CSM	361	Biomedical, Solar Astronomy, Earth Science	First true, functional space station and space laboratory
Skylab Orbital Workshop	USA	1973	14.7	6.5	35,400	336	Life Science, Biomedical, Earth Observations	Derived from Saturn upper stage
Apollo-Soyuz Test Project	USA/ USSR	1975	20m w/ CSM & Soyuz	2.3-- 3.9	21,900	na	Life Science, space science	First International cooperation in a Space Laboratory
Salyut-6	USSR	1976	13.1	2.0 - 4.15	19,825	~80	Life Science, Space Science	Earlier Salyuts similar
Salyut-7	USSR	1982	13.1	2.0- 4.15	19,825	~80	Life Science Space Science	
Spacelab	ESA	1983	10m + pallet	4.25	10,000 ±1,000	142	Materials Science, Life Science, Space Science	Flew in the Shuttle Columbia Cargo Bay
Mir Core	USSR	1986	13.13	4.15	20,900	90 380 total Mir Cluster	habitation, power, life support, sleep stations, toilet	Added Radial docking ports to Salyut design
Mir-Kvant-1	USSR	1987	5.8	4.15	11,050	30	Astrophysics	
Mir-Kvant-2	USSR	1989	13.7	4.15	18,500	61.9	Logistics, EVA airlocks, toilet	
Mir-Kristall	USSR	1990	11.9	4.35	19,640	60.8	Materials Processing	
Mir-Spektr	Russia	1995	9.1	4.35	19,640	~60	Geophysical Science	Refurbished to receive US payloads on orbit
Mir-Priroda "Nature"	Russia	1996	9.7	4.35	19,700	~60	Remote Sensing, Earth Science, Oceanography	Designed to incorporate US research
"Zvezda" Space Station Alpha Core (SSA)	Russia	1999	13.1	4.25	20,900	90	Habitation, power, life support	Similar to Mir
SSA-Destiny Lab	USA	2000	8.5	4.25	14,515	120	Diverse experiments	
SSA-Columbus Lab	ESA	2002	10	4.25	11,000	142	Microgravity, fluid physics, life science	Similar in size to Spacelab
SSA-Kibo, "Hope," Japan Experiment Module (JEM)	Japan	2002	12	4.05	13,000	170	Life Science, Microgravity, Space Environment	External Exposure Facility, JEM Robot Arm
Russian Research Lab	Russia	2003	8.13	4.35	19,000	~60	Unknown	Attaches to Russian SSA core

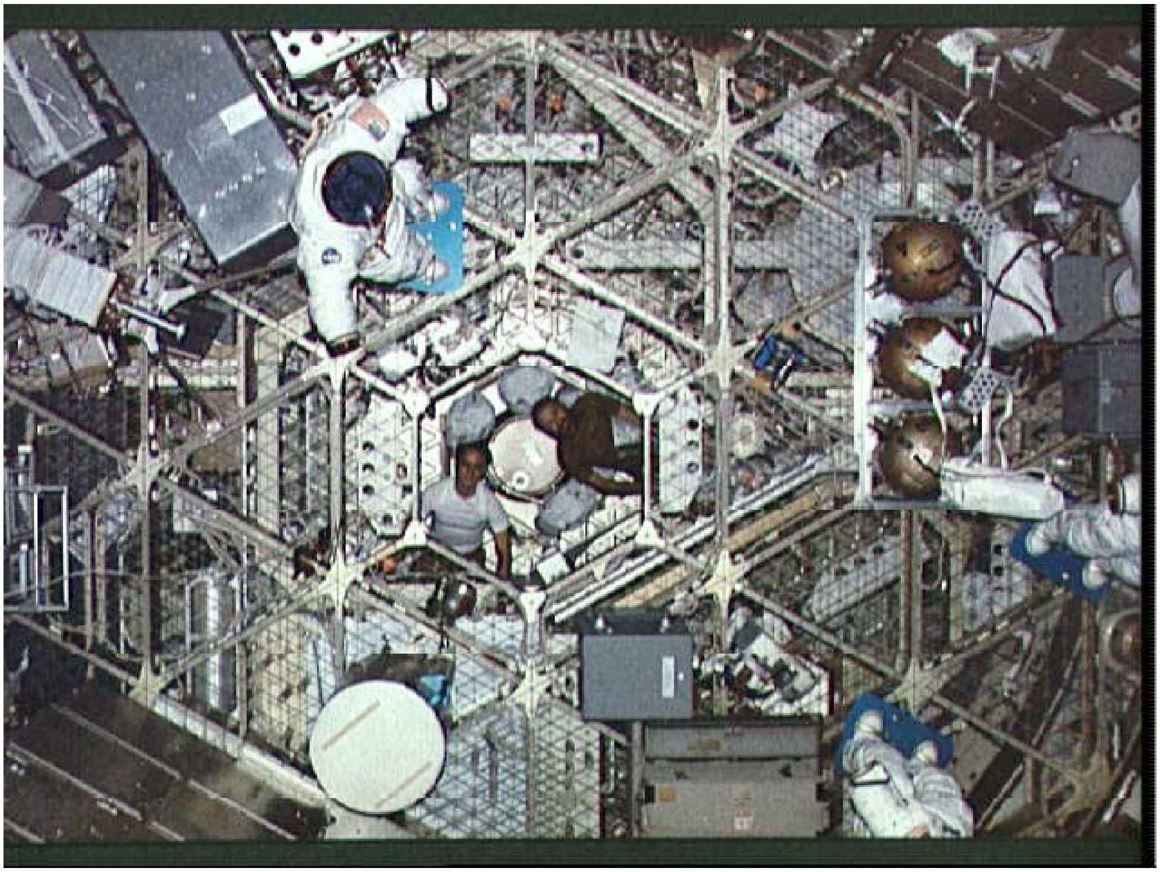

FIGURE 3. The quintessential view of the Skylab interior, showing its vast spaciousness and huge scale. View from airlock hatch looking down length of the Skylab Orbital Workshop. Skylab 4 Scientist-Astronaut Edward G. Gibson, science pilot, and Astronaut Gerald P. Carr, commander, look up the passageway. NASA Photo ID: SL4-150-5062, 1974.

FIGURE 4. Longitudinal view of the Spacelab Module as typically outfitted with payload racks for flight. The Spacelab racks bend inward at 45° at the top to make better use of the upper volume. Note the handrails that follow this angle. Courtesy of NASA- Marshall Space Flight Center.

FIGURE 5. Artists rendering of the Apollo-Soyuz Test Project (ASTP) courtesy of NASA Headquarters. This rendering shows the Soyuz and Apollo spacecraft mated together via a docking adapter that was designed and built at NASA-Johnson Space Center, and then carried into orbit on the Soyuz.

FIGURE 6. Tom Stafford and Alexi Leonov meet at the ASTP docking adapter hatch. Stafford and Leonov had made the first international handshake in space. Leonov is holding a camera. July 17, 1975 Courtesy NASA Johnson Space Center.

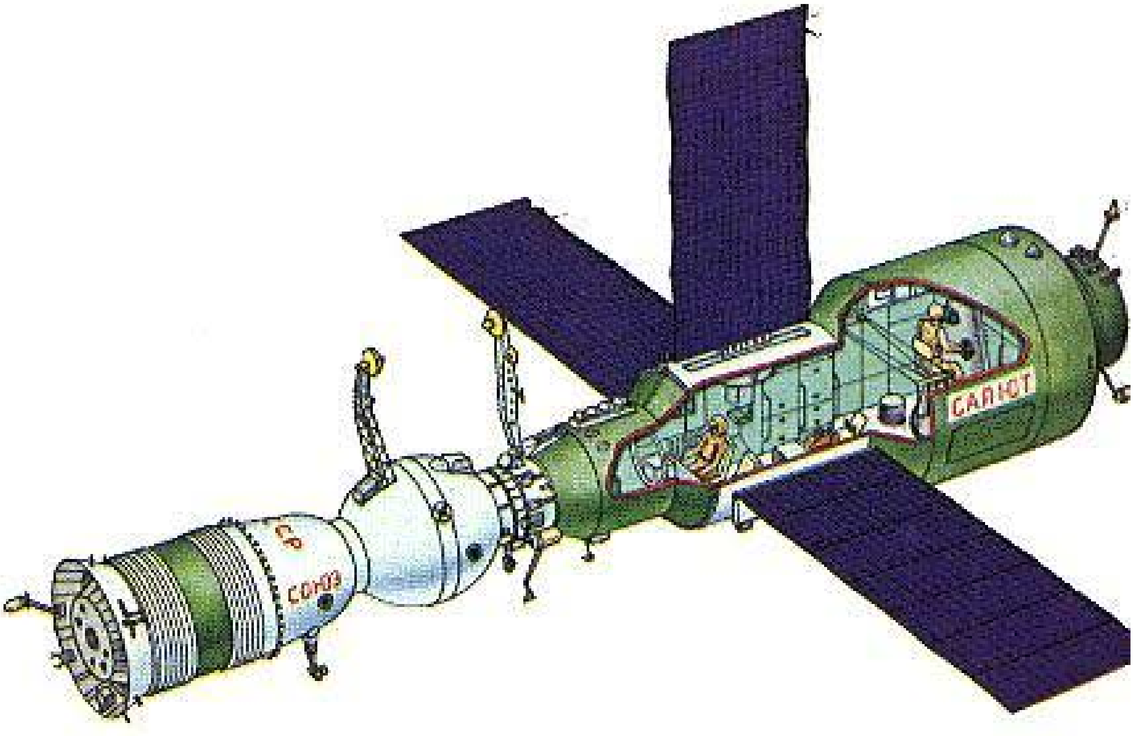

FIGURE 7. Salyut-6 Configuration with Soyuz vehicle berthed to it, 1977, courtesy of RKK Energia.

FIGURE 8. Mir core under preparation for launch at Biakonur Cosmodrome. Courtesy RKK Energia. The multiple berthing hub is visible “in front,” just to the right of the large support ring about the 2.9m diameter section.

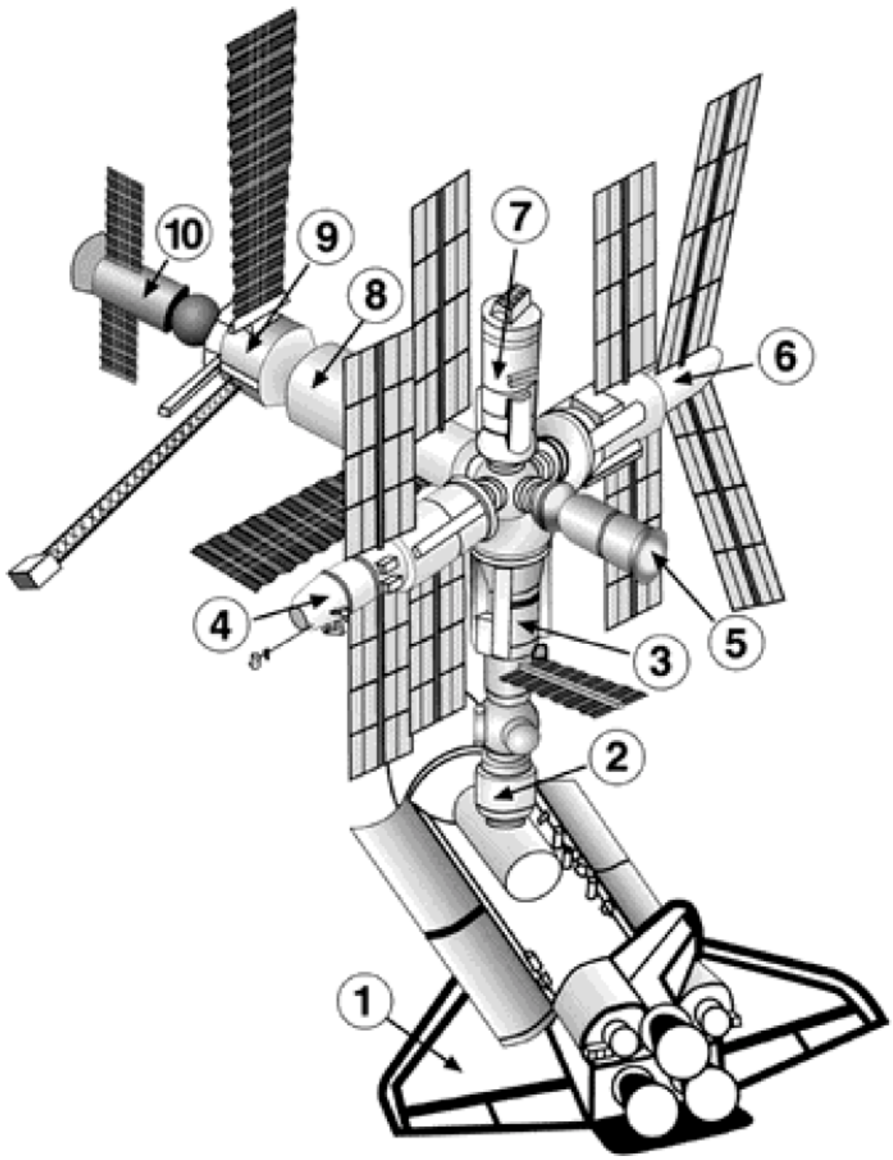

FIGURE 9. Diagram of Mir Space Station Cluster, with Shuttle docked to it. Courtesy of NASA Marshall Space Flight Center.

Key to Mir-Shuttle Docking Diagram:

1) U.S. Space Shuttle
2) Orbital Docking System—tunnel and adapter
3) Kristall module: materials processing, exercise treadmill, docking tunnel
4) Kvant-2 module: logistics, 2 EVA-capable airlocks, toilet
5) Soyuz-T transport vehicle, docked at multi-port node
6) Spektr module: geophysical sciences, some US experiments
7) Priroda module: U.S. facilities, Earth observation, US equipment for materials science
8) Core module: habitation, power, and life support
9) Kvant-1 module: astrophysics, docking port
10) Progress robot freight vehicle docked at Kvant-1 port on the -velocity vector.

