DESIGN CONSIDERATIONS FOR ON-ORBIT SERVICING

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1.0 INTRODUCTION

The advantages of on-orbit servicing and cost benefits thereof have been well presented in the previous papers of this Workshop. Accordingly, this paper will be focused on an overview of the general design of space vehicles serviced in orbit. The basic space vehicle systems, subsystems, modules, components, and associated appendages will comprise the elements to be considered. Primary emphasis will be given to the multi-disciplinary considerations in the development of requirements, and in particular, design of the space vehicle to facilitate orbital service by the extra-vehicular crew person(s). (See Figure 1 for flight crew allocation logic). Only minimal consideration will be given to airborne support equipment as that also has been generously covered elsewhere in this workshop.

2.0 REQUIREMENTS/DEFINITIONS

For purposes of this paper, it will be assumed that the 'Customer' has established and justified the need for on-orbit servicing of the space vehicle. Thus, through the application of standard 'system engineering processes', it can be further assumed that mission, system, launch vehicle (e.g., Space Shuttle), subsystem (including crew), and interface requirements/constraints (Figures 2 through 5) have been and will be in the development and refinement stages. Obviously, heavy participation by the conceptual engineering design team will play an important role in this process, thereby assuring basic design, integration, and performance feasibility.

Requirements for servicing generally fall into two categories: (1) Planned; and (2) Unscheduled. Planned servicing includes any on-orbit functions conducted to permit continued orbital operation of the space vehicle through planned maintenance implemented by changing out equipment, reconfiguring, replenishing depleted resources, or repair on known and identifiable (prelaunch) problems. These functions are known well in advance of the flight date and the crew has been familiarized, trained, and has conducted necessary simulation for these events prior to launch. Similarly, the necessary crew aids/devices/tools and support equipment (ASE) is carried aboard the Orbiter to support the planned (scheduled) servicing.

Unscheduled servicing is associated with those functions conducted to restore the space vehicle to an acceptable level of operational status for subsequent deployment/release to space, or for recovery and insertion into the Orbiter cargo bay for earth return. This servicing could also include crew activities associated with de-orbit of a space vehicle or explicit payload. Unscheduled servicing implies that the potential for a non-nominal situation had been anticipated, thus, the flight crew had been prepared (familiarization, training, simulation, etc.) and sufficient crew aids/devices/tools and support equipment (ASE) carried aboard the Orbiter for conduct of the task(s). These events are not planned for nominal servicing activities, but could be accommodated in the flight plan, as required.

Servicing is herein defined as being composed of five major categories:

- Deployment
- Retrieval
  - Stow
  - Berth/Dock
- Observe
- Support
  - Changeout
  - Reconfiguration
  - Resupply/Replenish
  - Repair
- Earth Return
  - De-orbit
  - Debris Collection
  - Orbiter Return

Servicing can also be categorized into the nature of the servicing function, e.g., critical, override, and nominal. Critical servicing is associated with sustaining the space vehicle and/or mission and occurs when a prime equipment item has failed or degraded and the redundant unit is on-line or also has failed, or where a principal consumable is near depletion or has been depleted. Override (Figure 6) is associated with the need to conduct a task, e.g., appendage extension, to enable space vehicle function or mission attainment. Nominal servicing is generally associated with non-sustaining space vehicle/mission functions. In this situation, servicing is frequently conducted on changeout of experiment items which have failed, degraded, or are planned to be updated (replaced with advanced state-of-the-art units or units with different functions). Preventative maintenance could also fall in this category.

3.0 APPROACH

The key to design of the space vehicle (composed of the spacecraft and payload) is to identify very early in the systems development phase of the program which items are planned to be serviced. Frequently, designers tend to 'bury' equipment, incorporate 15 to 30 connectors per box, provide special tooling for removal/replacement of components, etc., etc., etc. This is not implied to be a slap at designers, but rather they are not accustomed to designing for crew access, tool utilization, and component removal/replacement swept volumes. Thus, the next important and key element is education, and the dissemination of succinct, easily understood, and well illustrated design guidelines to assist the total systems and design team in the development and evolution of an easily serviceable system.

Figure 7 illustrates a very simplified flow diagram of a generalized methodology for the early phase of a development program. Note should be made of the early incorporation of mockups and simulation (e.g., 1-G shirtsleeve and occasional suited subjects) to aid in the design and integration of the servicing approach at the outset of the program. This is absolutely critical to assure that mid- and down-stream modifications, changes, etc., do not beset the program, resulting in major cost impacts/overruns and subsequent reduction of the degree of planned servicing.

In general, there are two classes of 'cargo' launched to orbit in the Space Shuttle which are of concern to this paper: these two classes are: (1) Sortie Payloads and (2) Free Fliers. Not included is the assembly/construction class. Sortie Payloads are generally considered those payloads which are launched in and stay with the Orbiter throughout the total mission phase to be subsequently returned to earth still mounted in the cargo bay. Free Fliers are those spacecraft or payloads which are launched in the Orbiter and subsequently deployed to orbit after which they may stay in a low earth orbit, be transferred to higher orbits, or launched out of the earth's gravitation field. Certain of the free fliers are recoverable by the Orbiter and thus, can be serviced or returned to earth for subsequent refurbishment. Figure 8 presents a generalized portrayal of the on-orbit disposition of space vehicles/payloads and potential earth return.

When only a single space vehicle is being procured and subsequently developed, extreme care must be given to the manufacturing aspects of the program. In particular, if spares (items to replace equipment already in orbit) are to be developed after the launch of the space vehicle, and there is no 'duplicate full-scale hard critically dimensioned mockup', then master tooling becomes a critical issue. Furthermore, this tooling must be identified during the proposal phases and developed prior to space vehicle launch. Almost never are there sufficient funds to develop the spares on the initial contract; thus, relegating their purchase to the 'operational phase' when additional out-year funding becomes 'available' dictates the need for master tooling during the initial contract.

A second major issue is the use of 'off-the-shelf equipment'. As the number and variety of space vehicles increases, so, too, will the number of subsystem equipment items. Thus, off-shelf equipment potential applicability across the programs becomes greater and the need to accommodate them grows ever more steadily. Accordingly, design for on-orbit servicing of these 'off-shelf' items very frequently requires early recognition and more often than not, the incorporation of supplemental hardware to permit their changeout on orbit, or override, depending on the item.

Many other key and lesser key issues will be presented in the following paragraphs relative to program and system/design concerns and considerations in design for on-orbit servicing.

