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Extravehicular Activity Compatibility Evaluation of Developmental Hardware for Assembly and Repair of Precision Reflectors

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Summary

This report presents results of tests performed in neutral buoyancy by two pressure-suited test subjects to simulate extravehicular activity (EVA) tasks associated with the on-orbit construction and repair of precision reflectors. The purpose of the tests was to evaluate the EVA compatibility of (1) joint hardware designed to enable quick assembly of truss structure components, (2) two different hardware designs for attachment of precision reflector surface panels to a supporting truss structure, and (3) panel replacement tool hardware designed to enable astronauts to replace a damaged panel during EVA. Although a precision reflector spacecraft would most likely have a doubly curved reflector surface, the purpose of these tests was achieved with flat mockup surface panels and a planar tetrahedral support truss. Two complete neutral buoyancy assemblies of the test article (tetrahedral truss with three attached reflector panels) were performed with the same procedure. Different panel attachment hardware was evaluated in each of the tests. The truss, sized to support three reflector panels, was assembled from 31 struts and 12 nodes with quick-attachment joints. Although the struts were identical, they were treated as unique and were assembled in a specified order, as necessary for a doubly curved truss. The struts were fabricated from aluminum tubing that was 3.18 cm in diameter, and each strut was neutrally buoyed and trimmed to maintain any given orientation. The truss nodes were spaced at intervals of 2 m. The panels were fabricated from aluminum sheet and their dimensional accuracy was not representative of precision reflectors. The spacing between adjacent panel edges was nominally 0.63 cm. One test was concluded by removal and replacement of a panel by the test subjects to simulate repair of a damaged panel. A special tool was designed and used for this purpose.

The truss structure (without panels) was assembled at an average unit assembly time of 41 sec per strut, about twice the predicted time. This rate was influenced significantly by the use of an existing assembly fixture originally designed for $1g$ hardware development testing. The existing assembly fixture incorporated fixed foot restraints that were positioned to allow the test subjects to perform all their required truss assembly tasks. In some instances, however, the test subjects had to reach to their maximum limits to perform truss connections. In addition, during assembly of the truss, the turnstile had to be manipulated more than anticipated to bring the work area within the reach envelope of each test subject. The predicted truss assembly time could not account for these anomalous operations. Thus, the time to assemble the truss, although of interest, does not reflect the time that would be representative of an optimized assembly procedure.

The operation and size of the quick-attachment joint hardware was found to be acceptable by the test subjects. The average time to install a panel from a position within reach of the test subjects was 1 min 14 sec. Both panel attachment designs were found to be EVA compatible, although one design was judged by the test subjects to be considerably easier to operate. The panel replacement tool was used successfully to demonstrate the removal of a damaged reflector panel in 10 min 25 sec.

Introduction

Precision reflector technology development activities at NASA support possible missions for the agency's Global Change Technology Initiative (fig. 1(a)) as well as other missions involving astrophysics (fig. 1(b)) and solar dynamic collectors (fig. 1(c)). These future missions will require large, moderate-to-high resolution precision reflectors. The proposed operational sizes of these reflectors exceed the capability of any current or envisioned launch vehicle. Thus, on-orbit deployment or construction by astronauts or robotic methods is required, and the reflector surface must be composed of many smaller panel segments compatible with the size of the launch vehicle. The panel segments are generally envisioned to be hexagonal in shape, as shown in figure 1. In addition, to minimize the use of active controls, a stiff, accurate truss structure will most likely be required to support the precision reflector surface.

Extravehicular activity (EVA) assembly is a construction option that shows considerable promise for precision reflector spacecraft. This observation is based on the results of previous simulated EVA structural assembly test programs involving construction of beam-like truss structures performed in neutral buoyancy (refs. 1, 2, and 3) and on orbit with the ACCESS experiment (ref. 4). Figure 2 shows a photograph taken during assembly of the ACCESS truss. Each of the truss beams studied in these references, however, consisted of struts of no more than two different lengths and nodes of no more than two different geometries. All struts and nodes that were identical were incorporated randomly during the assembly process. In contrast, construction of a doubly curved precision reflector structure involves packaging large numbers of unique struts and nodes, each of which must be presented to the astronauts in the proper sequence during construction for installation in a unique location. In addition, remote manipulator or astronaut handling and attachment of the reflector surface panels, which have maximum dimensions of 2 m or more, must also be addressed. Finally, if a panel is damaged after the reflector is operational, a method to replace that panel without disassembling any part of the rest of the spacecraft should be available. To avoid such disassembly, the damaged panel must be removed from the concave side of the reflector (opposite side from the truss). Thus, to prevent the closely spaced, curved panels from acting as keystones preventing their removal in this manner, the panel edges must be beveled to provide sufficient clearance. Interference from adjacent panel edges due to rotational misalignment must also be avoided, and the rotational orientation of the panel must be keyed to ensure that the replacement panel is installed in the correct orientation.

This paper presents results of tests performed in neutral buoyancy by two pressure-suited test subjects to simulate EVA tasks associated with the on-orbit construction of a precision reflector spacecraft. The purpose of the tests was to evaluate the EVA compatibility of (1) joint hardware designed to enable quick assembly of truss structure components, (2) two different hardware designs for attachment of precision reflector surface panels to a supporting truss structure, and (3) panel replacement tool hardware designed to enable astronauts to replace a damaged panel during EVA.

For these tests, an existing assembly fixture originally designed for $1g$ hardware developmental testing was used. The assembly fixture was effective for panel-to-truss attachment and damaged panel replacement activities performed in neutral buoyancy. The existing assembly fixture incorporated fixed foot restraints that were positioned to allow the test subjects to perform all their required truss assembly tasks. In some instances, however, the test subjects had to reach to their maximum limits to perform truss connections. In addition, the turnstile had to be manipulated more than anticipated during the truss assembly to bring the work area within the reach envelope of each test subject. The predicted truss assembly time could not account for these anomalous operations. *Thus, the truss assembly time, although of interest, does not reflect the time that would be representative of an optimized assembly procedure.* Nevertheless, predicted times to complete progressive stages of assembly including panel attachment are compared with test times for two complete neutral buoyancy assemblies of the structure. The assemblies were identical except that different panel attachment hardware was used in each of the tests. This paper also presents times for the removal and replacement of a panel by the test subjects to simulate repair of a damaged panel. The test hardware and the assembly and panel replacement procedures are described. Assumptions used for the predicted times are also presented.

The neutral buoyancy tests reported herein were conducted in the Underwater Test Facility at the McDonnell Douglas Space Systems Company (MDSSC), Huntington Beach, CA, under NASA/MDSSC Memorandum of Agreement no. 91090153. The authors would like to express their appreciation to David Anderson of MDSSC for his assistance in test planning and execution as well as data recording and reduction.

Test Apparatus

Truss Hardware

A sketch of the assembled truss hardware used in the tests is shown in figure 3. The truss represents a segment of a larger tetrahedral truss (fig. 3(a)) used as the structural support for the precision reflector surface composed of a number of smaller reflector panels. To minimize fabrication costs, all 31 struts are identical as are all 12 nodes. Thus, the assembled truss is planar instead of doubly curved. The three adjacent reflector panels are attached to the six nodes on the front of the truss. (See fig. 3(b).) The truss nodes are spaced at intervals of 2 m.

Struts. A photograph of a typical strut is shown in figure 4(a). The strut is labeled at each end with numbers that indicate a node and node port to which the strut end is to be attached. White numbers on a black background (shown in the photograph) indicate that the end of the strut is to be attached to a node on the front of the truss. Black numbers on a white background (not shown) indicate that the end of the strut is to be attached to a node on the back of the truss. Figures 4(b) and 4(c) show the details of a typical strut. A strut consists of a length of aluminum tubing, two buoyancy compensators, and two strut-end joint-half assemblies. (See fig. 4(b).) The tubing and buoyancy compensator material is black anodized 6061 aluminum. The strut-end joint-half material is 7075 aluminum. More detailed information of the strut-end joint halves is given in reference 5, in which the hardware is designated *1-in. (2.54 cm) diameter.* This 1-in-diameter hardware evolved from a 2-in-diameter design that was developed for application on Space Station *Freedom.* The 2-in-diameter design has been subjected to numerous hours of EVA compatibility testing by pressure-suited test subjects in neutral buoyancy. The present neutral buoyancy tests are the first for the 1-in-diameter hardware, and of particular interest is the pressure-suited test subjects' ability to operate the scaled-down version of the locking collar (fig. 4(b)). The test subjects must be able to rotate the locking collar (designated *rotating cam cover* in ref. 5) 45° about the longitudinal axis of the strut to complete the strut-to-node connection.

The buoyancy compensators are vented chambers that flood when the struts are immersed in water. (See fig. 4(c).) The buoyancy compensators also form bulkheads when screwed into the strut ends. O-ring seals are used so that the aluminum tube becomes an airtight chamber, which causes the strut assembly (fig. 4(b)) to have positive buoyancy (float) in water. Neutral buoyancy and trim—the ability of the strut to remain in any given orientation under water—of the struts are achieved by adding lead shot ballast to the flooded chamber of the buoyancy compensator at each end of the strut.

Nodes. Figure 5 is a photograph of a node assembly with nine attached node joint halves, which provide nine strut attachment ports. Nine struts are also shown attached to the node in figure 5. The node components were machined from 7075 aluminum. Although a typical interior node (fig. 3(a)) in a tetrahedral truss is required to accommodate nine struts, only node assemblies with three to eight node joint halves attached were required for the truss hardware assembled in the present tests. (See fig. 3(b).) The masses of the node components are given in figure 4. No attempt was made to neutrally buoy the nodes.