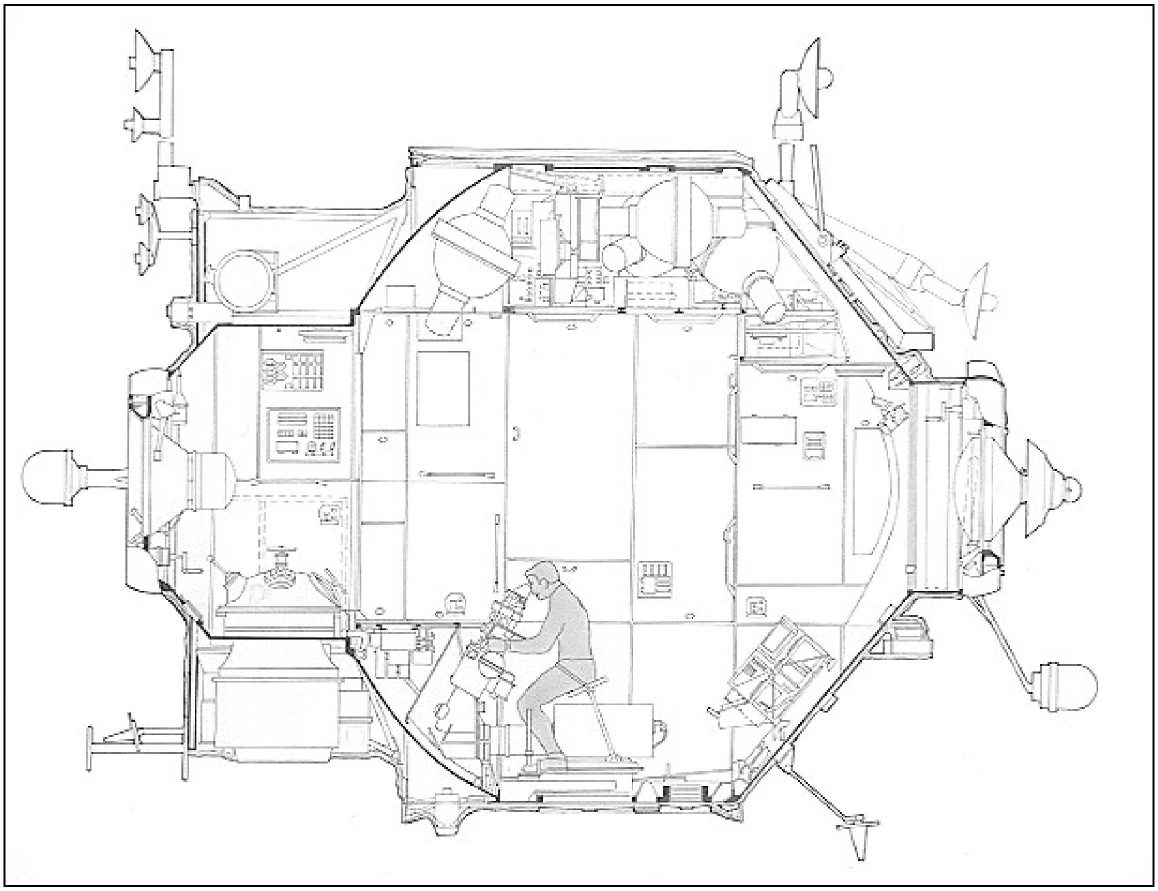

FIGURE 10. Kvant-1 Section Elevation line drawing, courtesy TsPK.

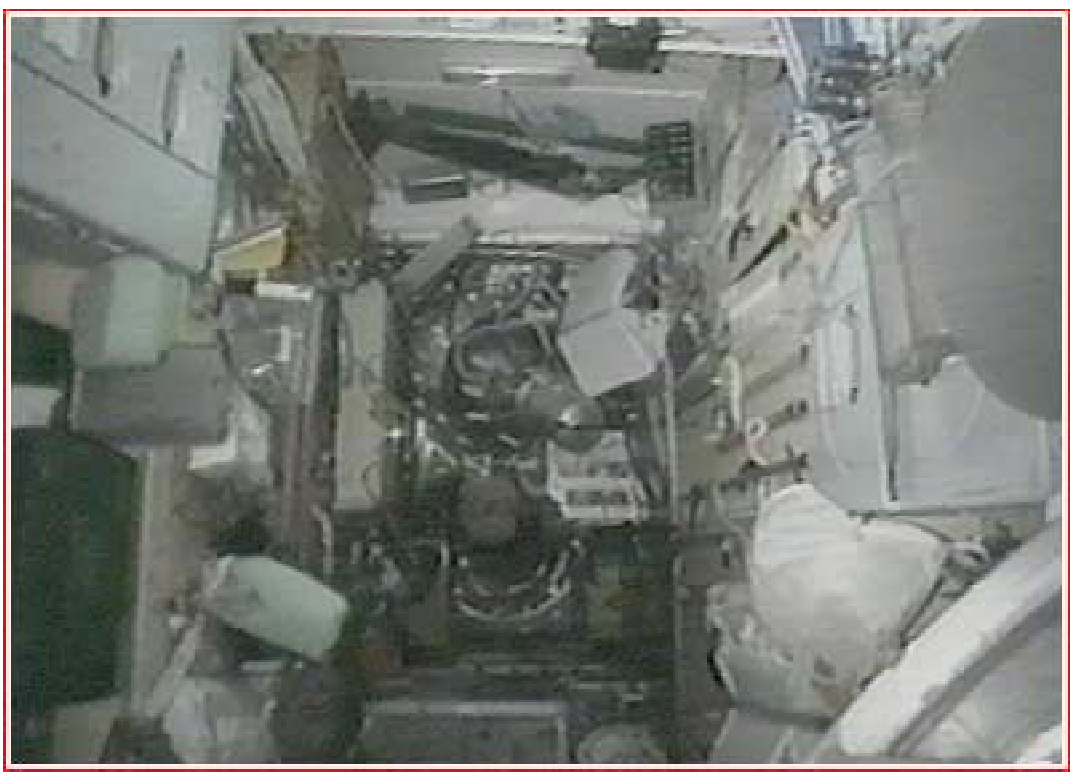

FIGURE 11. View of the Kvant-2 laboratory interior, credit NASA, photo taken by a Shuttle-Mir astronaut.

FIGURE 12. Astronaut Shannon Lucid on Mir, with a materials science glovebox, most likely in the Priroda Laboratory module, courtesy of NASA Headquarters.

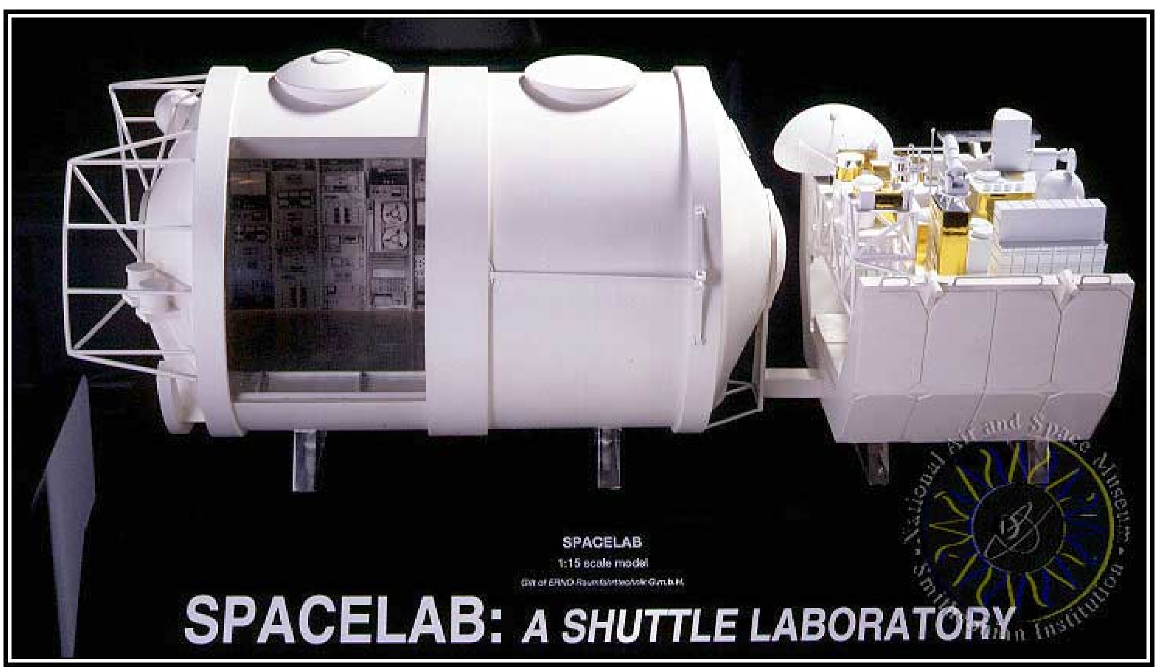

FIGURE 13. Excellent model of the Spacelab module with an external experiment carrier pallet, courtesy of the National Air and Space Museum. This representation was typical of the Spacelab configuration that flew in the Space Shuttle Columbia cargo bay.

FIGURE 14. Spacelab D-1 Mission, sponsored by DARA, the German space agency.   Visible in the photograph are astronauts, Guion Bluford (United States), Reinhard Furrer (West Germany) and Ernst Messerschmid (West Germany). Not pictured is Wubbo Ockels (Netherlands). NASA photo obtained from the National Air and Space Museum.

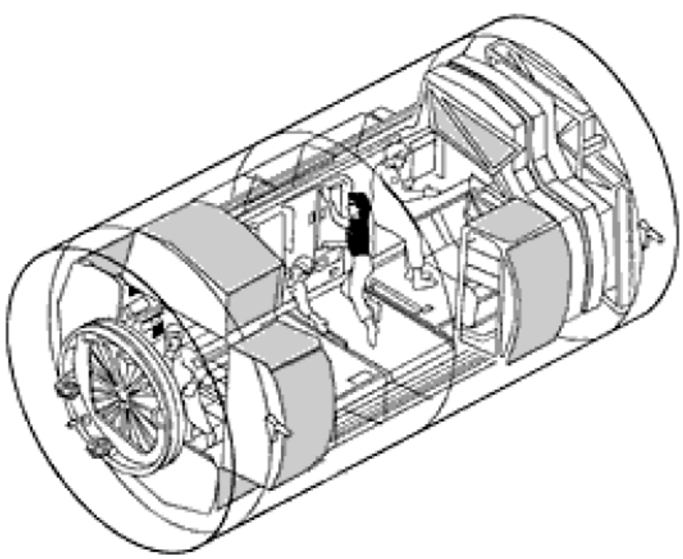

FIGURE 15. Space Station US Destiny Lab Module, courtesy NASA.

FIGURE 16. Computer Rendering of the Space Shuttle docking at the same node as the one to which the Destiny Lab is attached. Destiny appears just above the cargo bay, with a docking-port extension on its facing end dome, courtesy of NASA.

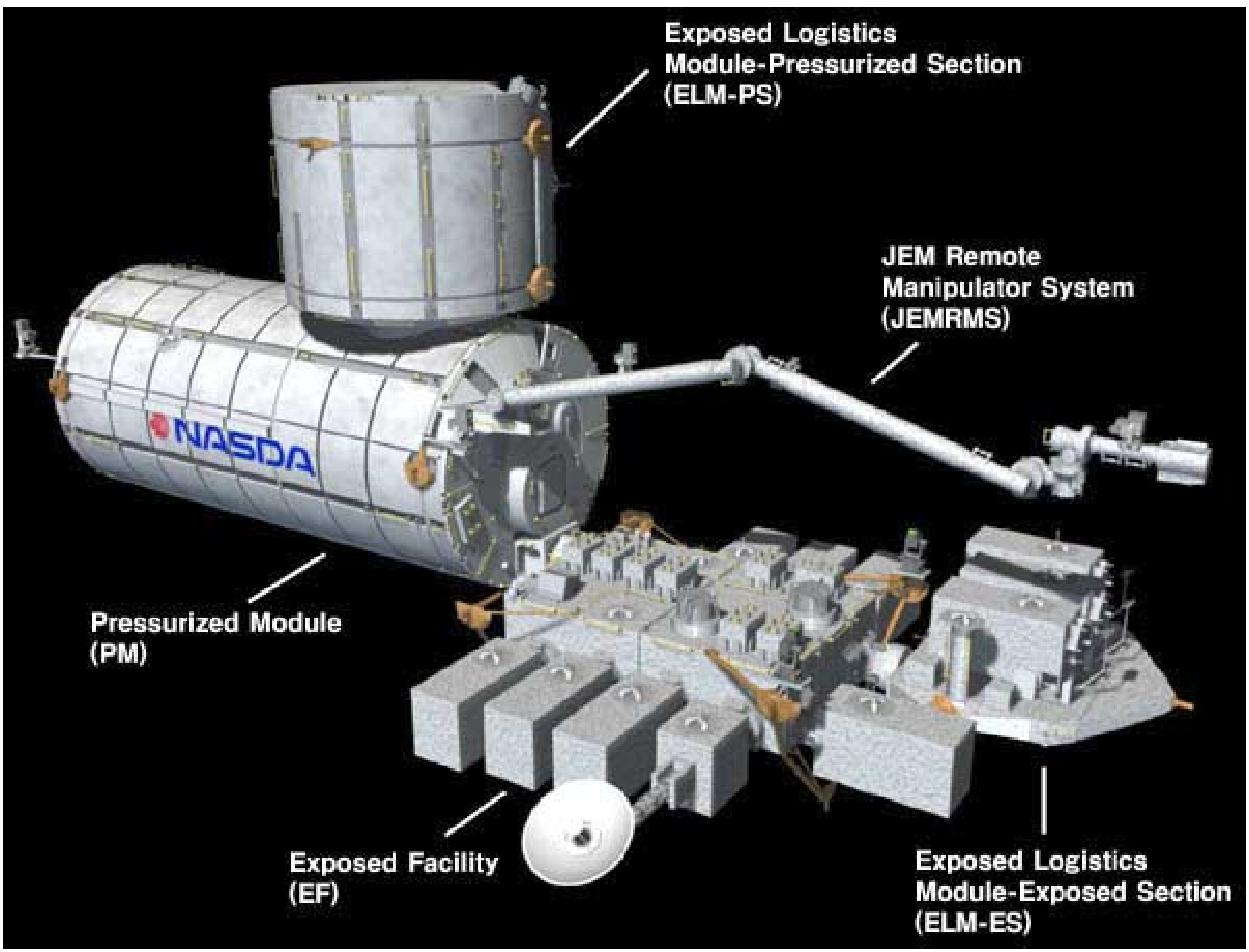

FIGURE 17. Detailed view of NASDA's Japan Experiment Module (JEM) "Kibo," courtesy of NASDA.