4.0 BERTHING

An extremely important consideration in the design of the space vehicle for on-orbit servicing is the basic accessibility of same relative to conduct of the servicing function(s). This implies that the airborn support equipment (ASE) need be carefully considered in developing the servicing approach, and can provide a viable base for servicing functions, together with the crew equipment/aids/tools. It is recognized that the servicing on-orbit will grow from Orbiter based activities, thence to 'near orbiter', obviously then to the SOC/SAMSP concept, and finally to high earth orbit (HEO).

Since this paper is primarily addressing Orbiter support for servicing, the use of berthing systems to augment the EVA tasks is crucial to the practicality, timelines, and safety of the servicing operation. To that end, a number of devices have been proposed (as evidenced in this Workshop), such as the MMS program's Flight Support System (FSS), Holding and Positioning Aid, and the Deployment and Maintenance Platform (DMP). Figure 9 illustrates an example of one of these devices.

The use of such a device significantly drives the methods for changeout of items, and therefore, the design of the basic space vehicle as well as the items to be replaced on orbit, e.g., line replaceable units (LRU's) or Orbital Replacement Units (ORU's). Furthermore, selection of the berthing device also affects the servicing approach/scenario, spares (LRU's or ORU's) containment, other ASE as required, and associated crew equipment/tools/aids.

Additionally, the berthing device significantly impacts the design of the space vehicle relative to: (1) Berthing 'pins', (2) Load paths, (3) Structural support, (4) Dynamics, (5) Targets, (6) Tooling, and (7) Interfaces. The interfaces are not insignificant and include such considerations as power, signal, fluid/gas transfer, and mechanical. Also, the interface to and with the Orbiter can be equally significant and includes such considerations as mounting to the sill and keel fittings, power/signal interfaces and connections, swept volumes and cargo bay envelope, thermal blockage (items overhanging the radiators), weight and CG factors, etc.

Thus, methods of 'holding and articulating' the space vehicle become very important as they relate to the overall system integration and interface issues. The consideration, therefore, of providing a 'berthing interface' on either the front or aft end of the space vehicle must be examined early in the conceptual phases to determine potential impacts and to ascertain the significance of the interfaces as they transcend the total servicing approach.

5.0 SPACE VEHICLE DESIGN FOR SERVICING

5.1 General

Design for on-orbit servicing in and of itself is not a new concept. Studies such as those conducted in the mid-1960's (MORL, LORL, MOL, AAP (Skylab), BIOLABS, Orbital Station, etc.) did not deal with the zeal and impact of the more recent programs, i.e., the Multimission Modular Spacecraft (MMS) and the Space Telescope (ST). The former program was designed for changeout of a discrete number of modules, while the ST provided the potential for changeout of over 100 ORU's via the EVA mode. The key in both of these example programs was the early determination of the need for and commitment to the on-orbit servicing approach and the incorporation of design methods to achieve this objective.

5.2 Space Vehicle

The initial conceptual design approach begins with the identification of those LRU's or ORU's which are to be considered for changeout on-orbit. Therefore, the examination of the basic space vehicle subsystems is necessary (Figure 10), and a rational decision made as to what need be changed out as a function of several factors including: (1) Reliability and MTBF factors, (2) Items highly suspect to malfunction but with limited flight reliability data, (3) Preventative maintenance considerations, (4) Wear-out lifetimes, (5) Degradation lifetimes, (6) Items which may receive inadvertent collateral damage, (7) Items subject to EMI or other 'signal' spectra damage, (8) Induced damage, e.g., loss of thermal control and subsequent change of temperature past survivability level, (9) Micro-meteorite penetration/damage, (10) Cascading failures or power surges, (11) Equipment/experiment item update/replacement, (12) New payload replacement, and (13) Complete subsystem replacement, etc.

Once the items to be changed out on-orbit have been initially identified, the next step is to identify a set of 'core' design features (Figures 11 and 12) to apply in the layout and design of both the space vehicle structure itself as well as the basic subsystems (Figure 13), including the LRU's or ORU's, and the associated interfaces, mounting provisions, cables, thermal protection, etc. Thus, the consideration of the application of design features (Figure 14) must be identified for the entire range of development activities and appropriately incorporated (and costed) for both on-orbit servicing and ground element implementation as well. Allocation of design features is an important early function since more than just the space vehicle is involved in an interface and integration sense. This becomes critical, relative to the need for close liaison between space vehicle development activity, subsystems and related on-going functions concerned with ASE development, crew support aids/equipment definition, and the critical interface with the Orbiter, both physically and functionally (including procedural interactions).

As expected, documentation plays a pivotal role in completion of the design features. All contractors have an existing and very formal set of hardware development documentation; a tried and proven set of approaches/methods very carefully employed, followed, checked/verified and documented. Similarly, the customer (NASA/DoD) also have sets of documentation (including program specific) which must be rigorously followed. Early examination and correlation of these two sources of documentation is very critical, both from an implementation (cost) and practicality standpoint. These documentation sources (Figure 15) which frequently differ (occasionally significantly), must be examined at the outset of the program, particularly as they relate to the space vehicle design service features. Often, these design features include approaches (e.g., dimensions which are not standard manufacturing practices), and therefore require early resolution to minimize cost and schedule impact.

A prime example of a dimensioning concern is the NASA required corner and edge radius for all equipment and structures with which the EVA crew person may come in contact during the servicing function. Obviously, these dimensions are not standard manufacturing practices and, by necessity, must be negotiated, identified, and cost increments specifically delineated.

It must be stated that the design process is an iterative one and as the maturity of the design progresses, continued review, revision, amalgamation, and standardization of the design features evolves. Inherent in the process is the necessary education of not only the designers, but also the systems team members, basic subsystem designers, etc., and as importantly (if not more so), the Program Office and Management Team. This latter cadre of personnel generally are not always fully responsive to the added effort, liaison, and the necessary interface meetings required to proceed with the design of items for on-orbit servicing. And often, certain of the customer program personnel are not fully acquainted with the necessary elements for design of the space vehicle and equipment for on-orbit servicing, thus, necessitating in certain instances the need to assist them in understanding the nature and significance of the objectives and design approaches. Herein, the enlistment of the NASA Astronauts and Air Force Manned Spacecraft Engineers (MSE's) can be of tremendous value in bringing the necessary high level attention to the particular problem or concern.