Reflector Panel Mockup and Attachment Hardware

For the present tests two different hardware designs for attaching hexagonal panels to an erectable tetrahedral truss were evaluated for EVA compatibility. Both designs are intended to permit essentially free thermal expansion of the panel while restraining rigid body motion. The designs are also intended to enable astronauts to attach large reflector panels to a truss structure with precision during EVA. Both designs are in the conceptual development stage; thus, details are limited and structural evaluation is beyond the scope of this paper.

Panels. Three identical hexagonal, aluminum sheet panel mockups were used to simulate precision reflector panels. A photograph of the back (side facing the truss) of a mockup panel is shown in figure 6. The mockup panels, which had a flat surface on the front (reflective side), were 5.10 cm thick at the edges and 7.60 cm thick at the centers. The panels were sized to have a nominal gap of 0.63 cm between adjacent panel reflective surface edges when installed on the truss. The edges of the panels were beveled to provide several centimeters of clearance between back-surface edges of adjacent panels to facilitate EVA installation. A panel is attached to three truss nodes. The attachment points on the panel are located at three of its six vertices (every other vertex as shown in fig. 3(b)). The mockup panels were equipped with fittings located at the appropriate vertices to accommodate both types of panel attachment hardware to be evaluated; thus the evaluation could be accomplished with only three panels instead of six. Three design 1 panel attachment fittings were located, one each, at every other vertex of a mockup panel. Design 2 panel attachment fittings were located at the remaining three vertices.

A fitting for use during the panel replacement activities was attached to the center of each mockup panel. This fitting was oriented such that during panel replacement activities (with the specially designed panel replacement tool discussed subsequently in this paper) the panel was guaranteed to be returned to the truss in the same orientation it had before it was removed. The mockup panels had a mass of 14 kg each and were neutrally buoyed and trimmed with a combination of closed-cell foam floatation around the edges and lead shot ballast contained in three flooded chambers attached at increments of 120° near the panel edges.

Design 1 panel attachment. Figure 7(a) is a schematic of the panel attachment concept designated design 1, and figure 7(b) is a photograph of the developmental hardware used in the tests. Each interior node (see fig. 3(a)) on the front of the truss has the following attached to it: a three-lobed alignment guide, a lower hinge pin seating plate, a latch support housing, three latches, and three latch actuation handles. Exterior nodes (located along the edges of the truss as shown in fig. 3(a)) require only two latches and two latch actuation handles. A corner node (represented in fig. 7(a)) requires only one latch and one latch actuation handle. The panel corner assembly is shown in figure 7(a). An upper hinge pin is used to connect the hinge to a panel corner fitting. A slender aluminum tube called a strap was used for the mockup panel shown in figure 6. This strap has the same thermal expansion characteristics as the truss, and it is attached to a lower hinge pin through a yoke. The opposite end of this strap is attached to the center of the panel.

The three hinges (nominally 120° apart) allow free thermal expansion of the panel. The three straps are intended to provide the primary restraint to in-plane rigid body motion of the panel; thus, the strap yokes are located as close to the center of the node ball as possible to reduce load eccentricity and coupling between panel in-plane motion and node rotation. The three hinges restrain out-of-plane rigid body displacement and in-plane and out-of-plane rigid body rotations of the panel. In addition, the three hinges, by virtue of their 120° orientation with respect to each other, act together to provide a secondary restraint from in-plane rigid body motion. This restraining effect can induce undesirable concentrated loads at the panel corners that tend to distort the panel reflective surface (a condition characteristic of panels supported on corner flexures). The straps, however, reduce these concentrated corner loads. The developmental panel attachment hardware was fabricated from aluminum.

Figure 8 shows the panel attachment sequence, and figure 8(a) shows a panel attached to a triangle of struts on the front of a support truss. The view shows the back of the panel. When the latch handle is in the center detent position, the lower hinge pin is captured by the spring-loaded latch (figs. 8(b) to 8(d) and fig. 7) as the panel is pulled into position on the alignment guide by the astronaut during EVA. The latch handle can then be moved into the locked position (fig. 8(e)) to preload the connection and thus complete the panel attachment. (Although this design requires the lower hinge pins at all three corners of the panel to be in contact with the alignment guides before the panel can be captured, the astronauts need only be concerned with simultaneously aligning two of the pins. The third pin is always aligned for capture when the other two pins are aligned.) To remove a panel, the latch handles must be rotated to the unlock detent position (fig. 7), which moves the latch away from its capture position over the lower hinge pin.

Design 2 panel attachment. Figure 9(a) is a schematic of the attachment concept designated design 2, and figure 9(b) is a photograph of the developmental hardware used in the tests. A more detailed description of this concept and hardware is presented in reference 6.

Each interior node on the front of the truss (fig. 3) has the following items attached to it: a flexure seat plate with three blade-like flexures, a movable cage with three panel capture mechanisms, a cage actuation handle, and three panel release levers. (Edge and corner nodes on the front of the truss require only two and one flexures, panel capture mechanisms, and panel release levers, respectively.) The cage surrounds and protects the precision flexures during attachment of the panel to the truss nodes.

A panel corner fitting (three per panel) with two machined seats is embedded in the panel. The larger of the machined seats, labeled *panel capture seat* in figure 9(a), allows the panel to be captured when it is guided onto the panel capture mechanism. The smaller of the machined seats, labeled *flexure tip seat,* accepts the flexure tip when the cage is retracted and serves as the final precision support for the corner of the panel. The panel corner is held on the flexure tip by the force of the panel hold-down spring that is compressed when the movable cage is retracted. The panel capture mechanism enables capture of a panel tilted up to 30°. This feature facilitates EVA assembly by providing additional clearance from adjacent panel edges. The development panel attachment hardware was fabricated from aluminum.

The attachment sequence is shown in figure 10. The panel corner is manually pulled onto the capture mechanism (figs. 10(a) and 10(b)). After two corners of the panel have been captured in this manner at two different nodes, the panel is rotated (fig. 10(c)) until the third corner is captured at a third node. Retraction of the cage by manipulation of the cage actuation handle sets the corner of the panel onto the flexure tip, where it is retained by the panel hold-down spring (figs. 9(a) and 10(d)). The cage at a particular node, however, must not be retracted until the corners of all the different panels that are to be attached to that node (up to three) are also captured by the other panel capture mechanisms at that node. The three blade-like flexures supporting the three corners of a panel are oriented at 120° with respect to each other and thus allow free thermal expansion of the panel while restraining all rigid body motion. (The panel capture mechanism support stud is housed in an oversized hole in the cage to provide no resistance to in-plane thermal expansion.)

To remove a panel, the cage at each of the three nodes to which the panel corners are attached must be extended by manipulation of the cage actuation handle. This motion, the reverse of the one shown in figure 10(d), unseats the panel corner from the flexure tip. Next, the panel release lever at each of the three panel corner-to-node attachment locations must be depressed and held (fig. 10(e)) until the panel corners are removed from the panel capture mechanism. The three corners of the panel must be removed simultaneously to avoid inadvertent recapture.

Panel Replacement Tool

If a panel of a precision reflector spacecraft becomes damaged, a method for replacement of that panel, which does not require disassembly of any other part of the spacecraft, is desirable. A tool designed for this purpose should have the following features: (1) it should accommodate hexagonal panels of slightly different sizes, and (2) it should position the replacement panel in the same rotational orientation as the damaged panel it replaces.

Figure 11 shows the panel replacement tool concept designed for evaluation in the present tests. A photograph of the tool is shown in figure 12. The tool consists of a guide pole and a sliding hub assembly. The guide pole and sliding hub assembly are keyed to maintain their orientation with respect to each other. The guide pole and panel have fittings that permit the attachment of the guide pole to the center of the back of the panel. The guide pole and panel center fitting can be mated only in one orientation. The hub assembly consists of a hub with bearings through which the guide pole can slide and three spokes with sliding clamps that lock onto the triangle of truss struts immediately behind the panel. Two of the spokes are pinned at the hub so that they are given limited rotational capability in the plane of the triangle to accommodate a variety of slightly irregular triangles of truss struts. The third spoke is fixed to the hub to preclude free rotation of the tool after attachment to the truss. There are three strut clamp assemblies. Each strut clamp assembly slides on its respective spoke in the axial direction of the spoke. A strut clamp assembly consists of a center body and two pinned strut seat fittings. The center body limits the rotation of the strut seat fittings to plus or minus several degrees and thus allows the fittings to accommodate a range of irregular triangles of truss struts. Each of the three strut clamp assemblies are linked to a strut clamp actuator located on longitudinal tracks attached to the hub. The actuators are used to clamp the sliding hub assembly to the triangle of truss struts.

The panel removal operation is depicted in figure 13, which shows edge views of the panel. First, the guide pole is attached to the center fitting on the back of the panel (fig. 13(a)). Second, with the strut clamps in the retracted position, the panel replacement tool hub assembly is slid along the guide pole until the extended lips of the strut seat fittings rest on the triangle of truss struts immediately behind the panel (fig. 13 (b)). Third, the strut clamp actuators are slid, one at a time, axially along the hub to seat and lock the clamps on the triangle of truss struts (fig. 13(c)). The damaged panel is then unlatched from the three truss nodes and removed by sliding the guide pole (with attached panel) out of the hub assembly and away from the reflector surface for handling safety (fig. 13(d)). The guide pole is then disconnected from the damaged panel and attached to a replacement panel. The panel replacement sequence is simply a reversal of the removal sequence. The developmental panel replacement tool, which was fabricated primarily from aluminum and had a mass of about 22 kg, was neutrally buoyed with closed-cell foam.

Assembly Fixture

Figure 14 is a schematic of the assembly fixture, and figure 15 is a photograph of the assembly fixture supporting the truss and three panels. The photograph was taken during $1g$ hardware checkout tests before installation in the neutral buoyancy facility. Two strut canisters are also shown in the photograph but are omitted from figure 14 for clarity. The assembly fixture consists of a turnstile for rotating the truss during the assembly, a turnstile carriage that slides up or down on a tower, two fixed foot restraints used during truss assembly, and two sliding foot restraints used during attachment of the panels to the truss. The turnstile as well as the turnstile carriage had predetermined detent positions for truss assembly and panel attachment.