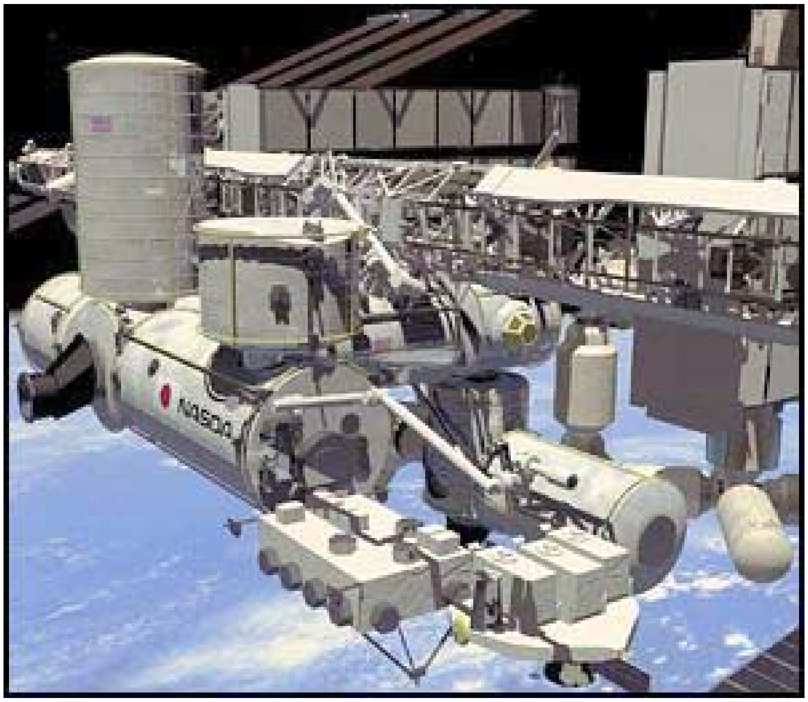

FIGURE 18. Computer rendering of the Japan Experiment Module "Kibo" attached to the Space Station, courtesy of NASA.

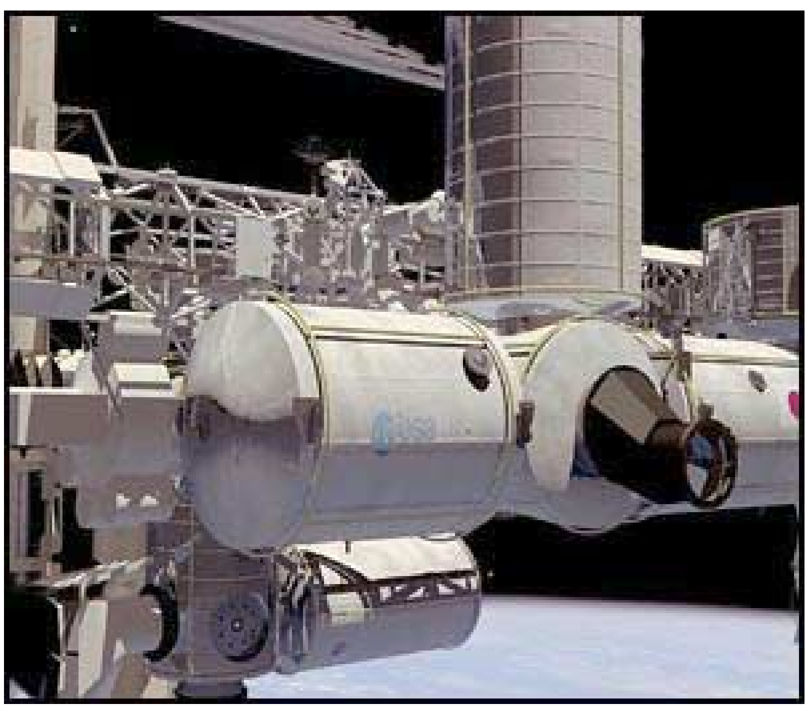

FIGURE 19. Computer rendering of the ESA Columbus Module attached to the Space Station, courtesy of NASA.

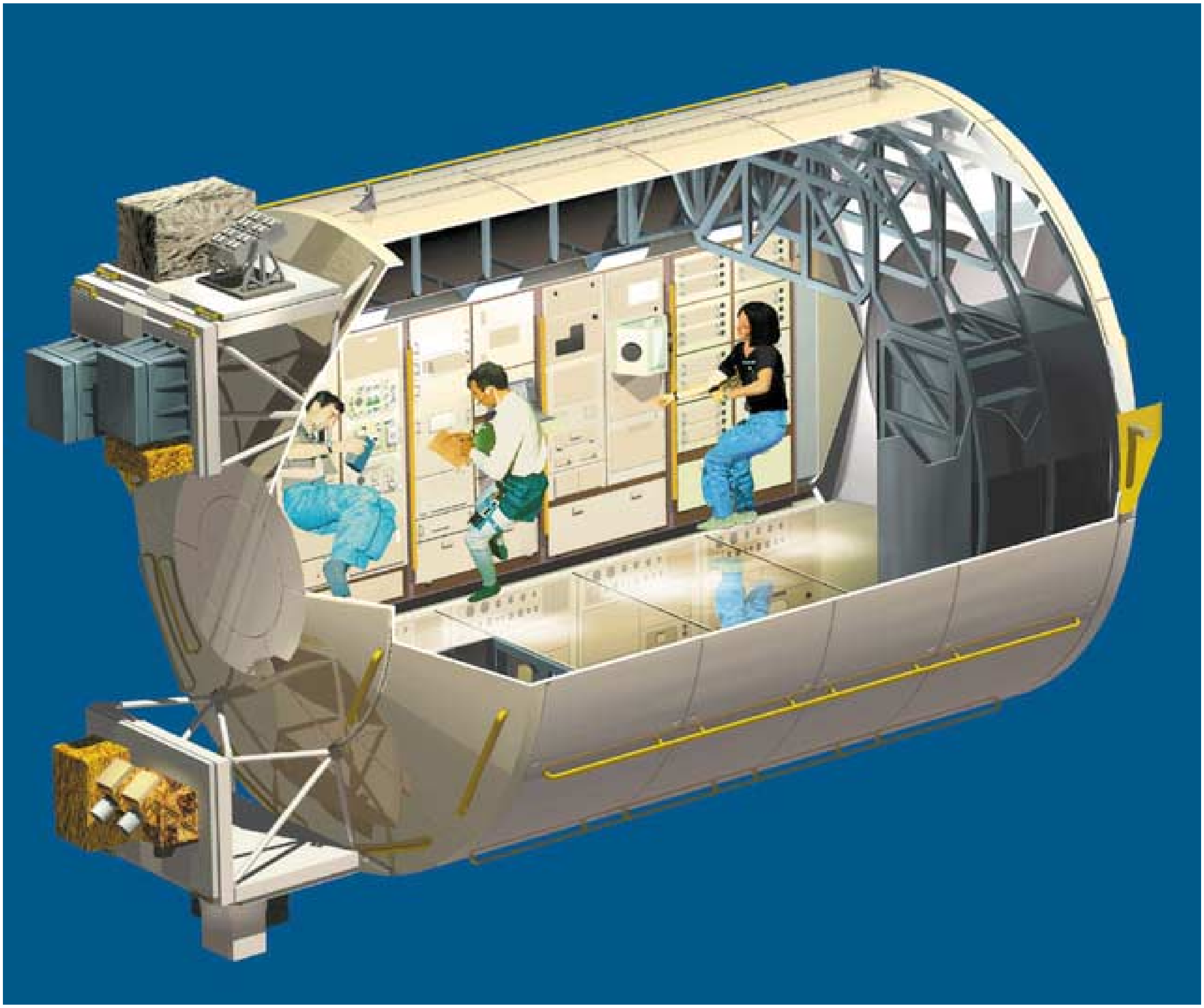

FIGURE 20. Artist's rendering of ESA's Columbus Laboratory Module, showing three crew members working on research in the module, courtesy of ESA.

FIGURE 21. ESA Fluid Science Laboratory (FSL) Rack, courtesy of ESA.

UNITS OF ANALYSIS

In developing this approach, it became necessary to define several sets of criteria as units of analysis. Each of these sets of criteria pertains to a different aspect or dimension of Space Laboratory design. These sets of criteria are:

SPACE LABORATORY SCIENCE DOMAINS.

1. Life Science
2. Microgravity Science and Processing
3. External Observations
4. External Operations

CREW PARAMETERS.

1. Crew Safety and Health
2. Crew Time
3. Meaningful Work

MODES OF OPERATION.

1. Ground Control
2. Crew Autonomy
3. Teleoperations from the Ground
4. Teleoperations from the Laboratory

SYSTEM DESIGN ISSUES.

1. Inseparable Design Issues
2. Infrastructural Design Issues
3. Cross-Cutting Design Issues

This Unit of Analysis approach necessarily generalizes, and for each generalization, there is no doubt an exception. However, a unit of analysis is more than a generalization, it attempts to capture the design values and considerations that go into space laboratory design. At the same time two units of analysis may overlap somewhat. The idea is not that they should be cleanly or mutually exclusive, but that an overlap or duplication suggests greater emphasis or importance in the conjunction.

SCIENCE DOMAINS— The science domains address four general areas of research and work for the crew to perform in a space laboratory.

Life Science—Life Science in space laboratories encompasses both human biomedical research and non-human animal and plant research. The non-human life science occupies a more extensive area of real estate in the laboratory modules, because of the need to accommodate the habitats, feeding equipment, surgical gloveboxes, and other rack or bulkhead-mounted apparatus that does not come into play for human medical subjects.

Purpose of Life Science Laboratory—Dalton, Searby, & Ostrach define the purpose of space life science experiments using non-human subjects:

> "The ultimate objective of all flights with an animal surrogate has been to evaluate and understand biological mechanisms at both the system and cellular level, thus enabling rational effective countermeasures for future long duration human activity under microgravity conditions . . ." (Dalton, Searby, & Ostrach, 1994, p. 1)

This definition could apply easily to human biomedical research as well, but NASA maintains a strict demarcation between animal life science and human biomedical research.

Centrifuge as Centerpiece—The centerpiece of Life Science research in space is the variable-gravity centrifuge, known as the Space Station Life Science Centrifuge (SSLSC). The complex of habitats, glovebox, and centrifuge are part of the Biological Research Project (SSBRP) facilities, which support the NASA Fundamental Biology Program. FIGURE 22 shows a view of the SSBRP, prominently featuring the 2.5m centrifuge that NASDA, the Japan Space Agency is building. Key components of the SSBRP include the Life Science Glovebox, developed by NASDA, and the Habitat Holding Racks, with the Habitats developed at NASA-Ames Research Center. FIGURE 23 shows the Life Science Glovebox for performing research procedures on animals and plants. FIGURE 24 shows a typical habitat for the SSBRP, the Advanced Animal Habitat. FIGURE 25 shows the two Habitat-holding racks. FIGURE 26 shows an alternate design for a Japanese habitat for fish.

It is not an exaggeration to state that the Centrifuge is the most compelling scientific reason to build and operate the Space Station. It will enable researchers to address the crucial question of what are the gravity cues necessary for normal biological processes, and what are the thresholds for effective counter-measures against the debilitating effects of microgravity. In the author's opinion, it is the most important enabling research on the Space Station to send humans safely to Mars.

FIGURE 27 illustrates another area of life science, human biomedical research. Unlike Dalton, Searby & Ostrach's definition, it concerns biomedical research on humans, without a surrogate. This direct approach is necessary for the many questions about uniquely human health and performance in space, for which a surrogate would not serve. A crewmember of Neurolab, sitting in the off-axis rotator, is ready to be spun, thus stimulating the inner ear. Also known as the Visual and Vestibular Integration System (VVIS), it was developed by ESA.

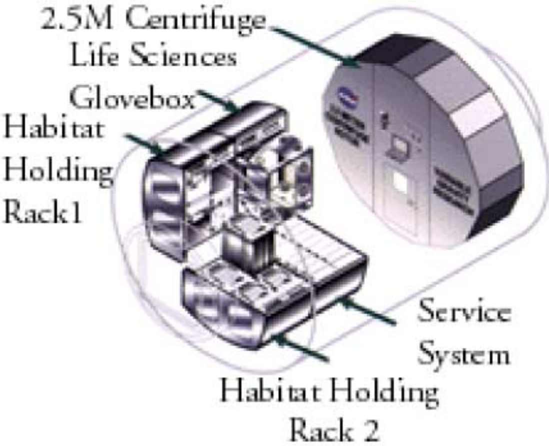

FIGURE 22. Isometric View of the SSBRP facilities, including the 2.5 m Centrifuge, Life Science Glovebox, 2 Habitat Holding Racks and the Service System Rack. NASA-Ames Research Center.

FIGURE 23. Life Science Glovebox, developed by NASDA, the Japanese Space Agency for SSBRP, courtesy of NASA-Ames Research Center

FIGURE 24. Advanced Animal Habitat for SSBRP, to be installed in a laboratory rack, courtesy of NASA-Ames Research Center.

FIGURE 25. Two Habitat Holding Racks comprise elements of the SSBRP, accommodating a wide range of habitat sizes and types, developed by Marshall Spaceflight Center for Ames Research Center.

