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National Aeronautics and
Space Administration

On-Orbit Servicing Steering Committee

ON-ORBIT SERVICING EXPERIENCE

A COMPILATION
OF
LESSONS LEARNED

Advanced Program Development Division
Office Of Space Flight

Preliminary Release – June 1990

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
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Reply to Attn of: 408

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TO: Distribution

FROM: Flight Projects Directorate
Satellite Servicing Project

SUBJECT: Satellite Servicing Lessons Learned Document

A copy of "On-Orbit Servicing Experience - A Compilation of Lessons Learned" is enclosed. This preliminary version represents the best efforts to date of the NASA On-Orbit Servicing Steering Committee to compile a history of satellite servicing experience. The important lessons learned are summarized and presented in a convenient reference format. A reference bibliography is also included.

The reader will surely notice that although an extensive body of experience has been reported, there is a significant amount of missing information. Further research and reporting is required to suitably complete this document. This additional work is continuing. The document is being distributed in this incomplete form to inform the satellite servicing community of the purpose and scope of this effort, and to solicit additional information from sources who have not yet contributed. All readers who are familiar with significant on-orbit servicing experience which is not adequately reported here are invited to contact the editors and make arrangements for including additional material in subsequent updates of the document.

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Enclosure

This document is the product of support from many organizations and individuals. SRS Technologies, under contract to NASA Headquarters, compiled, updated, and prepared this document.

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PREFACE

The preliminary release version of "On-Orbit Servicing - A Compilation of Lessons Learned" is enclosed. This document has been prepared under the direction of the NASA Office of Space flight, Advanced Program Development Division. Mr. James Moore of the Johnson Space Center, and Mr. Edward Falkenhayn of the Goddard Space Flight Center, as co-chairmen, have managed this effort. Mr. Greg Guthrie of SRS Technologies, Arlington, VA, has provided editorial and production support.

The editors wish to thank the many contributors to this document. Although an extensive agencywide effort was undertaken to collect material, the editors were unable to completely capture all prior on-orbit servicing lessons learned. Considering the limitations in this present document, we plan to actively maintain and to publish periodic revisions. Readers are encouraged to submit additional or new material, substantive comments or specific criticisms. Please provide your contributions to:

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ACRONYM LIST

ACCESS	Assembly Concept for Construction of Erectable Space Structure
ACS	Attitude Control System
AIAA	American Institute of Aeronautics and Astronautics
ARC	Ames Research Center
AXAF	Advanced X-Ray Astophysics Facility
BAPS	Berthing and Positioning System
CBSA	Cargo Bay Stowage Assembly
CCB	Configuration Control Board
CCTV	Closed Circuit Television
CETA	Crew Equipment Translation Aid
CLIP	Crew Loads Instrumented Panel
CRU	Contingency Replacement Unit
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
EASE	Experimental Assembly of Structures in EVA
ELV	Expendable Launch Vehicle
EMU	Extravehicular Mobility Unit
Eos	Earth Observing System
EP	Explorer Platform
EUVE	Extreme Ultraviolet Explorer
EV	Extravehicular
EVA	Extravehicular Activity
ft-lbs	Foot-pounds
FSS	Flight Support System
FTS	Flight Telerobotic Servicer
g	Gravity
GSO	Geosynchronous Orbit

GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ICD	Interface Control Document
IOC	Initial Operational Capability
IV	Intravehicular
IVA	Intravehicular Activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
LMSC	Lockheed Missles and Space Corporation
M&R	Maintenance and Refurbishment
MCC	Mission Control Center
MEB	Main Electronics Box
MFR	Manipulator Foot Restraint
MIT	Massachusetts Institute of Technology
MLI	Multilayer Insulation
MMS	Multimission Modular Spacecraft
MMU	Manned Maneuvering Unit
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Center
MST	Module Service Tool
MSFC	Marshall Space Flight Center
MSIS	Man/System Integrations Standards
MUT	Mission Utilization Team
NASA	National Aeronautics and Space Administration
NASREM	NASA/NBS Standard Reference Model
NBS	Neutral Buoyancy Simulator; National Bureau of Standards
NSTS	National Space Transportation System

OAST	Office of Aeronautics and Space Technology
OMV	Orbital Maneuvering Vehicle
ORS	Orbital Refueling System
ORU	Orbital Replacement Unit
OSCRS	Orbital Spacecraft Resupply System
OSSA	Office of Space Science and Applications
PDR	Program Design Review
PDRS	Payload Deployment & Retrieval System
PFR	Portable Foot Restraint
PIP	Payload Integration Plan
PM	Propulsion Module
POCC	Payload Operations Control Center
POP	Polar Orbiting Platform
PSA	Provision Stowage Assembly
RF	Radio Frequency
RMS	Remote Manipulator System
RSIS	Robotic Systems Integration Standards
SADE	Structural Assembly Demonstration Assembly Experiment
SAMSS	Space Assembly, Maintenance and Servicing Study
SBOSCOS	Space Based Observation Systems Committee on Standards
SES	System Engineering Simulator
SFOM	Shuttle Flight Operations Manual
SHOOT	Superfluid Helium On-Orbit Transfer
SMM	Solar Maximum Mission
SMRM	Solar Maximum Repair Mission
SPAS	Shuttle Pallet Satellite
SPDM	Special Purpose Dextrous Manipulator
SSS	Satellite Servicer System
SSSFD	Satellite Servicer System Flight Demonstration
SSSWG	Satellite Services System Working Group
STD	Standard
STS	Space Transportation System

TAM	Task Analysis Methodology
TBD	To Be Determined
TCAM	Technical Committee on Aerospace Maintenance
TDRSS	Tracking and Data Relay Satellite System
TMG	Thermal Meteoroid Garment
TPAD	Trunnion Pin Attachment Device
TRWCI	TRW Components International
TSR	Tumbling Satellite Retrieval
USAF	United States Air Force
WETF	Weightless Environment Training Facility
WPAFB	Wright-Patterson Air Force Base
XTE	X-Ray Timing Explorer

INTRODUCTION

Purpose:

This compendium strives to capture the experiences of the recent past of on-orbit satellite servicing, to extract the hard-earned and sometimes painful lessons resulting from this experience, and to provide a handy guide for future spacecraft and servicer developers based on this experience. It is a production of the NASA Office of Space Flight, Advanced Program Development Division, acting on behalf of the NASA Headquarters On-Orbit Servicing Steering Committee.

Scope:

This document is compiled from published reports, papers, etc., and also includes "recollections" and reporting of those who participated in these events. It is accurate to the extent of the accuracy of the source materials. Readers are encouraged to submit additional material on recent events, unreported events and on-going projects to the editor for inclusion in future editions.

In Part I, both recent and current satellite servicing experience is compiled in the form of project summaries highlighting the satellite servicing lessons learned on each project's flight mission or development and study efforts. In each case, the emphasis is on actual experience, whether on orbit or in development facilities. The study program's contributions are necessarily based on design trades, simulations, and analyses. All valid results of these activities are useful. Although on-orbit experience is considered to be more authoritatively validated, success on orbit can be predicated from analysis, simulation, and test on the ground prior to launch.

In Part II, the experiences described in the project summaries and the referenced documentation is presented again, reorganized along broad technical discipline and management categories. This arrangement is provided for the ease of use of developers who may value an experienced viewpoint relevant to their particular issue at hand, yet who may not be familiar enough with this history to access the prior experience by project name or document name.

Part III provides an extensive annotated bibliography of servicing mission documentation and servicing-related documentation from servicing agencies and study groups.

It is the current intention that future revisions of this compilation will more extensively cross-reference the lessons and experience in the technical and management categories of Part II to the mission summaries of Part I and reference documentation of the bibliography. When this is done, the reader will be able to more directly examine the experimental basis of the assertions stated as guidelines for Part II.

PART I - SATELLITE SERVICING EXPERIENCE

A. HISTORY

GEMINI PROGRAM

See Part III for reference documents.

APOLLO PROGRAM

See Part III for reference documents.

SKYLAB REPAIR AND IN-FLIGHT MAINTENANCE

See Part III for reference documents.

MULTIMISSION MODULAR SPACECRAFT

The multimission modular spacecraft (MMS) grew out of an effort in the mid-1970's to build a standard multipurpose spacecraft bus that would economically capture the broadest number of Earth and astrophysics remote sensing observatory missions. It was designed modularly to the subsystem level, with the basic MMS including subsystems for power, command and data handling, attitude control, and propulsion. Configurations for antenna, solar arrays, and propulsion are mission-specific and were not included in the generic bus. Other design considerations, e.g., the capability of launch, retrieval, and servicing from the Space Transportation System (STS), were low cost.

The MMS was designed as a low-cost spacecraft bus. This MMS bus has been selected for use by a number of programs, and, in each case, the decision has been made on the basis of cost. The modular design of the bus makes serviceability a byproduct of the design. Though the MMS bus offers this on-orbit servicing capability, not once has it been selected by a program because of that feature.

STS 41-B – SOLAR MAXIMUM REPAIR TECHNOLOGY DEMONSTRATION

A major objective of the STS 41-B mission was to demonstrate the overall readiness to proceed with the Solar Maximum Mission (SMM) satellite repair on STS 41-C. To this end, STS 41-B performed many space firsts: two EVAs on the same Shuttle mission, untethered EVAs in space, long-range translations by EVA crewmen (up to 320 feet from the Shuttle), flight testing of the manned maneuvering unit (MMU), flight testing of the remote manipulator system (RMS) with the manipulator foot restraint (MFR) and an EVA crewman attached, and flight testing of the Shuttle rendezvous system.

The two MMUs tested, one during each EVA, were found to function identically and essentially as planned. Three problems were encountered: (1) the center of mass of the extravehicular mobility unit (EMU)/MMU system turned out to be several inches above the center of thrust; (2) the propellant consumption was higher than was modelled in the System Engineering Simulator (SES); and (3) the flash characteristics and intensity of the MMU locator light were found to be inadequate to provide good tracking should an MMU have strayed during a night pass.

Two trunnion pin attachment devices (TPADs) (a primary and a secondary) simulating the system that would be used to capture the SMM satellite were tested in conjunction with the MMUs. Both TPADs performed satisfactorily in docking tests with trunnion pins on the cargo bay stowage assembly (CBSA) and on the Shuttle Pallet Satellite (SPAS-01), both fixed targets in the Shuttle bay. The secondary TPAD had a slightly lower tripping force and tended to slowly drift off the trunnion pin. An attempt to use the TPAD with a free-flying, rotating target was abandoned due to an RMS malfunction.

The MFR was used as a work platform for the simulated SMM main electronics box replacement test. All tasks involved in this test were completed successfully. The single problem noted with the MFR was that it was very difficult to restow, and required two crewmen to accomplish the task. The demonstration showed that additional restraint capability is needed, since the grasp afforded is not sufficient to allow simultaneous body positioning, latch actuation, and MFR positioning.

During the flight, a single series of RMS force applications was conducted on the port handrail. The RMS back drive in the position-hold mode was noted at approximately 35 to 40 pounds applied force. Brake slippage in the brakes-on mode came at approximately 25 to 30 pounds of applied force. It seemed clear that the arm's response to force inputs was considerably more tolerant in a position-hold mode than in the brakes-on mode.

STS 41-C – SOLAR MAXIMUM REPAIR MISSION

The Solar Maximum Repair Mission (SMRM) was the first formally planned and implemented on-orbit satellite servicing mission using the STS. The mission, STS 41-C, consisted of recovery of the satellite and its return to the payload bay. Repair consisted of replacement of the failed attitude control subsystem module, replacement of the white-light coronagraph/polarimeter main electronics box, and installation of a plasma baffle for the x-ray polychromater. Following this, the S-band high-gain antenna system was remotely deployed for its first use with the new Tracking and Data Relay Satellite System (TDRSS). The satellite was re-deployed for continuation of its precise solar observations. The mission continued until the observatory reentered the Earth's atmosphere December 2, 1989 (9 years, 10 months from launch).

Lessons Learned:

There are a number of lessons learned from this repair mission. One is the validation of the spacecraft design for on-orbit serviceability. This concept requires the spacecraft to be designed as a standard low-cost reusable vehicle providing subsystem modules capable of being serviced on orbit with minimum types of support equipment and tools.

A lesson learned is the importance of having detailed satellite documentation (including close-out photos of all equipment and interfaces as flown) available for the determination of feasibility of subsequent design approaches for particular on-orbit servicing tasks. The detailed drawings and photographs of the SMM instrument modules were used in designing special tools and workups and in developing operating procedures that proved successful on orbit.

Another lesson learned is that there should be redundant methods to accomplish a servicing task whenever practical. For example, the TPAD failed to grapple the spacecraft trunnion pin after three attempts. A manual EVA override should have been provided in the design.

The importance of battery-powered EVA hand tools to expedite servicing operations and to lessen astronaut fatigue was demonstrated during performance of the servicing tasks. Original planning provided for two 6-hour EVA periods with an intervening 40-hour rest period. Once observatory capture and berthing had been achieved, the remaining servicing activities required less than a single 6-hour EVA servicing period.

The mission demonstrated that a complicated module, which had not been integrated previously into the orbiting spacecraft, could be exchanged in space. The new attitude control system (ACS) module maintained a satisfactory pointing boresight relationship with the other scientific instruments of the payload. The serviceability features of the MMS module included acme-threaded jackscrews, which carried the 100 ft-lbs preloads necessary for launch conditions and were removable on-orbit by using the battery-powered Module Service Tool (MST). Also, the blind-mating electrical connector on the module functioned easily and successfully during the module exchange. No evidence was found of any cold welding problems with the mission.

The worth and flexibility of the MMS Flight Support System (FSS), which adapts the Shuttle for MMS servicing operations and the spacecraft's compatibility with the RMS, were demonstrated during this mission. No backup override features were used to achieve this successful servicing mission.