A remote-operated astronaut positioning system (APS) was also available at the neutral buoyancy facility where the present tests were conducted. Although the APS could not be used for truss assembly because of its limited reach capabilities, it was used to position one of the test subjects in front of the reflector surface during panel replacement activities, in a manner anticipated to simulate orbital operations.

Strut and Node Stowage Canisters

The struts were stowed in two canisters located within reach of the test subjects stationed in the fixed foot restraints. (See fig. 16(a).) The struts were stowed in individual tubular compartments in the order in which they were to be assembled. Each compartment was identified on the upper end of the canister with a label denoting the appropriate node and node port to which the upper end of the strut was to be attached. The labeling on the canister ensured the proper order of stowage as well as provided an on-site and easily referenced assembly procedure for the test subjects.

With the exception of three nodes that were preattached to the assembly fixture turnstile, the nodes were stowed on racks located on the sides of the canisters as shown in figure 16(b). The nodes were also labeled and stowed in the order in which they were to be installed.

Test Procedures

Truss Assembly and Panel Attachment Procedures

In an EVA assembly of a large precision reflector, it is envisioned that the attachment of the panels would be integrated with the truss assembly; that is, after enough truss structure has been assembled to support a row of panels, the panels would be attached. The truss would then be rotated, additional truss structure assembled, and another row of panels attached. This procedure would be followed until the reflector is completed. The same procedure was followed in the present tests; however, the test article was complete after three panels were attached and no additional assembly of truss components or panels was required.

Typical steps in the assembly procedure are depicted in figure 17. As shown in figure 17(a), the test subjects, designated EV-1 and EV-2, were located in the fixed foot restraints when a test was initiated. Nodes 102, 104, and 106 were preattached to the turnstile, and the turnstile was oriented such that node 104 was within the reach envelope of EV-1. The test subjects assembled the truss strut-by-strut in the order in which the struts were stowed in the canisters. Figure 17(b) shows a typical step in the assembly procedure. The struts to be attached by each test subject are listed in the rectangular boxes under the headings EV-1 and EV-2. In figure 17(b), EV-1 has attached one core strut and three back struts to back node 102, and EV-2 has attached one core strut and two front struts to front node 102 in the partially assembled truss. The turnstile must be rotated or raised and lowered during the assembly to bring the truss nodal locations within reach of the test subjects from the fixed foot restraint work stations. The predetermined assembly sequence was designed to minimize such operations within the practical limits of the assembly fixture used for the present tests. Most required rotations of the turnstile could be accomplished manually by the test subjects from the fixed foot restraints. Utility divers were used, however, when the turnstile was required to be moved out of reach of the test subjects from the fixed foot restraints. Raising and lowering the turnstile was accomplished manually by a utility diver. These functions would probably be automated on orbit.

To attach the panels to the truss, the test subjects translated to a second pair of foot restraints. (See fig. 17(c).) These foot restraints could be slid along a track and locked at appropriate work positions by the test subjects. It is envisioned that, on orbit, a dispenser canister containing the reflector panels would be positioned (possibly by a remote manipulator arm) within reach of the astronauts secured in their foot restraints. The astronauts would then remove each panel from the canister and manually attach it to the truss. As shown in figure 17(c), scuba divers simulated the function of the remote manipulator arm by swimming the panels into position within reach of the test subjects. Figure 17(d) shows that one of the test subjects was required to leave the foot restraint and manually translate to the upper corner of the panel to make the final panel-to-truss node attachment.

Panel Replacement Procedure

The panel replacement procedure is depicted in figure 18. As shown in figure 18(a), EV-1 is located in the fixed foot restraint behind the structure. On orbit, this foot restraint would probably be mounted on an astronaut positioning system. However, the APS available for these tests could not reach this location; thus, a fixed foot restraint is used. EV-2 is free floating inside the truss. EV-1 removes the panel replacement tool from its stowage location (on the strut canister, for convenience in the present tests) and passes it through the truss to EV-2 (fig. 18(a)) who attaches the guide pole to the panel center fitting. EV-2 then slides the hub assembly of the panel replacement tool along the guide pole until the strut clamps contact the triangle of struts behind the panel. The panel replacement tool is then locked onto these struts as indicated in figure 18(b). EV-2 then manually translates along the truss to unlock the three latches that hold the panel to the truss nodes. Using the attached guide pole, EV-2 pushes the panel outward and away from the front of the truss as shown in figure 18(c). While EV-2 is preparing the panel for removal, EV-1 translates to the APS foot restraint, which then moves him to a position in front of the structure where he removes the panel and attached guide pole from the truss (fig. 18(d)). To simulate installation of a replacement panel, the panel is reattached to the truss by reversing the removal procedure.

Assembly Time Prediction

Pressure Suit Encumbrance and Test Subject Fatigue

A significant factor to consider in predicting neutral buoyancy or EVA structural assembly time is the physical encumbrance of the pressure suit, which limits visibility and impedes physical dexterity. As a consequence of this encumbrance, structural hardware to be assembled has size limitations compatible with pressure suit gloves and should not require intricate manipulations. In addition, long duration or rapid physical activity and awkward working positions, which can lead to test subject (or astronaut) fatigue and premature work stoppage, should be avoided. Thus, the structural hardware to be assembled, the assembly procedure, and the associated assembly fixture should be designed to minimize physical activity.

The joint hardware used to assemble the truss components in the present tests was designed to enable quick attachment by EVA (or robotic) methods. The assembly procedure developed for the present tests, however, used an existing assembly fixture originally designed for $1g$ hardware developmental testing. While this assembly fixture was effective for panel-to-truss attachment and damaged panel replacement activities performed in neutral buoyancy, it did not provide optimum location and orientation of the test subjects to perform all the required tasks associated with assembling the support truss. However, the assembly procedure permitted the test subjects to perform most of their tasks from foot restraints. Thus, because the test article had relatively few components to be assembled, test subject fatigue was neglected in the predicted assembly time.

Assembly of Truss Components

For prediction purposes, 20 sec was estimated as the time required to retrieve a strut from stowage and connect one end of it to a node in the truss or to retrieve a node from stowage and connect it to the end of a strut in the truss. This estimate was based on experience obtained in previous truss assembly tests performed in neutral buoyancy with similar size truss struts but different joint hardware. Additional time for tasks such as completing the strut installation by connecting its opposite end as well as installing additional nodes was also considered. Mating of a strut-end joint half to a node joint half (see fig. 4) and rotating the locking collar to lock the joint can be accomplished in 1 to 2 sec in a shirtsleeve air environment. For the neutral buoyancy tests, the encumbrance of the pressure suit was not expected to impede this operation significantly because of the design of the joint hardware. Because the struts were stowed in two canisters and because two test subjects assembled the truss, many truss assembly tasks were performed in parallel. Thus, some judgment had to be exercised as to when the tasks added to the prediction time.

Assembly Fixture Turnstile Manipulation

The time for the test subjects to rotate the assembly fixture turnstile 120° was estimated to be 1 min. This conservative estimate was influenced by the assumption that the test subjects would rotate the turnstile without help from the utility divers and might, in some instances, have to leave their foot restraints. Conservative estimates of 1 to 4 min for raising and lowering the turnstile were used for the same reason.

Panel Attachment

Panel attachment time predictions could not be based on experience because the attachment hardware was new and the attachment procedure had never before been performed by the pressure-suited test subjects in neutral buoyancy. The panel attachment hardware, however, was designed for quick alignment as well as quick attachment of the panels. Based on results from $1g$ hardware development tests, panel attachment was assumed to require 2 min per panel. This estimate assumes that the panel has already been maneuvered into position within reach of the test subjects by a remote manipulator system (an activity that should be accomplished in parallel with other assembly tasks performed by the test subjects). Because the attachment procedure required only a minimum of panel manipulation by the test subjects, water drag was expected to have little impact. Other tasks associated with panel attachment, such as manipulating the turnstile and repositioning the sliding foot restraints, involved getting in and out of the foot restraints and translation by the test subjects. These tasks, which were not well defined, were estimated to require a total of 4 min per panel. (Panel replacement activities could not be rehearsed in $1g$; thus, panel replacement times in neutral buoyancy were not predicted.)

Test Results

Two complete assembly tests of the tetrahedral truss supporting three reflector panels were conducted in neutral buoyancy, each by the same pair of pressure-suited test subjects. The first test used the panel attachment hardware designated design 1, and the second test used the panel attachment hardware designated design 2. All other truss hardware and test procedures for assembly of the test article were identical in the two tests.

Truss Assembly

EVA compatibility of truss joint hardware. Figure 19 is a photograph showing the truss under construction with a strut being attached to a node on the front of the truss by EV-2. The strut-to-node attachments were easily accomplished by the test subjects when they could perform the task within their optimum viewing and reach envelopes. The locking collars of the strut-end joint halves (see fig. 4) were easily operated with one hand, and the 1-in-diameter hardware was large enough to handle comfortably with pressure suit gloves.

Truss assembly time. The existing assembly fixture incorporated fixed foot restraints that were positioned to allow the test subjects to perform all their required truss assembly tasks. In some instances, however, the test subjects had to reach to their maximum limits to perform truss connections. Additionally, in some instances, the turnstile had to be manipulated more than anticipated for the assembly time prediction to bring the work area within the viewing and reach envelope of each test subject. Such anomalous operations can be determined only from neutral buoyancy tests with the test subjects in pressure suits. Neutral buoyancy time for test subjects to develop and learn precise test procedures, however, was unavailable. The only practice time consisted of a modified assembly within the limits of a $1g$ shirt-sleeve environment and a scuba hardware checkout assembly. Thus, the predicted truss assembly time could not account for these anomalous operations.