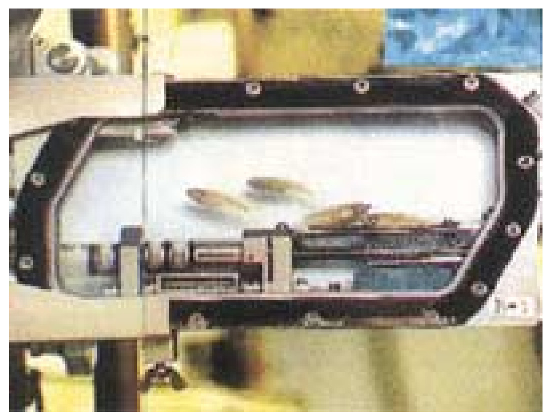

FIGURE 26. Japanese “Small Creature Growth Experiment, courtesy of NASDA.

FIGURE 27. Crewmember of Neurolab, a Spacelab payload, seated in the off-axis rotator, courtesy NASA MSFC.

Microgravity Science and Processing—Materials Science goes to the question of how materials behave in relation to gravity, and how they will form in the absence of gravity. The promise of microgravity materials science and processing includes the formation of protein and other biological molecules, the formation of crystals, and the discovery of new phenomena in the behavior of matter in all phases.

Materials Processing on Mir—The saga of Mir poses a valuable object lesson on how difficult the effective, economical and productive processing of materials can be. Andrew Salmon (1997) states that the goal of this Russian program was to develop gallium arsenide semiconducters with the assistance of microgravity. The goal was that eventually the Energia rocket would launch mass production platforms to LEO. Salmon explains:

> "The great hope of the Soviet Mir program appears to have been space-based semi-conductor production using the Kristall module, with its many furnaces. It was not to be. The problems were:

- Power shortages on Mir (a total of only 10 kW was being produced by its solar panels at the start of 1992 due to mutual shadowing of arrays and radiation degradation of the solar cells). In 1991 only 2 furnaces could be used at any one time due to power shortages
- Varying microgravity levels on Mir. It is not clear how serious this is but in 1991, it was claimed that the upper part of Kristall swinged [sic] when the treadmill on Mir was being used.
- Unreliable equipment. In 1991 it was claimed that only 1 of the 5 furnaces on Mir was "OK," with the others only working for short spells between repairs.
- Limited chances to fly samples back to Earth (partly eased by the Raduga return capsules)"

Fortunately, the US, European and Japanese Microgravity Materials Science programs enjoy a substantially greater measure of support and success than their counterpart in the Soviet/Russian Mir program. Also, the level of design and fabrication sophistication for these types of apparatus is generally higher today. Even when installed on Mir, the US devices functioned satisfactorily, within the limits of the resources Mir could provide.

One example of a successful project that returned valuable research was the MIDAS experiment from NASA LARC (Wise, et. al, 1995; Amundsen, et. al., 1998). This experiment to investigate superconducting properties at –80°C came equipped with its own quasi-cryo-cooler and was mounted in a Mir Storage locker in the Priroda lab module. The astronaut on Mir activated the MIDAS experiment by flipping a manual switch. "Some of the many challenges faced by project personnel were maintaining the HTS samples at cryogenic temperatures and in a vacuum, preparation and bonding of the samples, meeting the mass and volume limits imposed by the Shuttle and Mir, and performing all necessary testing to meet required performance standards" (Amundsen et. al., 1998, p. 1). All the laboratory facilities on Space Station Alpha should benefit from better support in all the areas in which Mir was deficient.

FIGURE 28 shows the Microgravity Glovebox developed for Priroda. FIGURE 29 shows the MIDAS hardware for installation and use in the Priroda module. This payload package typifies the "black box" approach to equipment development.

FIGURE 30 shows protein crystals being grown in a Japanese Microgravity science experiment.

FIGURE 31 shows the location of a glovebox as installed in the Mire Priroda laboratory module. This glovebox houses the microgravity isolation mount to provide isolation from vibration on Mir.

FIGURE 32 shows the Microgravity Science glovebox for Space Station Alpha, to be installed in the US Destiny Laboratory.

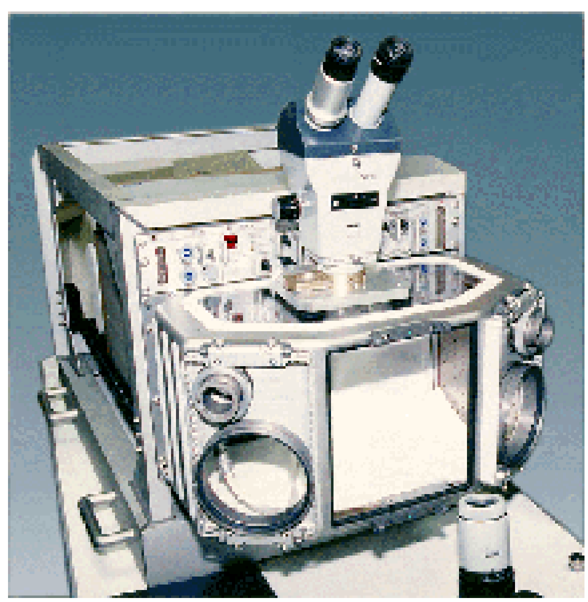

FIGURE 28. Microgravity Science and Materials Processing glovebox for Mir-Priroda, courtesy of NASA–Langley Research Center.

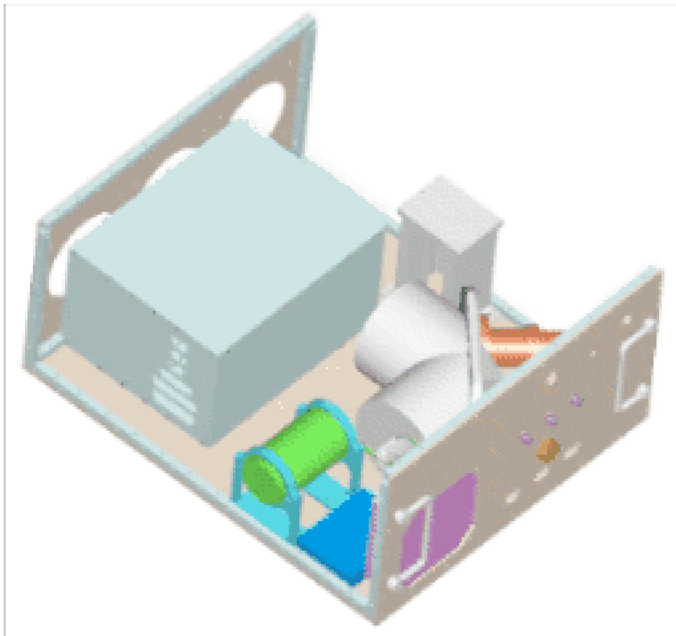

FIGURE 29. Flight Hardware configuration for the Materials in Devices and Superconductors (MIDAS) flight experiment on Mir-Priroda, courtesy of NASA-Langley Research Center.

FIGURE 31. View inside the Priroda laboratory module on Mir. Astronaut Michael Foale, in the background points to the "glovebox" unit, which houses the microgravity isolation mount, to isolate experimental procedures from vibration. Astronaut Jerry Linenger is in the foreground. NASA photo.

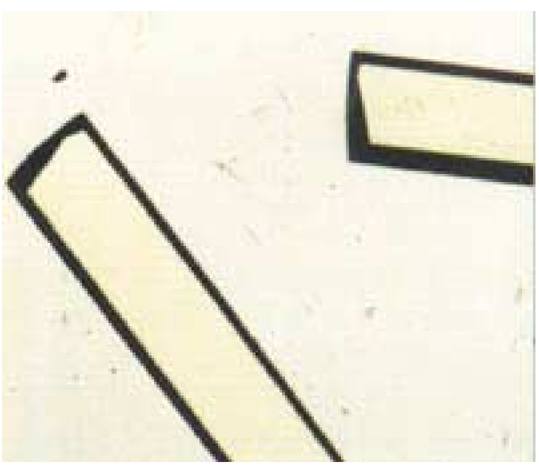

FIGURE 30. Protein crystals developed in a microgravity experiment to investigate the structure of proteins, courtesy of NASDA.

FIGURE 32. Microgravity Science Glovebox for Space Station, showing a versatile multi-port design, courtesy NASA-Marshall Space Flight Center.

External Observations—Space Laboratories provide a uniquely situated base from which crewmembers make a variety of external observations. These observations include Astronomy, Earth Science, Atmospheric Science, Oceanography, and studies of the space medium. Earth Observations are the most constant opportunity from a Space Laboratory or station. FIGURE 33 shows an example of a thermal-image Earth Observation.

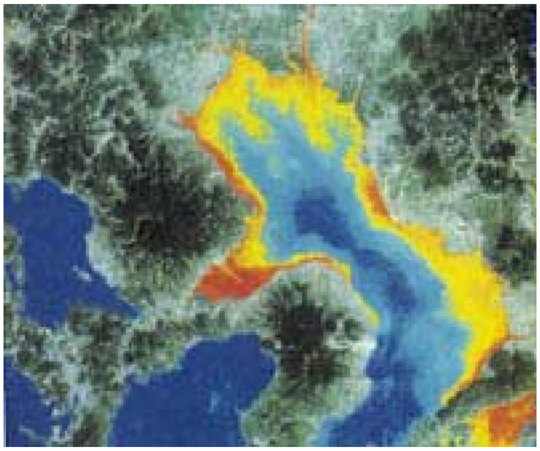

FIGURE 33. Earth observation of land, water, and atmosphere, showing temperature gradients, courtesy of NASDA.

Astronomical observations are less common from human-crewed space laboratories, but dramatic in their own way. The Apollo Telescope Mount (ATM) was a solar telescope that the Skylab crew used to make significant observations in solar astronomy. Because the Skylab was designed to fly solar-inertial, with one side always facing toward the sun to maximize the efficiency of its photo-voltaic arrays, it was ideally suited to serve as a solar observatory. Thus, it was simple to mount the ATM on the same side as the photovoltaic panels and always point toward the sun. The ATM was one of the most effective and rewarding crew-operated observatories sent into space to date. It achieved many milestones of observations. FIGURES 34 to 36 illustrate the ATM. FIGURE 34 shows the sun-facing side of Skylab. FIGURE 35 shows the Skylab 3 crew in the multiple docking adapter (MDA) on which the ATM was mounted and which housed the ATM control console. FIGURE 36 shows a detailed view of the ATM control console, from which the astronauts made their solar observations.

FIGURE 37 shows the dramatic image of “the great solar helium eruption” on the sun. This photograph of the sun was taken using the extreme ultraviolet radiation from ionized helium, in the 304 Angstrom wavelength, using the Naval Research Laboratory’s Solar Physics Branch SO82A Spectroheliograph on the Skylab ATM. In the author’s humble opinion, this image represents the single most exciting observation from a crewed space laboratory.

External Operation—Although external operations do not equate to a science *per se*, they can be a key to operating external devices from the space laboratory that are essential tools of scientific research. External operations may include the assembly, deployment, maintenance, repair, and operation of a variety of space facilities.

EVA is preeminently an external operation. Besides the use of the remote manipulator system (RMS) robot arm on the Space Shuttle, EVAs are the most extensive external operation that astronauts have conducted to date. Often, there is a trade-off between what the crew can do with the RMS and what they can do in an EVA. There have been several spacewalks on the shuttle to compensate for the inability of the RMS to complete certain tasks successfully. On the SSA, it is likely that a similar relationship will continue, with the Canadian robot arm performing much of the “heavy lifting” and “step n’ fetch-it” sorts of tasks, and the astronauts suiting up for “contingencies” or to compensate for shortcomings of the arm. A similar scenario is a possibility with the JEM/Kibo External Exposure Facility. Although the JEM robot arm is ideally situated to set-up and operate experiments on the External Exposure Facility, it is not yet clear the extent to which it can perform all the tasks set out for it.

A major role for EVA as part of external science operations is to install, repair and retrieve equipment or materials from the vacuum of space. One of the earliest and most dramatic examples was that on the last three Apollo lunar missions (Apollo 15, 16, and 17) the CSM pilot performed an umbilical-tethered EVA on the return trans-Earth injection to recover film and data tapes from the Service module. FIGURE 38 shows Apollo pilot Ron Evans retrieving film and data tapes from external instruments while in "deep space."

Perhaps the most notable deployment, maintenance, and repair of a scientific facility was the Hubble Space Telescope (HST). FIGURE 39 shows a detail of a Shuttle-HST servicing mission. On this mission, STS-82, the astronaut crew performed multiple spacewalks to replace a variety of equipment on the Hubble. With these EVAs HST signifies a nexus between external observations and external operations. Another example would be the remote operation of a robotic or teleoperated rover from a lunar or planetary base to a remote traverse site on the surface of the planet. In this case, the crew would be directing the mobile “observatory” in an external operation to go to the site of interest to make observations.

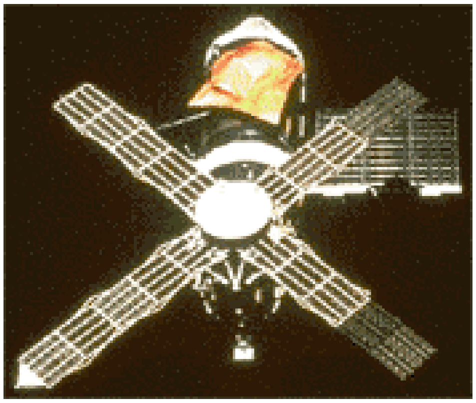

FIGURE 34. Skylab on orbit, with the ATM closest, surrounded by the "X" shaped solar arrays to power the solar observatory. The parasol erected by an EVA to protect the Saturn Workshop section where the shroud tore off on launch from overheating is visible behind the ATM.

FIGURE 35. The Second Skylab 2 (Skylab 3) Owen Garriott, Jack Lousma, and Alan Bean in the Multiple Docking Adapter to which the ATM was mounted and that housed the ATM Console.