The mission demonstrated that operational procedures should be strictly followed. The crew members did not observe the precautionary advice that the solar arrays should not be handled by their gloves for fear of loss of pressurization of the suit. An attempt to grab and stabilize a rapidly spinning spacecraft caused a serious tumbling motion in the spacecraft. The motion was finally overcome by magnetic controls sent from the ground stations before the spacecraft went into an undervoltage state.

The mission showed that, with considerable care and extensive rehearsals, it is possible to repair on orbit an instrument that has not been designed for servicing.

A problem arose with the spacecraft ACS component (fuse) failure, where proper space derating was not applied during addition of more electrical loads. This failure emphasizes the need for proper spacecraft design approaches, reliability analyses, and configuration management controls.

The subsequent ground replacement and retest of the 4-stage integrated current counter failures in the returned instrument main electronics box (MEB) emphasizes the necessity for spaceborne components to be adequately specified for procurement, to be required to meet 100 percent acceptance testing, and to be burned-in before installation in flight equipment. No piece-part failures were experienced with the replacement MEB assembly when the thousands of parts used with the 15 replacement stitch-welded boards were adequately screened.

The importance of having long-lead spare orbital replacement units (ORUs) available was demonstrated during the approval cycle of the SMRM mission.

An improved subminiature connector to replace the subminiature-D is needed for EVA remote teleoperated manipulator, and for EVA telerobotic operations. Perhaps the use of the new ROBOCON connector on the observatory cable harness would have made the MEB replacement significantly simpler in ensuring remating of the 11 subminiature-D's with 362 active leads. This observation suggests that on-orbit servicing may be practical at the sub-ORU level.

Extensive testing prior to and during integration and several detailed simulations prepared the operations team to make rapid, coordinated decisions when faced with contingency situations during the mission. Timely and accurate communication between the Payload Operation Control Center (POCC), Mission Control Center (MCC), and the flight crew was extremely important.

A final important result of the SMRM was the demonstration that satellite servicing could be economically viable. In the case of Solar Max, the repair mission was estimated at $45 million in FY1984 dollars, exclusive of launch costs. The SMM, including the development of MMS, cost $79 million in actual dollars when launched in February 1980. Replacement cost of the entire observatory in FY1984 dollars would have been $235 million. The servicing mission added over 5-1/2 years of scientific data to a mission life that had been severely limited to less than one complete year in the initial fine-pointing mode. The amount of data derived from the repaired coronagraph/polarimeter was about six times the initial amount and, more importantly, spread observations over most of the solar cycle, including periods of solar maximum and solar minimum. Thus, for an investment of only a fraction (19%) of its replacement cost, or some (57%) of its initial cost, the total value of the satellite has more than doubled.

STS 41-G – ORBITAL REFUELING SYSTEM

The Orbital Refueling System (ORS) was a fuel transfer and management experiment flown on STS 41-G. The experimental objective was to develop and demonstrate the equipment and procedures needed for a safe hydrazine fuel transfer system and the tools needed to interface with existing satellites to accomplish fuel transfer. To make the process as realistic as possible, the monopropellant hydrazine was chosen as the transfer fluid in the experiment.

During the EVA portion of the experiment, a few small problems were encountered. These proved to be annoying, but did not prevent the normal accomplishment of the ORS tool installation tasks. One of the problems was with the ORS EVA flashlight, which failed to illuminate. The problem was bypassed by using the EMU lights as well as the RMS end effector lights as substitutes for the ORS EVA light. Other problems involved the ORS foot restraint. EV-1 had difficulty moving his right foot in and out of this restraint because of interference of the thermal meteoroid garment (TMG) on his right boot with the foot restraint/heel retention bracket. Beginning with STS 51-A, this problem has been corrected by an EMU boot heel modification. The ORS foot restraint became loose in both the pitch and roll axes and had to be tightened by the second EVA astronaut. This problem has been corrected by modifying the portable foot restraint (PFR) adjustment knobs with a locking feature.

STS 51-A – PALAPA B-2 AND WESTAR VI RETRIEVAL

This flight involved the capture and return to Earth of the PALAPA B-2 and WESTAR VI satellites. The mission called for a rendezvous and a 6-hour EVA to be performed on flight days 5 (PALAPA B-2) and 7 (WESTAR VI). From these complex tasks, several important on-orbit operations lessons were learned which should be applied to future flights.

Regarding the EMUs, a few problems were noted. First, as had been the case on some previous missions, several EMU light batteries were defective, causing failure of the left-side lights of both sets of EMU lights. In this case, four of the eight batteries needed to operate the left-side lights were defective and the other four were not fully charged. The four partially charged batteries were combined to operate one set of EMU left-side lights during the first EVA. The other set was repaired using two AAA batteries (spares from personal microcassette recorders), which were taped in series and wired to the EMU contacts. The partially depleted set of batteries failed during the first EVA and also was repaired using AAA batteries for the second EVA. The recommendation in this case is that the EMU lights be modified to prevent depletion of the batteries in case of inadvertent activation.

Another problem encountered with the EMU involved the torque wrench handle extension. The hand grip diameter was at maximum for use by an EVA-gloved hand. A crewman with smaller hands could have encountered difficulty gripping the handle over extended periods. Also, the knurling of the handle caused noticeable wear on the thermal protection material on the palm of the glove.

The two MMU units used during this mission functioned well without any serious problems; however, the fuel capacity was questioned. The satellite capture task was not particularly demanding in terms of MMU fuel used, and the propellant usage was very close to that expected. Under these nonstrenuous conditions, about two-thirds of the available propellant was expended.

During this mission, a need for better stowage methods was apparent. Due to a lack of stowage space, the crew resorted to gray tape, tethers, straps and such to secure the items in the airlock. Stowage problems also were encountered with the provisions stowage assembly (PSA) unit for EVA tools and equipment, located in the cargo bay and used by the crew on both EVAs. The PSA door handle safety strap proved difficult to resnap, since both the male and female halves are mounted to fabric. Having no hard mounts, the snaps proved to be a moving target to the gloved hand of the EVA astronaut. Another problem encountered with the PSA was restowage of the trash bag. Its foam cutout was sized for an empty bag, not a full one, thus making restowage difficult. Stowage problems were also encountered with the stinger, which was used by the EVA astronauts to dock with the satellites. While restowing the stinger, the fit into the holding bracket was found to be too snug, creating a crew problem overcome by strength alone. A final general suggestion in regard to stowage was that all EVA zippers should have a zipper handle extension to make them easier to grasp with the EVA gloves.

Several tether-related opportunities for improvement were also evident. The first involved the hooks on the wrist tethers. These hooks proved to be much more difficult to operate in zero-g than they had been in 1-g testing, a problem that increases with the length of the EVA and growth of hand fatigue. Operation of the hooks is easier if both hands are used, but that leaves the EVA crewperson with no handhold while tethering. Due to workarounds and real-time changes in the EVA procedures, all available wrist tethers were used. Thus, it may be prudent to manifest additional wrist tethers on planned EVA flights for contingency purposes.

Two drawbacks were noted in regard to the safety tether equipment. First, the reel force taking up the slack in the line was too great, exerting a constant force on the crewman and thus partially nullifying the advantages of working in zero-g. Secondly, the reel can be locked, but both hands are required to do it, and the locking lever is difficult to operate. The tether reel force should be reduced as much as practical, and the locking lever should feature one-hand operation.

Given that this mission involved the EVA recovery of two satellites, much was learned about the zero-g handling of large and massive objects. Based on the experience gathered here, it is relatively easy for an EVA-suited astronaut to hold steady, to move slowly, and to control objects of mass up to 2,000 pounds and dimensions up to 10 feet, given that the astronaut is adequately restrained at the waist or below (in this case, in the MFR) and is provided guidance by a second person who has a view of the object being moved. The need for this guidance demonstrates the importance of the intravehicular (IV) crewman to the accomplishment of an EVA task. The extravehicular (EV) crewmen found it very difficult to determine the attitude and position at which they were holding the satellite because of their proximity and the size of the satellite. Therefore, it was necessary for a "third set of eyes," those of the IV crewman, to ascertain where the satellite was in relation to the bay and where it needed to go to accomplish the task.

In general, the ease of handling an object in zero-g is a function of both size and mass. In many ways, the larger, more massive objects are easier to handle than very small objects. Larger mass equates with greater stability. Smaller objects tend to drift and flail due to their small inertias and resultant sensitivity to tip-off forces. The most challenging objects to handle are those of light mass and large dimension, like a very flimsy girder, where gentle forces on one end could cause dramatic gyrations on the other end.

Some final EVA lessons learned from this mission should be considered in all EVA planning. Both EVAs performed on this mission were physically and mentally exhausting for all five crewmembers. The two EV crewmen and one IV crewman began EVA preparations 3 hours prior to airlock egress and worked continuously for the next 10 hours. The other two crewmen aboard were involved with rendezvous maneuvers starting 6 hours prior to EVA and were not unoccupied again until the EVA ended. Several thoughts come out of these facts. First, complex EVAs should not be planned earlier than flight day 4 of any mission. By this time, all crewmembers should be completely adapted to the environment and well rested. Second, one day of rest between EVAs is highly desirable and may be mandatory depending on the results of the first EVA. The crew of 51-A spent the intervening day replanning and rehearsing the second EVA as well as resting from the first EVA. If no intervening day had been provided, the crew would have been forced to work through sleep and meal times. Third, six crewmembers are highly desirable for complex EVAs. This would allow full involvement of five crewmen in the EVA and support operations, with a spare crewman available to handle Orbiter problems as well as assist with the EVA.

STS 51-D – LEASAT-3 DEPLOYMENT

The STS 51-D mission involved the deployment of the Leasat-3 satellite. The satellite failed to operate upon release, and the decision was made to re-rendezvous with it and to attempt repair. To attempt this repair, it was necessary on orbit to build two tools from parts available. These tools were devices similar to a fly swatter and a lacrosse stick. The fly swatter type was built from written instructions and the lacrosse stick type by verbal instructions from the ground. Though the tools were built correctly in each case, the astronauts desired pictures of the final product. A facsimile system would have simplified the task considerably.

The EVA portion of this mission involved the two EVA astronauts attaching the "fly swatter" and the "lacrosse stick" to the RMS, an activity that had never been practiced in the Weightless Environment Training Facility (WETF). The crew was in real-time communication with an astronaut on the ground who had simulated the required activity. The contact proved to be of great assistance to the EVA astronauts.

A few problems were encountered during the EVA. Difficulty was experienced in unstowing and restowing equipment from the PSA. The waist tethers were too long to hold the EV crewman close in to the PSA, forcing him to use one hand for restraint and one hand for tool acquisition/stowage. Also, as had been the case on STS 51-A, the PSA door handle safety snap was difficult to resnap.

Another problem encountered, which had also been experienced on previous missions, was communications breakup. This affected EVA operations to the extent that repeated transmissions were required frequently and excessive concentration was demanded by the EV crewmen to comprehend/decipher the partially intelligible transmissions.

EMU thermal problems also were encountered during this EVA, a problem echoed on other EVA reports. Both astronauts complained of becoming very cold during parts of the EVA, though they had the EMUs set on MAXIMUM HOT. A solution may have been to shut off the feedwater supply in the EMU, but neither EV crewman was comfortable with this idea, being concerned about pump restart. This thermal problem is of particular concern during night EVAs and at periods of low energy expenditure. It should be taken into account when designing EVA tasks, ensuring that the astronauts are kept busy, causing enough energy expenditure to stay warm. Another possible solution could be to incorporate a larger range of temperature control in the EMU.

STS 51-I – LEASAT-3 RETRIEVAL AND RELAUNCH

The STS 51-I mission involved the deployment of the AUSSAT and the Syncom IV satellites, as well as retrieval, repair, and redeployment of the Leasat-3 satellite, which had malfunctioned on deployment from STS 51-D. The Syncom IV deployment was nominal; however, the sunshield for the AUSSAT failed to open on deployment and had to be repaired. This repair task consisted of using the end effector on the RMS to tap open the sunshield from its obstruction. To open the sunshield, it had to be nudged from the far end with respect to the Orbiter. Thus, the RMS had to be snaked around the satellite and pushed back towards the Orbiter. The task would have been much simpler if the RMS could have had a hook attached to the end effector, such that the sunshield could have been pulled open rather than pushed. Given the many unanticipated ways the RMS may be used, it would be useful to have some sort of general purpose tools that could be attached to the end effector.

The repair and redeployment of the Leasat-3 was basically nominal even though the RMS was capable of only degraded-mode, single-joint operation as a result of damage incurred during the repair work on the AUSSAT. Once again, during the EVA portion of the repair, there was a complaint about the ability of the suit to handle the temperature extremes. The EVA astronaut in this case was forced to shut off water circulation in the suit to increase body temperature. This is not an acceptable solution, since it causes the suit visor to steam up. Particular design attention should be paid to a method of keeping the hands of the EVA astronauts warm.

STS 61-B – EASE/ACCESS

History:

A structural assembly program at Marshall Space Flight Center (MSFC) began in the mid-1970's. A key aspect of this program rested in the periodic tests of assembly techniques in the MSFC Neutral Buoyancy Simulator (NBS) using aluminum beams. From the mid-to-late 1970's, numerous plans were developed for a flight demonstration on-orbit beam manufacturing and the assembly of very simple structural configurations using the manufactured beams.

These plans were replaced in the early 1980's by a simpler assembly concept called SADE (Structural Assembly Demonstration Experiment). As conceived, SADE was a 100-foot-long truss built in space in the Shuttle bay using both the deployable and the erectable construction methods and several different types of connector joints. SADE assembly tests were run in the NBS in 1983 and 1984.