Although the assembly time is not the minimum to be expected, it is of interest to compare the predicted assembly time with those resulting from the tests to evaluate the prediction assumptions. Figure 20 presents a series of sketches showing the completion of various steps in the assembly of the test article along with the elapsed times from the two tests and the predicted times. The predicted times shown in figure 20 were derived from the assumed assembly times for each truss component (see previous section). However, in instances where visibility and reach to the strut connection were anticipated to be significantly better or worse than average, judgment was used to increase or decrease the predicted time from the nominal values. Steps 1 to 21 depict the truss assembly discussed in this section, and steps 24 to 32 depict the panel attachment activities discussed in the next section. (Steps 22 and 23 were simply a lowering and a rotation, respectively, of the turnstile to put the completed truss in position to attach the first panel.) The test subjects remained in their respective fixed foot restraints at the back and front of the truss to complete steps 1 to 21. The truss struts (designated *nnn-p*) and nodes (designated *nnn*) that were installed by each test subject are listed in the sketches in rectangular boxes under the headings *EV-1* and *EV-2*. Raising, lowering, and rotating the turnstile are indicated in the sketches by bold arrows.

As shown in step 21, the test times for the truss assembly appear to compare favorably with the predicted times. However, if the turnstile manipulation times are extracted from the times presented in the earlier steps and from the elapsed times for truss assembly given in step 21, the time taken to actually assemble the truss components is 22 min 20 sec for test 1 and 20 min 52 sec for test 2. Thus, the average unit assembly time is about 41 sec per strut. The corresponding predicted time is 10 min (a unit assembly time of about 19 sec per strut). Thus, in actuality, the truss assembly took about twice as long as predicted, and turnstile manipulation took about one quarter of the predicted time. The discrepancy in structural assembly times can be attributed to the sometimes awkward working positions of the test subjects (imposed by the use of the existing assembly fixture hardware). In some instances, these awkward positions had to be overcome by unanticipated manipulations of the turnstile. The original truss manipulation estimates were overly conservative because utility divers aided in manipulating the turnstile, and the test subjects never had to get in or out of the foot restraints or translate to perform this task. These results emphasize the fact that accurate prediction times require each element of the assembly procedure to be known—and this knowledge comes only from realistic simulation tests.

Panel Attachment

EVA compatibility of panel attachment hardware. Figures 21 to 24 show the attachment of a panel with the panel attachment hardware designated design 1. (See figs. 7 and 8.) Utility divers (simulating the function of a remote manipulator) maneuvered the panel to a position within reach of the test subjects (fig. 21). Figure 22 shows the test subjects attaching two of the panel corners to the truss nodes, and figure 23 shows this activity from the back of the panel. Figure 24 shows one free-floating test subject connecting the third and final corner of the panel to a truss node.

The two panel attachment hardware designs were found to be EVA compatible in both size and operation, and each design enabled rapid attachment of the panels to the truss. The panels were easily aligned for capture and the capture was accomplished in seconds. The guides on both designs were sufficient for the test subjects to avoid contact of the panel being installed with adjacent panels. The guides, however, are not foolproof and reasonable care would be required by astronauts working in unison during EVA. A major influence on panel installation time is the time required for the RMS (or other robotic device) to maneuver the panel canister into position within reach of the astronauts. If this task is accomplished before panel attachment activities (while other assembly tasks are being performed), idle time for the astronauts is avoided and panel attachment is accomplished efficiently.

The design 1 panel attachment hardware was judged by the test subjects to be, generally, easier to operate than the design 2 hardware. Design 1 provided the test subjects with more assurance of a successful operation because of the positive captured, locked, and unlocked detent positions of the locking handles. The detent springs used in design 2 were not stiff enough to maintain the detent positions of the T-handle when the handles were inadvertently bumped by the test subjects during panel installation. In addition, the springs used to hold the panel on the flexures were not stiff enough to give the test subjects a "positive feel" to ascertain whether the panels were locked onto the flexure supports. These disadvantages of the design 2 hardware, however, can be remedied with relatively minor design changes.

The panels used in this test did not have handles on their back for EVA manipulation. Although the stiffening ribs (see fig. 6) provided a means to grip the panels from the back, they were not designed for EVA compatibility and were awkward to use. Thus, on occasion, the test subjects inadvertently gripped the edge of a panel (see fig. 22) during the installation—a situation that would not be allowed with precision surface panels. Consequently, EVA-compatible handles must be attached to the back of the panels and properly located for efficient use.

Panel attachment time. Steps 24 to 32 in figure 20 depict the various stages of panel attachment activities along with the elapsed times for the two tests and the predicted times. For the panel attachment activities, the test subjects were stationed in the sliding foot restraints. The total time to install three panels on the truss was 10 min 43 sec with design 1 panel attachments and 10 min 51 sec with design 2 panel attachments. Most of this time, however, involved relocation of the sliding foot restraints and turnstile manipulation by the test subjects as well as some idle time while utility divers moved the panels within the reach envelopes of the test subjects (e.g., steps 27 and 30). The average time to attach a panel to the truss after the panel was brought into position by the utility divers (see step 30) was 1 min 4 sec with design 1 panel attachments and 1 min 19 sec with design 2 panel attachments.

Damaged Panel Replacement

EVA compatibility of panel replacement tool. One of the neutral buoyancy tests also included the removal and replacement of a panel by the test subjects to simulate repair of a damaged panel. The design 1 panel attachment hardware was used for this activity. The design 2 hardware did not have an unlocked detent position for the panel release levers. (See fig. 9.) To remove a panel attached with this hardware, the test subjects must depress and hold the three spring-loaded panel release levers located at the three panel corners attached to the truss nodes. If all three corners of the panel are not released simultaneously, they tend to be recaptured by the panel capture mechanism. Because of the 2-m spacing of the nodes, it was impossible for the test subjects to release all three corners simultaneously.

Figure 25 shows a panel being replaced after it was initially removed from the truss. EV-1 is shown in the APS foot restraints while inserting the guide pole with attached panel into the hub of the panel replacement tool clamped to the truss. EV-2 is shown waiting inside the truss. The panel replacement tool is shown clamped to the triangle of struts (directly behind the panel) on the front of the truss. After EV-1 finished inserting the guide pole, he was moved to clear the work area. Then, EV-2 pulled the guide pole through the hub of the panel replacement tool until three corners of the panel were captured by panel attachments located at the three nodes. EV-2 then locked the panel to the truss nodes and removed the panel replacement tool.

Maneuvering the neutrally buoyed panel replacement tool into position and attaching it to the truss was easily accomplished by the test subjects. The panel attachments were easily released and easily detected (both by sight and by feel) when they were unlocked. The guide pole provided a convenient means for the test subjects to manipulate the panel without touching the reflective surface. Although the guide pole was keyed to the hub assembly, excessive play occurred between the two parts and collision with adjacent panel edges was possible. This problem can be eliminated with minor changes to the design.

Panel replacement time. The series of sketches in figure 26 depicts the various stages of panel replacement activities along with the elapsed test times. (Panel replacement times were not predicted.) Step 1 shows EV-1 passing the panel replacement tool through the back of the truss to EV-2, who is free floating (not secured in foot restraints) inside the truss. Step 2 shows EV-2 unlatching the last of the three panel-to-truss node attachments. EV-2 has already attached the guide pole to the center of the panel and clamped the replacement tool to the triangle of truss struts behind the panel. Step 3 shows the panel pushed away from the front of the truss by

EV-2 using the attached guide pole. The end of the guide pole is retained in the hub of the panel replacement tool by EV-2. Meanwhile, EV-1 (not shown in the sketch) has translated to the APS foot restraints and is being moved to the front of the truss where he removes the panel and attached guide pole (step 4). The panel replacement tool was used successfully to demonstrate the removal of a damaged reflector panel in 6 min 32 sec. The time to return the panel and attached guide pole to the panel replacement tool and latch it to the truss was 3 min 53 sec. This time, however, does not include removal of the panel replacement tool from the truss and restowage of the tool. Because of time restrictions, the test was terminated before these activities could be performed.

Concluding Remarks

Structural assembly tests were conducted by two pressure-suited test subjects in neutral buoyancy to evaluate the EVA compatibility of quick-attachment truss joint hardware, two different panel-to-truss attachment designs, and a tool designed to enable replacement of a damaged panel in a precision reflector spacecraft. Two tests were conducted. Each test included the assembly of a flat tetrahedral truss consisting of 31 struts and 12 nodes and the attachment of three surface panels. The truss nodes were spaced at intervals of 2 m. The panels were fabricated from aluminum sheet and their dimensional accuracy was not representative of precision reflectors. The spacing between adjacent panel edges was nominally 0.63 cm. One of the tests was concluded by removal and replacement of a panel with the panel replacement tool. The struts, panels, and panel replacement tool were neutrally buoyed.

The use of an existing assembly fixture designed for 1g hardware development testing precluded assembly of the test article truss by an optimized procedure in the neutral buoyancy tests. Some truss assembly tasks had to be accomplished outside of the optimum viewing and reach envelopes of the test subjects, and exact procedures for accomplishing these tasks were not known (before the tests) for assembly time predictions. Consequently, the reduced visibility and excessive reach requirements associated with working outside of the ideal envelope caused some tasks to take significantly more time than predicted. This result emphasizes the importance of knowing every detail of the assembly procedure for accurate time predictions, and this knowledge comes only from simulation tests. The present test results also reinforce the importance of developing an assembly procedure and associated assembly fixture that ensures EVA structural assembly operations are performed within the ideal viewing and reach envelopes of the astronauts.