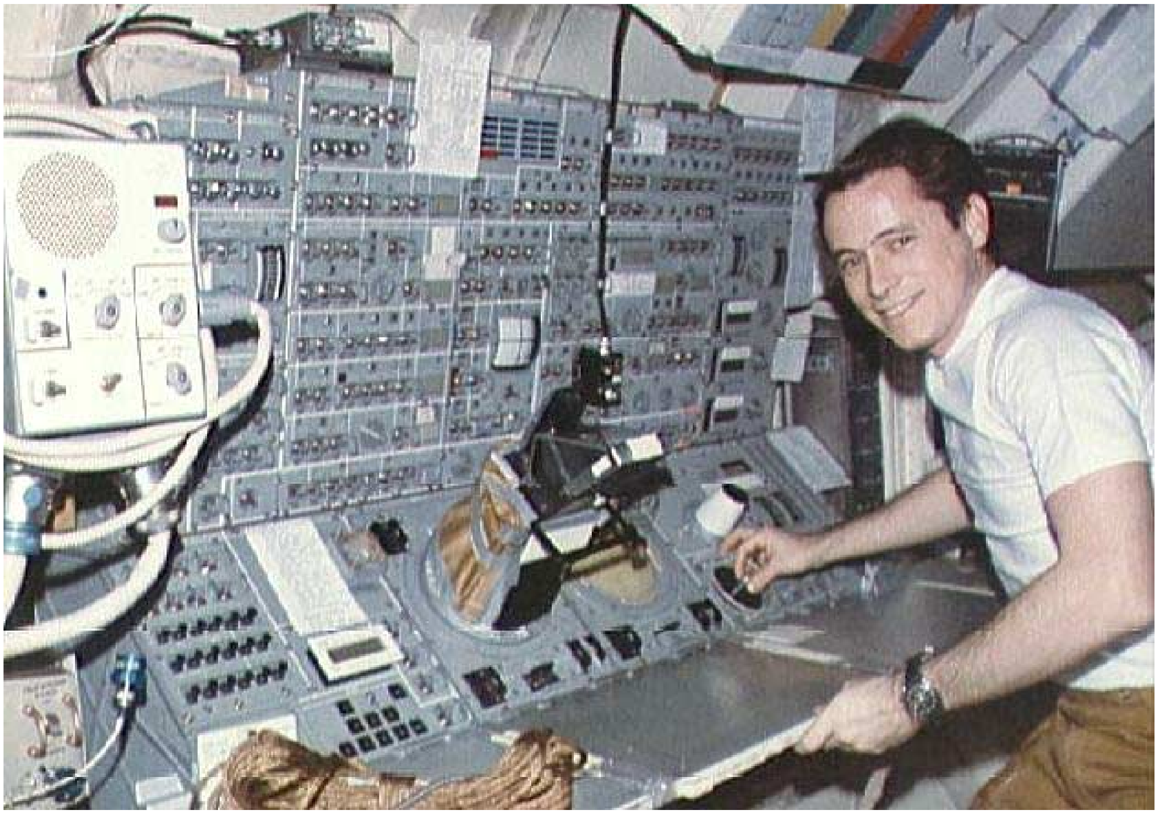

FIGURE 36. Skylab 4 Astronaut Edward Gibson at the Apollo Telescope Mount control console in the Multiple Docking Adapter. Courtesy of NASA-Johnson Space Center.

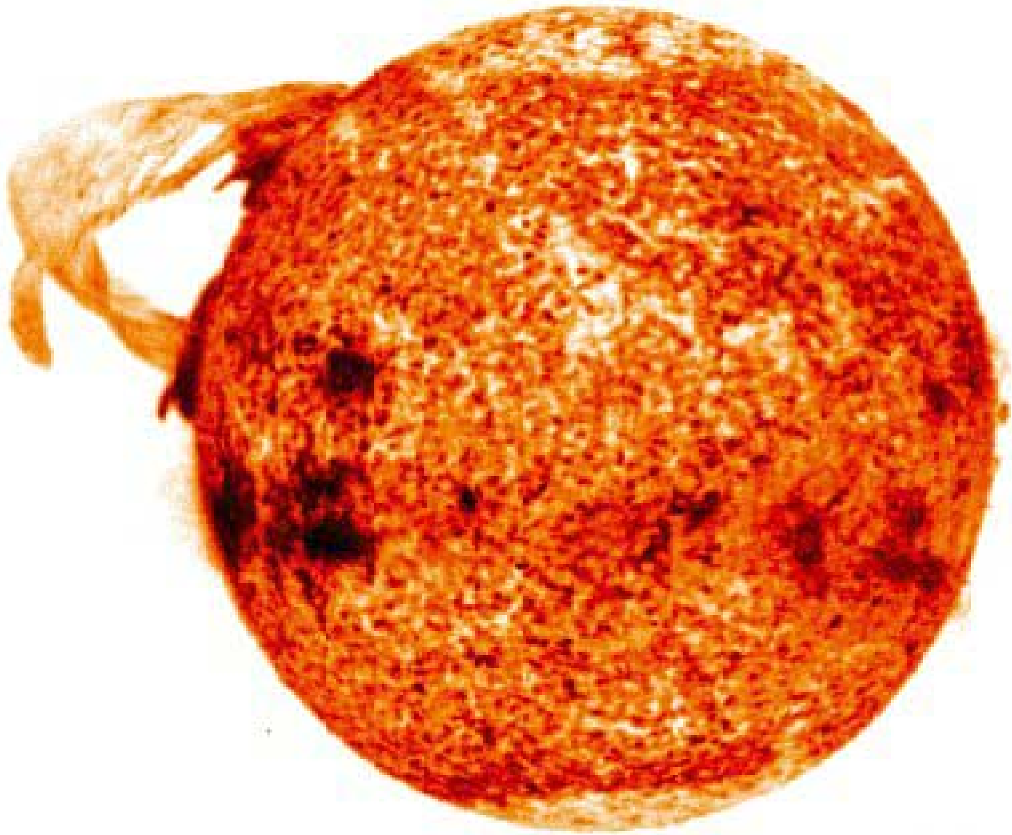

FIGURE 37. The “Great Solar Helium Eruption” captured by the Skylab ATM solar observatory in 1973.

FIGURE 38. (RIGHT) Ron Evans, Apollo 17 CSM Pilot performs a solo EVA in “deep space” to retrieve film from cameras and data tapes from instruments mounted on the service module during the return flight from the moon in1972. Photo courtesy NASA archives.

FIGURE 39. (ABOVE) Rendering of STS-82 servicing mission to the Hubble Space Telescope, EVA 4, Feb 17, 1997. Astronauts Harburgh & Tanner replace the Magnetic Sensing System Covers, with HST secured in the shuttle cargo bay. Credit: Lockheed-Martin.

A laboratory may host another kind of "external operation," which although not necessarily a science operation, has far-reaching implications for the lab and the station. This arrangement is the use of the laboratory to accommodate station-essential capabilities, such as the *Mir* Kvant-1 and Kvant-2 labs housing the gyrodyne CMGs to stabilize Mir and help it maintain its attitude. On the US Destiny Lab, 11 of the 24 racks are committed to station operations purposes, including "command and control, data management, robotics workstations, atmosphere revitalization and control, power distribution and management and thermal control" (Jones, 2000, p. 9). Although some of these functions support science payloads indirectly, it represents a significant impact on science capability when nearly half the accommodations in a lab module go to non-science infrastructural purposes.

CREW PARAMETERS—After extensive reading of design studies and mission reports, three crew parameters emerge as the dominant themes for crew activity in the space laboratory: Crew Safety, Crew Time, and Meaningful Work.

<u>Crew Safety</u>—Crew Safety and Health is NASA's highest priority. In the NASA value system today, Safety always comes before Mission or any notion of productivity. Safety is a prerequisite for productivity. In the landmark Rockwell International study for Space Station Crew Safety, Raasch, Peercy and Rockoff (1985, Vol. II) identified eight general threats to Crew Safety, and in addition, Rockoff, Raasch and Peercy, (1985, Vol. III) found ten Human Factors Safety issues. These concerns appear in TABLE 2. This paper treats a few of these safety issues that emerge as ***peculiar concerns*** for Space Laboratories: Fire, Contamination, and Noise. Scheduling and Territorial Issues arise separately in other parts of the discussion of laboratory operations. In addition, with the strong effort in biological research, both in orbit and in searching for life on Mars, it is now advisable to add specific Biohazards as its own topic (Funk & Johnson, 1991, pp. 2-3; Cohen July, 1999; Cohen, July 2000).

However, it is vital to recall that the Spektr Laboratory module on Mir was involved in the worst on-orbit accident ever. FIGURE 40 describes the trajectory that the Progress flew when the crew attempted a manual-remote docking. FIGURE 41 shows the damaged solar panels on the Mir Spektr Laboratory Module, following the collision by an unmanned Progress cargo vehicle in 1997 during a quasi-robotic docking maneuver. The Russians had refurbished the Spektr from its original military purpose to serve as the home for the joint US-Russian cooperative science program. All the US supplied scientific experiments were in Spektr when the near-catastrophic collision occurred, causing a life-threatening depressurizing leak in the Spektr.

Stephen Ellis investigated the causes of the collision, and found that the three immediate causes concerned how the cosmonaut was remotely maneuvering it:

1. The higher than planned initial closing rate,
2. Late realization that the closing rate was too high and
3. Incorrect final avoidance maneuvering.

However, Ellis probed deeper and found human factors causes at the root of the problem, including stressors from overscheduling, overwork, conflict with mission control in relation to whom the cosmonauts were in a subordinate position. (Ellis, 2000). These same types of stressors, mis-perceptions and antagonisms could cause an accident in a laboratory module as readily as they did in maneuvering Progress 234. In this vital respect, the space community should not regard this collision purely as an anomaly, but rather as an object lesson for what can happen if common, everyday stressors develop into degraded performance that results in human error.

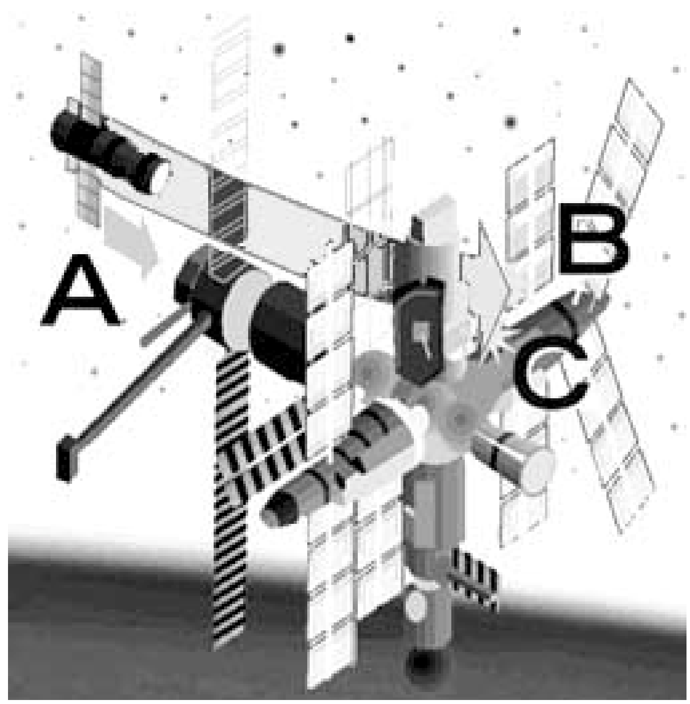

FIGURE 40. Arrow shows the approximate collision path of Progress 234. It approached Mir from above, passing along the Base module from A and striking the Spektr Module's solar panels at B and Spektr itself at C, courtesy of Stephen Ellis, NASA-Ames Research Center.

TABLE 2. Crew Safety Issues from the Rockwell Space Station Crew Safety Alternatives Study (Peercy, (1985)

Threat Concerns in **Bold** apply to the Progress collision with the Spektr module on Mir in 1997.

Threat Concerns in *Italics* apply to the fire and coolant leak on Mir.

Threat Concerns in ***Bold Italics*** apply both to the collision and the other incidents on Mir.

General or Constant Threats to Safety Volume II Raasch, Peercy, Rockoff	Safety Impact of Human Factors (Volume III) Rockoff, Raasch, Peercy	Space Station Safety Plan (Volume V) Mead, Peercy, Raasch Addresses ALL of Vol. II & III Plus:
Fire	***Crisis Management***	**Leakage**
Biological and Toxicological Contamination	Confinement/Isolation	**Tumbling/Loss of Control**
Injury/Illness	Acoustics and Noise	**Grazing/Collision**
Explosion/Implosion	Territorial Issues	*Corrosion*
Loss of Pressurization	***Behavioral Protocols***	**Mechanical Damage**
Radiation	**Scheduling**	Out of Control IVA/EVA Astronaut
Meteoroid Penetration	*Cleaning/Disinfecting*	**Inadvertent Operations**
Space Debris impact	Hygiene	***Lack of Crew Coordination***
	Recreation	
	Violation of Safety	

FIGURE 41. Damaged solar panels on the Mir Spektr Laboratory Module, following the collision by an unmanned, Progress cargo vehicle in 1997 during a robotic docking maneuver, Courtesy of NASA-Johnson Space Center.

Fortunately, soon after the collision, the Mir crewmembers were able to disconnect the cables and ducts that were routed through the Spektr's open hatch, so that they could close and seal the hatch. This action saved Mir from complete depressurization because all the other hatches were similarly unable to seal quickly as they were also being used as power and data cable conduits. The unfortunate consequence of the depressurization and sealing the hatch was that the US payloads became inaccessible to Michael Foale, the NASA crewmember aboard at that time. TABLE 2 shows in **bold** the threats that the Rockwell Crew Safety Alternatives Study predicted in 1985 that occurred in the 1997 accident and earlier incidents. The threats in italics show the ones that occurred in other Mir episodes, notably the fire in Kvant-1 and the coolant leak***. Bold italics*** apply to both the collision and the other incidents.

Fire Safety—Fire is a constant safety concern in all human habitations. Microgravity combustion research generally shows that flame spreads less readily than in a gravity field on Earth. Ironically, in microgravity space laboratories, fire is a double concern because of these same experiments in combustion research. FIGURE20 shows an experimental and control flame from one such combustion experiment. Robert Friedman touches precisely on this concern and the role of combustion research to improve fire safety:

> "Fire is a particularly feared hazard in confined enclosures, as in spacecraft. A serious fire in an orbiting spacecraft is an event of low probability; nevertheless, some fire threats are foreseeable. Obvious examples include those of electrical and heating overloads, spills and resulting aerosols, ***energetic experiment failure***, and ignition of accumulated trash [emphasis added](Friedman, 1999, p. 1)."