Although SADE flight proposals were unsuccessful, the NBS test experiences were the seedbed for a proposal to NASA in November 1982 for a simpler assembly experiment called EASE (Experimental Assembly of Structures in EVA). This proposal was accepted, and a contract was signed in October 1983.

The engineers at the Langley Research Center (LaRC) had, for some time, advocated deployment as their preferred approach for structural assembly in space, and, since EASE was more of an erectable approach, i.e., stick-to-stick construction, NASA decided to test both construction methods by including the Langley concept called ACCESS (Assembly Concept for Construction of Erectable Space Structure) as a part of the EASE project. Three years after the original proposal, in November 1985, the EASE/ACCESS experiment was successfully carried out on Atlantis.

Goal:

The purposes of the EASE/ACCESS mission were to demonstrate that large structures can be built in space, and to confirm the usefulness of ground-based structural assembly tests prior to flight.

Results:

Two basic structural shapes, using different construction techniques for each shape, were constructed in the first of two EVA periods. The EASE assembly involved astronaut movement from one construction site to another; whereas, ACCESS involved stationary astronaut locations while the truss was built in assembly-line fashion as it moved through an assembly fixture.

EASE was a tetrahedron-shaped structure made of six aluminum beams, 12 feet in length, joined by connectors designed especially for space construction. It was assembled eight times. Two astronauts, moving from one connector point to another, built the EASE structure in an average of 10 minutes and disassembled it in an average of 8 minutes. By comparison, the average times in the NBS were 11.4 minutes and 10 minutes, respectively.

ACCESS was a 45-foot long aluminum truss made up of 10 bays. Each bay was 4.5 feet tall and triangular in cross-section with a side length of 4.5 feet. The bays were constructed in an assembly fixture and raised on guide rails one bay-length at a time to make room for construction of the next bay. In this way, two astronauts were able to construct the entire 45-foot truss in 25.6 minutes while remaining in a fixed position throughout the construction operation. Disassembly was done in 18.2 minutes by reversing the process. The entire operation, including set-up, inspection, storage, and clean-up took 52.5 minutes. By comparison, the same operation in an NBS took 44.3 minutes at Johnson Space Center (JSC) and 58.3 minutes at MSFC.

In the second EVA period, the astronauts practiced manipulation of the structural members and the entire assembled structures to gain knowledge and experience about their ability to handle masses in space. Other activities practiced on the second EVA included a structural repair task on ACCESS.

In both EVA periods, the ACCESS activities were accomplished completely before the EASE activities were begun.

Future Applications:

The results of the EASE/ACCESS experiment have provided critical information and insight about space construction to the engineers designing the construction techniques for the Space Station. The results also indicated the value of an NBS for the ground-testing of construction activities to take place in space.

A key program lesson learned centered on the importance of having an extremely simple concept and tightly focused objectives when project funding levels are minimal.

SHUTTLE IN-FLIGHT MAINTENANCE

See Part III for reference documents.

SOVIET EXPERIENCE

See Part III for reference documents.

B. CURRENT DEVELOPMENT

HUBBLE SPACE TELESCOPE

The Hubble Space Telescope (HST) is expected to revolutionize modern astronomy. For maximum benefit, however, the telescope must remain in operation for many years. Failure of the observatory is simply not affordable, scientifically or economically, nor is it practical to design the spacecraft with sufficient backup systems to protect against all contingencies.

Four conditions warrant orbital servicing:

- Normal degradation;
- Random equipment failure or malfunction;
- Future advanced technology; and
- Orbit decay requiring reboost.

The HST maintenance and refurbishment plan provides for orbital repair or hardware exchange to meet each of these conditions.

Originally, planners assumed that the HST would be retrieved and returned to the ground every 5 years for major maintenance and refurbishment. However, this plan was set aside on technical and economic grounds. Servicing on the ground could require as much as two and a half years, a period without new scientific data, and an expensive clean room and support facility with a large engineering staff. Servicing in space can be accomplished within a week, a brief interruption in normal operations, and without any additional facilities and staff. The risk of damaging or contaminating the highly sensitive telescope during return and servicing on the ground is significant, and the costs of orbital servicing compare favorably with those for return, refurbishment, and relaunch. Therefore, the decision has been made for all servicing of the HST to occur in space.

Modularity:

Candidate items for servicing were identified early and designed as modular ORUs. These units include critical subsystems for spacecraft operation and science data collection, as well as candidates for future upgrading. Most of these modules are self-contained boxes that are to be installed or removed by simple fasteners and connectors. Rather than attempt intricate handling of individual parts, planners decided to simplify the task by designing entire component assemblies for replacement.

During the first HST servicing mission, items that degrade the fastest will be replaced--batteries, solar arrays, and sensors. On later missions, items that degrade less quickly--computers, reaction wheels, and tape recorders--will be replaced, and some instruments may be exchanged for newer models. Selection of items to be replaced on each mission is to be based on predicted performance and actual operational experience. Reliability assessments and flight data are among the factors taken into account when determining the failure probability of each ORU and in identifying the candidates for servicing on a given mission.

Accessibility:

To be serviced in space, an item must be seen and reached by a pressure-suited astronaut or be within range of the appropriate tool. Items deep inside the telescope cannot be repaired or replaced. In the HST, most ORUs are mounted in equipment bays around the perimeter of the spacecraft. These bays open with large doors so components can be inspected and handled.

Crew aids, such as handrails, foot restraint sockets, and tether attachments, are important features for accessibility. An astronaut needs safe, conveniently located worksites near the components to be serviced. There are 225 feet of handrails and 31 foot-restraint receptacles at strategic locations on the HST. These aids give the crew mobility and stability during servicing tasks. Other crew aids, such as portable lights, tools, and installation guiderails, improve the astronaut's visual and physical access to serviceable components.

Standardization:

To reduce the number of unique components and tools that must be kept in inventory and packed for a servicing mission, designers have standardized many common elements, such as bolts and connectors. Although there are deviations, the HST design features considerable commonality.

Items identified as ORUs at the outset and designed accordingly, for example, are all held in place by captive bolts with 7/16-inch double-height hex heads. Rather than several tools for removing and installing these ORUs, the crew needs only a 7/16-inch socket that can be fitted to a power tool or manual ratchet.

Other ORUs were selected later when reliability assessments and ground testing indicated that some additional items required replacement. Because these ORUs were added to the list after their design had matured, there is more variety in the fasteners, such as non-captive 5/16-inch hex head bolts and connectors without wing tabs. These departures from standardization and accessibility add more tools to the tool kit and more complexity to the servicing task.

Larger scale interfaces also are standardized to control hardware compatibility. The telescope has longeron/keel trunnions and a three-point docking interface with mechanically mateable umbilical connectors to make it compatible with the FSS on the Space Shuttle, the Space Station Freedom servicing facility concept, and the Orbital Maneuvering Vehicle (OMV).

The design of the HST reflects a commitment to on-orbit servicing that is based on new opportunities, prior experience, and compelling scientific, technical, and economic reasons. The maintenance and refurbishment plan provides for various conditions that warrant orbital servicing. The plan also provides for sustained servicing capabilities throughout the full 15-year orbital life of the telescope.

Lessons Learned:

Although designing for maintenance and repair is a complex matter, program managers and designers may find it useful to keep the following lessons in mind.

Philosophy:

Establish maintenance and refurbishment (M&R) requirements and responsibilities early; include astronauts in design and development phases; and incorporate M&R in all planning and reviews.

Modularity:

Identify all ORUs and candidate ORUs as soon as possible, then put them in boxes. Treat any critical item with a risk of early failure as an ORU. Repairs by individual replaceable parts takes too much time and effort. When not replaced on a suitable subsystem basis, the actual source of failure may be predicted inaccurately posing a servicing failure mode.

Standardization:

Minimize the types of fasteners, electrical connectors and tools to be used for servicing.

Simplicity:

Minimize procedures by grouping several components in one module and by grouping electrical connectors so they mate and demate automatically when the ORU is replaced. Subsystem packaging minimizes the number of interconnecting leads that must be routed, which can pose a greater number of system failure modes.

Access:

Put ORUs within eyesight, arm's length, and hand's grasp. Locate enclosed ORUs on or behind doors, which may be hinged when serviced. Do not stack or crowd ORUs, or block access with cabling. Separate removal of an ORU, without requiring other ORUs to be disturbed, is desirable.

Simulation:

Test concepts with computer-aided design and three-dimensional real-time solids modeling; then move to full-scale mockups and neutral buoyancy facilities to verify M&R capabilities. Use feasibility, collision avoidance, and development simulations before proceeding into crew training activities.

Logistics:

Include spares and/or critical long-lead components in flight article contracts and assure vendor support. Save unique test equipment and all final documentation.

Configuration Control:

Photograph and measure the flight article to document the as-built design, and store the information in a readily accessible data retrieval system. Update drawings and mockups to match the as-built configuration. Ensure that there is a minimum of the documentation necessary to enable servicing by a party who did not participate in the design or development of the spacecraft and its payload.

ADVANCED X-RAY ASTROPHYSICS FACILITY

The Advanced X-Ray Astrophysics Facility (AXAF) observatory complies fully with the requirement to be on-orbit serviceable. It is designed for servicing at 5-year intervals during the mission, thereby reducing life-cycle costs by more than $100 million.

The baseline approach is to service AXAF at the Shuttle. In the STS servicing activities, EVA astronauts will replace planned maintenance items, perform necessary contingency servicing, and replace consumables. The spacecraft and servicing equipment design allows these same operations to be performed in the Space Station by EVA astronauts using many of the same tools and procedures.

The serviceable elements of AXAF may be replaced under any of three conditions: when required to restore failed critical functions or redundancy lost by component failure; when telemetry data indicates a potential malfunction; or when units with newer designs and enhanced performance become available. Consumables, such as liquid helium for the x-ray spectrometer, also may be replenished during planned servicing at the Space Station or the Shuttle. All serviceable unit attachment mechanisms and connections are simple and require only standard tools.

The orbital servicing space support equipment has been designed to minimize complexity of EVA operations and to take advantage of existing designs and technology. For example, the AXAF ORU carrier uses a Spacelab pallet designed for compatibility with the STS cargo bay and the Space Station servicing facility storage area. It has provisions for ORU handling and temporary storage, and can accommodate two focal plane scientific instruments and a complement of observatory ORUs.

The FSS is used to berth AXAF during STS servicing. A universal payload adaptor will provide the same support in Space Station servicing.

ORU Design Approach:

All AXAF components except structure and cabling are candidates for on-orbit removal and replacement. The spacecraft is designed to make them as accessible as possible during EVA. Thus, the spacecraft equipment is mounted externally on MMS modules or packaged as individually replaceable units, and the telescope equipment is mounted on the optical bench behind access doors.

All new equipment will be designed for ease of access and EVA serviceability, with a minimum number of standard fasteners, EVA handles, and EVA-compatible connectors.

Existing hardware will be mounted in locations that provide maximum accessibility. Existing Class II ORU hardware will be modified to ensure serviceability, and will be verified by neutral buoyancy simulations. The serviceability of existing contingency replacement unit (CRU) hardware will be verified by engineering analyses and 1-g simulations.

Nearly all ORUs and CRUs are placed on the outside of the spacecraft module to increase productivity of EVAs and to comply with both the time constraints for servicing and the criteria of NASA-STD-3000. The spacecraft structure uses flat accessible faces for mounting replaceable units, and all ORU and CRU interfaces are designed for easy replacement. Flight-tested interfaces such as the MMS modules are used extensively. Neutral buoyancy simulations were used to determine the best locations for EVA support equipment. EVA handholds and PFR sockets are positioned so as to optimize crew work station configurations.

Replaceable Unit Categories:

All elements of the AXAF except structure and cabling are designed as replaceable units and categorized:

(1) Class I ORUs include units with known wear-out mechanisms which will almost certainly have to be replaced on routine servicing missions. Science instruments are included in this category.

(2) Class II ORUs are the units which may be needed on an emergency servicing mission to restore the survivability of the flight system to an acceptable level.

(3) CRUs are those which would be needed to restore the scientific performance of the observatory to an acceptable level.

Class I ORUs will be available in time for routine servicing missions. Class II ORUs will be available to meet the lead time for an emergency servicing mission. CRUs will be available, if required, to meet the nominal 3-year time line for missions involving restoration of scientific performance. At the conclusion of AXAF development, all residual development spares will be refurbished and stored for use in servicing.

EXPLORER PLATFORM

The Explorer Platform, based on the MMS, is being built to provide the capability of exchanging science instrument payloads on orbit. The first user is the Extreme Ultraviolet Explorer (EUVE). The Explorer Platform will be launched on a Delta II from Kennedy Space Center in April 1991, with the EUVE payload module mated to the platform. After a 3-year mission for EUVE, the second Explorer

Platform user, the X-Ray Timing Explorer (XTE), will be launched on the Space Shuttle using the FSS . The Shuttle will rendezvous with the Explorer Platform, and the RMS will be used to grapple it and berth it on the FSS. Then, using the RMS, EVA astronauts, and/or a teleoperated manipulator on the FSS, the EUVE payload module will be removed from the Explorer Platform and the XTE payload module will be installed. Any servicing (module exchanges) required to maintain or repair the Explorer Platform will be performed on the same Shuttle flight.

A new module interface was designed to carry the heavy payload modules on the FSS during Shuttle lift-off and landing and to provide precise and stable alignment of the payload module on the Explorer Platform for its mission. This interface was based on components from the MMS module interface technology adapted for the more strenuous requirements of the Explorer Platform mission. The interface uses three acme-threaded jackscrews with alignment fittings, and three G&H technology blindmate connectors. A standard payload attachment plate is provided to all Explorer Platform users to ensure that their side of the interface will mate in space with the Explorer Platform. All payload plates are made to the same template and verified against the same high-fidelity verification fixture, including the first plate (for EUVE).