The truss assembly time, although of interest, had no effect on the evaluation of the hardware. All assembly tasks required of the test subjects were performed successfully, and all hardware evaluated was judged to be compatible with the EVA pressure suit. The 1-in-diameter truss joint hardware was large enough to be handled comfortably with pressure suit gloves, and the one-handed operation of the locking collars simplified the connection task. The strut-to-node attachments were easily accomplished by the test subjects when the task was performed within their optimum viewing and reach envelopes. Both panel attachment hardware designs permitted rapid attachment of the panels to the truss, although design 1 was judged to be slightly easier to operate. Additional tests are needed to evaluate attachment of more closely spaced panels. (About 0.63 cm separated adjacent panel edges in these tests.) Manually operated locking devices on the panel attachment hardware should have detent positions that are easily located by feel and sight, and these positions should be secure from change by inadvertent contact during assembly. The panels should be equipped with EVA-compatible handles attached to their back to facilitate manual manipulation. Removal and replacement of a damaged panel was shown to be feasible by EVA methods with a panel replacement tool.

NASA Langley Research Center
Hampton, VA 23681-0001
August 4, 1992

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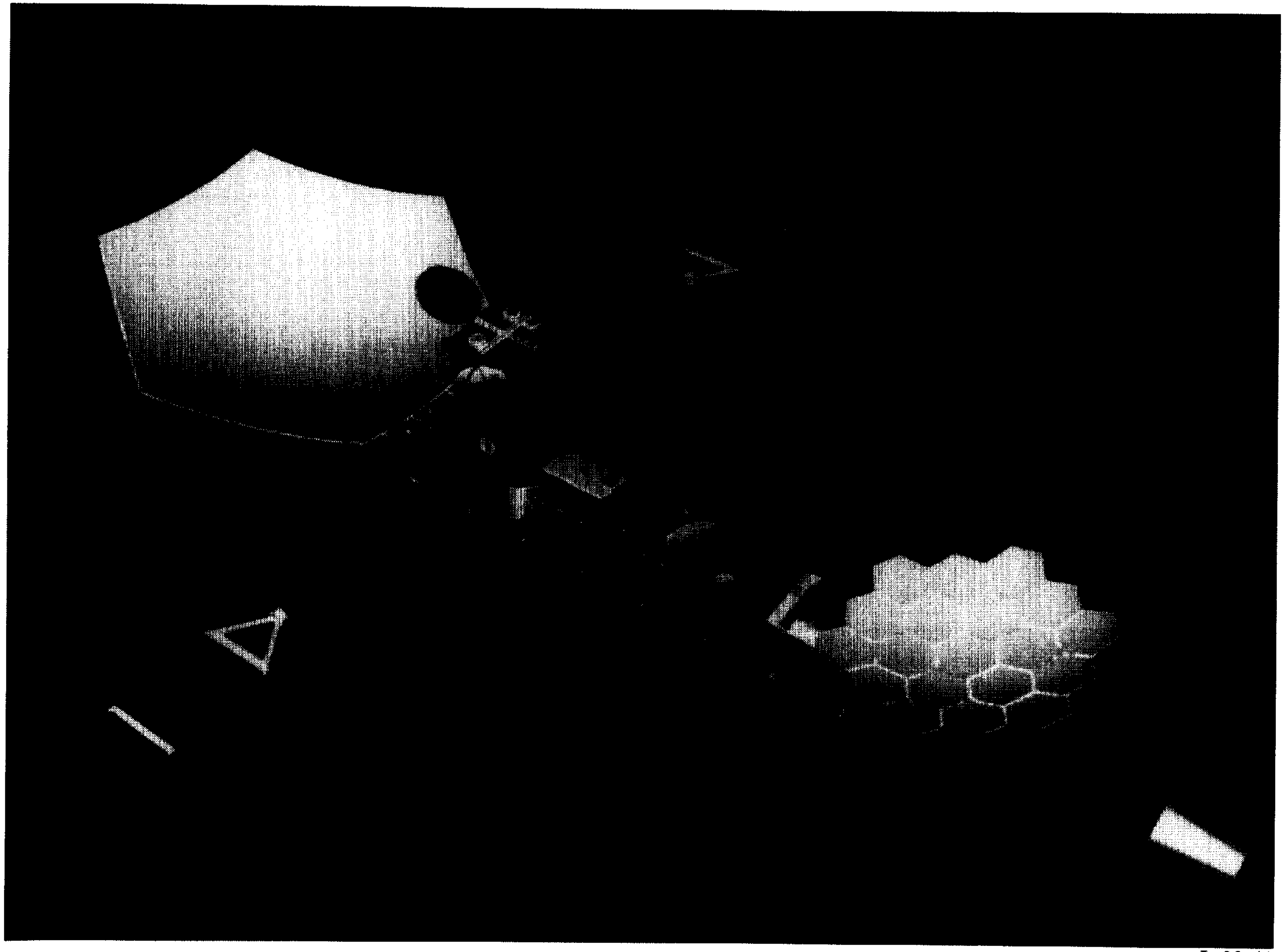
5. Bush, Harold G.; Herstrom, Catherine L.; Heard, Walter L., Jr.; Collins, Timothy J.; Fichter, W. B.; Wallsom, Richard E.; and Phelps, James E.: Design and Fabrication of an Erectable Truss for Precision Segmented Reflector Application. *J. Spacecr. & Rockets*, vol. 28, no. 2, Mar. Apr. 1991, pp. 251 257.

6. Miller, Richard K.; Thomson, Mark; and Hedgepeth, John M.: *Concepts, Analysis and Development for Precision Deployable Space Structures.* NASA CR-187622, 1991.



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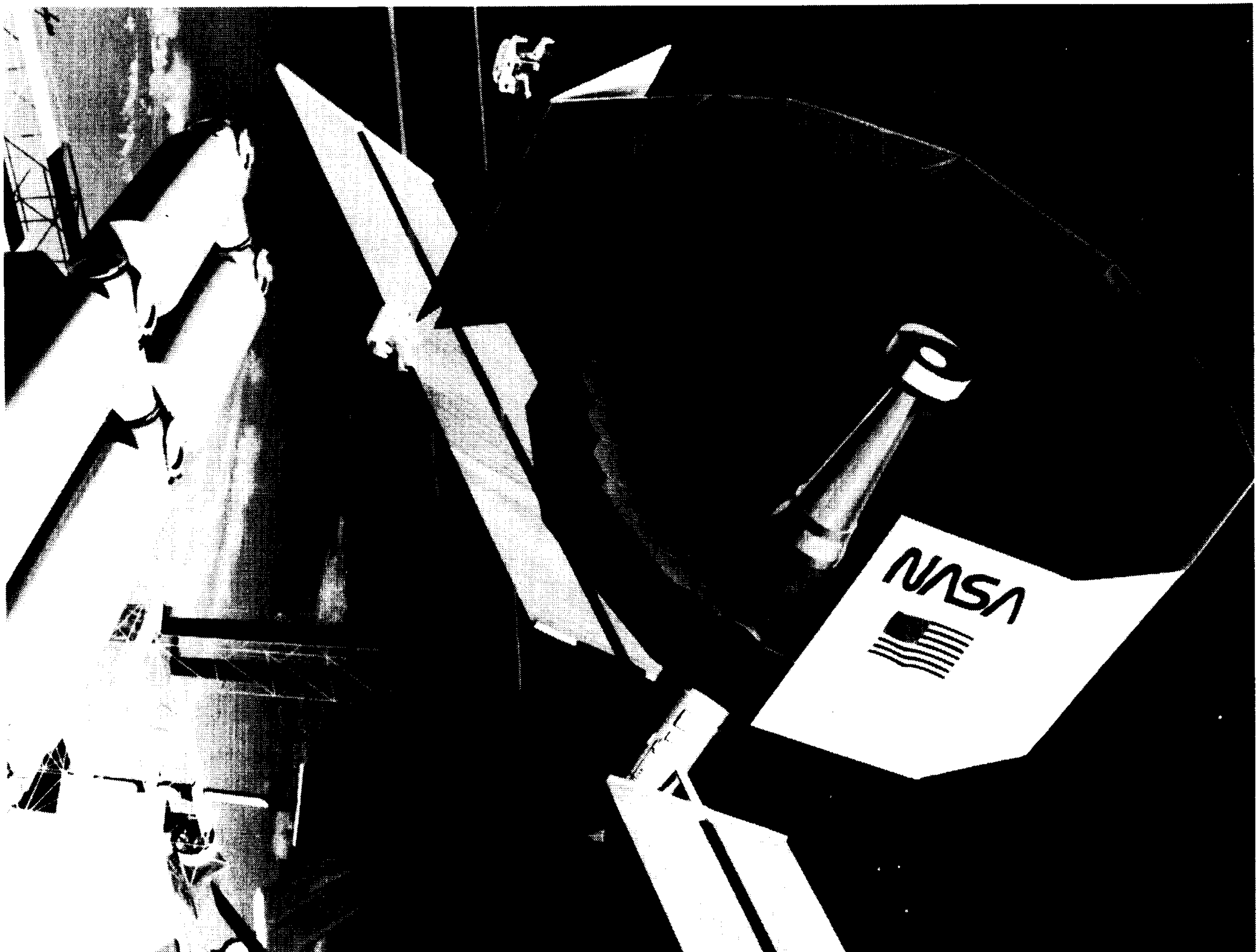
(a) Global Change Technology Initiative spacecraft.

Figure 1. Proposed missions that require precision reflector technology.



