Space Station Proximity Operations and Window Design

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ABSTRACT

On-orbit proximity operations (PROX-OPS) refers to all EVA within one km of the Space Station. Because of the potentially large variety of PROX-OPS, very careful planning for Space Station windows is called for and must consider a great many human factors. This paper reviews some of these human factors using as its outline a NASA Technical Memorandum in preparation by the author. The following topics are discussed: (1) basic window design philosophy and assumptions, (2) the concept of the local horizontal - local vertical on-orbit, (3) window linear dimensions, (4) selected anthropomorphic considerations, (5) displays and controls relative to windows, (6) full window assembly replacement, (7) Summary and Conclusions, and (8) References.

INTRODUCTION

Relatively little has been written on the important subject of Space Station windows. A NASA Technical Memorandum (TM) now in preparation (Haines, 1986) documents most of the prior technical references dealing with the optical, geometric, and structural properties of windows installed on prior US and Soviet spacecraft and will not be repeated here. Good window designs result from a deliberate and painstaking analysis of all of the tasks which the viewer must carry out through the window(s), the operational capabilities and limitations of the entire Space Station on-orbit, the perceptual and physiological capabilities and limitations of the viewer over time, and a host of other factors too complex to deal with here. As stated in NASA report JSC-19989 (1984; pg. 3) describing the so-called Reference Configuration for the Space Station, "One of the principal advantages of this configuration is the good viewing afforded to all payloads, both externally-mounted and internally mounted." Such viewing will require properly designed windows.

Figure 1 presents the Table of Contents for the forthcoming TM by the author with a mark at those subjects that are discussed (briefly) here.

Figure 1

Table of Contents of NASA TM Entitled
"Space Station Proximity Operations Windows: Human Factors Design Guidelines"
(Haines, 1986)

Figure 1 – Continued

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Figure 1 – Concluded

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A. Mercury Capsule Windows and Related Details

B. Gemini Capsule Windows and Related Details

C. Apollo Command Module Windows and Related Details

D. Apollo Lunar Excursion Module Windows and Related Details

E. Skylab Windows and Related Details

F. Space Shuttle Vehicle Windows and Related Details

G. Soviet Vostok Capsule Windows and Related Details

H. Soviet Voskhod Capsule Windows and Related Details

I. Soviet Soyuz Capsule Windows and Related Details

J. Soviet Salyut Vehicle Windows and Related Details

I. *BASIC WINDOW DESIGN PHILOSOPHY AND ASSUMPTIONS*

The overall design philosophy for PROX-OPS windows include the following elements: (a) all windows shall support the greatest degree of external and internal situational awareness as possible, (b) all windows shall provide the greatest level of bodily protection possible from external radiation sources, and dangers resulting from changes in pressure, temperature, etc. (c) each window shall not allow visual degradation to occur due to veiling glare, flash blindness, or other unexpected luminous event during critical operational periods, and (d) each window shall provide as large a horizontal and vertical field of view (FOV) as possible.

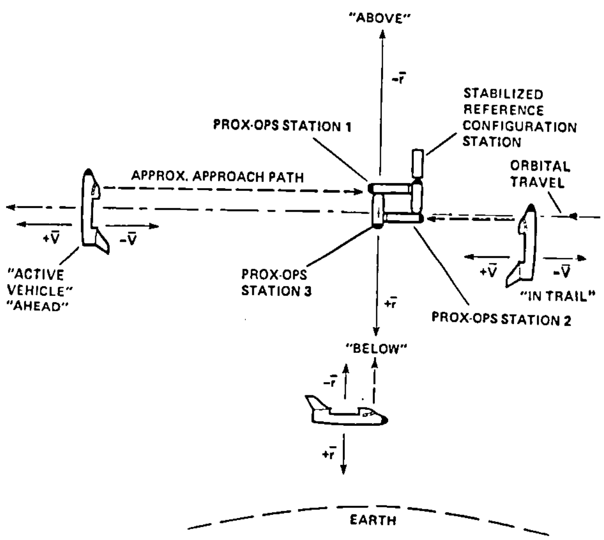
Several basic assumptions have been made which take into account other engineering and mission requirements presented elsewhere (Donahoo and Anderson, 1985; Mcdonnell Douglas Astronautics, 1985; Oberg, 1982). They include: (a) for most PROX-OPS out-the-window activities there will be only one viewer per window, (b) a maximum window dimension of 20 inches will be allowed. Nevertheless, it is reasonable to assume that a 20" x 30" (50.8 x 76.2 cm) rectangular window will be permitted from a structural design standpoint, (c) round windows will not be used for PROX-OPS (primarily) because such a window shape eliminates any (target vehicle) roll cues or body orientation cues for the viewer, (d) window panes will be flat glass with an inert, dry gas filling inner cavities, (e) the thickness of window frames surrounding each window will be as small as possible to reduce visual occlusion of external objects, (f) all windows that are to be used for making color discriminations shall possess neutral spectral transmission so that perceived target object hues are not altered, and (g) each window shall be designed to accommodate a "design eye volume" (DEV) of approximately 0.6 cubic meter centered on the center of the window and set back 12" (30.5 cm) from the inner most pane.