5.3 Mockups and Simulation

Very early in the program, preferably in the conceptual phases, introduction of models and mockups to aid in portrayal of the systems and engineering effort, ideas, approaches, and interfaces is most necessary. The early mockups can be of simple construction employing Fomcor as the basic material and, accordingly, a material that the engineers can work with without concern for a 'union grievance' - a most important consideration! Initial mockups can be table top items subsequently progressing throughout the following general steps (although not necessarily in this order):

- Models (1/50th to 1/20th scale)
- Small scale wood, plastic, and/or Fomcor representations
- Full scale wood, metal, and/or Fomcor mockups of selected areas/ items
- Full scale hard mockups of partial space vehicle segments or equipment constructed of wood, metal, and Fomcor
- Full scale hard mockups of items wherein certain features are functional to a specifically limited degree; various materials are herein used
- Full scale hard mockups of space vehicle elements, e.g., payload, spacecraft (housekeeping) section, and major appendages; various materials
- Full scale hard mockups of space vehicle elements used for engineering test bed; various materials
- Full scale soft and hard mockups (part task trainers) used for crew systems activities and verification/training
- Full scale hard mockup replica of space vehicle ranging from non-functional to fully functional; various materials
- Full scale hard mockups for water immersion, KC-135 flights, etc.

The development of mockups is, without doubt, one of the key elements in the implementation of the servicing approach and, obviously, attendant design of the space vehicle and associated items for changeout in addition to the ASE, interfaces to/with the Orbiter (or Space Station), and the functional/procedural aspects. The prudent and early use of mockups can and does result in significant overall program savings measured in terms of engineering time, smoothed integration, more simplified definition of interfaces and requirements, earlier 'verification', greater and earlier crew acceptance, less re-direction and re-design, and increased awareness of manufacturing to the explicit development needs and tooling.

Simulation also plays a vital role and begins with the earliest development of the full-scale mockups. General simulation activity categories are as follows:

- 1-g shirt sleeve
- 1-g suited
- KC-135
- Water immersion

Suited simulation is, obviously, more costly than shirt sleeve activities. This is of course due to the increased support team and necessary safety aspects. Water immersion (neutral buoyancy) simulation is more costly yet, however, for certain crew interface, functional task accomplishment, and fidelity requirements, water immersion simulation is nearly mandatory. Experience shows that for crew tasks associated with space vehicle servicing which are conducted 'in situ' or in a specific location wherein crew translation from point to point is not needed, 1-G suited simulation is nearly always acceptable. Additionally, 1-G simulation is considerably less costly, thereby making it a highly useful and cost effective method to conduct: (1) More frequently, (2) Earlier on in the program, and (3) Involving the atronaut community earlier. For tasks requiring manual manipulation of large items (not fully restrained or coupled to a 'rail system'), or when significant translation from point to point is required, there is generally no substitute for water immersion suited simulation.

The key to use of mockups and simulation is the effective participation of the systems, integration, and design team members as parties to the simulation which has been set up with specific objectives to be met relative to the design or integration factor under consideration. The simulation should not always be crew systems specific, but rather carefully tailored to meet the multi-disciplinary needs of the total program team. For example, typical engineering uses of the mockup during simulation runs include examination, assessment, and evaluation of the following:

- Black box/component layout and arrangement features and interfaces
- Power/signal cable layout, bend radii, potential interferences and paths
- General connector access
- Handling methods for demated connector/cables
- Grounding strap runs/paths and handling techniques
- Basic mounting technique access, arrangement, grounding & thermal interfaces
- ASE interface examination, access, and mounting
- Fluid transfer line layouts, vulnerability, connector interfaces
- Door/cover hinge locations, mounting, open/close features and 'tie-down'
- Protrusions, sharp corners/edges potential, and snag features
- Areas wherein crew loads are imposed - purposely and inadvertently
- Multi-layer insulation (MLI) layup, tie down, and crew impact vulnerability
- Removal/replacement swept volume envelopes & collateral damage assessment
- Basic safety features and provisions
- Potential hazard identifications
- Mounting location identifications and feasibility determinations
- Critical module/component mounting and alignment

Thus, as evidenced in the aforementioned mockup and simulation uses, a total program team utilization approach is vital. And lastly, it can't be emphasized too greatly that the earlier the total team begins to participate in mockup use and even simplified crew simulation exercises (shirt sleeve), the greater the payoff to the program.

5.4 Specific Design/Integration Considerations

It is not the intent of this paper to be presumptious and pretend to tell designers how to design. Rather, it is intended to inform the designers of many of the multitude of factors which must be 'emphasized' and/or included during the design and layout of the space vehicle to be serviced on-orbit. These factors must also flow from system inception through fabrication and ultimate test and verification. The following paragraphs shall attempt to identify some of the more important factors as they relate to overall design and integration.

5.4.1 General Accessibility

This set of considerations includes concern not only for the on-orbiting servicing requirements but should give reasonable attention to manufacturing, assembly, test, verification, and integration. Primary emphasis is given, however, to those considerations most pertinent to design for on-orbit flight crew EVA servicing.

A. Design for 5th percentile female to 95th percentile male
B. Suited crew motion, reach, and visual anthropometrics (Figure 15)
C. Tool swept volume utilization
D. Removal and replacement access and swept volume envelopes
E. Tool insert and engagement access
F. Visual access with and without head/body movement
G. Illumination path(s) to work site
H. ASE installation/integration access
I. Protective devices (e.g, cover) access, stowage, and remove/replace swept volumes
J. Demated connector/cable management and positioning 'out-of-the-way' temporary restraint and handling
K. Motion of appendages (swing/rotation, etc.) and crew locations/access
L. Large item transfer/translation/transport and crew access/safety
M. Access around or through structure and adjacent items
N. Visual access to guides, rails, alignment aids, etc.
O. Access to fasteners, hold-down/release devices, clamps, etc.
P. Access to umbilicals, e.g., overrides, demate/remate features

5.4.2 Equipment Mounting

This area includes a host of potential design features which can be significantly influenced by design for on-orbit servicing. Further, the range of impact can include such major considerations as determining overall space vehicle diameters, basic 'internal compartment' vs external equipment mounting, load carry doors vs structure, etc. Of necessity, this element must be considered at the beginning of the concept layout stage, and the candidates carefully traded off as the requirements and definition become more firm. Herewith, are a series of typical items to consider in equipment mounting:

A. Large item (LRU or ORU) location in relation to design for changeout:
   - Mounting orientation
   - Volume - size
   - Removal/installation swept volume
   - Cable routing
   - 'System interface'
   - Loads
   - Isolation
   - Environ. Protection
   - Alignment
   - Hold-down techniques
B. Basic LRU or ORU installation and crew interaction
C. Loads to or on structure (basic) or doors
D. Grounding as it may affect changeout techniques
E. Thermal interfaces as they relate to mounting techniques for on-orbit changeout
F. Proximity to associated equipment(s)
G. Shock or vibration and associated attenuation techniques
H. Alignment features-coarse and fine for items to be changed out on-orbit
I. Center of gravity and mass arrangements as they relate to changeout potential