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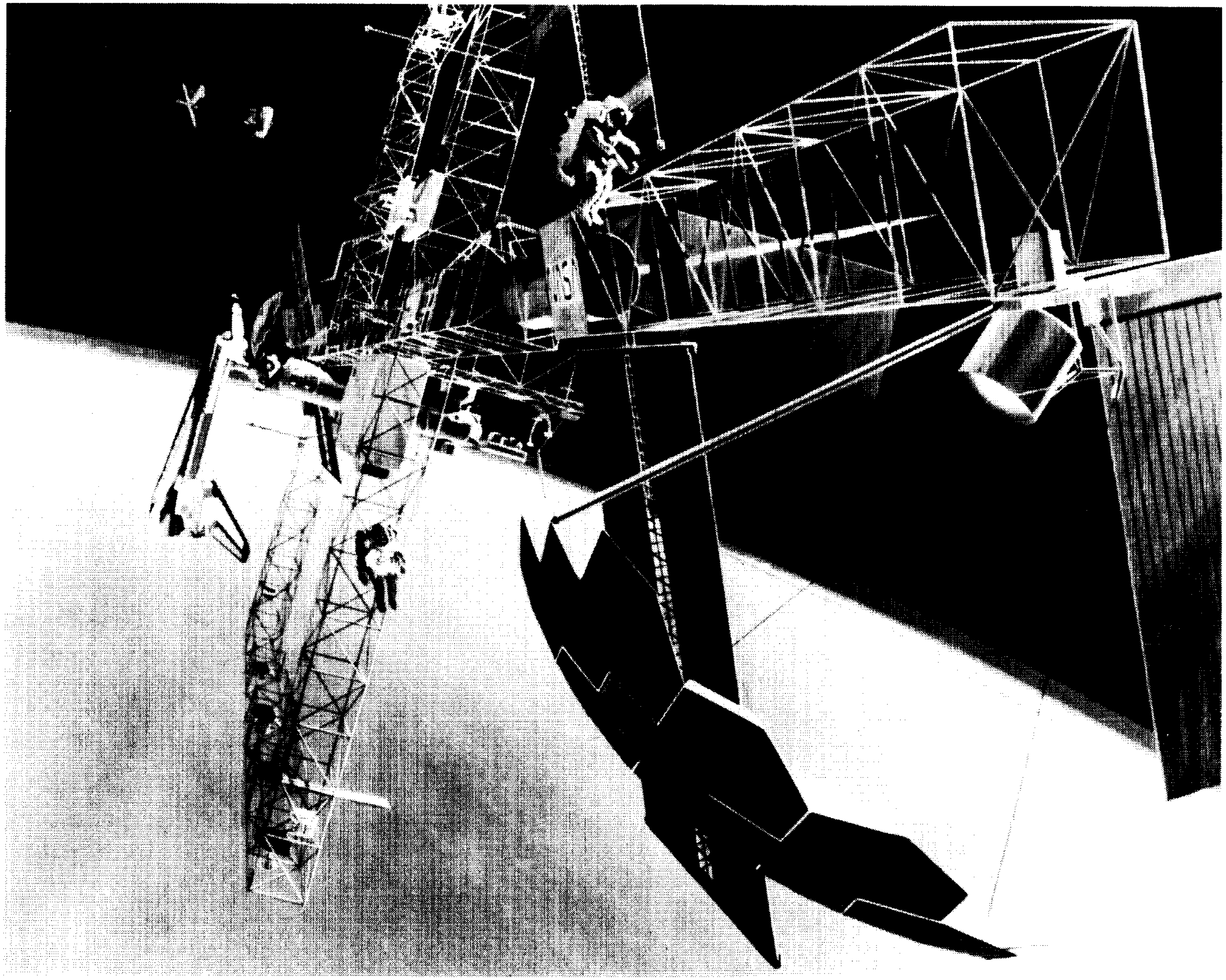
(b) Submillimeter astrophysical observatory.

Figure 1. Continued.



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(c) Space Station *Freedom* configuration with solar dynamic collectors.

Figure 1. Concluded.

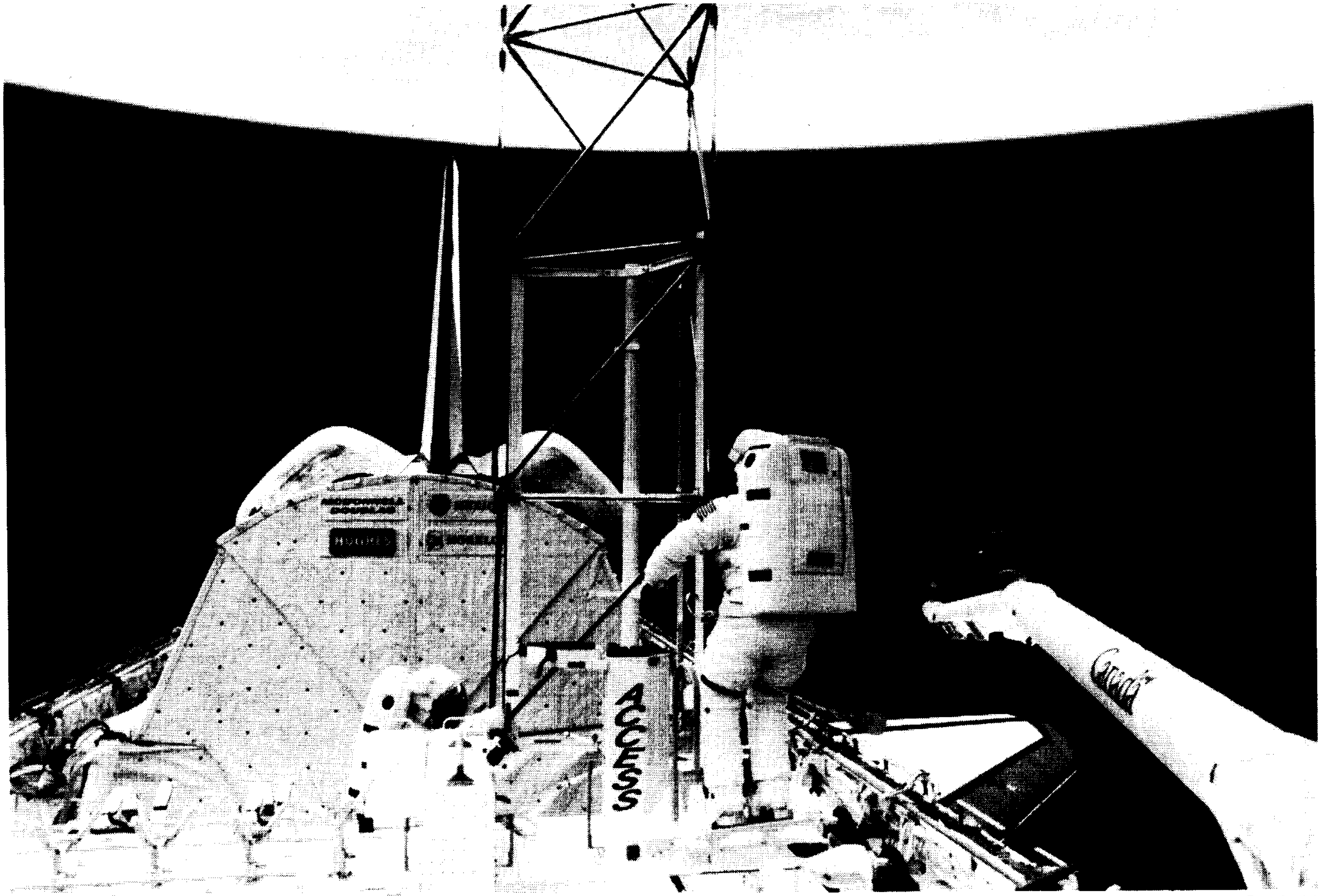

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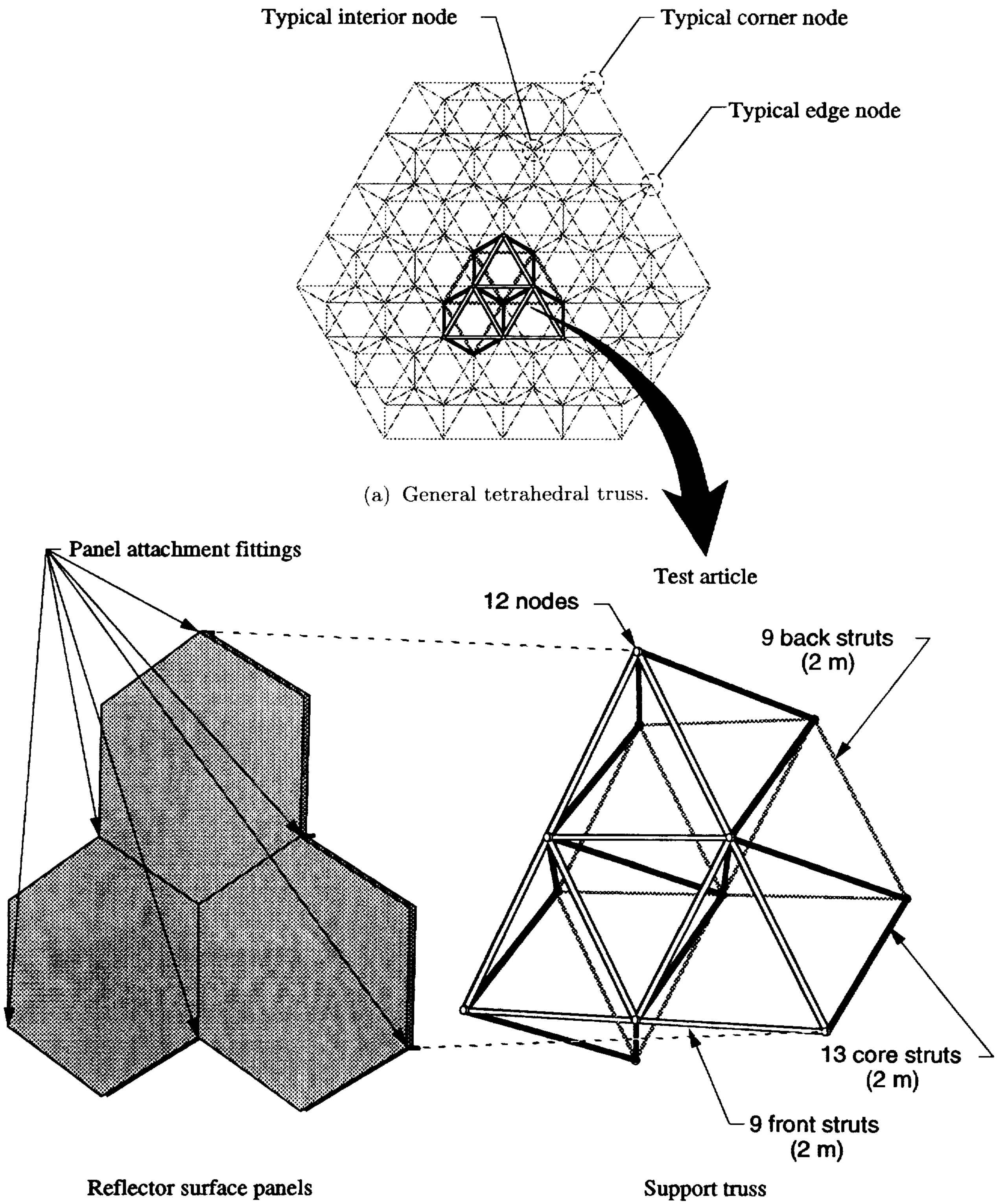
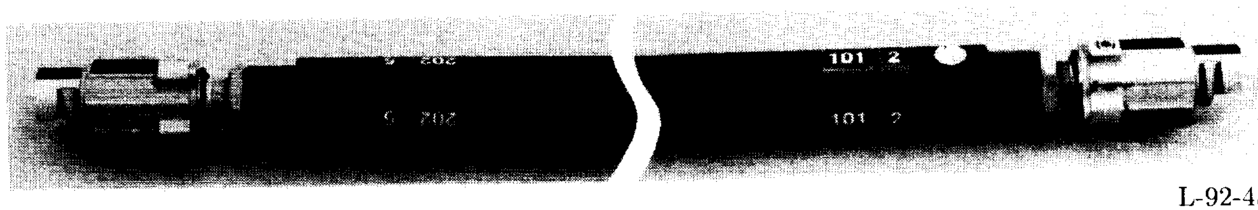
Figure 2. ACCESS truss assembly.