II. *THE LOCAL HORIZONTAL - LOCAL VERTICAL CONCEPT* OF ON-ORBIT SPACE STATION STABILIZATION

Figure 2 illustrates the local horizontal-local vertical (LH-LV) concept of Space Station stabilization on-orbit and related nomenclature. The particular configuration of modules shown is not important. Throughout its orbital travel, the Space Station will pitch so as to maintain the center of the earth directly below it.

Figure 2

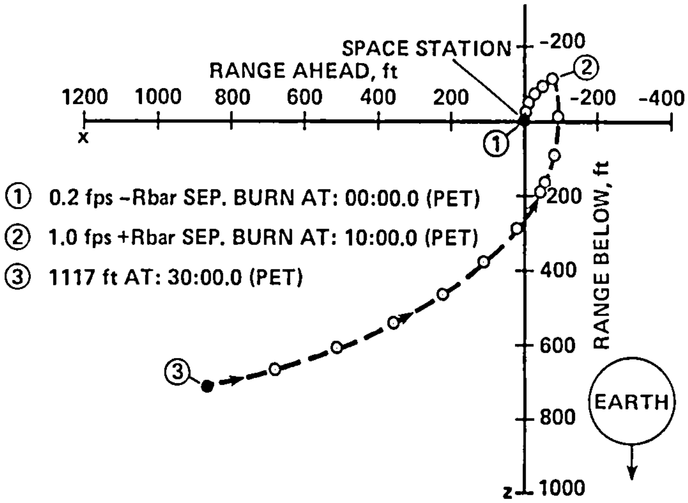
Local Horizontal - Local Vertical Space Station Stabilization



For certain approach trajectories (e.g., the minus R bar shown in Figure 3), the approaching target vehicle will not be visible from windows located in the end-cap of a module that are facing only in the minus V bar direction until the vehicle is very near the Space Station [typically under 100 ft (31 m)]. The windows must accommodate a large vertical FOV for this type of approach maneuver.

Figure 3

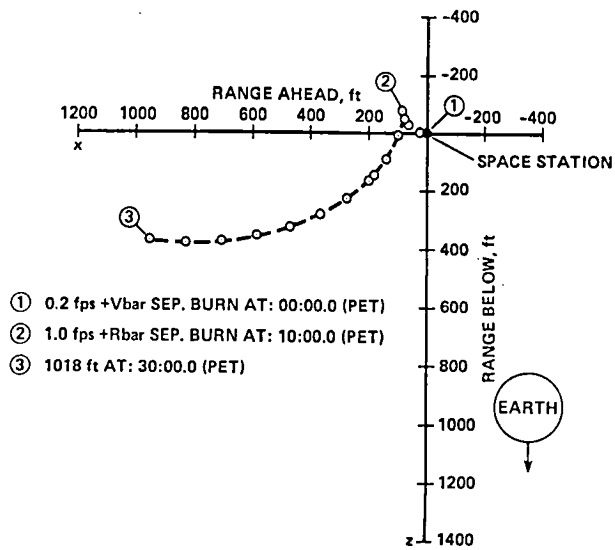
Nominal Minus R bar PROX-OPS Approach Trajectory



For other approach trajectories such as the plus V bar shown in Figure 4, the PROX-OPS windows must face in the direction of the velocity vector looking in the general direction of the rising sun. This will place the approaching target vehicle between the sun and the viewer and create many practical problems of target visibility along with optical design problems.

Figure 4

Nominal Plus V bar PROX-OPS Approach Trajectory



III. WINDOW LINEAR DIMENSIONS

The geometric variables which will determine the total available FOV of a window are shown in Figure 5. Figures 6 and 7 present the total FOV angle for a 9" (23 cm), 18" (46 cm), and 48" (122 cm) wide window as a function of the lateral offset distance (X - X1 in Figure 5) for a 6" (5 cm) and 18" (46 cm) set-back distance. Clearly, both set-back distance and lateral offset play crucial roles in limiting the available FOV. When anthropomorphic considerations are taken into account, nominal window sizes may be determined (cf. Figure 8) which will then permit operational planners to know, in advance, whether an approaching vehicle following a particular trajectory will remain visible in a given window or not and at what point in its approach will it first appear. Such prior knowledge is very useful.