J. Installation and removal features for both ground and on-orbit
K. 'Plumbing' routing and interfaces particularly for on-orbit ORU's
L. Mounting footprint vs removal devices and access potential
M. Collateral damage potential during changeout on-orbit
N. Positive registry/guides for placing/positioning/remove/replace tasks
O. Features for 'quick' removal associated with items to be jettisoned
P. Elimination of sharp edges/corners/protrusions to eliminate suit damage

5.4.3 Cables/Harnesses and Layout

Design for cables and harnesses takes on a new perspective when designing for on-orbit changeout or replacement. These elements can no longer be routed, 'nailed-down', hidden, bundled in massive runs, etc., leading to inaccessibility or non-flexibility of bending in the case of door (hinged) mounted LRU's or ORU's. Furthermore, certain LRU/ORU items may be externally mounted thereby exposing the cable or harness assembly to environmental impact heretofore not encountered as they previously may have been routed underneath structure or external features. The following items are typical of those which must be considered in design for on-orbit servicing:

A. Cable/harness motion due to location on hinged elements (Figure 18)
   - Flexing
   - Damage exposure
   - Connector access
   - Strain and relief
   - Length
   - Size/diameter vs flexing
B. Methods for the crew person to reposition the cable/harness and temporarily stow during LRU/ORU changeout
C. Coding of cables/harnesses and associated connectors
D. Connector design to permit gloved mate/demate
E. Reliability associated with cable/harness flexing
F. Protective features relative to ground/flight crew inadvertent contact
G. Protection (as required) against environmental impact
H. Captive screws and fasteners (used to secure cables/harnesses) which do not create snag, tear, rip potential for the suit
I. Connector 'protection' when not interconnected, e.g., during changeout

5.4.4 Removal and Replacement

A host of considerations are involved in design for the changeout of an item on-orbit. Often these changeout features are somewhat peculiar to the item and the location within or on the space vehicle. Also, the item to be changed out may have certain unique features which substantially impact the method for changeout. And finally, the actual ASE to be used in the changeout process may also interact with and drive the changeout methodology. Following are a composite of typical factors to consider:

A. Removal swept volume envelope
B. Guides and/or rails to aid in removal or insertion
C. Tool access to fastening device
D. Handholds/handrails for EVA crew person grasping, holding, positioning
E. Tether attach points (e.g., 'D-rings')
F. Protection of sensitive 'areas' to damage potential
G. Guide or rail interface engagement and design feature(s) on the LRU/ORU
H. Unique ASE attachment or engagement features
I. Elimination of sharp edges/corners/protrusions of both LRU/ORU and basic space vehicle and ASE

J. Unemcumbered removal and replacement transfer path/volume
K. Door or cover access envelope for 'pass-through' of item
L. Method of handling during the transfer process as it relates to both the LRU/ORU and ASE (Figures 19 and 20)
M. Illumination to facilitate crew vision during the changeout task
N. C-G of the item and its basic mass distribution to be taken into account during the changeout task
O. Basic size of the item to be changed out:
   - Crew handling
   - Crew transfer
   - Handling aids
   - 'See-around'
   - Shape vs mass/CG distribution
   - Handling aid locations
P. Connector and grounding strap mate/demate - remove/replace
Q. Captive vs 'loose' fasteners

5.4.5 Safety and Crew Considerations

Safety is a key design factor when, and in particular, considering the on-orbit flight crew. Safety encompasses not only the space vehicle but the ASE, the basic Orbiter, and the integration of the aggregate of hardware into the operational system which also includes procedures, software, and 'firmware'. Crew considerations transcend the entire orbiting element including the Orbiter itself. Two major design guidelines are available for major crew system design and integration considerations, and are:

- SHUTTLE EVA DESCRIPTION AND DESIGN CRITERIA, May 1976 (Under Revision), JSC-10615, NASA-JSC
- MAN/SYSTEM REQUIREMENTS FOR WEIGHTLESS ENVIRONMENTS, Dec. 1976, MSFC-STD-512A, NASA-MSFC

Since both of these documents cover 'crew considerations' fairly well, it is proposed to leave this area to the reader through reference to both of these two documents (guidelines). Safety is also called out in both documents, as well.

Design for safety includes a range of responsibilities and subject areas. Accordingly, a synopsized overview of the subject areas is included which will then necessitate that the systems, integration, design, test/verification, and simulation team member further expand this list as required.

A. General safety considerations (Figure 21)
B. Operations safety
C. Crew induced loads and potential collateral damage
D. Equipment design safety factors
E. Structural design safety factors
F. Airborn support equipment safety factors
G. Electrical design considerations
H. Explosive, nuclear, pyrotechnic, jettison considerations
I. Shrouds, coverings, insulation, thermal blanket considerations
J. Protrusions, edges, contours, corners, surfaces considerations
K. Equipment transfer/transport/handling considerations
L. Life support considerations
M. Procedural and interface safety factors
N. Fluids/gasses transfer safety
O. Crew tethering
P. Mass handling and constraint

A general top-level safety document relative to the STS has been re-issued by the NASA. This document is SAFETY POLICY AND REQUIREMENTS FOR PAYLOADS USING THE SPACE TRANSPORTATION SYSTEM, dated 9 Dec. 1980, NHB 1700.7A, Rev. A, NASA-HDQ. Although developed as a general safety policy document sufficient data exists therein to provide tangible substance to developing more detailed safety design guidelines and requirements.

5.4.6 Reliability and Spares

Although reliability is beyond the scope of this paper, something must be stated on this subject due to the major interplay between reliability and selected items for changeout/replacement on oribt. A general breakdown of the reliability tasks as they relate to providing the necessary information for LRU/ORU identification is as follows:

A. Establish desired on-orbit lifetime design goal
B. Identify critical and non-critical items
C. Establish subsystem/equipment/component reliability lifetimes
D. Determine MTBF's for candidate equipment and components
E. Identify candidate LRU or ORU items
F. Aid in identifying spares approach based on A-E above
G. Assist in specifying service timelines and candidate mixes of spares

Obviously, the aforementioned reliability tasks are not fully representative of the reliability program, but rather tend to indicate the integral participation of this discipline with the design for servicing effort previously discussed.

Identification of spares becomes critical to the program based on overall sizing and cost factors. Additionally, depending on the overall configuration of the LRU or ORU, and the constituent elements thereof, spares (or replacement units) can become a major program driver, particularly relative to cost. A suggested and greatly simplified approach to this effort which is in absolute unison with the design and reliability efforts is presented as follows:

A. Aid in the identification effort of candidate LRU or ORU items
B. Assist in determining single vs multiple components for the LRU/ORU
C. Provide cost estimates for the various single/multiple LRU/ORU mixes
D. Examine impact of developing spares to match LRU/ORU mix
   - Sizing/weight
   - Handling
   - Hardware availability
   - Longevity of manufacturer
   - Storage and downstream availability
   - Quantity of items and mixes
   - Cost paths
   - Redundancy potential

Needless to say, the spares development approach is not as simple as briefly identified; nonetheless, it is an important element in the overall design process.