In the design of the Explorer Platform, the MMS was augmented to provide additional services, including driven solar arrays and a power distribution system. These services are accommodated in on-orbit replaceable modules mounted in a new equipment deck, which also supports the new payload module interface. Spare modules accommodations were provided for future growth or special payload requirements; on the first mission, these are used for system development experiment hardware. The new modules on the deck are smaller than MMS modules, but use basically the same interface technology applied to a smaller geometry. The solar arrays may be removed separately or together with their solar array drive modules. Astronaut EVA is needed to fold the arrays. The high gain antenna with its pointing mount is built as another on-orbit replaceable module. This module could be repackaged for fitting on to an equipment deck module. A future mission may bring up a repackaged antenna module and use the former antenna site for accommodating a propulsion module. Although the Explorer Platform is baselined for Shuttle-based servicing, serviceability is based on module exchange. Therefore, it is feasible to perform the servicing with a remotely operated servicer, if one becomes available during the lifetime of the platform (over 10 years). Solar array exchange by remote operation may need some special tool development.

ORBITAL MANEUVERING VEHICLE

The OMV is unique in that it is the first spacecraft primarily designed both to do servicing and to be serviced. Scenarios have even been developed wherein one OMV (with a servicing "kit") could be called on to service another. Thus, it is necessary to discuss OMV and servicing from two different aspects: (1) how the OMV could be used to service other spacecraft; and (2) how the OMV is intended to be serviced.

Obviously, since no OMV flight vehicle has been built or flown, it might seem inappropriate to speak of lessons learned from the extensive studies and its design at this time. However, there have been some significant discoveries in both arenas mentioned above, and consideration of these circumstances could prove beneficial to other projects or to NASA as a whole.

Much of the consideration for using an OMV as a servicing platform has centered on the development of extensive, and often expensive, kits that utilize various combinations of robotic devices to accomplish the exchange of ORUs and fluid transfer. Other more innovative kits have been investigated to allow the OMV to capture tumbling satellites and to transport personnel.

The OMV's capabilities alone are not sufficient to establish it as an on-orbit servicing resource. The lack of a NASA-wide docking standard for free-flying spacecraft is already limiting potential OMV mission capture, even though an OMV may not be launched for several years. However, quasi-standards exist for the RMS end effector grapple and the FSS three-point docking interface.

Today's new satellites will become tomorrow's space debris. The OMV could soon become highly useful in reboosting, deboosting, or even removing such spacecraft from harm's way. A standard OMV- and RMS-compatible docking interface will be needed to fully implement this capability. Spacecraft recovery appears to be the most straightforward and likely servicing use of the OMV, and it is certain that an OMV-type vehicle will be built eventually. Once that vehicle is operational, a backlog of orbiting spacecraft that lack a simple standard interface may prove to be an operational nuisance.

The OMV serviceability strategy appears to have been driven by three underlying considerations:

(1) Certain fixtures and appendages had to be stowed before STS reentry, and thus, had to have an EVA mechanical override for stowage or jettison. These devices were built to be serviceable primarily for STS safety considerations.

(2) A second design consideration was in regards to refueling/propulsion technology and was driven by the desire to build a propulsion module that could be exchanged on orbit, serviced on the ground, and then brought back to orbit while the exchanged propulsion module was in use on orbit. The desire to avoid the complexity of unproven refueling couplers and tankers, plus the desire to have an enhanced thrust capability, seems to have driven the OMV propulsion design such that the entire bipropellant PM became a single, self-contained ORU. The monopropellant capability (e.g., for HST reboost) remains with removal of this module.

(3) All other ORUs are generally associated with the various subsystems or the grapple interfaces, and were built with the intent of being serviceable by the use of a module service tool in a robotics or EVA mode. This was accommodated in some cases with a "one-bolt" on/off design.

Several observations, based on one relatively thorough series of neutral buoyancy tests (July 1988), and on various subsystem design issues that have been raised (Program Design Review - September 1988), can now be made concerning OMV ORUs and the servicing approach in general:

(a) A one-bolt ORU release does not appear adequate for realignment and retention. In the NBS, the lack of tapered guides and alignment marks made it very difficult to determine when ORU retention bolt threads were engaging or were being stripped.

(b) Many ORUs were hard to replace, even by two-man EVA teams, and would appear impossible for current robotic devices. The difficulty to replace these boxes was increased because the configuration of the boxes often obscured the corners, making the reference location hard to distinguish. Again, the lack of guide marks, guide pins, and alignment aids made ORU installation far more difficult than removal.

(c) Subsystem ORU sizes were limited by maximum propulsion module sizing and the STS bay envelope. ORU size initially appeared adequate, but certain subsystem ORUs have grown to the point that there may no longer be adequate clearance between the ORU boxes. All ORUs should be specifically sized to allow for the clearance needed in removal and installation with the multilayer insulation (MLI) attached.

(d) In some cases, it has been determined that there is marginal space and area left for the attachment of hand holds, foot restraint sockets and ORU tether points. Earlier crew involvement would have helped prevent these problems.

FLIGHT TELEROBOTIC SERVICER

The Flight Telerobotic Servicer (FTS) is being developed as part of the Space Station Freedom program. It will be used for assembly, maintenance, inspection, and servicing of the Space Station as well as the attached payloads. Future applications may include use with the OMV to perform servicing tasks remote from the Space Station. Thus, current development of the FTS must allow for evolution of capability over the life of the program.

To make provision for such growth, the NASA/National Bureau of Standards Standard Reference Model (NASREM) Architecture for Space Station Telerobot Control System, which defines the functional requirements and high-level specifications of the control system for the Space Station initial operational capability (IOC) FTS, has been conceived. NASREM, in general, defines a logical computing and control architecture for telerobotics. It is derived from concepts arising from such research programs as: the NASA Office of Aeronautics and Space

Technology (OAST) telerobotics programs at the Jet Propulsion Laboratory (JPL), LaRC, Oak Ridge National Laboratory, JSC, and MSFC; the artificial intelligence program at Ames Research Center (ARC); the Intelligent Task Automation program sponsored by Defense Advanced Research Projects Agency (DARPA) and Wright-Patterson Air Force Base (WPAFB); supervisory control concepts pioneered at the Massachusetts Institute of Technology (MIT); and the hierarchical control system developed for the Automated Manufacturing Research Facility at the National Bureau of Standards.

The NASREM telerobot control system architecture defines a set of standard modules and interfaces that facilitate software design, development, validation, and test, and make possible the integration of telerobotics software from a wide variety of sources. It is hierarchically structured into multiple layers such that a different fundamental mathematical transformation is performed at each layer. At layer one, a servomechanism is used to transform joint positions, velocities, and forces. At layer two, mechanical dynamics are computed. At layer three, obstacles are observed and avoided. At the fourth level, tasks on objects are transformed into movements of effectors. At level five, tasks on groups of objects are sequenced and scheduled. At the sixth layer, objects are batched into groups, resources are assigned to worksites, and parts and tools are routed and scheduled between worksites. Additional levels are possible, if necessary. Standard interfaces also provide the software "hooks" necessary to incrementally upgrade future flight telerobot systems as new capabilities develop in computer science, robotics, and autonomous system control.

Another important output from the FTS program has been the development of a Task Analysis Methodology (TAM), which provides:

- a method to develop operational scenarios for telerobotic systems;
- a method to analyze and evaluate telerobotic systems' task performance capabilities;
- a common language for space station telerobotic users (i.e., operational planners, hardware and software developers, and program managers);
- a method to optimize telerobotic operations on Space Station Freedom by assessing task scenarios and recommending task and hardware design requirements; and

- a standard format for inputting operational scenarios to off-line planning system software.

The TAM consists of six levels of hierarchy, analogous to the NASREM control architecture model. The highest level task covers the entire scope of work to be done during a space station mission. Each lower level comprises groups of subtasks of the task on the immediately preceding level. In descending order, the TAM task groupings are mission, work force actions, telerobotic tasks, elementary moves, primitive motions, and servo motions.

A final important development that has come out of the FTS program has been the compilation of the Space Station Robotic Systems Integration Standards (RSIS) document. This document is the fourth volume of the RSIS family of reference documents. It provides specific information for use in ensuring proper integration of robotic systems with those of other aerospace disciplines as applicable to the on-orbit space environment for Space Station Freedom. The document is designed for use by design engineers, systems engineers, maintainability engineers, operation analysts, human factors specialists, robotic specialists, and others engaged in definition, development, and integration of equipment to support the Space Station Freedom program.

The document establishes performance, design, development, and integration requirements for robotic system accommodation at the Space Station Freedom. It follows the format (and much of the content) of the Man-Systems Integration Standards, NASA-STD-3000, with modifications to incorporate the requirements for robotic systems. It should be used as reference material by all those involved in robotic systems work with the Space Station Freedom.

C

CURRENT STUDIES

SPACE STATION FREEDOM

See Part III for reference documents.

EARTH OBSERVING SYSTEM

The Earth Observing System (Eos) is the centerpiece of the Mission To Planet Earth effort to study and understand global change. It will consist of a series of polar orbiting platforms (POP) carrying scientific instruments aimed at understanding the Earth as a system, and determining those processes that contribute to our environmental balance, as well as those that may result in change.

Currently, the Eos platforms are baselined for a 5-year lifespan without planned servicing. However, there is the possibility that servicing may be added to the program. Studies of this possibility have identified several servicing design constraints, including: all servicing systems will have to operate within the mass limitations of the POP reaction wheel; servicing would be at 2.5-year intervals given a projected lifespan of 15 years; the ORU/payloads will be designed for robotic replacement; ORU changeouts will be done without real-time video supervision; the engineering and weight scarring for serviceability will be limited to TBD maximums; and the time required for ORU changeout will not be a constraint.

Trade studies performed have shown that: the servicer complexity, size, and weight is reduced when the ORU footprint is standardized; a single, larger ORU is desirable for serviceability when compared to multiple smaller ORUs; adequate system reliability must be achieved within the maximum weight limit; and replacing the function of the MMS ORU spreader beams with two additional bolt attachments to the structure reduces the total ORU weight.

Several key issues impacting Eos platform servicing are that: platform program managers are interested in science, not servicing, and are therefore unwilling to accept cost or weight impacts beyond critical limitations required for servicing; the new POP Program Design Requirements Document will remove all requirements for servicing, but the platforms will be serviceable; modular design is desired to control interfaces; payload experiments require standard interfaces; servicing versus not servicing cost was equivalent for 15-year serviceable and 5-year not serviced designs; the 15-year life design up-front research cost and risk, and logistics costs are not acceptable; and Space Station Freedom system commonality requirement would increase weight by 4000 lbs.

SATELLITE SERVICING WORKSHOPS AND WORKING GROUPS

See Part III for reference documents and meeting topics.

SSSWG INTERFACE STANDARDS COMMITTEES:

The Satellite Services System Working Group (SSSWG) has established six Interface Standards Committees, headed by William J. Hungerford of JSC, to review interface standards in the areas of mechanical (Al Thompson - Martin Marietta), electrical (Robert Davis - GSFC), optical (Albert Haddad - LMSC), thermal (Otto Ledford - ATI), fluids (Captain Wayne Foote - USAF), and data communications (Shlomo Dolinski - NASA HQ). Committees are composed of interested members of DoD, NASA and industry. The committees' goals are to: (1) foster communication, cooperation and coordination among spacecraft systems designers through common use of shared standards for serviceable spacecraft architectures and satellite/servicer interfaces; (2) facilitate standardization of serviceable spacecraft interfaces to minimize development, production, life-cycle costs with enhanced assembly, servicing, repair, and maintenance; (3) promote consensus and formal adoption of interface standards; and (4) assess the feasibility for expanded serviceability standards for serviceable satellite buses. The committees also serve to coordinate the myriad of independent on-going activities in the servicing area and to develop standards projects intended to fill gaps necessary for implementing servicing on orbit.

Each Interface Standards Committee has identified and prioritized interface standards needing development. These standards are listed below in descending order.

- Mechanical Interface Standards:
  - Flight releasable grapple fixture
  - Tool interfaces
  - Standardized tools
  - End effectors
  - Robotic end effector exchanger system
  - Fastener - 7/16-inch double-height hex bolt and socket
  - MMS and Modular Structure Assembly
  - Satellite grasping/berthing
  - ORU - size and weight
  - ORU container interface

- Electrical Interface Standards:
  - Robocon EVA/robotic electrical connectors
  - Tool interfaces
  - Mate/demate tool
  - Satellite and servicer power buses

- Fluid Interface Standards:
  - Automatic refueling coupling
  - Universal refueling interface system (URIS)
  - Leak detection techniques
  - Fluid coupling
  - Automated umbilical connector
  - Tank gauging technique

- Optical Interface Standards:
  - Label and color coding (NASA-STD-3000 and FED-STD 595A) combined with existing standard bar code labels
  - Status indicator design
  - Cameras, viewing angles, and mounts
  - Lighting

- Thermal Interface Standards:
  - Method for replacing thermal insulation
  - Insulation thermal resistance
  - Conductive/convective servicer/satellite interfaces
  - Test methods with space ratings

- Data Communications Interface Standards:
  - Fiberoptic connectors
  - Laser wavelength
  - Communication control architecture protocol
  - Data formats
  - Servicer and satellite data buses
  - Warning/message signals

The Interface Standards Committees have also identified the following key issues needing resolution:

1) Standard units of measure - metric has been recommended
2) Standard terminology for satellites
3) Organization of standards information
4) Interface standards and commonality
5) EVA/robotic compatibility
6) Standards categories
7) Level of detail
8) Servicing design requirements
9) Ground support - military version

PART II - DESIGN AND PLANNING GUIDELINES

A.