Figure 5

Geometric Variables Which Determine the Visual Angle for a Single Window

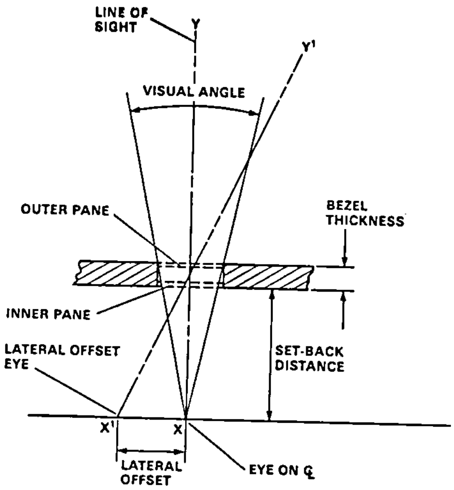


Figure 6

Visual Angle (deg.) for Three Window Sizes as a Function of Lateral Offset (in.) for a Six Inch Eye Set-Back Distance

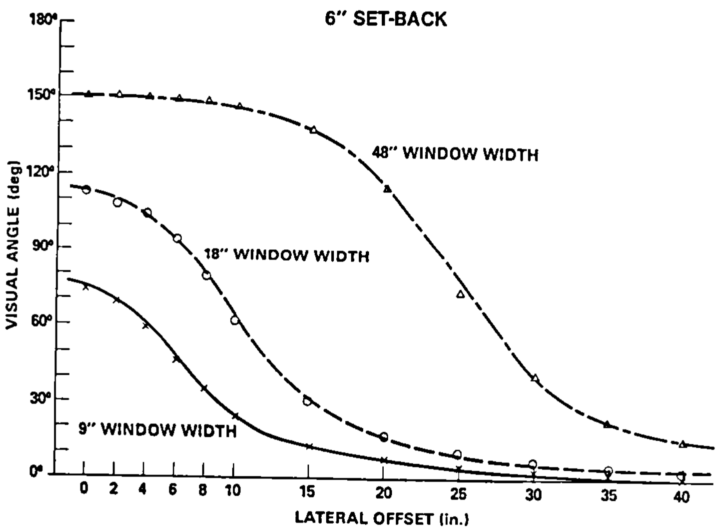


Figure 7

Visual Angle (deg.) for Three Window Sizes as a Function of Lateral Offset (in.) for an 18 Inch Eye Set-Back Distance

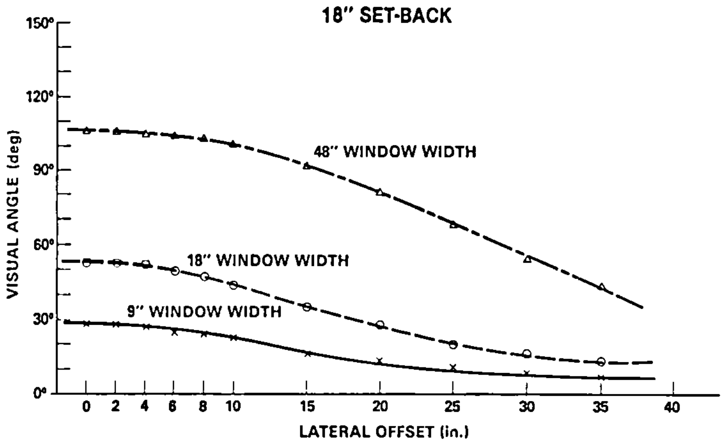
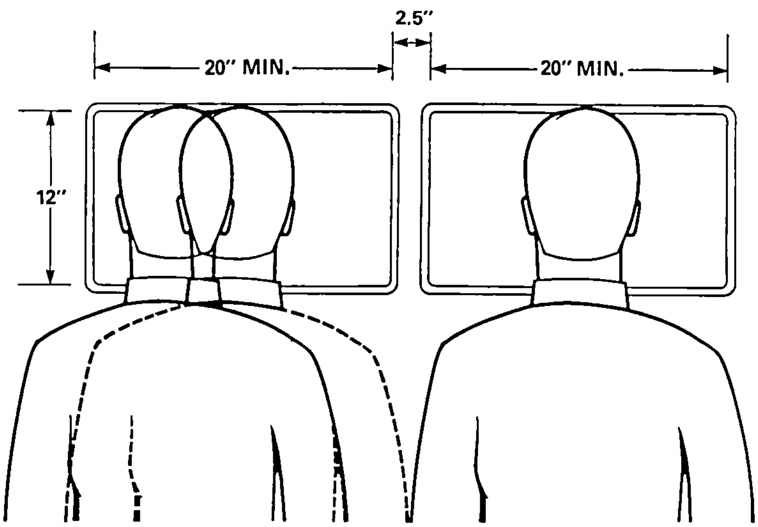


Figure 8

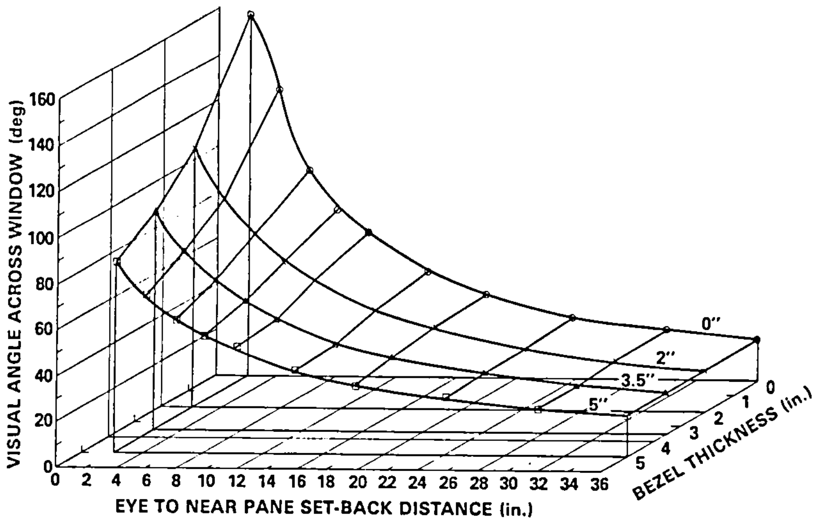
One Viewer Per Window Spacing Recommendation for a Small Set-back Distance