5.4.7 Integration

This area, perhaps of all, is the most fluid and elusive to pin point discrete tasks. However, it is critically important to the general design effort as it relates to many connected and oft-times seemingly unconnected elements. The integration effort should be part of the systems and design team and be represented at all appropriate contractor, subcontractor, and customer meetings. Frequently, these meetings are referred to as Interface Working Groups (IFWG's) and generally drive out basic issues, concerns, constraints, and problems. Thus, the IFWG team members share in exposure of these factors and directed assignments and completion dates can be made to resolve same.

Orbiter integration should become more 'standardized' once the OFT series is complete and the main line vehicles become operational. However, there still may be significant differences between vehicles and, as such, integration will continue to play an ever-important role.

Integration of the payload and spacecraft into the overall space vehicle also provides a major effort. Subsumed within this task is equipment/sensor, experiment, consumable, etc. integration along with the standard interface features. Crew 'integration features' must also be considered as must be the ASE interfaces complimented by the Orbiter interfaces (mounting, power/signal, fluid/gas, etc.).

Procedural, operational, software and firmware interfaces and integration are also pertinent to the integration process as is the ground cycle. The ground elements include mission control, ground integration at KSC or VAFB, and any integration associated with hardware/systems, etc. which meet or integrate outside of the prime contractor(s) facility such as at the launch site. Each of these phases has some measure of involvement with on-orbit servicing and obviously include spares and subsequent installation of ASE for the servicing flights.

6.0 SUMMARY

The intent of this paper has been to discuss design for on-orbit servicing. It is hoped that, by now, the reader will have some comprehension of the overall top-level consideration involved and the absolute need for a total team approach to this systems, design, integration, and verification process.

Spares definition, reliability and integration are elemental to the design process and should be incorporated from the conceptual stage onward. And finally, safety must be considered each step of the way.

A methodical and well-developed program plan for an orbit servicing design should be prepared and detailed milestones developed to ensure adherence to the plan. Liberal use should be made of the many excellent documents in this area; however, it should be noted that many should be used as guidelines only, thereby allowing the systems, design, and integration team the necessary latitude for interpretation and flexibility needed to develop a viable and cost-effective serviceable space vehicle.

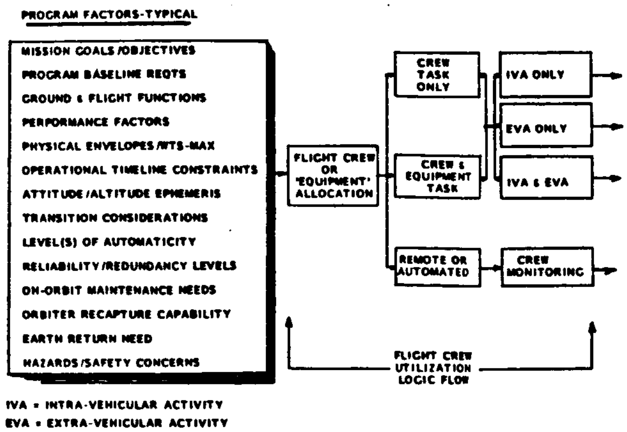


FIG. 1 FLIGHT CREW UTILIZATION (ALLOCATION) LOGIC

PHYSICAL
A. SUIT ENCOMBERANCES
B. STRENGTH
C. PHYSICAL OUTPUT DURATIONS
D. BTU OUTPUT MAXIMUMS
E. ANTHROPOMETRICS
F. DEXTERITY/MANIPULATION
G. CONTAMINATION OUTPUT
H. VISUAL ACCESS LIMITS
I. MASS HANDLING LIMITS
J. PRODUCTIVITY RANGES
K. POSSIBLE INCAPACITATION

PROCEDURAL/OPS
A. PROCEDURAL DIFFICULTY/COMPLEXITY
B. EXTENSIVENESS OF PROCEDURE
C. TIMELINE AVAILABLE - EVA
D. NO. OF EVA CREWPERSONS
E. SAFETY/HAZARDS
F. COMMUNICATIONS AVAILABILITY
G. TRAINING LEVELS ACHIEVED
H. WORK/REST CYCLES
I. CREW ACTIVITY PLANNING COMPLEXITY
J. PROCEDURAL COORDINATION/INTERFACE

FIG. 4 CREW IVA/EVA CONSTRAINTS - TYPICAL

DESIGN/ACCOMMODATIONS	OPERATIONS
IVA & EVA GUIDELINES/CONSTRAINTS	CREW TASK ELEMENTS
CREW CAPABILITIES/LIMITATIONS	CREW FUNCTION ALLOCATIONS
CREW IV SUPPORT NEEDS	TIMELINES & LIMITATIONS
CREW EV SUPPORT NEEDS	0-G CONSTRAINTS
CREW ACCOMMODATIONS	SAFETY/RESCUE FACTORS
EVA SUPPORT PROVISIONS	CREW MIX/SKILLS/SIZING
LIFE SUPPORT ACCOMMODATIONS	FAMILIARIZATION & TRAINING
PART TASK & FULL-SCALE MOCKUP NEEDS	GENERIC SHUTTLE KNOWLEDGE/TRNG
PAYLOAD ACCOMMODATIONS FOR EVA	SIMULATION NEEDS
ANTHROPOMETRIC FACTORS	PROCEDURAL/DATA FILE ELEMENTS

FIG. 2 CREW REQTS DERIVED FROM DESIGN/OPS ELEMENTS

- EXTERNAL SURFACE CHARACTERISTICS - GLARE
- EVA MANUAL OVERRIDES - AVAILABILITY
- EVA CREW TRANSLATION/STABILITY AIDS - AVAIL.
- STRUCTURAL ADAPTABILITY TO EVA INDUCED LOADS
- EVA COLLATERAL DAMAGE POTENTIAL
- APPENDAGE JETTISON CAPABILITIES/FEATURES
- CONTAMINATION SENSITIVITY TO EVA EFFLUENTS
- EVA & VISUAL ACCESS TO CRITICAL MECHANISMS
- BERTHING/DOCKING/GRAPPLE FEATURE AVAILABILITY
- EVA SAFETY HAZARDS