ORU DESIGN

SUBSYSTEM PARTITIONING:

- Minimizes system complexity
- Bus structure for high-rate communications between modules
- Hierarchical system is readily partitioned
- Keeps functional subsystems intact or closely associated
- Permits easy subsystem simulations before ORU exchange

ORU SIZING:

- Handling limits of astronauts or robots
- View and angle clearances
- Large subsystem-level ORUs:
    - Minimize number of modules
    - Minimize number of module types and footprints
    - Keep interface simple
    - Keep functional subsystems intact
    - Reduce integration and testing schedule and costs
- Component-level ORUs:
    - Less expensive than subsystem-level ORUs with an increased number of items in inventory
    - More users for generic components than for generic subsystems

SPACECRAFT INTERFACES:

- Use of blind-mate connectors for electrical, thermal, and fluid requirements
- Self-aligning kinematic mounts
- Preload to withstand launch/landing environment and return optical axis boresighting

- Space assembly obviates large preload
- Preloaded ORU to sustain launch loads requires stiff frame
- Minimize number and types of ORU interfaces
- External mounting gives access for servicing

TOOL INTERFACES:

- Small volume interface hardware on ORU
- Complexity in tool can allow simpler and more reliable module design
- Design module for mission use and adapt tool to module although "standard" box sizes may be considered first
- Design to use existing power and hand tools
- Unique ORU may require unique tool
- Minimize tool requirements
- Torque take out should preferably be close to drive
- Interface jackscrews and torque-takeout fittings should allow adequate mechanical mating tolerances for EVA and telerobotic modes
- Design expected temperature extremes

CARRIER INTERFACES:

- Carrier interface reuse of module-spacecraft interface
- Protective enclosure or isolation may be needed when carrier environment is not equivalent to mission environment

INTERFACE CONTROL DOCUMENTATION:

- Launch vehicle:
  - Platform
  - Carrier
  - Servicer

- Platform:
  - Payload
  - ORU
  - Servicer docking
  - Servicer tool
- ORU:
  - Payload or platform
  - Servicer carrier
  - Servicer manipulator or tool
- Tool:
  - Servicer carrier
  - Servicer manipulator
  - ORU

SERVICING THERMAL AND ENVIRONMENTAL INFLUENCES:

- Carrier protective enclosure or isolation may be needed
- Protection during transfer may be needed or operations may be impacted
- Heating or cooling of ORUs and tool may be needed before use

OPERATIONAL CONSIDERATIONS:

- Minimize EVA timeline and enhance remote intravehicular activity (IVA) and/or robotic capability.
- Develop contingency procedures by redundant and preferably generic methods/hardware.
- 2-fault tolerance for safety-critical items with possible EVA or other remote overrides
- Exposure during ORU transfer impacts illumination, release of contaminants, cleanliness requirements of servicer hardware and astronauts, radio frequency (RF) emissions.

B. FLUID TRANSFER AND SERVICING

SERVICING ENABLES EXTENDED MISSIONS:

- To be supplied.

SPECIAL MEASURES NEEDED TO AVOID HAZARDOUS LEAKING OF HYPERGOLICS, OXIDIZERS, CRYOGENS:

- To be supplied.

QUICK DISCONNECT FITTINGS NEEDED:

- To be supplied.

C. TOOL DESIGN

EVA TOOLS:

- Use power tools to reduce astronaut fatigue and timeline.
- Use electrical, tactile, and/or visual cues for change of state (latch/free).
- Visibility and access for operation and tool control
- Storage holster requirement for launch/landing, heating, etc.

ROBOTIC TOOLS:

- EVA power tools can be adapted readily for robotic use but may not be optimum design for either purpose.
- Certain hand tools may not be readily adapted for robotic use.
- End effector interface should be light, compact, stiff, reliable, quick changeout, and usable by all available manipulators. Power may be needed.
- Tool must not release workpiece or bits inadvertently. They should be locked to the robot manipulator, or remote storage rack (with requirements noted above).
- Tethering is generally inappropriate for teleoperated or telerobotic servicing operations.

ERGONOMIC GUIDELINES:

- Refer to NASA-STD 3000

D. CARRIER DESIGN

SYSTEM INTEGRATION:

- Carrier attaches to and operates with servicer
- Reach access for servicer transfer of ORUs or fluids from carrier to platform
- Minimize weight, volume, power, and complexity of remote servicer carrier.

LAUNCH INTERFACES FOR ORUs AND TOOLS:

- Isolation system may be needed to make launch environment equal to or better than original platform launch.
- Third interface needed for tools:
    - Manipulator
    - Workpiece or ORU
    - Launch support

SERVICING HANDLEABILITY:

- Minimize length, width, and weight of carrier
- Access to ORUs on carrier

E.

SERVICER DESIGN

UMBILICAL FUNCTIONS:

- Power to platform
- Keep alive power
- Safety verification
- Support test after repair
- Fluid couplers

PARTS HANDLING:

- ORU labeling and servicing data base required - see future work on ORU labels
- Documentation required for servicing

ORU ENVIRONMENT PROTECTION:

- Compatible with ORU storage specifications

F. SPACECRAFT DESIGN

IMPACTS OF SCARRING FOR SERVICEABILITY:

- Minimal for modular design
- Defines mechanical, electrical, optical, and thermal interfaces
- Docking interface is needed

DOCUMENTATION REQUIREMENTS:

- All serviceable items and general configuration must be documented in detail as flown
- Clear, crisp, high-contrast photography of all handling and mating interfaces, worksites, and general configuration (color can enhance cabling, routing, etc.)
- Annotated line drawings and photographs
- Index with key words, cross-references
- Test data and procedures
- Specifications, user's guides, etc.

INTERFACE CONTROL:

- Interface Control Documents (ICDs) required
- Formal Configuration Control Board (CCB) procedures required for changes to any and all servicing or handling interfaces
- ORU labeling for EVA teleoperations and telerobotic modes of servicing

ENVIRONMENTAL EXPOSURE DURING SERVICING:

- Operations constraints vs. self-protection via aperture doors, seals, enclosures, etc.

MODULARITY:

- Permits simulation of full subsystems before flight hardware is received
- Reduces integration time and cost
- Partitions system with minimum switching, connectors, if done judiciously

ACCESSIBILITY:

- External mounting of modules/ORUs
- Visibility access to areas requiring manipulation
- Envelope for motion of tool or EVA glove(s)
- Translation path clearances
- Translation to/from carrier
- Robotic manipulator reach
- High maintenance items readily accessible

DOCKING INTERFACE:

- Reuse of launch interface
- Compatibility of launch and servicer interfaces
- Reach and access of servicer to ORUs
- Reboost interface through center of gravity for maximum control system efficiency and minimum fuel use.

RENDEZVOUS AIDS:

- Passive aids: visibility markings, laser, and radar reflectors
- Active aids: radio beacons, tracking transponder, lights, and Global Positioning System (GPS)
- Use of minimum operational aids to reduce complexity, cost, weight

OPERATIONAL CONSIDERATIONS:

- Power off while servicing
- Keep-alive power on isolated circuits for heaters, aperture closure, safety monitors
- Software program loading and hardware testing after servicing
- Contingency procedures
- Safehold mode(s)

HUMAN FACTORS:

- Refer to NASA-STD-3000

FEASIBILITY CONSIDERATIONS:

- On-orbit failure analyses
- Closeout photography
- Closeout documentation
- Systems specifications
- Test results
- Test procedures
- Project upgrade and contingency plans
- Sparing status
- Support tools infrastructure

G.

SAFETY AND HAZARDS

TWO-FAULT TOLERANCE AGAINST HAZARDS TO ASTRONAUTS DURING ALL PHASES OF SERVICING:

- Propellants
- Contaminants
- Stored Energy
- Pyrotechnics
- Radiation sources
- Jettisoning items
- Collision

- Refer to NSTS 1700.7 B

H. OPERATIONS, TIMELINES AND TRAINING

MISSION PLANNING:

- Flight Crew:
    - Astronaut fatigue
    - Footholds, handrails, tethers, tool boxes, holsters, etc.
    - Access at worksite
    - Visibility
    - Timelines
    - Training
- Ground Crew:
    - Full system support
    - Fax drawings
    - Simulations (prior and during missions)

SIMULATIONS AND MOCKUPS:

- One-g and zero-g simulations invaluable
- Hi-fi worksite mockup required
- Operations simulations with failures and contingency training necessary
- Flat floor
- Graphics

I. MISSION ORBITAL CONSTRAINTS

ACCESSIBILITY:

- Anything other than Shuttle orbit (28.5°, 500 km or less) requires upper stage with autonomous rendezvous and docking capability or payload ascent/descent stage.
- High-energy stages needed for round trip to geosynchronous, polar, or elliptical orbits; most satellites use these high-energy orbits; e.g., communications, Earth observation, military.

NODAL REGRESSION:

- Orbital planes of satellites move relative to each other at a rate proportional to altitude separation.
- Space-based servicer may align with user's orbital plane only once in several years; window duration may be less than a month.
- Ground-based servicer can launch directly in plane with user by launching at the correct inclination and time of day.
- Minor plane change can be made with STS or OMV.

RENDEZVOUS OPERATIONS:

- MMU
- STS
- Expendable Launch Vehicle (ELV)
- OMV

J. LOGISTIC SUPPORT

SPARES QUANTITIES:

- Standard ORUs could have a larger market at lower prices by sharing of spares
- Possible dual serviceable ORU approach for both components (batteries, tape recorders, gyros, reaction wheels) and full subsystem modules (e.g., MMS modules)
- Keeping plant production lines, R&D open for support

SERVICING EQUIPMENT READINESS:

- Tradeoffs of short-notice availability vs. support to multiple users vs. servicer system capability and logistic support

LAUNCH FREQUENCY AND SCHEDULING:

- Infrequent launch opportunities may drive preventive maintenance strategy.

PAYLOAD AVAILABILITY FOR OPERATIONS:

- Payload system reliability and redundancy permit graceful degradation and some failures between repair visits.

PAYLOAD AND PLATFORM UPGRADES:

- Servicing enables evolution of orbiting capital assets.

K. MANAGEMENT

EARLY COMMITMENT TO SERVICEABILITY:

- Introduction of serviceability requirement late in developmental cycle is extremely costly.
- Introduction of serviceability requirement early imposes minimal impact to program.
- Utilize available servicing infrastructure.

SHARED PLATFORMS AND REDUCTION OF RECURRING COSTS:

- Development cost of dedicated point-design spacecraft justification vs. multiple-instrument platform/facility

REDUCTION OF LIFE CYCLE COSTS:

- Replacement spacecraft and instruments vs. modular servicing/upgrade

NEW TECHNOLOGY CONFIDENCE AND APPLICATIONS:

- Evolution by modular upgrade for increasing performance, reliability, economy, and safety
- New technology must provide a benefit to the program

PART III - REFERENCE DOCUMENTS

A. EXTRAVEHICULAR ACTIVITY

A-1) ICD-HSD-3-0045-02-0, Astronaut Boot to Foot Restraint Mechanical Requirements, Lyndon B. Johnson Space Center, Houston, TX (current issue).

A-2) JSC-17324, Contingency EVA Operations: STS-### Flight Supplement, JSC, 1987.

A-3) JSC-ATS-CONT-OPS-2102, Contingency Ops 2102 Workbook, March 1988. Should not be used as a design reference, but imparts the type of contingency situations that require the crew to go EVA.

A-4) JSC-14063, Rev A, Data Requirements for EVA, Payload Integration Plan (PIP) EVA Annex 11, JSC, Houston, TX. Explains how to write the PIP EVA Annex 11; should be used with a previously completed mission annex for a good understanding of the data required. The actual annex should define the hardware and operations support requirements and specific design configurations for payload hardware to STS hardware interfaces associated with the payloads.

A-5) NSTS 21000-A11, Data Requirements for the Extravehicular Activity Annex, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Defines the design data, operational data, and documentation required for the payload user to prepare the EVA Annex to the Payload Integration Plan (PIP).

A-6) JSC 20466, EVA Catalog Tools and Equipment, Systems Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Catalog of available and proposed Shuttle crew aids, devices, tools, and support equipment.

A-7) NSTS 07700, Vol XIV, Appendix 7, EVA System Description and Design Data, March 1988. Describes the constraints, limitations, and capabilities needed to perform an EVA. Also describes the EVA equipment design requirements.

A-8) MSC 05878, Extravehicular Activity Experience in Manned Space Operations, Manned Spacecraft Center, Houston, TX, September 1970. A NASA General Working Paper that provides a summary of flight crew operations experience gained from the planning and conduct of extravehicular activity through Apollo 12, including descriptions of the equipment used.

A-9) SSP-30256, Rev C, Draft 3, The Extravehicular Activity System Architectural Control Document, March 1989. Establishes EVA architectures, the requirements that control the interchangeability of ORUs, and the requirements that control distributed systems' common items for U.S.-provided systems.

A-10) JSC 17325, Flight Data File, EVA Checklist, All Vehicle, Operations Division, Lyndon B. Johnson Space Center, Houston, TX (current issue).

A-11) NASA-STD-3000, Volume 1, Chapter 14, Man/System Integration Standards (MSIS), Man-Systems Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Provides general EVA information, as well as information on EVA physiology, anthropometry, workstations, restraints, mobility, translation, tools, fasteners, connectors, and enhancement systems.

A-12) NASA-STD-3000, Vol. 4, Chapter 14, Man/System Integration Standards (MSIS), Man-Systems Division, Lyndon B. Johnson Space Center, Houston, TX, (current issue). Provides general Space Station EVA information, as well as information on EVA physiology, anthropometry, workstations, restraints, mobility, translation, tools, fasteners, connectors, and enhancement systems.