Friedman leads one to infer the irony of an experiment in combustion safety suffering an "energetic failure," thus creating the very hazard it hopes to avoid. FIGURE20 illustrates microgravity research in flame propagation and combustion, showing the omni-directional flame spread in microgravity. Friedman goes on to discuss the role of atmosphere selection in preventing fires, suggesting the possibility of atmospheres that "support human life yet inhibit fire spread" (Friedman, 1999, p.4). However, after discussing options for "oxygen-diluent atmospheres," Friedman raises a serious objection:

> "One argument against unconventional atmospheres is the need for reference air atmospheres for ***medical and biological experiments in space***. More compelling negative arguments are the logistic and structural impacts of gas-pressure and gas-storage changes and the unknown effects of long-term exposure to modified atmospheres on the crew performance and health under the stressful conditions of space operations" [emphasis added] (Friedman, 1999, p. 4).

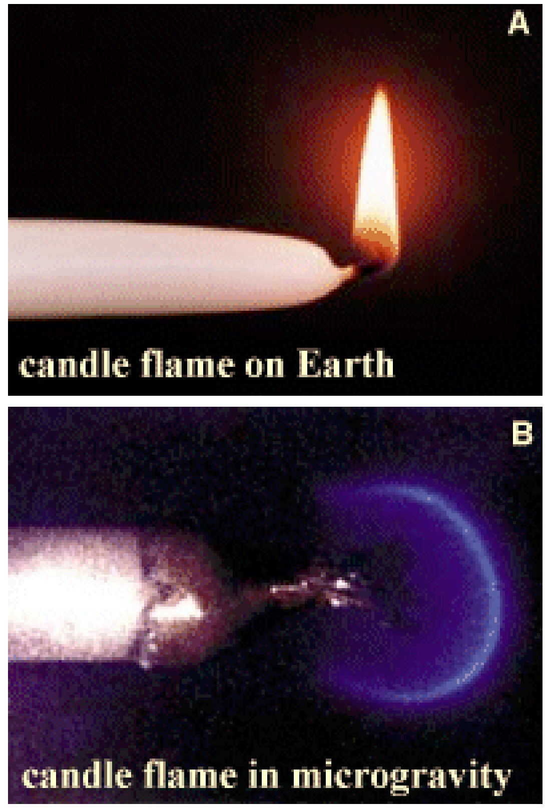

FIGURE 42. Illustration of comparative flame spread in microgravity in a space laboratory and in 1 gravity on Earth.

Although Friedman downplays the significance how peculiar atmospheres may affect biological and medical research, it goes to the heart of why the space laboratory should exist. A vital design decision for the International Space Station, back in the mid-1980s when it still carried the title Space Station Freedom concerned this very choice of atmosphere. The decision was to ***not*** introduce new unknowns into the research equation by having a different atmosphere on SSF than in laboratories on the ground, but instead to have one uniform atmosphere of one bar to facilitate biomedical research.

In a paradoxical sense, the *Mir* fire in the Kvant-1 lab module in February of 1997 was a fire aggravated by the presence of a "special atmosphere." The fire was caused by the failure of an "oxygen candle" – a solid fuel oxygen generator (SFOG) and the "special atmosphere" was the enriched oxygen from the SFOG itself. Friedman states succinctly: "The Mir fire propagated in a highly convective local environment, at an elevated oxygen concentration, self-generated by the source of the fire. It is no surprise that these conditions favor rapid flame spread even in microgravity" (Friedman, 1999, p. 5).

Solutions for Fire and Contamination—Evacuating a Module—One solution of nearly last resort is to purge a module of its atmosphere to extinguish a fire or to expel contaminated air. Robert Friedman remarks on this measure for rapid venting of a module. He goes on to point up that clean up after a fire will be a substantial challenge that can severely and adversely effect laboratory equipment and payloads:

> "Atmospheric revitalization to remove even trace quantities of fire and extinguishment contamination may tax the environmental-control system and require the use of portable crew breathing equipment and filters for periods of time. On a longer time scale, the subtle toxic and corrosive aftereffects of the fire on equipment, systems and payloads must be recognized and appropriately controlled (Friedman, 1999, 11)"

Contamination Control—Inventory Management—Hector Garcia argues for effective inventory control systems as a primary means to prevent and control chemical and biological contamination.

> "During the many years that the ISS will be in use, a great number and variety of chemical and biological materials will be located in the pressurized volume of the ISS. These will include materials that are components of scientific or medical experiments as well as utility chemicals within systems of the ISS modules such as the environmental control system and life support systems, fire suppression systems, and spacesuits. The list of materials will be constantly evolving as additional materials are brought on board, and stored and/or processed, or removed from the ISS. . . . Chemicals and biologicals are assessed for toxicity and assigned a hazard rating . . ." (Garcia, 1999, p. 1).

Although Garcia does not specifically discuss the laboratory modules on the Space Station, it is self-evident that a major demand for new toxic or hazardous materials will derive from laboratory experiments. These biological and chemical substances are the ones Garcia intends to track with hazmat stickers, bar codes, and other descriptive labeling.

The Modular Habitat Principle—Bonting, Arno, Kishiyama and Johnson were the first to articulate the "modular habitat principle" to achieve reliable bioisolation on the space station. They identified three main problems from the early Spacelab Life Science experiences when some small quantities of matter and odors escaped from the research animal holding facility (RAHF) rat cages:

- Release of **particulate matter**, e.g. food particles, hair, and fecal matter into the cabin;
- Passing of **microoganisms**, especially pathogenic ones, from animals to crews and vice versa;
- Presence of **odors** from the animals and their waste products into the cabin atmosphere [original emphasis] (Bonting, et. al, 1988, p. 1).

To prevent these contaminants from escaping, Bonting, et. al., envisioned the modular habitat principle, which involves "primary bioisolation at the cage level and additional levels of bioisolation beyond the cage." This philosophy results in a system of enclosure envelopes or layers, starting with the cage unit and building outward to the habitat enclosure, which in turn is installed in a specially engineered habitat holding rack that provides the crucial air supply and filtration system.

NASA Ames Research Center built a prototype Space Station animal habitat prototype. Five years after Bonting et. al.'s seminal analysis, the rodent habitat bioisolation system was subjected to testing. Strength et. al., found that the two levels of bioisolation were shown in rigorous testing "to meet stringent NASA requirements" (Strength, et. al., 1993, p. 5).

Chemical contamination is equally a concern. NASA developed the General Purpose Work Station (GPWS) for the Spacelab Life Sciences-1 mission for among other objectives, the high priority purpose of containing the chemicals required in the experiments. The chemical containment model for GPWS specified the maximum allowable chemical release in terms of the Spacecraft Maximum Allowable Concentration (SMAC) level and the chemical spill residue within the GPWS itself. The GPWS flew successfully on SLS-1, SLS-2, SL-J, and several subsequent Spacelab flights. (Schmidt & Flippen, 1994, pp. 1,4,5).

Evacuating Lab Module Atmospheres—Barker, Alalusi and Horstman studied purging the atmosphere in a laboratory module as a way to eliminate fire and contamination. To suppress a fire, they predicated an evacuation by lowering the partial pressure of oxygen in a module to 51.7mm Hg (1.0 psia) in ten minutes. To remove a hazardous (e.g., contaminated) atmosphere, they would lower the total atmosphere pressure to 20.7mm Hg in 24 hours. One of their concerns was that with the humid atmosphere rushing out through the depressurization valves, ice could form in the ventilation relief valve (VRV) assembly (Barker, Alalusi & Horstman, 1999). Evidently, these safety concerns and potential countermeasures will remain ever in the forefront for space laboratory safety.

Noise—Noise in the space station or laboratory can be all pervasive and inescapable. It is a continuing source of concern and environmental stress on the crew.

> "Noise constantly effects astronauts physically, psychologically and functionally, and comes out high on the list of irritating environmental pollutants on spacecraft. The irritant effects of noise are well documented. It can cause stress and pain, disorientation, vertigo, nausea, fatigue, loss of appetite and interfere with sleep and normal speech communication." (Rockoff, Raasch & Peercy, 1985, p. 33).

On SSA, the baseline noise from the environmental control system comes from the common cabin air assembly (CCAA) including the thermal humidity control (THC) that distributes air for heating, cooling and ventilation to each of the modules in the Space Station except the Mir-like Russian core. The noise is worse in the US-made nodes (than in the Destiny Lab) because the intermodule ventilation fans (IVM) are located there to distribute conditioned air to the adjoining modules (Wang, 1999, pp. 1-2).

Tico Foley points out that the noise environment in the Space Station will be both qualitatively and quantitatively different from the typical experience on Earth. The major difference is that on the Station, there will be no retreat from the noise. The crew will spend not just eight hours in a noisy working environment and then "returning home to relative quiet," but instead will spend 24 hours in a total noisy living and working environment. Foley states: "These extended exposure times could result in communications difficulties and cause hearing damage; they could also be annoying and stressful and cause degradation in work performance" (Foley, 1998, p. 6).

More recently, Malcolm M. Cohen documented how fluid shifts in the body due to microgravity can make non-verbal communications more difficult. This finding is important because in a noisy environment, people tend to rely more on non-verbal cues for communication, including looking at each other's mouths and facial expressions. However, when the face is changed or distorted by excess fluid, it can impair or deny space crewmembers this common ability to work-around the difficulties of a noisy environment (Cohen, Malcolm, 2000 September, p. A55).

<u>Crew Time</u>—Crew time is a limited resource, vulnerable to many mission impacts. Garegnani & Allen (1990) presented a detailed accounting of how crew time might be allocated on the Space Station, and described a multiplicity of "subtractions" from crew time that might otherwise be available for mission or payload activities. TABLE A-1 presents a breakdown of crew time for six crewmembers adapted under somewhat different assumptions from Garegnani & Allen's analysis. TABLE A-1 is based on the severe time constraints on a Space Station crew of six performing laboratory work. Out of a 24-hour day, it will be challenging for each crewmember to devote more than about six hours to work in the laboratory.

Skylab 4 Experience—Skylab 4 was the first mission on which the pressure of intensive scheduling over a very long period of operations provoked an adverse reaction in the crew. It was a clarion call for a different way to approach mission operations design, management and scheduling.

> "Midway through the 84-day mission, the third crew refused to conduct assigned tasks. This one-day "strike" was imposed to protest the overloading of time by mission controllers. The crew spent the day in individual pursuits, mostly looking out the window. . . . The third Skylab crew demonstrated the problems associated with overscheduling. With boredom a constant threat of potential stress, it is often seen as wise to make days extremely busy, leaving little time for reflection or inactivity." (Rockoff, Raasch & Peercy, 1985, pp. 9, 44).

Unfortunately, this "wise" concern to keep the crew frantic with busy-work may lead to greater stressors than from unencumbered time.

Crew Timelines—As early as 1979, Sieber, et. al., who conducted the Spacelab Mission Development Test III (SMD III), identified part of the basis of the scheduling problem in assuming Earth-normal time lines for space laboratory operations. These "Earth-ideal estimates" create unrealistic expectations of the laboratory crewmembers who perform the work. In SMD III, Sieber, et. al., found that these realistic timelines, including "appropriate goals, lead times, staff and budget," are a pre-condition to proper human-machine engineering, particularly to adapt science procedures to space conditions. Beyond the planned payload design, development, training and operations, Sieber, et. al., make a strong case for serendipity.

> " Realistic contingency time lines must be established so that unexpected scientific findings can be responded to. The purpose of manned scientific missions is to provide a system component ***— a person — who is able to respond to the unexpected scientific event.*** Yet time lines typically do not take such contingencies into account" [emphasis added](Sieber, et. al, 1979, p. 7).

All space laboratory payload planning attempts to incorporate an allowance for the difference between Earth-normal and microgravity conditions. For the NASA Spacelab Life Science, this time margin was typically 20% (Wynn, 2001). However, despite this precaution, in all space laboratory programs—Skylab, Salyut, Mir, Spacelab—the crew have often been overloaded with work and fallen behind in their work schedules, making up their assignments by "working overtime" during their "off-duty" hours. Six years later, Rockoff, Raasch, and Peercy of the Rockwell International Safety Office observed *these **inseparable** properties* regarding Task Timelines and Workspace:

> "It has been noted on the Shuttle/Spacelab flights that work space within a module is at a premium. The allocation of work tasks should be incorporated into the timeline to ensure that people will not be working on top of each other. On one of the Russian flights, a personnel problem occurred when one of the cosmonauts proceeded to do the other's work." (Rockoff, Raasch and Peercy , 1985, p. 41).

The discussion of inseparable system design issues appears below.

One of the most provocative statements in the space crew work load/health literature came in an anonymous interview with a pre–shuttle astronaut conducted by Bill Douglas, flight surgeon for the original Mercury 7 astronauts.

> "Lets ease off on the work load. Let's let the astronomers have some time to just sit there and look through telescopes. What's wrong with that? That's where all the great astronomers got all their great ideas anyway (Douglas, 1986, p. 41)."

This notion of crew time being open-ended to enhance the opportunity for new discoveries segues into the idea of meaningful work.

Scheduling Affects Health and Safety—The general perception of the relationship between habitability and productivity is that habitability in its fullest sense—including food, sleep, health, recreation, and companionship—should foster and support productivity in the work arena. However, there is significant data, which indicate that a difficult or unsuitable working condition can rebound upon the health and well being of a long duration space crew. Vander Ark, Curtis, Holland, and Flynn state

> "In any space or analogue environment there are consequences for work underload, work overload, unrealistic schedules, and 'make work.' Each exacts a toll on the psychological health and well being of humans operating within that environment. If previous experience is an indicator, it will also be necessary to remind managers, mission planners, and controllers throughout the mission of work and schedule issues' affect on psychological health and well being, ***preferably before the crew grows too irritated***. [emphasis added] (Vander Ark, Curtis, Holland and Flynn, 1997, p. 5).