- REPAIR FEASIBILITY/ACCESS
- ALIGNMENT FEATURES - EVA COMPATIBLE
- EVA ALIGNMENT FEATURE 'OVERRIDE'
- ALIGNMENT TOLERANCES - EVA ATTAINABLE
- ADJUST. ALIGNMT. FEATURES - EVA WORKABLE
- LARGE ITEM REPLACEMENT PRACTICALITY
- POWER ISOLATION FOR EVA
- SUSSEPTABILITY TO EVA MOTION DURING ALIGNMT.
- SIGNAL/PWR CABLE MGNT. - EVA UTILITARIAN
- TRANSLATION (EVA) PATH SAFETY ROUTES
- SIZED TO PERMIT 5TH TO 95TH %TILE EVA CREW ACCESS

ORBITER	FLIGHT FACTORS
A. IN/NEAR BAY ILLUMINATION AVAILABILITY	A. DAY/NIGHT ILLUMINATION CYCLES
B. SURFACE REFLECTIVE CHARACTERISTICS - GLARE	B. ORBIT ALTITUDE/INCLINATION VS RADIATION
C. CCTV & WINDOW VIEWING LIMITS	C. PROPULSION USE - PLUME EFFECTS
D. COMMUNICATIONS INTERFERENCE	D. ATT. CONTROL SYS. USE - MOTION/LOADS INDUCED
E. THERMAL RESTRICTIONS	E. STATION KEEPING LIMITS VS EVA CREW DISTANCE
F. CONTAMINATION/EFFLUENTS	F. PROXIMITY OPERATIONS EFFECTS
G. CARGO BAY ENVELOPE VS S/C (IN-BAY) RESTRICTIONS	G. ORBITER MOTION VS COUPLING TO SERVO CONTROL PLTFMS
H. S/C, EQUIPMT. & CREW AID INSTALLATION LOCATIONS	H. FLIGHT CREW 'HOUSEKEEPING' MANDATORY TIMELINES
I. AIRLOCK REPRESURIZATION LIMITATIONS (QUAN.)	I. HEAT REJECTION VS S/C PROXIMITY
J. ORBITER PROVIDED SUPPORT/CONSUMABLES LIMITS	J. ON-ORBIT MISSION DURATION

FIG. 3 ORBITER AND FLIGHT CONSTRAINTS - REPRESENTATIVE

FIG. 5 S/C EVA CREW DESIGN CONSTRAINTS - TYPICAL

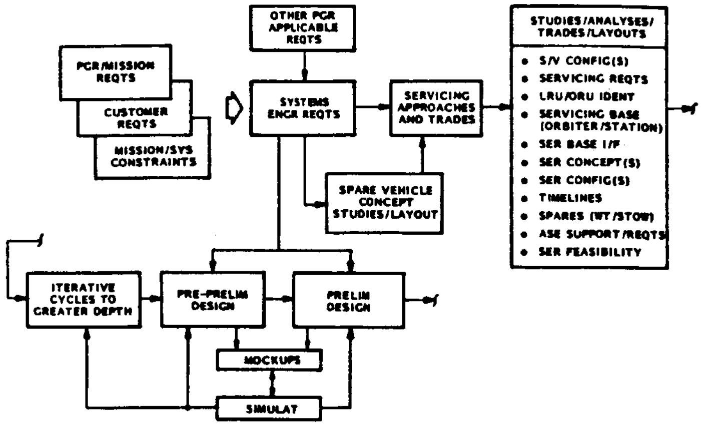


FIG. 6 DESIGN STUDY FLOW & I/F DIAGRAM - TYPICAL

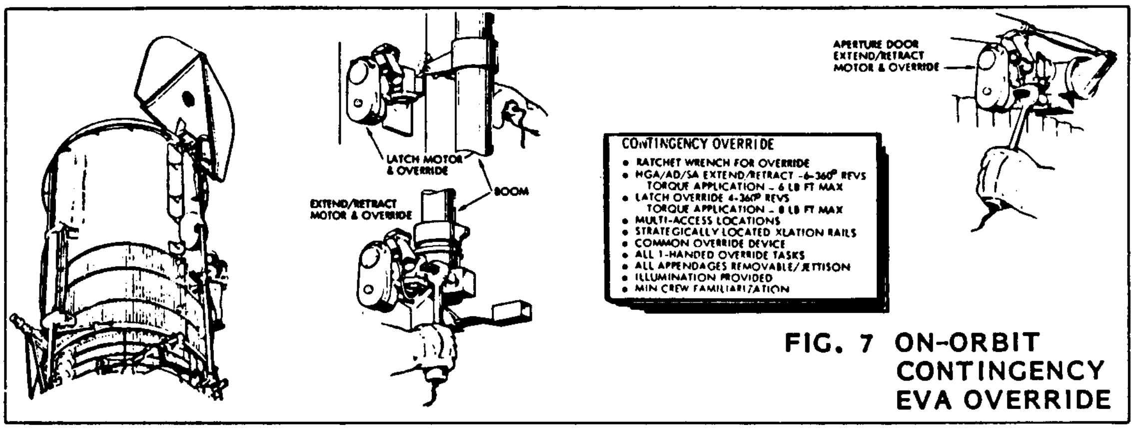
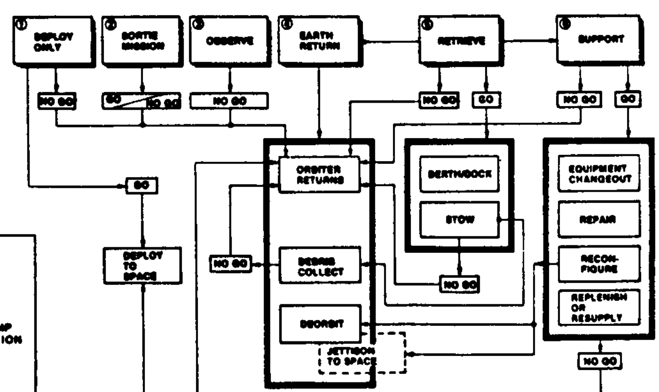


FIG. 7 ON-ORBIT CONTINGENCY EVA OVERRIDE

FIG. 8 SERVICE ELEMENT INTERACTION



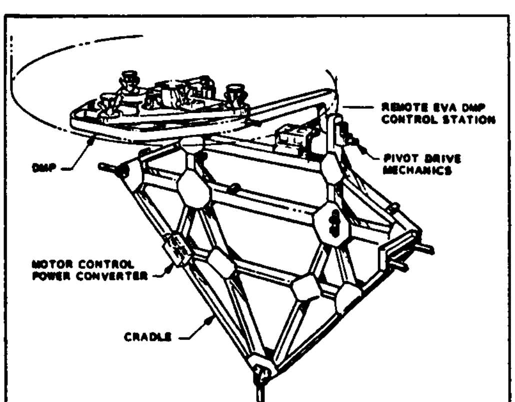


FIG. 9 DEPLOYMENT MAINTENANCE PLATFORM (DMP)