A-13) SD72-SH-0107, Requirements/Definition Document, Crew Station and Equipment, Book 7, Space Division, Rockwell International (current issue). An internally controlled, Rockwell International document that defines the requirements for the Orbiter crew station and equipment, including interfaces and supporting hardware for EVA. Specifies design criteria for Orbiter sharp edges, corners, and protrusion hazards.

A-14) JSC 12770, Shuttle Flight Operations Manual, Volume 15, EVA, Training Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Contains functional descriptions and operational procedures for all Shuttle EVA equipment and supporting Orbiter provisions. This document is the prime source of detailed operations data on all EVA systems and hardware.

A-15) AAS74 120, Skylab Extravehicular Activity, D. C. Schultz et al. Paper presented to the twentieth annual meeting of the American Astronautical Society, Los Angeles, CA, August 1974. Discusses the use of EVA techniques during the Skylab program for accomplishing major mission objectives, and major and minor repair work outside the Skylab orbital workshop.

A-16) JSC 20527, Space Station EVA User Interface Design Guidelines, June 1987. Describes EVA provisions and requirements that pertain to Space Station Freedom; outlines the user's responsibility for EVAs and planned interaction to ensure safety, flight planning, procedures development, and crew training.

B. FLIGHT ACTIVITIES

APOLLO PROGRAM

B-1) JSC 09423, Apollo Program Summary Report, Lyndon B. Johnson Space Center, Houston, TX, April 1975. Includes descriptions of EVA hardware used during the Apollo program, concentrating on the EMU.

B-2) MSC 05878, Extravehicular Activity Experience in Manned Space Operations, Manned Spacecraft Center, Houston, TX, September 1970. A NASA General Working Paper that provides a summary of flight crew operations experience gained from the planning and conduct of extravehicular activity through Apollo 12, including descriptions of the equipment used.

GEMINI PROGRAM

B-3) MSC 05878, Extravehicular Activity Experience in Manned Space Operations, Manned Spacecraft Center, Houston, TX, September 1970. A NASA General Working Paper that provides a summary of flight crew operations experience gained from the planning and conduct of extravehicular activity through Apollo 12, including descriptions of the equipment used.

B-4) NASA SP-138, Gemini Summary Conference, Manned Spacecraft Center, Houston, TX, February 1967, pp.67-146. A series of five papers describing experience gained and lessons learned during the Gemini program EVA efforts.

B-5) NASA-SP-149, Summary of Gemini Extravehicular Activity, Manned Spacecraft Center, Houston, TX, 1967.

SKYLAB PROGRAM

B-6) MSC 05878, Extravehicular Activity Experience in Manned Space Operations, Manned Spacecraft Center, Houston, TX, September 1970. A NASA General Working Paper that provides a summary of flight crew operations experience gained from the planning and conduct of extravehicular activity through Apollo 12, including descriptions of the equipment used.

B-7) NASA-SP-4208, Living and Working In Space: A History of Skylab, W. David Compton, 1983.

B-8) NASA-TM-X-64860, MSFC Skylab Lessons Learned, Marshall Space Flight Center, 1974.

B-9) AAS74 120, Skylab Extravehicular Activity, D. C. Schultz et al. Paper presented to the twentieth annual meeting of the American Astronautical Society, Los Angeles, CA, August 1974. Discusses the use of EVA techniques during the Skylab program for accomplishing major mission objectives, and major and minor repair work outside the Skylab orbital workshop.

B-10) Skylab Lessons Learned as Applicable to a Large Space Station, William Schneider, The Catholic University, 1976.

SPACE SHUTTLE PROGRAM

B-11) JSC-ATS-CONT-OPS-2102, Contingency Ops 2102 Workbook, March 1988. Should not be used as a design reference, but imparts the type of contingency situations that require the crew to go EVA.

B-12) AAS85-060, The Dynamics of SMM Spacecraft Capture and Redeployment on STS 41-C, K. Grady, February 1985. Describes control and stabilization of the SMM using a portable failed attitude control system prior to rendezvous, during astronaut capture attempts, during stabilization, and during RMS capture from the space repair mission.

B-13) EASE/ACCESS Postmission Management Report, Marshall Space Flight Center, Huntsville, AL. Summary of EVA construction demonstration mission.

B-14) Mission Operations Overview of On-Orbit Servicing Activities, Mission Operations Directorate, Systems Division, Lyndon B. Johnson Space Center, Houston, TX, January 1989. Presentation to the On-Orbit Steering Committee (NASA Headquarters) as an input and recommendation for a coordinated NASA on-orbit servicing strategic plan.

B-15) 408-00234, Proceedings of SMRM Degradation Study Workshop, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, May 1985. (GSFC Doc #408-SMRMR-79-0001) Results of analyses on the module returned by the SMRM after 4 years of exposure in space. Atomic oxygen effects, hypervelocity impacts, etc., described.

B-16) 408-01929, The SMRM Final Report, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, June 1985. Summary of the SMM Repair Mission.

B-17) SMRM Lessons Learned, Presentation by Frank Ceppolina, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD. A distillation of the experiences of the SMRM: spacecraft, Shuttle, operations, safety, training, and tools.

B-18) 408-01105, SMRM Summary Final Report, CTA, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, October 1984. Summary of the SMRM.

B-19) Space Shuttle Mission 11 (STS 41-C), Challenger, Robert Davis, Magill's Survey of Science: Space Exploration Series, Salem Press, 1988/1989, Vol. IV, pg. 1719-1726.

B-20) JSC-20361, Space Shuttle Satellite Retrieval Mission STS-51A Project Final Report, Flight Projects Engineering Office, JSC, Houston, TX, February 1985.

B-21) STS-3 Flight Crew Report, Mission Operations Directorate, JSC, Houston, TX, October, 1982.

B-22) <u>STS-4 Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX.

B-23) <u>STS-5 Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX, March 1983.

B-24) <u>STS-6 Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX, April 1983.

B-25) <u>STS-26 Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX.

B-26) <u>STS-27 Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX.

B-27) <u>STS-30 Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX.

B-28) <u>STS 41-B Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX, June 1984. Includes SMM repair technology demonstration and first flight test of the MMU.

B-29) JSC-19537, <u>STS 41-B Technical Crew Debriefing</u>, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, April 1984. Includes SMM repair technology demonstration and first flight test of the MMU.

B-30) <u>STS 41-C Flight Crew Report</u>, Mission Operations Directorate, JSC, Houston, TX. Describes astronaut activities relating to the SMRM.

B-31) JSC- , <u>STS 41-C Technical Crew Debriefing</u>, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, May 1984. Describes astronaut activities relating to the SMRM.

B-32) STS 41-G Flight Crew Report, Mission Operations Directorate, JSC, Houston, TX. Describes astronaut activities relating to the testing of the ORS.

B-33) JSC- , STS 41-G Technical Crew Debriefing, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, November 1984. Describes astronaut activities relating to the testing of the ORS.

B-34) STS 51-A Flight Crew Report, Mission Operations Directorate, JSC, Houston, TX. Describes astronaut activities involved in the retrieval and return to Earth of the PALAPA B-2 and WESTAR VI satellites.

B-35) JSC-20202, STS 51-A Technical Crew Debriefing, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, December 1984. Describes astronaut activities involved in the retrieval and return to Earth of the PALAPA B-2 and WESTAR VI satellites.

B-36) STS 51-C Flight Crew Report, Mission Operations Directorate, JSC, Houston, TX.

B-37) STS 51-D Flight Crew Report, Mission Operations Directorate, JSC, Houston, TX. Describes astronaut activities related to the Syncom Leasat-3 deployment and subsequent failure.

B-38) JSC- , STS 51-D Technical Crew Debriefing, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, May 1985. Describes astronaut activities related to the Syncom Leasat-3 deployment and subsequent failure.

B-39) JSC-20782, STS 51-I Technical Crew Debriefing, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, December 1985. Describes astronaut activities during the retrieval, repair and relaunch of the Syncom Leasat-3 satellite.

B-40) JSC-20959, STS 61-B Technical Crew Debriefing, Mission Operations Directorate Training Division, Johnson Space Center, Houston, TX, January 1986. Describes astronaut activities during the EASE/ACCESS demonstration.

C. FLIGHT OPERATIONS

C-1) PIP Annex 3: NSTS 21000-A03, Data Requirements for the Flight Operations Support Annex, Lyndon B. Johnson Space Center, Houston, TX (current issue). Identifies payload operations support plans; defines flight operations decisions, joint operations interface procedures, and malfunction procedures; and includes payload electrical power and command interface drawings.

C-2) PIP Annex 2: NSTS 21000-A02, Data Requirements for the Flight Planning Annex, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Includes data required to define: launch window and orbital parameters; electrical power and cooling requirements; deployment, retrieval, proximity operations requirements; crew activity requirements; attitude and pointing; extravehicular activities; pointing/timing target data for deployment of upper stages.

C-3) JSC-17321, In-Flight Maintenance Checklist, Mission Operations Directorate Systems Division, Johnson Space Flight Center, Houston, TX, February 1988.

C-4) In-Flight Maintenance Services, Mission Operations Directorate, Systems Division, Lyndon B. Johnson Space Center, Houston, TX, January 1989. Presentation to the On-Orbit Steering Committee (NASA Headquarters) as an input and recommendation for a coordinated NASA on-orbit servicing strategic plan.

C-5) SFOM Vol. 4D: JSC 12770, Shuttle Flight Operations Manual Volume 4D: Television (CCTV), Training Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Describes major system components, operational overview, functional description, command capability, telemetry provisions, and peripheral loose equipment.

C-6) JSC 12770, Shuttle Flight Operations Manual, Volume 15, EVA, Training Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Contains functional descriptions and operational procedures for all Shuttle EVA equipment and supporting Orbiter provisions. This document is the prime source of detailed operations data on all EVA systems and hardware.

D. FOREIGN ACTIVITIES

D-1) NAGW-659, Soviet Space Stations, An Analog, 2nd Edition, Dr. B.J. Bluth and Martha Helppie, May 18, 1987.

D-2) Soviet Manned Space Program, Philip Clark, Orion Books, 225 Park Avenue South, New York, NY, 10003, 1988.

E. INTERFACE STANDARDS

PAYLOAD INTEGRATION

E-1) NSTS 14046, Payload Verification Requirements, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Specifically addresses payload interface verification; includes descriptions of those requirements pertaining to the Orbiter payload services preflight interface verification.

E-2) NHB 1700.7, Safety Policy and Requirements for Payloads Using the Space Transportation System (STS), NASA Headquarters, Washington, DC (current issue). Establishes the safety requirements applicable to all NSTS payloads and their ground support equipment. Defines hazards and measures to monitor, control, or inhibit them.

E-3) NSTS 21000-IDD-MDK, Shuttle/Payload Interface Definition Document for Middeck Payload Accommodations, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Defines and controls the interfaces between the payload and the middeck area and defines and controls all constraints.

E-4) NSTS 07700, Vol. XIV, Space Shuttle System Payload Accommodations, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Provides an overview of the STS and its payload accommodations to support the conceptual design of payloads and their integration into the Space Shuttle. This document, its Attachment, and its Appendices describe the interfaces between the Space Shuttle system and Space Shuttle payloads.

E-5) JSC 16742, STS/Payload Integration Guide for Detached Payloads, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue.) Defines data submittal requirements for cargo integration. Contains a standard integration plan and annexes.

E-6) NSTS 07700, Vol. XIV, Appendix 1, System Description and Design Data - Contamination Environment, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Information on the environments to which the payload is exposed while in or around the the Orbiter payload bay.

E-7) NSTS 07700, Vol. XIV, Appendix 8, System Description and Design Data - Payload Deployment and Retrieval System, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Describes the PDRS system, operations and constraints, payload design considerations, mission definition and design, and real-time operations and capabilities.

GENERAL

E-8) 408-EP-403-001, Rev A, Explorer Platform Users Guide, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, August 1989. Describes an augmentation to the standard MMS design to accommodate payload exchange on orbit with upgraded capabilities and design for growth.

E-9) S-700-42, Revision B, General Specifications for Connectors, Electrical and Rectangular for Space Flight Use, GSFC, Greenbelt, MD. Describes scoop-proof, blind-mating connectors suitable for use in servicing interfaces. Several sizes and connector inserts are available.

E-10) 408-2106-0015, General Specifications: Connectors, Electrical, Robotically Operated (ROBOCON), and Rectangular, for Space Flight Use, GSFC, Greenbelt, MD, March 1990 (Preliminary).

E-11) Satellite Services System, Interface Design Considerations for Robotic Satellite Servicers, September 1989 Draft, Satellite Services System Working Group, Lyndon B. Johnson Space Center, Houston, TX. Preliminary document to provide engineers with interface design considerations for robotic satellite servicers. The considerations are also applicable to nonrobotic satellite servicing methods such as IVA or EVA servicing.

E-12) Satellite Services System, Interface Design Considerations for Serviceable Satellites, September 1989 Draft, Satellite Services System Working Group, Lyndon B. Johnson Space Center, Houston, TX. Preliminary document to provide engineers with interface design considerations for serviceable satellites. The design considerations are also applicable to nonserviceable satellites to enhance design, fabrication, and ground checkout.

E-13) S-700-11, Multimission Modular Spacecraft External Interface Specifications and Users Guide, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, April 1986. Describes a standard spacecraft, serviceable by the Space Shuttle using FSS and astronaut EVA with tools.

E-14) 408-2112-0004, Multimission Modular Spacecraft Flight Support System Users Guide, April 1978. Describes a Shuttle-compatible structural cradle system with a three-degree-of-freedom payload positioning capability and a three-point docking interface. Electrical umbilicals interface payloads to Shuttle avionics. Compatible with all MMS users, HST, Gamma Ray Observatory, and others.

E-15) S-700-10, Rev. A, Multimission Modular Spacecraft (MMS) System Specification, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, April 1986. Describes subsystems capabilities and interfaces for the MMS.