The last geometric variable considered here in regard to the maximum achievable FOV through a given window is that of bezel thickness, i.e., the thickness of the wall in which a window is installed. In Figure 5 this is shown (for convenience) as being equivalent to the separation distance between the innermost and outermost window panes. Calculations have been made of the visual angle across a 12" (30.5 cm) wide window with the eye on centerline but set-back various distances. Figure 9 presents the results of such calculations as a function of bezel thicknesses from zero to 5" (12.7 cm). It may be noted that visual angle through the window increases with decreasing set-back distance and also with decreasing bezel thickness in a regular fashion. Such data may be used to perform engineering trade-off studies of various geometric designs.

Figure 9

Visual Angle (deg) for Various Set-back Distances and Bezel Thicknesses for a 12" (30.5 cm) Wide Window

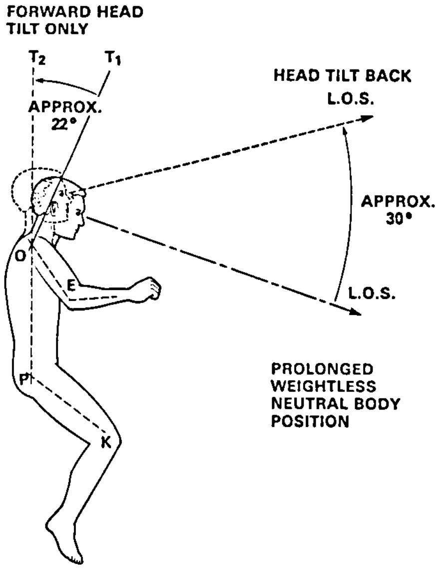


IV. SELECTED ANTHROPOMORPHIC CONSIDERATIONS

Among the many anthropomorphic considerations related to Space Station window design are those related to micro-gravity body posture (Griffin, 1978; Jackson et al., 1975). The basic situation is illustrated in Figure 10 for a set-back distance of 12" (30.5 cm) from the innermost pane. Because the head flexes forward, the average line of sight (LOS) is depressed by about 20 to 30 deg arc compared to its nominal direction in one g. The legs and arms also tend to bend somewhat as shown.

Figure 10

Approximate Neutral Body Position in Prolonged Weightlessness



When the viewer must look through a Space Station window for prolonged periods of time using relatively small set-back distances and (hand, knee) body clearance (cf. Figure ll), the body axis angle T-O-P must approach 180 deg rather than flex forward to about 150 deg. This can result in neck tension, pain and fatigue. By increasing the eye set-back distance, the body can assume a more natural and comfortable posture as is shown in Figure 12.

Figure 11

Illustration Showing the Deviation from the Neutral Body Position Required to View Through a Window that is 12 Inches Away

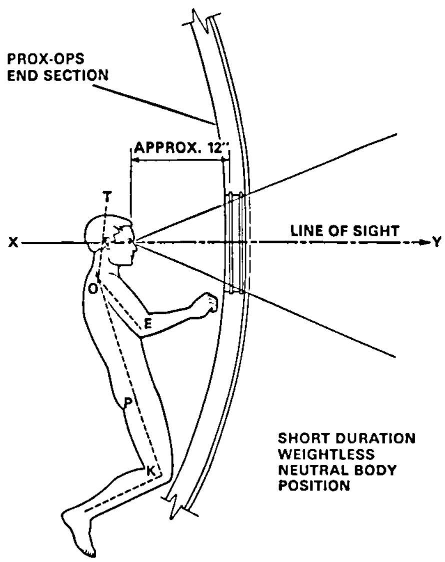
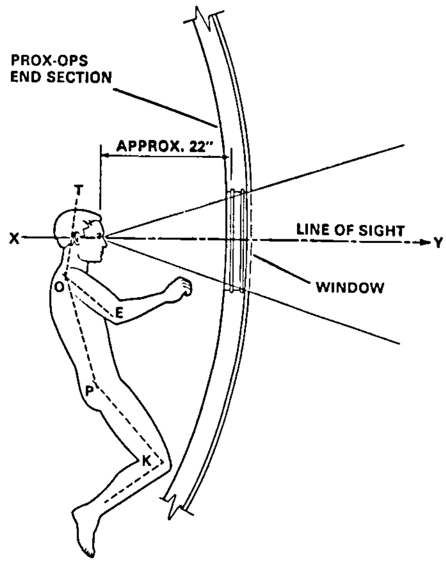


Figure 12

Illustration Showing the More Natural and Comfortable
Body Position Possible by Increasing the
Eye to Window Set-back Distance