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ELECTRICAL POWER SYSTEM
- BATTERIES/FUEL CELL
- CHARGE CONTROLLER
- DIODE UNITS

THERMAL CONTROL SYSTEM
- THERMISTORS
- HEATER BLANKETS
- MULTI-LAYER INSULATION

POINTING, CONTROL, AND STABILIZATION SYSTEM
- REACTION WHEELS
- GYRO ASSEMBLY
- STAR TRACKER

COMMUNCATIONS SYSTEM
- TRANSMITTER
- RECEIVER
- ANTENNA-DISH/OMNI

DATA MANAGEMENT SYSTEM
- COMPUTER
- DATA INTERFACE UNIT
- DATA MANAGEMENT UNIT

INSTRUMENTATION SYSTEM
- SIGNAL CONDITIONER
- CONTAMINATION MONITOR

PROPULSION SYSTEM
- TANK(S)
- SOLID STAGE
- PLUMBING

STRUCTURE
- PANELS/COVERS
- DOORS/HATCH
- FASTENERS

PAYLOAD SYSTEM
- ANTENNA
- MODULE/BUS MODULE OR COMPONENT

FIG. 10 SATELLITE SUBSYSTEM ELEMENTS - TYPICAL

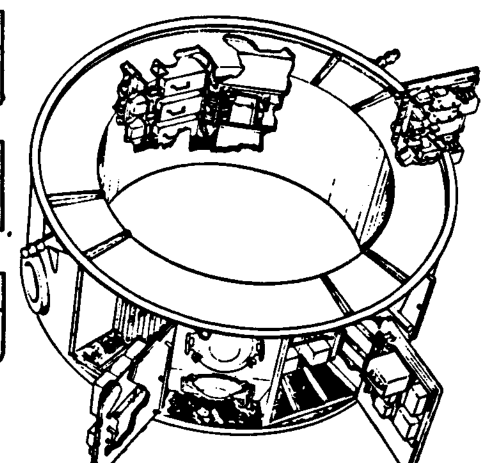

FIG. 13 TYPICAL P/L EQUIPMT SECTION

SAFETY
- SAFEING DEVICES
- LABELING/CAUTION FLAGS/LABELS
- RADIATIONS SHIELDS
- PYROTECHNICAL SHIELDS
- POWER BUS(ES) LINE STATUS INDICATORS
- POWER DEACTIVATE/REACTIVATE SWITCH BREAKER

EQUIPMENT CHANGEOUT
- POWER DEACTIVATE/REACTIVATE SWITCH BREAKER
- SET/RESET ELECTRICAL SWITCHGEAR
- COVER/DOOR FASTENERS
- LABELING/CAUTION FLAGS/LABELS
- CONTAM PROTECT. DEVICES/TECH

SERVICE
- LABELING/CAUTION FLAGS/LABELS
- CONTAM PROTECTION DEVICE/TECH
- POWER DEACTIVATE/REACTIVATE SWITCH BREAKER
- PRESSURE/LEVEL/STATUS INDICATORS
- VENT/PURGE OVERRIDE DEVICE
- FLUID/GAS ISOLATION VALVE
- PCS/PROP REPLENISH SERVICE FEATURE

FIG. 11 CORE DESIGN FEATURES

CORE DESIGN FEATURE APPLICATION
- MANUFACTURING ASSEMBLY
- GROUND TEST, SIMULATION, AND CHECKOUT.
- GROUND HANDLING AND ORBITER INSTALLATION
- REMOVE/REPLACE — FACTORY/PAD
- SHIRTSLEEVE AND SUITED SIMULATION
- ON-ORBIT CREW IVA AND EVA OPERATIONS

CORE DESIGN FEATURE ALLOCATION
- STRUCTURE
- SUBSYSTEMS
- COMPONENTS/MODULES
- CREW SUPPORT ELEMENTS
- AIRBORNE (SPACE) SUPPORT EQUIPMENT
- INTERFACE HARDWARE — ASE/SSE, ORBITER, SATELLITE

FIG. 14 CORE DESIGN FEATURES APPLICATION/ALLOCATION

OBSERVATION/CHECKOUT
- LABELING/CAUTION FLAGS/LABELS
- VISUAL INSPECTION ACCESS ENVELOPE
- PRESSURE
- LEAK DETECTOR
- TUBING/M
- INTERNAL

RENDEZVOUS/CAPTURE BERTH/STOW
- DESPIN PACKAGE ATTACH FEATURE
- GRAPPLE FIX(ES) AND RECEPTACLES
- CABLE-LINE ATTACH FIXTURE
- RENDEZVOUS/DOCKING LIGHTS
- RENDEZVOUS/CAPTURE/BERTH MARKINGS
- BERTHING FIXTURES/PINS/DEVICES

OVERRIDE/RECONFIGURATION
- APPENDAGE OVERRIDE DEVICE(S)
- SENSOR/BOOM/COVER OVERRIDE DEVICE
- MECHANISM-LATCH OVERRIDE DEVICE
- APPENDAGE/BOOM JETTISON
- COMMAND/COMM (GROUP) RECONFIGURATION

EVA ACCESS
- TRANSLATION RAILS AND TRAILS
- FOOT RESTRAINT RECEPTACLES
- HANDHOLDS/RAILS
- TETHER ATTACH POINTS
- CREW WORK STATION ATTACH DEVICES
  TOOL ACCESS AND SWEPT USE ENVELOPE

FIG. 12 CORE DESIGN FEATURES - CONTINUED

CORE DESIGN FEATURE DOCUMENTATION (REPRESENTATIVE)
- COMPANY DESIGN STANDARDS
- COMPANY DRAFTING MANUAL
- COMPANY PREFERRED PARTS HANDBOOK
- COMPANY STANDARD MATERIALS HANDBOOK
- COMPANY PROCESS SPECIFICATIONS MANUAL
- COMPANY SAFETY, QUALITY, AND RELIABILITY STANDARDS
- COMPANY MODEL SPECIFICATION
- CUSTOMER SPECIFICATIONS
- CUSTOMER STANDARDS
- CUSTOMER DESIGN/REFERENCE DOCUMENTATION
- CUSTOMER SRLs AND SRDs
- CUSTOMER/COMPANY DEVELOPED ICDs AND IRDs
- NASA 10615 AND 512A (EVA DOC)
- MIL SPECS (E.G., 1472B, ETC.)