(a) General tetrahedral truss.

(b) Test article.

Figure 3. Truss and panel configurations used for assembly tests.



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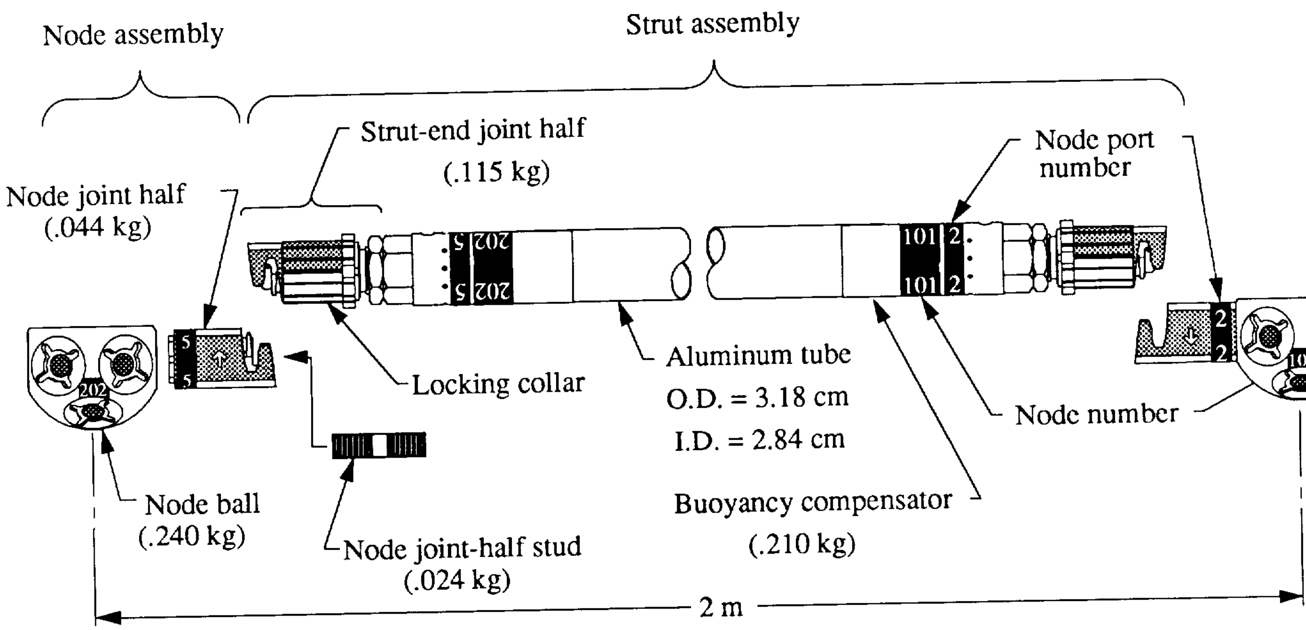
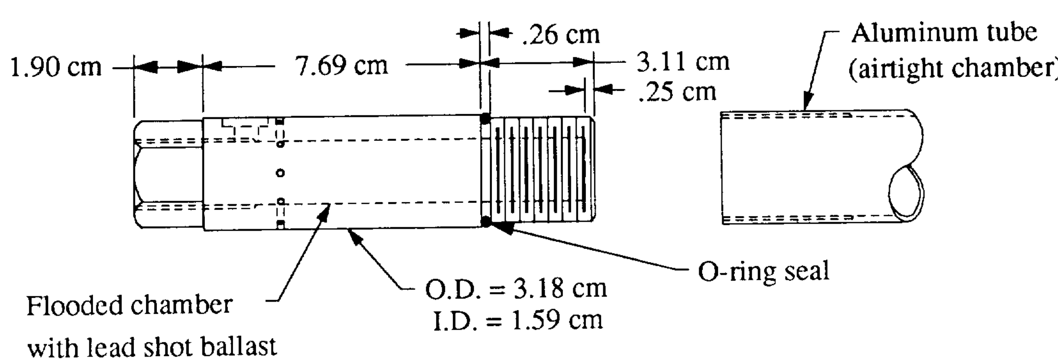
(a) Photograph of strut.



(b) Strut and node assemblies.



(c) Buoyancy compensator.

Figure 4. Details of strut hardware.

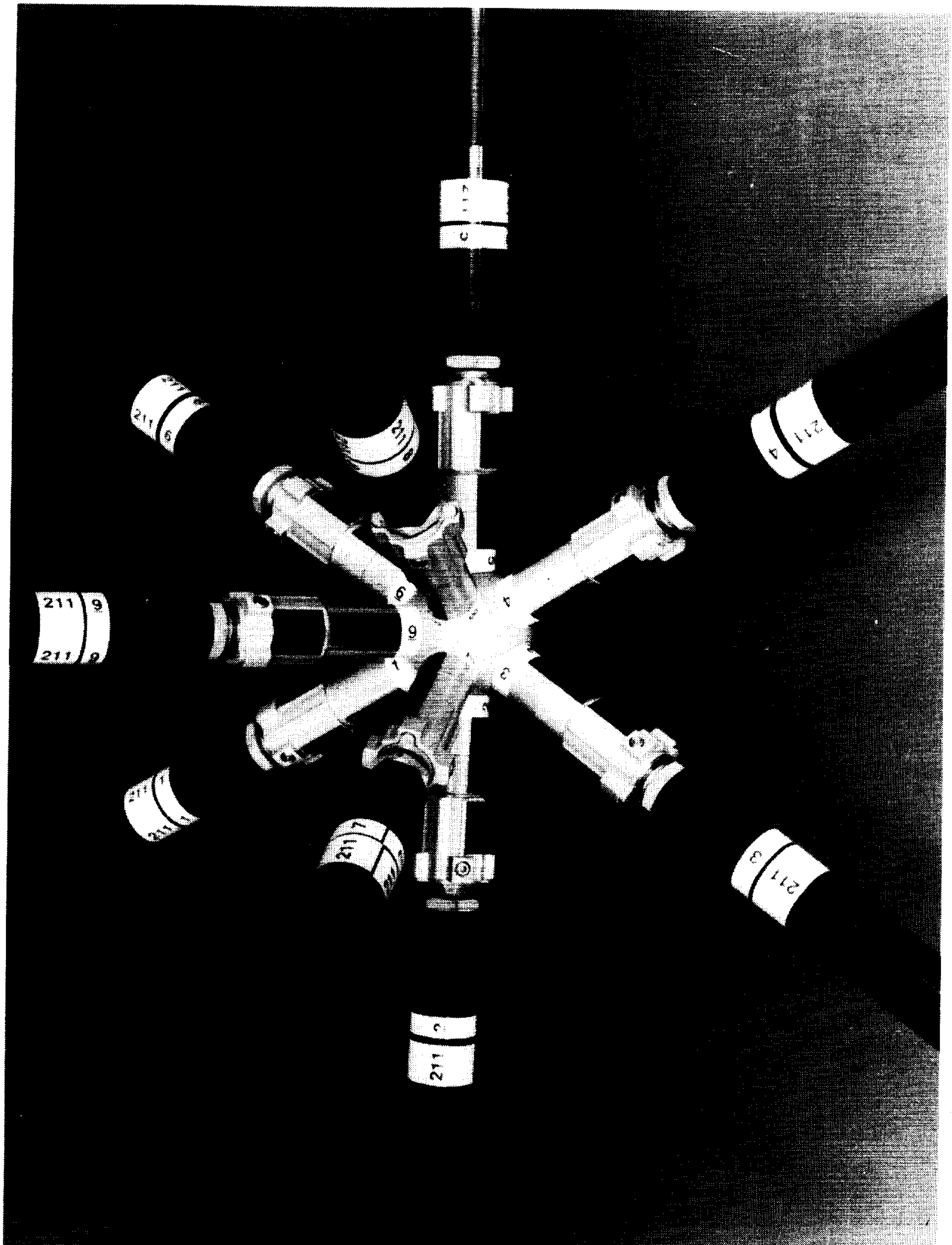


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Figure 5. Node with nine strut attachments.