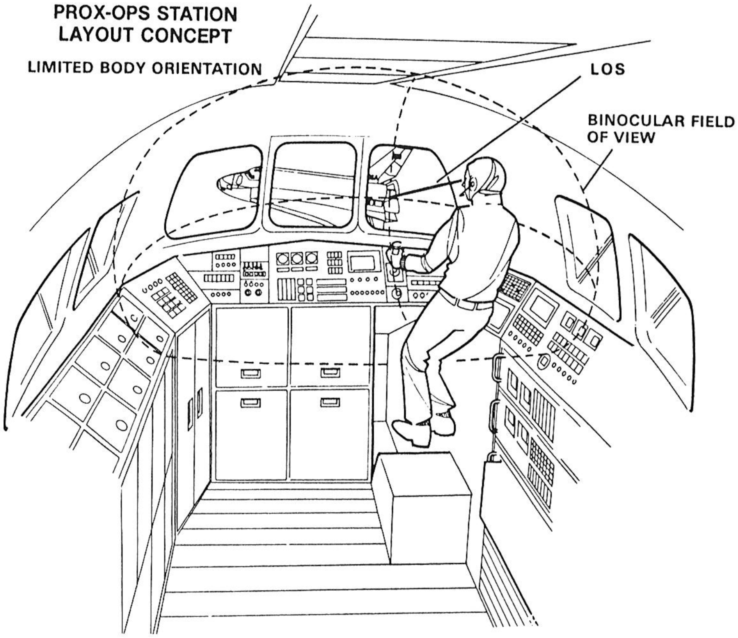
V. DISPLAYS AND CONTROLS RELATIVE TO WINDOWS

The human factors specialist familiar with traditional aircraft cockpit layout and design should be consulted in regard to how best to locate informational displays and controls in a PROX-OPS station. A fundamental difference between the two design environments is the fact that, on-orbit, the design eye *point* turns into a design eye *volume*. Due to the fact that viewers in prolonged micro-gravity will not need to be as physically constrained as they are in the cockpit of an airplane, they will necessarily experience more (voluntary and involuntary) slow head translation per unit time. For most extra-vehicular observing tasks this should not prove to be a problem. For many interior observing tasks, such as monitoring a precision TV display during the final stages of berthing, head translation may lead to some serious perceptual and operational problems.

Another consideration with regard to the proper layout design of PROX-OPS displays and windows has to do with maintaining as much relevant display information as possible within the viewer's binocular visual field while he or she is viewing out a window. This concept is illustrated in Figure 13. A design eye volume of approximately 0.6 cubic meters is recommended for each window such that the viewer could move any place within this volume and be able to perceive the same quantity and quality of interior (panel) information. Such a design requirement will help the viewer maintain a high degree of situational awareness. Space does not permit a fuller treatment of this topic. The interested reader should consult Haines (1975) and its references for further information.

Figure 13

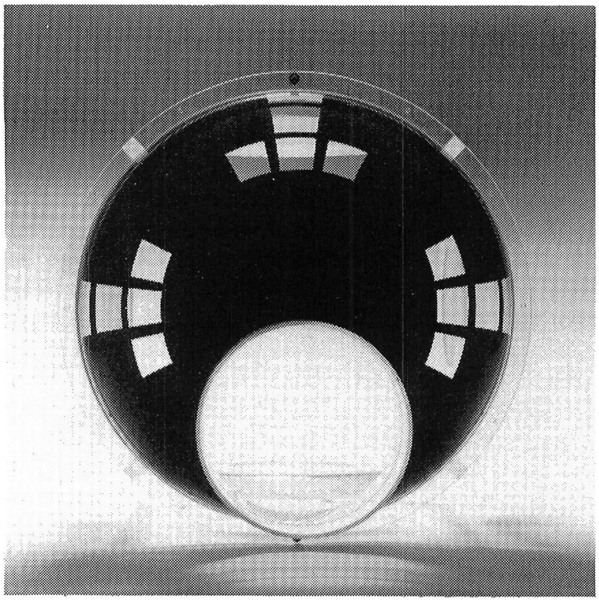
Proximity Operations Control Station Concept to Achieve Full Binocular Visual Sensitivity While Viewing Through a Given Window



Locating PROX-OPS displays and controls must take into account the location, spacing, shape, number, and size of the windows present. A candidate window arrangement that is being evaluated at Ames in the Proximity Operations Simulator consists of five windows arranged in an inverted T. Figure 14 shows this arrangement.

Figure 14

Front View of a Scale Model Ellipsoidal End Cap Designed by Marc M. Cohen, AIA, Showing a Candidate "Inverted T" Arrangement of Windows.