FIG. 15 CORE DESIGN FEATURE DOCUMENTATION - TYPICAL

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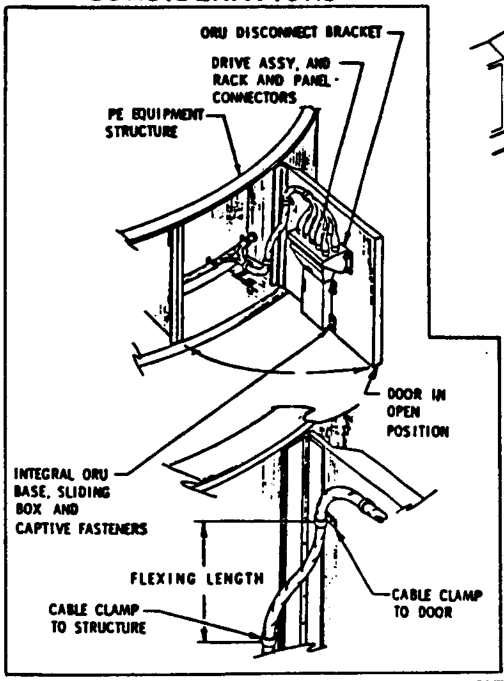
1. NEARLY ALL TAKS CONDUCTED ABOVE WAISTLINE
2. SPECIFIC REACH ZONES ARE:
   A. DESIGNED WITHIN A VERTICAL 20 IN. ENVELOPE
   B. SOME TASKS REQUIRE REACH UP TO 30° ABOVE HORIZONTAL
      - TASKS INCLUDE CONNECTOR MATE/DEMATE AND ORU POSITIONING
      - EYE/HAND COORDINATION REQUIRED
      - CREWPERSON IS VOLUMETRICALLY BOUNDED BY STRUCTURE
   C. INTERNAL CAVITY (E.G., EQUIP. BAY) ACCESS
      - FULL REACH DEPTH REQUIRED
      - CHEST PAK AND 'TOOL CADIE' RESTRICT REACH DEPTH
3. SUIT MOTION
   A. CERTAIN TASKS RESULTED IN:
      - 'LEANING' SIDE TO SIDE WHILE REACHING UP TO 30° ABOVE HORIZONTAL
      - 'LEARNING' FULL BACKWARD WHILE CLOSING EQUIP. SECTION DOOR
      - REMOVING 1 FOOT FROM FOOT RESTRAINT AND LEANING (SIDEWAYS) TOWARD WORK SITE
   B. BODY FATIGUE
      - SHOULDER AND UPPER ARM FATIGUE NOTED IN SUBJECTS CONDUCTING REACH (EXTENDED) HELMET LEVEL (OR HIGHER) TASKS

FIG. 16 SUIT MOBILITY/UTILIZATION RANGES - TYPICAL

FIG. 17 REMOVE/REPLACE & ALIGNMT TECHNIQUES (PARTIAL LISTING)

TECHNIQUE	RANGE TOLERANCE (GENERAL	COMMENTS
1. HOLE PATTERN A. FASTENERS (SCREW/BOLT) 2 OR MORE B. PINS IN HOLES C. FASTENERS WITH ADJACENT PINS • ALONG ONE EDGE • ON OPPOSITE EDGES	0.006 TO 0.0002 0.013 TO 0.0003	• IN BASE FLANGE OF SUBSTRATE • PIN TANGENT TO PART ALIGNMT EDGE
2. GUIDES A. CORNER BRACKETS • COARSE USING PINS FOR FINAL ALGNMT • FINITE WITH INTEGRAL PINS B. INCLINATION (DRAFT)	0.1 TO 0.06	• COARSE ALIGNMENT ONLY • PROVIDES ANGULAR HOMING ONLY
3. EXPANDING BOLTS - FILLS HOLE	0.0005 TO 0.0002	• CONCENTRICITY TOLERANCE QUESTION
4. THREADED PART A. TURNBUCKLE B. THREADED SCREW	0.05 TO 0.01	• REQUIRES SUPPLEMENTAL MEASMT. • COARSE ALIGNMENT - VERT/ROLL
5. SLIP A. SLOT/KEY	0.04 TO 0.02	• ACCEPTABLE FOR FLATS MTD. ON SUBSTRATE

FIG. 18 CABLING CONSIDERATIONS



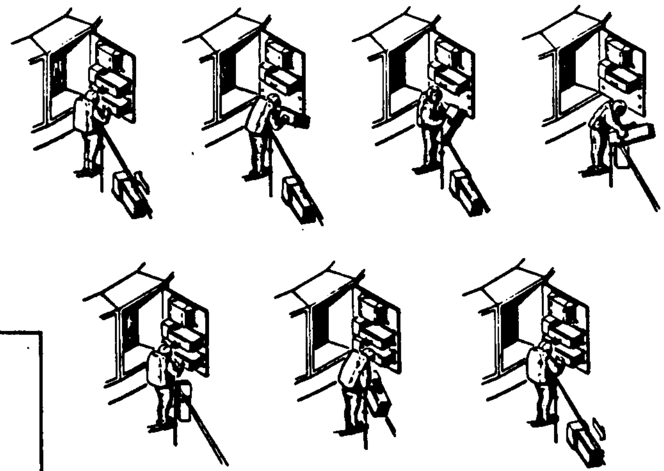


FIG. 19 ON-ORBIT EQUIPMT XFER - EV CREW AIDED

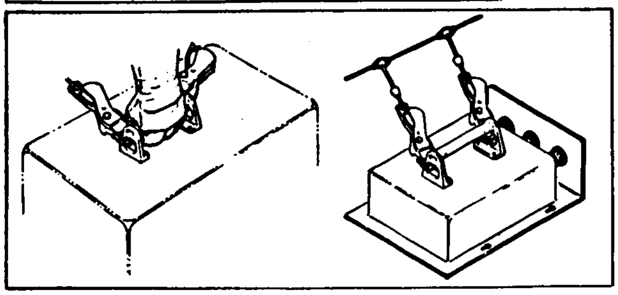


FIG. 20 EQUIPMENT TRANSFER & HANDLING

1. CAPTIVE SCREW/BOLT DOME NUTS
2. RECESSED SCREWS
3. MACHINE RADIUSED CORNERS/EDGES
4. SUPPLEMENTAL CORNER/EDGE PROTECTIVE MATERIAL
5. SMOOTHED SURFACE FINISHES
6. PROTECTIVE COVER
7. ELIMINATION OF STOWED ENERGY DESIGN APPROACHES
8. RECESSED EQUIPMENT
9. ELIMINATION OF EXPOSED 'ELECTRICALLY-HOT' CONNECTOR PINS
10. MINIMUM HEIGHT (THREAD EXPOSURE) CAPITIVE BOLTS
11. ELIMINATION OF BURRS THROUGH MANUFACTURING PROCESSES
12. SELECTION OF MATERIALS WHICH DON'T SPLINTER, GALL, SHREAD, ETC.

FIG. 21 TYPICAL SAFETY PROVISIONS & PROCESS