Ironically, many articles on space habitability do not address these critical working conditions. Even when an article specifically refers to ***humans working in space***, it is not unusual for it to say nothing directly about the space laboratory working environment (e.g., Bishop & Eckart, 1999). The crew selection literature also is singularly silent on the question of long term scientific undertakings. While the literature addresses substantially the crew selection criteria for long duration missions in general, (e.g., Galarza and Holland, 1999) there does not appear to be anything that goes to space laboratory work in specific.

Meaningful Work—The crew members--especially the mission and payload crew—need the opportunity to be intellectually involved in their work. Helmreich, Wilhelm and Foushee (1988, p. 5) emphasize the importance of "crews with meaningful work" for the validity of all space-related research in human factors. While their focus is upon analog studies, the same principle applies to actual space crews as well. They need to be engaged in meaningful work, not just tending a machine. The design of the space laboratory and all its payloads, payload accommodations, and systems to support high intellectual level tasks goes to the heart of *meaningful work*. The essential question is whether the people serve the machines or the machines server the people.

Writing the same year as Helmreich, Wilhelm and Foushee, the Astronaut Byron K. Lichtenberg linked the precepts of meaningful work and automation, and stated a philosophy with far-reaching implications for the design of space laboratory systems:

> "The workstations of the future should support automation and possibly artificial intelligence. The crew should have the benefit of working on ***intellectually valid tasks***, not simply controlling a parameter like DC offset or gains. The philosophy should be to use the person in the higher level control of experiments rather than closing the loop to control a specific parameter. . . . Research concepts that need to be explored include the degree to which automated systems control experiments." (Lichtenberg, 1988, pp. 2-3).

Thus, the top-level question for space laboratory design with respect to the crew is: can the crew fulfill this philosophy with the support of design, engineering, operations, scheduling, automation, training, and communications? Ideally, system designers should be able to derive an algorithm to optimize for these factors, but it is beyond the scope of this paper. The design of space laboratory facilities, missions, and payloads, and the operations, training, logistics, crew selection, and communications to support them still to occur on a case-by-case basis.

MODES OF OPERATION—These four modes of operation correspond generally—but not entirely—to modes of control. These modes are *ground control, crew autonomy, teleoperations from the ground,* and *teleoperations from the laboratory*.

Ground Control—With respect to Space Laboratories, ***Ground Control*** refers generally to the role of principal investigators on the ground, who work through a Payload Operations Control Center (POCC), giving directions and receiving data from the space laboratory crew. FIGURE 43 shows the POCC at NASA-Marshall Spaceflight Center, via which researchers may interact with the Space Station crew members who are operating or servicing their payload experiments.

FIGURE 43. Spacelab Payload Operations Center at NASA Marshall Spaceflight Center in Huntsville, AL., courtesy NASA-MSFC.

Crew Autonomy— As the Skylab 4 mission revealed in 1973, the relationship between the crew and ground control has the potential to become highly problematic. Autonomy can cut both ways, both in terms of the crew being thrown upon its own resources and ingenuity. The causes can derive from a lack of support from the ground and conversely because of "too much" support from the ground (e.g., "micromanagement,") or perhaps support of the wrong kind, such as inadequately empowered, oriented, prepared, supported, or trained or ground control personnel . In this section, two quotations present these two perspectives. The Russian experience on Salyut and Mir was to develop a remarkable degree of crew autonomy and ingenuity to compensate for a lack of ground support and the American experience consists of dealing with a different system of ground support.

Russian Experience: Communications and Autonomy—In some cases, crew autonomy is not a purely voluntary choice or deliberate design decision. This "involuntary autonomy" arose on *Mir* because of the long zone of exclusion times (ZOE) due to the lack of Russian tracking station coverage—especially in the post-Soviet era—compared to NASA's TDRSS satellite system, which gives almost zero ZOE. Savage, Jahns & Schnepp (1998, pp. 4-5) describe the situation the NASA Fundamental Biology payloads encountered on *Mir*.

> "The long duration mission operations associated with the NASA/*Mir* program were characterized by significantly less voice and data downlink than typical Shuttle/Spacelab missions. Due to the lack of long communications passes with Russian ground control personnel, crew comments relative to experiment status were limited to negative reporting, primarily. This meant that unless something had gone wrong with an experiment, no status information would be provided. The primary exception was if specific data was required to be voiced down as part of an experiment procedure. With limited communications to the ground, then, ***the onboard Mir crew was responsible for more autonomous problem resolution*** than typical Shuttle/Spacelab missions" [emphasis added].

Although the cosmonaut crews on the Salyuts and Mir developed a remarkable degree of self-reliance and resourcefulness, in a command sense they rarely asserted true autonomy. The reason for this contradiction is that the Soviet and later Russian mission control operations exerted very strong lines of authority over virtually every decision that the cosmonauts made. Working with the team and supporting the communal effort tends to be a higher Russian cultural value than individualism, which is reflected in their command and control infrastructure.

American Experience: Crew need for Autonomy—Vander Ark, Curtis, Holland and Flynn discuss the problem of overbearing intrusion from flight control personnel on the ground. They state

> "Another key issue for successful exploration mission [sic] would also be the best countermeasure . . . . That is providing a significant amount of crew autonomy. Science, maintenance, housekeeping, and other task scheduling should be done largely in situ at the discretion of the CDR and the crew. Since communication will eventually become cumbersome, flight rules should be established

before launch that guide routine activities, science or payload activities, and other operations such as in-flight training. Optimally, these activities will be scheduled by the crew***. Though diametrically opposed to current spaceflight operations***, this approach would be in the best interest of the crews, who will know best how to manage their workload, how to efficiently accomplish their tasks, and how best to share and rotate regular maintenance and housekeeping" [emphasis added](Vander Ark, Curtis, Holland and Flynn, 1997, p. 5).

It is a typically American reaction to espouse self-reliance, and rugged individualism as the solution to a wide variety of problems. Yet, in a situation where "communications become cumbersome" as on a human mission to Mars with 40 minute communication delays, such autonomy may become essential and inevitable. Indeed, a degree of crew independence from mission control may facilitate crew bonding and team building to the benefit of long-duration missions.

Automation • Autonomy—Much of the discussion of crew autonomy revolves around automation, and often the two become confused. The essential issue is whether the people serve the machine or the machine serves the people (Cohen, 1990, p.353). If the people are controlled by scheduling from a machine, regardless of how highly automated that machine is, they lack autonomy. If the crew enjoys a real measure of true autonomy, they will direct the machines to support them. Teamwork should include the role of automation as a "team player," (Malin, J. T., et al, 1991).

Mary Connors describes a parallel reservation that emerged in the commercial aviation world: "Although the rationale for increased automation was reduced crew workload (allowing a reduction in flight crew size from three to two) some were beginning to express skepticism by the mid 1980s about the value of automation, and more importantly about its safety" (Connors, 1993, p. 4.)

The design process should evaluate the allocation of tasks between human crewmembers and machine crewmembers also known as automation (Billings, 1991). This evaluation includes full consideration of automation failure modes and their effects. (Palmer, E., 1995; Malin, et. al., 1991,). Designers of automated systems should consider the principles of Human-Centered Automation set forth in Billings (1991), particularly the caveat "Do not automate any function without a good reason for automating it." According to Billings, automation should be: accountable, subordinate, predictable, adaptable, comprehensible, flexible, dependable, informative, error resistant, error tolerant, and simple enough for the human operators to understand.

The conception and design of automation can provide a great boost to human productivity or may undermine it with the need to make constant adjustments and exceptions not needed for manual operations. According to this philosophy, the guiding principle of Human Centered Automation should be to implement systems that will make the crew most productive at higher level activities and functions -- not simply to automate those functions that appear easiest to automate or that appear most easily segregated from other functions. Ideally, automation should increase productivity by relieving crew members of boring, routine, or repetitious tasks that are prone to errors or omissions because of their intrinsic nature OR that would diminish the crew's situation awareness, distracting them from vital responsibilities. Automation should become more active with increased workload on the crew off-loading lower level tasks from the crew, and become less active with decreased workload on the crew, passing tasks back to the crew.

Tele-Operations from the Earth to the Lab—Telemedicine represents perhaps the best-developed exemplar of teleoperations from the Earth to the space laboratory. In this case, telemedicine would support crew health, which generally falls within the area of habitability, but the principles apply perfectly to space laboratory payloads and experiments. Simmons, et. al., present an illuminating table of Telemedicine Modalities, reproduced in the APPENDIX as TABLE A-2.

Teleoperation Latencies—Simmons, et. al., refer to three modes of this system of teleoperation*: Real-time, Just-in-time,* and *Store-and-forward,* distinguished by variable latency or time delay. Real-time is best, with a latency of <5 seconds that allows "natural person-to-person interactions." Just-in-time is next best, with a latency of 5 seconds to 30 minutes that causes "uncomfortable person-to-person interactions." Finally, the Store-and-forward mode, with a latency of >30 minutes yields "unnatural or no person-to-person interactions."

Modes and Missions—These latencies apply to space laboratories in specific ways. Teleoperation to a space station in Low Earth Orbit would be *real-time*. Teleoperation to the moon or to an interplanetary vehicle on route to Mars or returning from Mars on a conjunction class trajectory would most often fall within the Just-in-time mode. Teleoperations from Earth to Mars fall in either the *Just-in-time* or *Store-and-Forward* mode, depending upon the relative proximity of the planets. Teleoperations from the Earth to an interplanetary vehicle beginning its return from Mars in an Opposition class mission would most likely be store-and-and forward.

The term "Just-in-time" merits attention. It derives from the Japanese automobile industry, where the just-in-time inventory system allowed suppliers and manufacturers to reduce their stock on hand, and to ensure timely delivery of parts to workers on the assembly line, where it served as an essential concomitant of the "team concept." The full translation from the Japanese is: "just in time — respect for workers."

<u>Tele-Operations from the Lab</u>—Teleoperations from the lab appear somewhat counter-intuitive at first. Why should NASA spend the cost of sending a crew member to Mars, only to have her do work that can be done much less expensively from Earth – operating a robotic rover, for example. Exploration scientists offer an alternative scenario:

Telerobotic Work Station— Stoker, McKay, Haberle and Anderson (1991, p. (4)81) propose a telerobotic exploration system that relies upon a system of "geostationary"—or perhaps more correctly, "arestationary"—communications satellites so that a telerobotic control station anyplace on Mars could control a rover anywhere on Mars. Operating a rover from the science laboratory on Mars will give the exploration crew the opportunity to explore an area in virtual space and more or less real-time before undertaking the risk of a rover traverse expedition and associated EVAs. The telerobotic work station is an essential component in this system of virtual exploration. David Lavery describes how NASA is developing experience in planetary exploration by telerobotic rover. These rovers can operate from a control station in a laboratory in the manner of the Ranger Telerobotic Flight Experiment that flew as a Spacelab external pallet experiment (Lavery, 1998, pp. 2-5). The Rover Control Workstation for the Pathfinder/Sojourner Rover represents a step in the development of such a control console (Wilcox and Nguyen, 1998, pp. 3-4).

In a very far-reaching concept, Kozlov and Schevchenko propose a mobile lunar base, in which the entire base is comprised of pressurized, crew operated rovers. In this scenario, the mobile base:

- deploys geophysics stations in a network in various regions of the moon
- deploys astronomical robotic stations incorporating optical and radio telescopes, instruments for recording cosmic radiation, laser ranging retro-reflectors for Earth observations, etc.
- mounts and deploys operational experimental and industrial facilities to search for lunar resources and to "recover" them.

The mobile base would control and operate all of these installations telerobotically while continuing to travel over the lunar surface, picking up old stations and placing new ones (Kozlov & Schevchenko, 1995, p. 49).

The shortness of crew time emerges as a major design driver in the selection and allocation of teleoperated systems. The station or planetary crew's main interest in teleoperation will be to control vehicles or robots relatively close to where they are situated to take maximum use of the real-time mode. For lower-level or routine tasks in the such as monitoring experiments, it will be more advantageous to delegate those functions to teleoperation from the Earth or automated monitoring. The teleoperations from the Earth present a different advantage for very high level expert skills not available at the space laboratory, such as telemedicine or telesurgery.

SYSTEM DESIGN ISSUES—From this study of space laboratories, there emerge three sets of system design issues: *Inseparable* Issues, *Infrastructural* Issues, and *Cross-Cutting* Issues.

- *Inseparable issues* arise from particular characteristics or needs of a component in the laboratory ensemble. This component may be an experiment, payload, item of hardware or software, or operating procedure. The important feature of an inseparable issue is that it tends to be singularly resistant to substitutions, trade studies, and other attempts to rationalize it away within a larger system of resource allocation or infrastructure. Many space endeavors encounter problems because of a lack of proper appreciation for inseparable issues. These inseparables emerge most readily in a bottom-up system analysis of a facility or a function.
- *Infrastructural issues* derive from the top down mission architecture view of a space laboratory. In a space laboratory, the need to be able to issue announcements of opportunity to researchers that explain what resources and accommodations the space agency provides will tend to drive the rationalization of infrastructure. Infrastructure must generally account for all the resource-allocation questions such as rack space, cooling, power load-shedding and availability of crew time.
- *Cross-cutting issues* affect several activities or elements in common, usually triggered by a complex interaction. Although they may intersect the other system design issues, cross-cutting issues constitute a third dimension, distinct from the other two. Human Factors issues stand out prominently within the cross-cutting domain.

The typical "intersection" that generates a cross-cutting human factors problem is almost syllogistic in its logic:

1. The schedule *as infrastructure* allots a specified amount of time to do a task.
2. The task is *inseparable* from the science equipment and it takes twice as long as scheduled.

3. The crew must finish the task, which impinges on the rest of the schedule, stressing the crew, making them work longer hours, and creating tension with the ground controllers who wrote the schedule, which is a recurring, *cross-cutting human factors problem* on many missions.

It is important to recognize that this type of cross-cutting issue evolves beyond the mere accomplishment of a task. It is also more than a question of resource allocation as it takes on a life of its own, regardless of the zero sum game of how crew time is distributed among tasks.