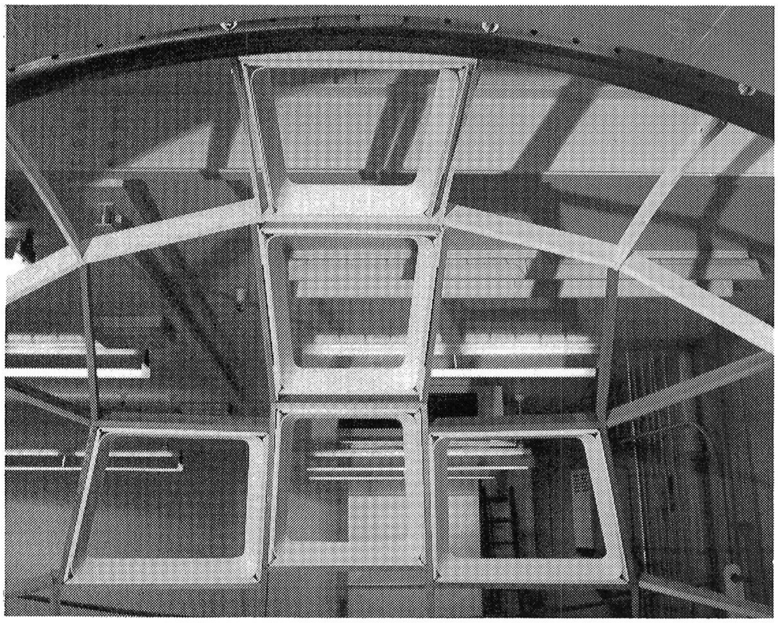


This arrangement of five windows is repeated 90 degrees to the left and 90 degrees to the right as well. This end-view photograph is of a scale model module end-cap with an off-center berthing port shown near the bottom. This arrangement of 15 separate windows offers a number of advantages which include: (1) overlapping fields of view by two or more crew who are viewing through different sets of windows, (2) wide field of view in both the horizontal and vertical directions simultaneously through any single set of five windows, and (3) use of standardized window assemblies in at least three of the five window locations. This window layout will also allow for radial rib construction radiating from a common center.

Figure 15 is a photograph taken inside the Proximity Operations Simulator at Ames showing the initial layout and construction of the windows. The following window design features may be noted with regard to each grouping of five windows: (1) The design eye volume is approximately 0.6 cubic m which permits a maximum horizontal field of view of 125 degrees arc and a maximum vertical field of view of just under 100 degrees. Excellent external situational awareness is ensured by this layout. (2) The two lateral windows flanking the center window are mirror images of each other in shape. (3) The two upper-most windows are identical.

Figure 15

Photograph of Full Scale Mockup During Construction
Showing Array of Five Prox-Ops Windows



(4) All window frames are smallest at the outer glass surface, i.e., the frames are larger on the observer's side than on the space side. This ensures that the observer will always know that the maximum external scene is visible without having to move the head to make sure. (5) The top and bottom (horizontal) window frames are all parallel with the local horizontal of the Space Station. This features aids in making judgments of the horizontality of approaching target vehicles when necessary. (6) The height of the center window is slightly raised relative to the height of the left- and right-hand windows which permits greater down-looking capability to each side. (7) All window frames are painted with a medium reflectance (approx. 65 percent) flat grey to ensure a low contrast window frame surround at

all times, i.e., the observer will always be able to see the window frame and use it to assist in making relative target motion judgements. (8) As many as five persons can view out of each group of five windows by assuming different body orientations relative to each other. As many as three persons can view out of each group of five windows when their body axes are parallel and their feet are in the same direction.

Other PROX-OPS station viewport concepts have been proposed by Bell and Trotti (1985) using a module connecting node as the location for viewing windows. They are reproduced in Figures 16 through 18. Each succeeding figure presents increasing FOV and exterior situational awareness. The hemispheric viewport proposed in Figure 18 appears to be beyond the current level of optical material processing in terms of keeping line of sight distortions at any penetration point to an acceptable level.

Figure 16

Flat Windows Located Within the Conncting Node Wall
(Concept by Bell and Trotti, Inc., 1985)