E-16) ORUs/EVA Servicing, ORU Designers Workshop, Session I, Goddard Space Flight Center, Greenbelt, MD, 9-10 March 1989. 24 presentations: Session I - ORUs/EVA Servicing; Session II - ORUs/Remote Servicing; Session III - ORU Standards.

E-17) Satellite Services Handbook Interface Guidelines, prepared by Lockheed Missiles and Space Co; for Lyndon B. Johnson Space Center, Houston, TX, December 1983. Handbook is the first attempt to identify satellite interfaces for on-orbit servicing, both manned

and unmanned. This document covers only EVA and IVA items.

E-18) Satellite Services Fluid Transfer Interface Requirements Workshop, Lyndon B. Johnson Space Center, Houston, TX, February 1984 (Two volumes). Describes requirements, concepts, designs, etc., for the development of an interface for fluid management and transfer on orbit. Vol. 1 - Workshop Presentations; Vol. 2 - Workshop Results.

E-19) ICD 2-19001, Shuttle Orbiter/Cargo Standard Interfaces, NSTS Integration and Operations Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). This document is Attachment 1 to NSTS 07700, Vol. XIV. Defines and controls the Shuttle system interfaces and constraints.

E-20) JSC 20527, Space Station EVA User Interface Design Guidelines, June 1987. Describes EVA provisions and requirements that pertain to the Space Station; outlines the user's responsibility for EVAs and planned interaction to ensure safety, flight planning, procedures development, and crew training.

F. INTRAVEHICULAR ACTIVITY

F-1) JSC-17321, In-Flight Maintenance Checklist, Mission Operations Directorate Systems Division, Johnson Space Flight Center, Houston, TX, February 1988.

F-2) NSTS 07700, Vol. XIV, Appendix 9, IVA System Description and Design Data.

G. TECHNOLOGY DEVELOPMENT

G-1) NASA Technical Paper 2314, Autonomous Rendezvous and Docking: A Parametric Study, George C. Marshall Space Flight Center, Huntsville, AL, May 1984. Description of functions of rendezvous and docking components; discussion of simulation results of docking performance, fuel/time efficiency, and noise-related effects.

G-2) LOCDOC: Autonomous Rendezvous and Docking, Lockheed Missiles and Space Co., Sunnyvale, CA (No date). Presentation to NASA and DOD describing performed mission analyses, and specifying guidance/sensor design requirements and interface criteria, vehicle configurations, and operational limits and requirements.

G-3) Satellite Services System, Interface Design Considerations for Robotic Satellite Servicers, September 1989 Draft, Satellite Services System Working Group, Lyndon B. Johnson Space Center, Houston, TX. Preliminary document to provide engineers with interface design considerations for robotic satellite servicers. The considerations are also applicable to nonrobotic satellite servicing methods such as IVA or EVA servicing.

G-4) NASA Conference on Space Telerobotics, Final Program (sponsored by all seven NASA Field Centers), Pasadena Center, Pasadena, CA, January 1989. An international conference resulting in several hundred abstracts with a general theme of man-machine cooperation in space.

G-5) Space Construction, NASA Conference Publication 2490, Proceedings of a Conference sponsored by the Offices of Space Flight, Aeronautics and Space Technology, and Space Station, NASA Headquarters, Washington, DC, and held at the NASA Langley Research Center, Hampton , VA, August 6-7, 1986.

G-6) SSP-XXXXX, Vol IV, Space Station Robotic Systems Integration Standards, Space Station Program Office, April 1, 1989 Draft.

G-7) Telepresence Work Station System - Definition Study, NAS9-17230, Martin Marietta study for the Lyndon B. Johnson Space Center, Houston, TX, January 1987. A two-part, two-volume study to define a system that will be capable of performing a wide variety of robotic missions in space.

G-8) Telerobotic Work System: Space Station Truss-Structure Assembly Using a Two-Arm Dextrous Manipulator, NAS9-17229, Grumman study for the Lyndon B. Johnson Space Center, Houston, TX, November 1986. The study evaluated two aspects of teleoperation using two types of dextrous manipulator arms. Also, a teleoperation control station design was evaluated.

H. SATELLITE SERVICING OVERVIEWS

H-1) Satellite Services System, A Guide for Evaluating Costs Associated With Satellite Servicing, June 1988, Satellite Services System Working Group, Lyndon B. Johnson Space Center, Houston, TX. An aid to design engineers in performing preliminary tradeoff studies.

H-2) On-Orbit Spacecraft/Stage Servicing During STS Life Cycle, (Contract NASA9-15800). Lockheed Missiles and Space Company for the Lyndon B. Johnson Space Center, Houston, TX, January 1984. Describes six study tasks, including identification of representative STS payloads, classes of service functions, development of servicing vs. spacecraft matrices, identification of servicing hardware and kits, and applicability of hardware and kits to the Space Station.

H-3) JSC 20109, NSTS Optional Services Pricing Manual, Lyndon B. Johnson Space Center, Houston, TX (current issue). Provides U.S. commercial and foreign NSTS users with cost data, reimbursement schedules, and rules and policies regarding standard and optional services costs, and shared missions, including examples.

H-4) Satellite Servicing - A NASA Report to Congress, NASA Headquarters, Office of Space Flight, Washington, DC, March 1988. A general document describing NASA interpretation of congressional requirements for satellite servicing and the NASA management and technical approach to meet those requirements.

H-5) JSC 22658, Satellite Services System Book of Key Issues, Engineering Directorate, Lyndon B. Johnson Space Center, Houston, TX, August 1987. A book of key issues compiled by NASA, DOD, industry, and international participants. Key issues are separated into two classes--engineering and programmatic.

H-6) Space Assembly, Maintenance and Servicing Study (SAMSS), June 1987 (Five volumes). Final report of a 16-month study sponsored jointly by DOD and NASA; performed by TRW et al., under Contract F04701-86-C-0032. Addresses the requirements, concepts, and planning for full implementation of a U.S. space assembly, maintenance, and servicing capability by the early 2000's. Vol. 1 - Executive Summary; Vol. 2 - Systems Analysis; Vol. 3 - Design Concepts; Vol. 4 - Concept Development Plan; Vol. - 5 Neutral Buoyancy Simulation.

H-7) Space Assembly, Maintenance and Servicing Study (SAMSS), July 1987 (Five volumes). Final report of a sixteen-month study sponsored jointly by DOD and NASA; performed by Lockheed Missiles and Space Co. et al., under Contract F04701-86-C-0030. Addresses the requirements, concepts, and planning for full implementation of a U.S. space assembly, maintenance, and servicing capability by the early 2000's. Vol. 1 - Executive

Summary; Vol. 2 - Systems Analysis; Vol. 3 - Design Concepts; Vol. 4 - Concept Development Plan; Vol. - 5 Neutral Buoyancy Simulation.

H-8) Space Logistics On-Orbit Maintenance Study, NASA Headquarters, October 1988. A general study of all elements of satellite on-orbit maintenance. Presents alternative technical approaches as well as some cost vs. benefit analysis.

I. SERVICEABLE SPACECRAFT

EARTH OBSERVING SYSTEM

I-1) Eos Servicing Study, Final Report, GE Astro-Space Division, Valley Forge, PA, August 21, 1989; for GSFC Eos Project Office.

I-2) Polar Orbiting Platform - ELV Servicing Mission Study, Mission Requirements and Instrument Design Report, Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA, March 1989. Summarizes a series of study activities supporting the POP Phase A Servicing Study.

I-3) Polar Orbiting Platform Lessons Learned for the Implementation of Servicing Standards, Robert Radtke, Tracor Applied Sciences; presented to the AIAA Serviceable Spacecraft Committee on Standards Workshop at Johnson Space Center, Houston TX, November 30, 1989.

EXPLORER PLATFORM

I-4) 408-EP-403-001, Rev. A, Explorer Platform Users Guide, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, August 1989. Describes an augmentation to the standard MMS design to accommodate payload exchange on orbit with upgraded capabilities and design for growth.

HUBBLE SPACE TELESCOPE

I-5) Designing an Observatory for Maintenance In Orbit, The Hubble Space Telescope Experience, Hubble Space Telescope Project Office, Marshall Space Flight Center, Huntsville, AL, April 1987.

MULTIMISSION MODULAR SPACECRAFT

I-6) S-700-11, Multimission Modular Spacecraft External Interface Specifications and Users Guide, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, April 1986. Describes a standard spacecraft, serviceable by the Space Shuttle using FSS and astronaut EVA with tools.

I-7) 408-2112-0004, Multimission Modular Spacecraft Flight Support System Users Guide, April 1978. Describes a Shuttle-compatible structural cradle system with a three-degree-of-freedom payload positioning capability and a three-point docking interface. Electrical umbilicals interface payloads to Shuttle avionics. Compatible with all MMS users, HST, Gamma Ray Observatory, and others.

I-8) S-700-10, Rev. A, Multimission Modular Spacecraft (MMS) System Specification, Satellite Servicing Project, Goddard Space Flight Center, Greenbelt, MD, April 1986. Describes subsystems capabilities and interfaces for the MMS.

J. SERVICING INFRASTRUCTURE

GENERAL

J-1) JSC 22976, Satellite Services System Servicing Equipment Catalog, March, 1988, New Initiatives Office, Lyndon B. Johnson Space Center, Houston, TX (current issue). Identifies existing and planned equipment items that could be used for on-orbit satellite servicing.

J-2) JSC 22970, Satellite Services System Technology Assessment for a Robotic Satellite Servicer System, New Initiatives Office, Lyndon B. Johnson Space Center, Houston, TX, May 1988 (Four volumes). Vol. 1 - Information Sources and Terminology Related To Aerospace Robotic Applications; Vol. 2 - Literature Related To Aerospace Robotic Applications and Technology Assessment; Vol. 3 - Robotics Hardware Availability for a Satellite Servicer System; Vol. 4 - NASA/JSC Satellite Services System Working Group Robotics Technology Assessment.

FLIGHT SUPPORT SYSTEM

J-3) Flight Support System Servicing Aid Tool, Presentation by Robert Davis, Proceedings of the Second European In-Orbit Operations Technology Symposium, Toulouse, France, September 12-14, 1989, pg. 73-76.

FLIGHT TELEROBOTIC SERVICER

J-4) FTS-DR3-01, Flight Telerobotic Servicer Definition and Preliminary Design, July 1988 (Two volumes). Technical analyses, conceptual design considerations, and trade studies of the FTS system; includes: worksite attachment methods, telerobotic communications, mobility, self-powered operational capabilities, control system architecture, etc. NOTE: This report may contain competition sensitive materials. The report should only be obtained through the contractor or GSFC.

J-5) Flight Telerobotic Servicer Task Analysis Methodology, Flight Telerobotic Servicer Mission Utilization Team, Goddard Space Flight Center, Greenbelt, MD, 14 April 1989 (Release for review only). A guide for operations planners and hardware developers in preparing space telerobotic operations.

J-6) SS-GSFC-0042, Final Report, Flight Telerobotic Servicer (FTS) Tinman Concept In-house Phase B Study, September 1988 (Two volumes). GSFC in-house version of a Phase B study for the basic concept development of the FTS system.

J-7) Flight Telerobotic Servicer (FTS) Trade Study Report, February 1988 (Contract NAS5-30249). A contractor trade study performed to describe the requirements on user hardware for accommodating the telerobot (FTS system) for each function. NOTE: This report may contain competition sensitive materials. The report should only be obtained through the contractor or GSFC.

J-8) SS-GSFC-0071, Flight Telerobotic Servicer Utilization for Space Station Freedom Assembly, Flight Telerobotic Servicer Mission Utilization Team, Goddard Space Flight Center, Greenbelt, MD, September 1989.

J-9) SS-GSFC-0027, NASA/NBS Standard Reference Model for Telerobot Control System Architecture (NASREM), National Bureau of Standards Robot Systems Division and Goddard Space Flight Center, Greenbelt, MD, March 13, 1987. Defines a logical computing architecture for telerobotics as a set of modules and interfaces, and makes possible integration and incremental upgrade of telerobotics software from a variety of sources for use on FTS.

J-10) Short-Term Evolution for the Flight Telerobotic Servicer, Flight Telerobotic Servicer Project, Goddard Space Flight Center, Greenbelt, MD, April 11, 1989 Draft.

MANNED MANEUVERING UNIT

J-11) MMU-SE-46, MMU Users Guide, Martin Marietta Corporation, Denver, CO (current issue). Users guide for the Manned Maneuvering Unit.

ORBITAL MANEUVERING VEHICLE

J-12) Concept Evaluation/Test for the Tumbling Satellite Retrieval Kit, Final Review, NAS8-36641, Grumman study for the George C. Marshall Space Flight Center, Huntsville, AL, October 1988. An executive overview and technical briefing, including design concept, trades, test hardware and design, and simulation and test plans.

J-13) Remote Tanker and Servicer Analysis - Final Review, TRW Space and Technology Group, George C. Marshall Space Flight Center, Huntsville, AL, January 1989 (Report 51000.89TD005-003). Presents findings relating to the OMV tanker/servicer analysis, including mission and system requirements, several design concepts, options, and cost analyses and comparisons.

SATELLITE SERVICER SYSTEM

J-14) JSC [TBD], Final Report, Satellite Servicer System Flight Demonstration Program Pre-Phase B Studies, Satellite Servicing Systems Project Office, Lyndon B. Johnson Space Center, Houston, TX, December 1989. Report describes the results of NASA in-house, intercenter studies and technology assessments relating to the Satellite Servicer System Flight Demonstration Program.