Two examples shall serve to illustrate these definitions of the three types of issues for space laboratories: stowage and a surgical procedure.

Stowage offers lessons. Dalton, Maese & Ostrach (1999, p. 5) provide a segue from Neurolab:

- Never presuppose the stowage requirements until thoroughly understanding the equipment requirements. . . .
- From the crew: Provide packets of materials at one source rather than scattered around the laboratory stowage.

Thus—given the above lessons—within this System Design Issue construct:

1. The *inseparable issue* for stowage is that each laboratory experiment, payload, or support equipment comes with its own unavoidable stowage requirement. This requirement translates to volume, attachment conditions, and proximity to the point of use.
2. The *infrastructural issue* for stowage is that the station must provide stowage as a resource to all activities. There is a budget of stowage space, not only in specific modules or locations, but throughout the station.
3. The *cross-cutting issue* arises when the stowage for one element interferes with access to another element or its proper use. The typical instance is a stowage bag blocking the front of a rack, or even blocking one of the few windows in the modules.

A more complex example derives from a hypothetical life science payload (yes rats again!). The context is the scheduling of a surgical procedure on a specimen.

1. The *infrastructural issue* is how much crew time to allocate to that task, and what will be its impact on the other tasks that will need to wait.
2. The *inseparable issue is:* will the crewmember scheduled to perform that task be expert in extracting and snap-freezing the middle ear?
3. *The cross-cutting issue* is: what is the effect of that timing on that crew member's interaction with other crew members, ground control, and his ability to communicate with the principal investigator on the ground via the POCC?

<u>Inseparable Issues</u>—The idea of inseparable design issues apply with great particularity of space laboratories, science experiment payloads and the equipment, training, operations, scheduling, and crew members that support them. The primary inseparable issues that emerge from this effort are:

- Crew expertise in experiment operations
- Crew time required to perform specific procedures
- Communications with the PI for the experiment
- Stowage of equipment for that payload and the ability to retrieve it.
- Cooling requirements for that payload
- Power requirements for that payload
- Data requirements for that payload
- Crew access to essential equipment for operating or servicing that payload
- Appropriate controls and displays for each payload
- Ability to move equipment into the work space and break it down after use.

Inseparable Incompatibilities—Novak and Addy describe three types of human engineering observations that they found during Space Station human engineering technical reviews (Novak & Addy, 1998, pp. 2-3). They describe these observations as:

- Hardware to Hardware incompatibility
- Hardware to Task incompatibility, and
- Restraint and Mobility Aid availability (R&MA).

These categories are rather self-explanatory, but still they illuminate how an item of hardware that is designed for its own optimum set of requirements may conflict with another item that was similarly designed. Hardware to task incompatibility may be more problematic insofar as it is not possible to consider the hardware as designed to an optimum set of requirements if it cannot perform the task. R&MA availability goes to both the inseparable nature of restraints and aids as forming a complete ensemble with any space laboratory work station and the fact that the suite of R&MA provisions devolve from the system infrastructure. Novak and Addy put their finger precisely on the spot where these different system design approaches come into conflict: when an item does not perform the task for which it is intended.

Infrastructural Issues—Infrastructural issues encompass the resources and capabilities that a space laboratory module provides to all its experiments, payloads, operators, and users. Common and recurring Infrastructural Issues include all forms of resource allocation such as:

- Rack space or volume for payload installation
- Design of structural stand-offs to attach laboratory racks
- Availability of resupply capacity on logistics carriers
- Availability and timeliness of crew time in the Space Station schedule
- Availability and timeliness of voice communications to the ground.
- Electrical Power load-shedding
- Cooling capacity
- Data bandwidth to accommodate downloads from all payloads
- Commonality of payload and other system controls and displays.

Scientists and their Payloads—Crawford & Cannon present a careful analysis of the relative capabilities and roles of humans and computers in a space laboratory. They seem careful to avoid the well-worn terms automation and artificial intelligence. Instead, they focus on what scientists in space will ***need*** from a top-down, infrastructural perspective:

> " Accommodating scientists and their payloads requires more than just providing a laboratory. It includes granting them a great deal of latitude in how their experiments are performed. . . .Space station planners use the payload's operating envelopes to schedule payload combinations that can operate simultaneously with the space station's available resources without disturbing other payloads' rights and privileges" (Crawford & Cannon, 1990, p. 5).

In Crawford and Cannon's scheme, the computers merely "assist" to accomplish this system of checks and balances by monitoring limits, comparing and analyzing the various combinations, and factoring start and stop times. A typical example of how this infrastructural imperative works is that each payload must connect to a station-wide local area network (LAN) through which the crew and their computers can monitor and control the various payload operations (Johnson, 1990, p. 8).

Common Controls and Displays—Novak, Liddell, and Sampaio made a case study of the lack of common displays throughout the Space Station. Although it intertwines with all the human factor issues, the notion of commonality is essentially an infrastructural imperative.

> "Currently, there is a lack of a programmatic Human Computer Interface standard for the ISS. As a result, there is a high probability that core displays, which are developed in isolation, will have a very different appearance and functionality. This lack of a common "look-and-feel" could increase learning time, errors, and time spent on tasks" (Novak, Liddell & Samaio, 1997, p. 2).

Cross-Cutting Issues—Cross-cutting issues emerge in often unexpected places and ways. In the largest sense, all human factor issues are cross-cutting issues that may apply to nearly all aspects of the Space Laboratory.

- Space Station maintenance, repair and cleaning time
- Automation of various functions such as system monitoring
- Choice of what systems to automate and at what level
- Who controls crew scheduling the criteria for choices of tasks
- Who communicates with the ground and when
- Contingency EVA time, which may make a big impact on all other scheduled activities
- Equipment Sharing
- System and technology validation.

Human Engineering—Human Engineering constitutes the consummate set cross-cutting system design issues. It bridges the inseparable and the infrastructural system design issues in a vital way, by tracing how the crewmembers can cope with these often contradictory imperatives. Connors identifies the first order challenge of what it takes to improve system performance: "Advances in hardware/software ***are not sufficient to ensure improved system performance***. Systems that lack an easy human interaction can negate potential gains, or worse, can introduce new problems" [emphasis added](Connors, 1993, p. 1).

Human-Centered Design emerges as a touchstone of *cross-cutting* space laboratory system issues. In this respect Mary Connors defines Human Centered Design as "a philosophy that overtly and specifically designates the user as the central consideration in the design and implementation of intelligent, automated systems" (Connors, 1993, p. 2).

Equipment Sharing—Equipment sharing affords a valuable insight as a cross-cutting issue. One of the ways in which a Space Laboratory may hope to become more efficient is by equipment sharing. Dalton, Plaut, and Meeker (2000, p. 7) address the question of equipment sharing for Human and non-human research among the international community. Equipment sharing is now a feature of joint international life science announcements of opportunity. Since the equipment to be shared may come from different proposers in different countries, it is neither an infrastructural issue nor an inseparable issue, because plainly if the equipment can be shared it is not truly inseparable. Rather, it emerges as a cross-cutting issue because it suggests an arrangement of trading and bartering among researchers.

Design, System, and Technology Validation—Research in technology development can be one of the thorniest *cross-cutting* issues in that it goes to the heart of how valid are the development methodologies. Here it is essential to make a distinction between research in design and technology development and the trial-and-error then test-test-test methods of equipment development that still prevail in many organizations as business-as-usual. The essence of this cross-cutting issue concerns the proper use of modeling as a research development tool. It is possible and convenient to develop computational models of diverse processes and phenomena that can serve as an economical and faster alternative to trial-and-error. Advanced modeling also averts another problem associated with trial-and-error approaches, that arises often when the would-be developer tests an especially unsatisfactory embodiment of an idea, and jumps to the conclusion that everything based on that idea must be equally bad (Null, 2001).

Sophisticated modeling helps to avoid the Kantian pitfall that *perception is empirical experience and experience is empirical knowledge* (Kant). All to often, engineers see a design project or product that may not work well for a specific application, and so they may jump to erroneous "trial-and-error" conclusions because they have witnessed or experienced such a short-coming. Therefore, they ***just know*** that something won't work. If an improvement or a new application of that technology comes along, the critic is certain it will not work because he already experienced it.

Instead, the use of a modeling approach empowers the evaluator to try many alternatives to the first failed version before drawing any conclusions, and actually encourages the testing of multiple design hypotheses before zeroing in on one do-or-die concept. Modeling approaches help designers, engineers and evaluators keep an open mind. This *units of analysis* methodology provides a basis for developing design and operational models.

CONCLUSION

Space Laboratories are a challenging and complex area of architectural design research. The history of space laboratory design, development, and operation is now sufficiently rich and detailed to treat them as a building typology. Within this typology, there are demonstrable characteristics that shape and inform the working environment for the crewmembers. Given the set of architectural precedents of space laboratories and the design issues that emerge from them, it is now possible to generate a set of Units of Analysis with which to plan and evaluate future designs.

The design of space laboratories encompasses four broad domains: laboratory science, crew, modes of operations, and system design issues. This approach treats laboratory science in the categories of life science, microgravity science, external observations and external operations. The crew parameters cover crew safety and health, crew time, and meaningful work—all of which are key to productivity in performing the laboratory science. Together, the crew and ground support will accomplish this work through four modes of operation, including ground control, crew autonomy, teleoperations from the ground and teleoperations from the laboratory. The juxtaposition of these three domains generates a fourth domain of the three inseparable, infrastructural, and cross-cutting system design issues. This paper presents a new design methodology to identify and analyze these system design issues. This methodology appears as the "units of analysis" approach that the paper presents.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ACM: Apollo Command Module

ASTP: Apollo-Soyuz Test Project, 1975

ATM: Apollo Telescope Mount, solar observatory

CAM: Centrifuge Accommodation Module

CCAA: common cabin air assembly

CDR: Commander

CMG: control motion gyro

CSM: Apollo Command and Service Module

ESA: European Space Agency

EVA: Extravehicular Activity, to venture outside the pressurized crew cabin in a space suit.

GPWS: General Purpose Work Station, the glovebox that first flew on SLS-1

HMP: Haughton Mars Project

HST: Hubble Space Telescope

HZE: Heavy ion particle, a galactic cosmic ray particle having an atomic number Z>2.

ICES: International Conference on Environmental Systems

ISS: International Space Station

IVM: intermodule ventilation fan

JEM: Japanese Experiment Module, laboratory on the International Space Station.

Kibo: Japanese name for JEM.

LEO: Low Earth Orbit

M.A.R.S.: Mars Arctic Research Station

MDA: Multiple docking adapter on Skylab, to which the ACM docked, and accommodated the Apollo Telescope Mount console. The ATM attached to the MDA.

MIDAS: Materials in Devices and Superconductors, NASA flight experiment on Mir

NASA: National Aeronautics and Space Administration

NASDA: National Space Development Agency of Japan

POCC: Payload Operations Control Center

RAHF: research animal holding facility (rat cage) on Spacelab

R&MA: Restraint and Mobility Aid

RMS: Remote Manipulator System, robot arm on the space shuttle

SAE: Society of Automotive Engineers

SFOG: Solid Fuel Oxygen Generator

SLS: Space Life Science

SMD III: Spacelab Mission DevelopmentTest III

SSA: Space Station Alpha

SSBRP: Space Station Biological Research Project, the Ames Research Center life science centrifuge project for space station.

SSF: Space Station Freedom

THC: thermal humidity control

TsPK: Gagarin Cosmonaut Training Center in Zvezdny Gorodok (Star City), RUSSIA

VRV: ventilation relief valve assembly, which is part of every space station module in one form or another

VVIS: Visual and Vestibular Integration System

ZOE: Zone of Exclusion

APPENDIX

TABLE A-1. Space Station Crew Timeline for a Crew of Six

0700 hours 1900

0700

07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	01	02	03	04	05	06

SO	HANDOVER	System Ops	L	System Ops	U	Exercise	HANDOVER	Pre-Sleep	Sleep	Post Sleep
SS	HANDOVER	User Ops	L	User Ops	U	Exercise	HANDOVER	Pre-Sleep	Sleep	Post Sleep
SS	HANDOVER	User Ops	L	User Ops	U	Exercise	HANDOVER	Pre-Sleep	Sleep	Post Sleep
SO	HANDOVER	Pre-Sleep	Sleep			Post Sleep	HANDOVER	System Ops	L	System Ops	U	Exercise
SS	HANDOVER	Pre-Sleep	Sleep			Post Sleep	HANDOVER	User Ops	L	User Ops	U	Exercise
SS	HANDOVER	Pre-Sleep	Sleep			Post Sleep	HANDOVER	User Ops	L	User Ops	U	Exercise

KEY:

SO = System Operator

SS = Station Scientist

L = Lunch

U = Unscheduled work time

Pre-Sleep includes Dinner

Post-Sleep includes Breakfast

Exercise is scheduled into the work day

Sleep is – or should be -- inviolable

Note: The crew should enjoy the autonomy to arrange or rearrange their work schedule to off-set exercise, work, and lunch time from each other within the 12 hour shift.

TABLE A-2. Definition of Telemedicine Modalities, (from Simmons, et. al., 1998, p. 2)

MODE	CHARACTERISTICS	EXAMPLES	LATENCY
Real-Time	• Data transmitted as they are generated and received with no perceived delay • natural person-to-person interactions • high-bandwidth or short distance telecommunication	• patient monitoring in Intensive Care Unit • local telephone conversation • full-motion videoconferencing • communications between Shuttle and Earth	< 5 Sec
Just-in-Time	• Data temporarily buffered or received with perceived delay, but within current medical exam • uncomfortable person-to-person interactions • moderate-bandwidth or moderate distance telecommunication	• "surfing" the WWW using a browser with a modem • trans-oceanic telephone conversation • Internet videoconferencing • communications between moon and Earth or early in Earth/Mars transfer	5 Sec. To 30 Min.
Store-and-Forward	• Data collected off-line • data received after medical exam • unnatural or no person-to-person interactions • low-bandwidth or long distance telecommunication	• electronic mail • voice mail • tele-radiology • communication between the Earth and Mars	> 30 Min.