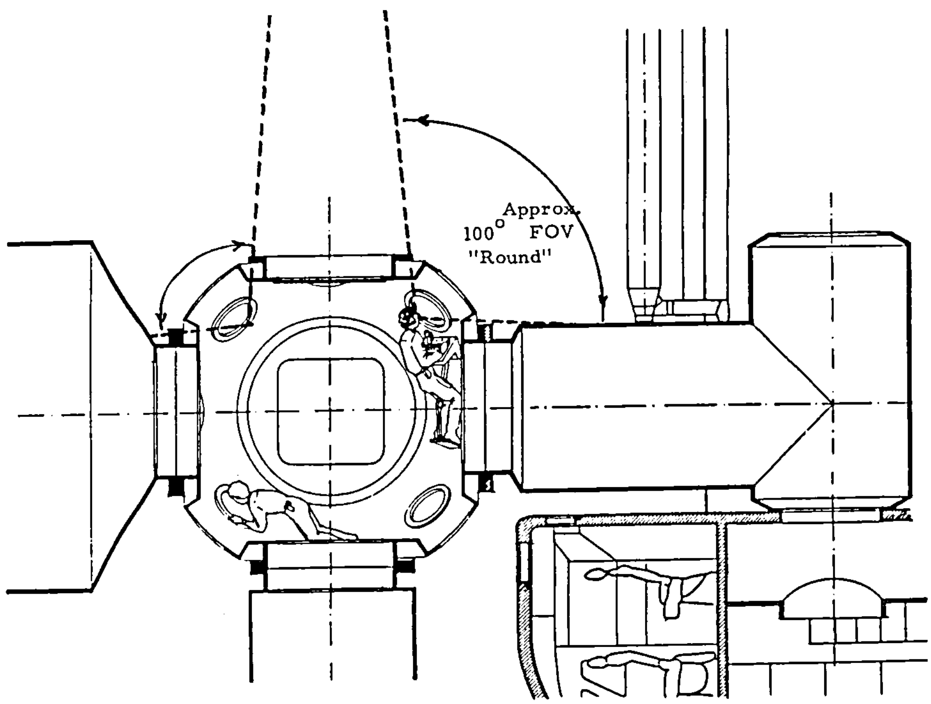
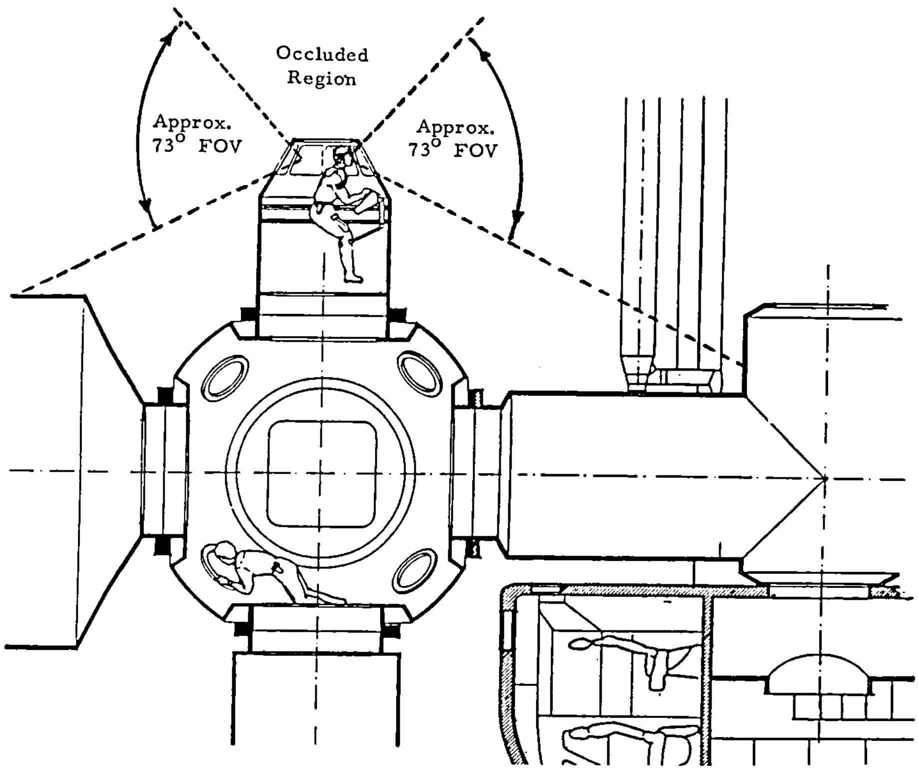


Figure 17

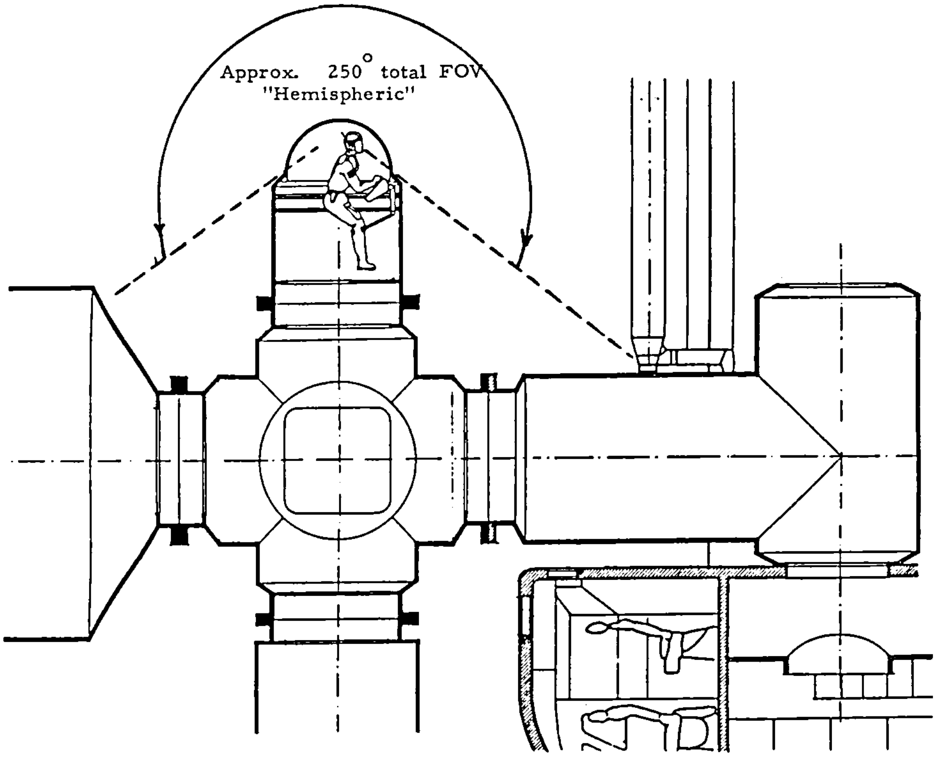
Flat Windows Located Within a Special Turret
Attached to a Connecting Node
(Concept by Bell and Trotti, Inc., 1985)