J-15) Satellite Servicer System Flight Demonstration Program (SSSFD) Pre-Phase B Technology Assessment, Jet Propulsion Laboratory, California Institute of Technology, June 1989. Assesses technologies required for the SSSFD program, including available technologies from the OMV and the FTS; assesses developing technology programs sponsored by the NASA/OAST which might be appropriate for the SSSFD program.

SPACE STATION FREEDOM

J-16) NASA-STD-3000, Vol 4, Chapter 14, Man/System Integration Standards (MSIS), Man-Systems Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Provides general Space Station EVA information as well as information on EVA physiology, anthropometry, workstations, restraints, mobility, translation, tools, fasteners, connectors, and enhancement systems.

J-17) OSSA Space Station Servicing Data Book, November 1987 (Final report, contract NASW-4152). Identifies top-level Space Station servicing requirements of currently planned Office of Space Science and Applications (OSSA) missions. The report is based on survey and analysis of servicing needs of candidate OSSA missions.

J-18) SSP-XXXXX, Vol IV, Space Station Robotic Systems Integration Standards, Space Station Freedom Program Office, April 1, 1989 Draft.

J-19) JSC 20527, Space Station EVA User Interface Design Guidelines, June 1987. Describes EVA provisions and requirements that pertain to the Space Station; outlines the user's responsibility for EVAs and planned interaction to ensure safety, flight planning, procedures development, and crew training.

J-20) Telerobotic Work System: Space Station Truss-Structure Assembly Using a Two-Arm Dextrous Manipulator, NAS9-17229, Grumman study for the Lyndon B. Johnson Space Center, Houston, TX, November 1986. The study evaluated two aspects of teleoperation using two types of dextrous manipulator arms. Also, a teleoperation control station design was evaluated.

K. TRAINING

K-1) SFOM Vol 4D: JSC 12770, Shuttle Flight Operations Manual Volume 4D: Television (CCTV), Training Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Describes major system components, operational overview, functional description, command capability, telemetry provisions, and peripheral loose equipment.

K-2) JSC 12770, Shuttle Flight Operations Manual, Volume 15, EVA, Training Division, Lyndon B. Johnson Space Center, Houston, TX (current issue). Contains functional descriptions and operational procedures for all Shuttle EVA equipment and supporting Orbiter provisions. This document is the prime source of detailed operations data on all EVA systems and hardware.

K-3) JSC 16908, Weightless Environment Training Facility General Operating Procedures, Man-Systems Division, Lyndon B. Johnson Space Center, Houston, TX (current issue).

K-4) JSC-EC-R-88-2, Weightless Environment Training Facility Integration Document, Man-Systems Division, JSC, Houston, TX. Recommended and helpful guide to WETF users as it thoroughly explains WETF test procedures, facilities, and equipment. The guide is a summary of JSC-17050, WETF General Description; JSC-16908, WETF General Operating Procedures; JSC-16941, WETF Standard Operating Procedures; and JSC-16961, WETF Training Plan.

L. SATELLITE SERVICING WORKSHOPS

L-1) JSC , Satellite Services Workshop I, June 1982.

L-2) JSC 20677, Satellite Services Workshop II, Flight Projects Engineering Office, Lyndon B. Johnson Space Center, Houston, TX, November 1985. Documents presentations given at an EVA conference held November 6-8, 1985.

L-3) Satellite Services Workshop III, GSFC, Greenbelt, MD, June 9-11, 1987 (Five volumes). Vol. 1 - NASA/DoD Policy; Vol. 2 - Satellite Servicing Standards; Vol. 3 - Serviceable Spacecraft Designs; Vol. 4 - Servicing Aids, Tools, and Facilities; Vol. 5 - Servicing at Space Station.

L-4) JSC 23655, Satellite Services Workshop IV, Lyndon B. Johnson Space Center, Houston, TX, June 21-23, 1989 (Four volumes). Vol. 1 - Space Shuttle Experience, Space Station Considerations, and Servicer/Satellite Design; Vol. 2 - Servicing Operations; Vol. 3 - Tools and Equipment; Vol. 4 - Future Opportunities.

M. Satellite Services System Working Group Presentations

The Satellite Services System Working Group (SSSWG) continuously conducts meetings with formal presentations. The first four meetings stressed the organization of the working group and defined areas of interest and responsibility. No formal documentation exists for these meetings; however, many of the presentations contain materials relating to lessons learned. The following list identifies those SSSWG formal presentations that are available. It should be noted that the presentations do not include name of author or organization.

Working Group Meeting No. 5

Date: May 21-22, 1987
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Plume Impingement Considerations
Standard Optical Interfaces for RMS Operations
Current Satellite Servicing Projects at TRW
Telepresence and the Enhanced Astronaut
Development of Standard Connectors for ORUs

Working Group Meeting No. 6

Date: June 18-19, 1987
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Joining Technologies for Maintenance and Construction in Space
Customer Cost Guide and Hypothetical Cost Exercise
Satellite Servicing Equipment
Fluid Coupling Video

Working Group Meeting No. 7

Date: July 16-17, 1987
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Servicing Equipment and Lessons Learned from Solar Max Repair Mission
Component Level Repair Requirements for Space Station Repair

Working Group Meeting No. 8

Date: August 27-28, 1987
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Industrial Space Facility
Space Repairs
Syntactic Machine Vision System
Satellite Services
Communications Satellite Design
Space Station Component Repair
Satellite Servicing

Working Group Meeting No. 9

Date: September 24-25, 1987
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Satellite Holding Device
Mobile Autonomous Remote Manipulator System Controller
Enhanced End Effector Concepts

Working Group Meeting No. 7

Date:	July 16-17, 1987
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Servicing Equipment and Lessons Learned from Solar Max Repair Mission Component Level Repair Requirements for Space Station Repair

Working Group Meeting No. 8

Date:	August 27-28, 1987
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Industrial Space Facility Space Repairs Syntactic Machine Vision System Satellite Services Communications Satellite Design Space Station Component Repair Satellite Servicing

Working Group Meeting No. 9

Date:	September 24-25, 1987
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Satellite Holding Device Mobile Autonomous Remote Manipulator System Controller Enhanced End Effector Concepts

Working Group Meeting No. 10

Date:	October 22-23, 1987
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Satellite Servicing Equipment Underwater Robotics and Tools Supervisory Control Technologies for Satellite Servicing Serviceable Satellite Concept (Explorer Platform) Design for Robotic Assembly

Working Group Meeting No. 11

Date:	January 28-29, 1988
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Satellite Servicing Activities (Ball Aerospace) Interface Connectors Astronaut Considerations Satellite Servicing Activities (GSFC) Utilization of Customer Cost Guide and Critique Prior to Publishing Preliminary Review of Robotic Equipment Survey Results

Working Group Meeting No. 12

Date:	February 25-26, 1988
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Manipulator EVA Retriever Robotic Technology Survey Assessment

Working Group Meeting No. 13

Date: March 23-25, 1988
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Design for Assembly
Overview of "Design for Assembly"

Working Group Meeting No. 14

Date: April 28-29, 1988
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Modular Power Subsystem
Space Serving
Underwater Robotics Activities
Summary of Robotic Technology Assessment
Portable Space Welding
Panel Meeting: Transfer of Underwater Technology to Space Robotics

Working Group Meeting No. 15

Date: May 26, 27, 1988
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: Close-out Photographic Requirements
Implications of Remote Servicing on Robot Conceptual Design
Automated Robotic Cera System Control
HST Servicing
Electro-Chemical Gas Supply Subsystem
Panel Meeting: Autonomous Robotic Systems

Working Group Meeting No. 16

Date: June 22-23, 1988
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: OMV Update
OMV/Polar Platform Servicing
Aeroassist Flight Experiment
Robotic End Effectors
Automation and Robotics Needs for Exploration Missions
Panel Meeting: [No title]

Working Group Meeting No. 17

Date: August 26-27, 1988
Location: McDonnell Douglas Aerospace
5301 Bolsa
Huntington Beach, CA 92647
and
TRW Components International (TRWCI)
19951 Mariner Avenue
Torrence, CA 90503
Presentations: Results of Robotic Assembly Operations
Space Station Servicing and External Maintenance Overview
Space Station Assembly and External Maintenance
Space Station Mobile Transporter
EVA Systems Operations and Description of Capabilities for Space Station
Space Station ORU Design Selection Criteria
Capabilities of Intelligent Robotic Systems
Sensor-Based Control of Manipulators
Sensorized End Effector for Collision Avoidance
Model-Based Computer Vision Applied to Structured Objects
Recent Simulation Experience of Pilot Control of OMV with Time Delays

	Advanced Robotic Arms
	International Update and Overview of TRWCI
	Fluid Systems Components
	Space Station... a Unique Opportunity for Fluid System Components Standardization
Panel Meeting:	Satellite Servicing - Who Needs It?

Working Group Meeting No. 18

Date:	October 27-28, 1988
Location:	Martin Marietta Denver, CO 80201
Presentations:	Space Assembly Maintenance Servicing Study
	TRW Review
	Lockheed Missles and Space Company Review
	The Commercial Value of Satellite Servicing
	Consumable Resupply Concepts and Issues
	Robotic Servicing of the Orbiter Platform
	Comprehensive Operational Support Evaluation Mode for Space
	Robotics Research and Development Overview
	Center for Space Construction
	Standardized User Interface Concepts for the Satellite Servicer System
Panel Meeting:	Satellite Servicing - What is Needed?

Working Group Meeting No. 19

Date:	January 26-27, 1989
Location:	Lyndon B. Johnson Space Center Houston, TX 77058
Presentations:	Proposed Space Station Node
	Telerobotic Application to EVA
	Experiment Opportunities on Explorer Platform
	Robotics Functional Equipment to EVA

Satellite Services Lessons Learned and In Progress
SDI Standardization Program
Spacecraft Partitioning and Interface Standardization Program Overview
Space Logistics - Another Perspective
SSSWG Standard Meeting
Utility Distribution System - Space Station Projects Office Work Package 2
Design Criteria for Extravehicular Activity Electrical Connectors
EVA Tool Catalog Status

Working Group Meeting No. 20

Date:	March 30-31, 1989
Location:	General Electric Astrospace Princeton, NJ 08543
Presentations:	The Polar Platform and the SSS ORU Standard Interface Connectors and End-Effector Design Concepts Principles of Logistic Support Analysis Overview of the AIAA Space-Based Observation Systems Committee on Standards GSFC ORU Designers Workshop Meeting Summary Technology Assessment for a Polar Orbiting Platform Robotic Exchange System Attached Payload Accommodations Equipment SSSWG Standards Meeting Rendezvous and Docking Sensor for Polar Platform Servicing Bearing-Only Guidance Law

Working Group Meeting No. 21

Date:	September 27-29, 1989
Location:	Goddard Space Flight Center Greenbelt, MD and Fairchild Space Company Germantown, MD
Presentations:	An Automated Fluid Interface System
	The Resupply Interface Mechanism
	Video: Automated Fluid Supply Demonstration
	Enhancements in the Flight Support System Spacecraft Servicing Through Adding a Servicing Aid Tool
	Calibration of Sensors During On-Orbit Servicing
	Establishing an AIAA Committee on Serviceable Spacecraft Standards
	The Explorer Platform
	Standardized ORU Interfaces for the Explorer Platform
	Making On-Orbit Structural Repairs to Space Station
	Review of "Interface Considerations for Robotic Satellite Servicers"
	Review of "Interface Considerations for Serviceable Satellites"
	Goddard Flight Projects
	ORU Design Considerations
	Hierarchy of On-Orbit Servicing Interfaces
	USAF/SDI Standardization Program
	Spacecraft Acronyms Definition and Terms Development
	Tejas: A Standardized Multimedia Database/Programming Utility for the EVA and Telerobotics Community
	Goddard History/Activities
	Robotics Program at NASA Goddard
	Consensus for What and When Standards Need To Be Developed
	Status Report: AIAA Technical Committee on Aerospace Maintenance (TCAM)

Servicing Standards Activity Within the AIAA/SBOSCOS (Space Based Observation Systems Committee on Standards)

Working Group Meeting No. 22

Date: November 28-29, 1989
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations: The Mission Continues
Satellite Servicing Guidelines
Robotic Servicing in the Nuclear Industry Applied to the Needs of Satellite Servicing and Lunar and Mars Exploration
Remote Servicing Standards in the Nuclear Industry
Space Station External Maintenance Requirements Status
Precision Assembly on the Space Station
Long-Term Environmental Exposure on Spacecraft
The Servicing Capabilities of the Space Station Mobile Servicing Center
STS-37 EVA Flight Experiments: Crew Equipment Translation Aid (CETA) / Crew Loads Instrumented Pallet (CLIP)
Robotic Applications Within the Strategic Defense System
Considerations for Human-Machine Interfacing in Teleoperations

Standards Panel Meeting

Date: February 21, 1990
Location: Tracor Applied Sciences
Austin, TX
Purpose: Committee members should identify (1) what standards need to be developed, (2) the maturity of each standard, and (3) when the standards are needed. Committee categories included: mechanical interfaces standards, electrical interface standards, fluid interface standards, optical interface standards, thermal

interface standards, data communications interface standards. The committee chairmen will present a report of their findings at the 23rd SSSWG Working Group meeting

Working Group Meeting No. 23

Date: March 14-15, 1990
Location: Lyndon B. Johnson Space Center
Houston, TX 77058
Presentations:
AIAA Serviceable Spacecraft Committee on Standards
Standards Development
AIAA Standards Projects in Autonomous Spacecraft and Operations
Summary of Standards Activities
Standards Interface Panels' Status Reports
Satellite Interface Standards Survey
Working Group Standards Implementation Plans
Space Station Connector Standardization Status
FSS Robotic Servicing Aid and Draft Document Status
Cost-Effective Orbit Transfer Modes for Satellite Retrieval and Servicing
Fault-Tolerant Manipulator Development
Dexterous End Effector Flight Demonstration

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