Referring to Figure 17, the turret concept affords excellent external visibility with a dedicated control station. It also permits flat glass panes to be used of moderately small dimensions.

Figure 18

Hemispheric Window Located Within a Special Turret
Attached to a Connecting Node
(Concept by Bell and Trotti, Inc., 1985)



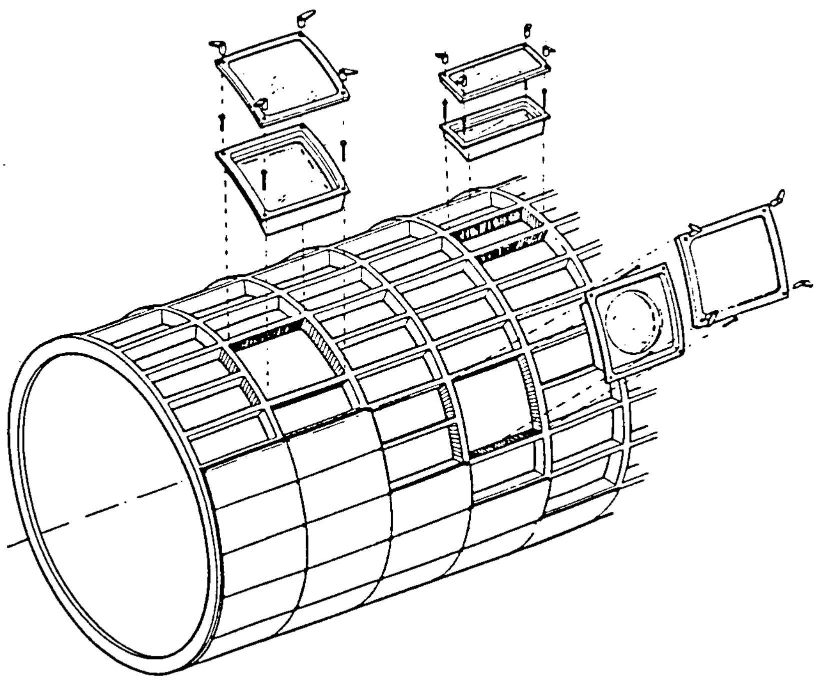
VI. FULL WINDOW ASSEMBLY REPLACEMENT

All manned U.S. space vehicles prior to Space Station have been flown back to earth (except Skylab). In most cases (e.g., Mercury, Gemini, Apollo) the capsule was not designed for more than one flight so that the windows were analyzed post-flight and then stored. The Orbiter windows are inspected after each flight with replacements/repair made as necessary on earth. For Space Station, however, it will be necessary to do all inspection, maintenance, and replacement on-orbit. This requirement raises some very interesting and challenging human factors questions and calls for new and creative structural designs.

Development of window pane crack development monitoring system should receive high priority along with the actual engineering design of the windows themselves. Such a monitoring system would significantly reduce the chance that small developing cracks would progress to a fracture point. Should an entire window assembly require replacement on-orbit, the human factors impact upon the entire crew would (likely) be enormous. One possible approach to window assembly replacement is illustrated in Figure 19 (from Bell and Trotti, 1985).

Figure 19

Full Window Assembly Replacement Concept
Proposed by Bell and Trotti (1985)



Some of the operational procedures which this approach would involve include: (1) all consequences of lowering the internal air pressure to zero (e.g., isolating the entire module or section of module, donning a pressure suit, etc.), (2) locating, unstowing, transporting new window assembly to installation area, (3) removing damaged window assembly, (4) cleaning and seating wall members to receive the new assembly, (5) cleaning, installing, and correctly seating the new assembly, (6) packing, marking, inventorying and stowing the damaged assembly, (7) repressurizing the module (or part of module), (8) performing window assembly integrity checks, and (9) preparing, unstowing, stowing, updating, referring to various procedural manuals.

VII. SUMMARY AND CONCLUSIONS

This brief presentation cannot begin to cover all of the myriad human factors associated with the design, placement, installation, check-out, monitoring, maintenance, spares storage, inventory control, and replacement of PROX-OPS windows. Some of these subjects are treated in greater detail elsewhere (Haines, 1986). This paper has outlined some basic design philosophy and assumptions for PROX-OPS windows for Space Station. The human factors engineer should be brought into the design process as early as possible in order to reduce the chance that critical window design characteristics will be incorporated which will reduce the operational capabilities of the windows.

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