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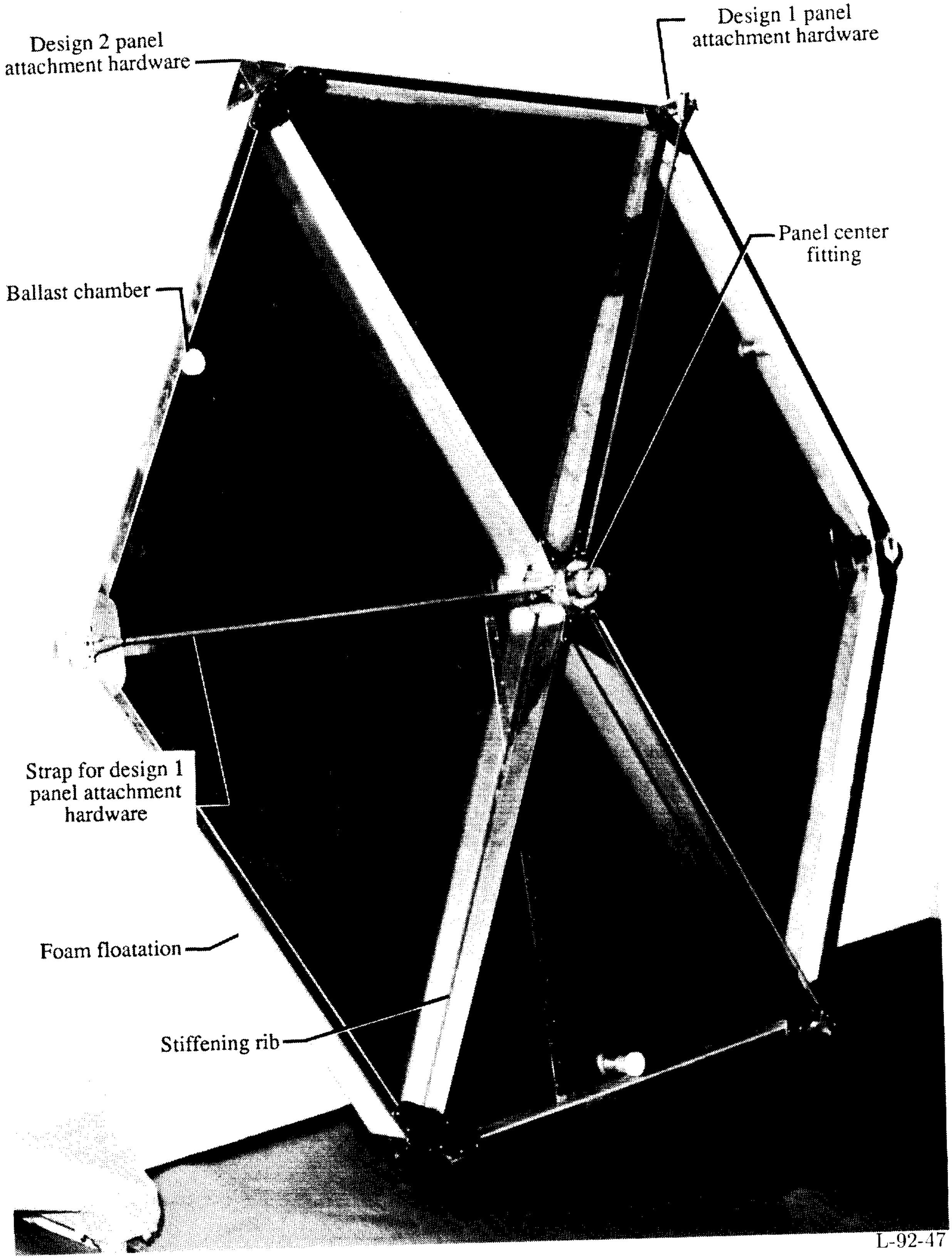
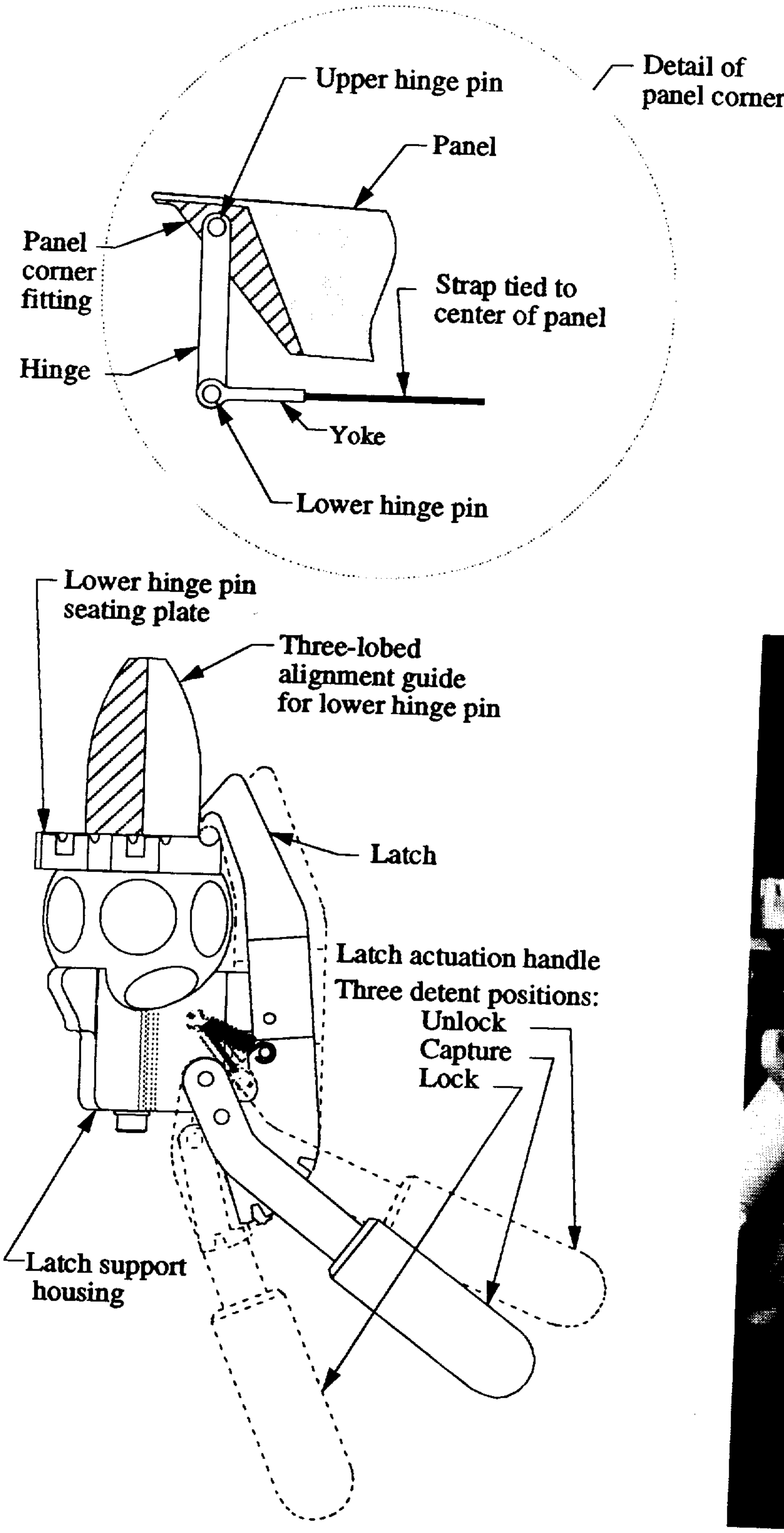
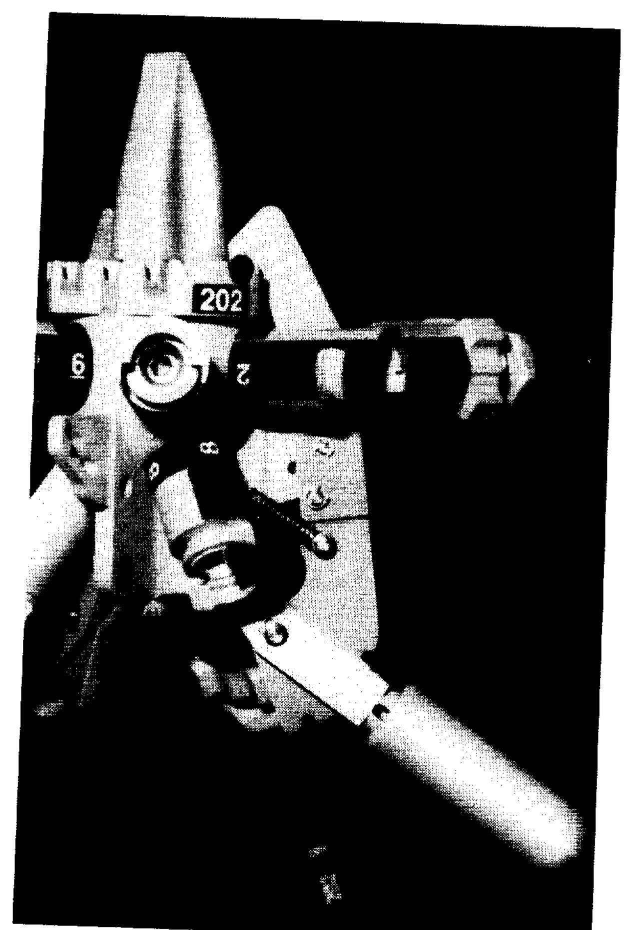


Figure 6. Photograph of mockup reflector panel.



(a) Schematic of developmental hardware.



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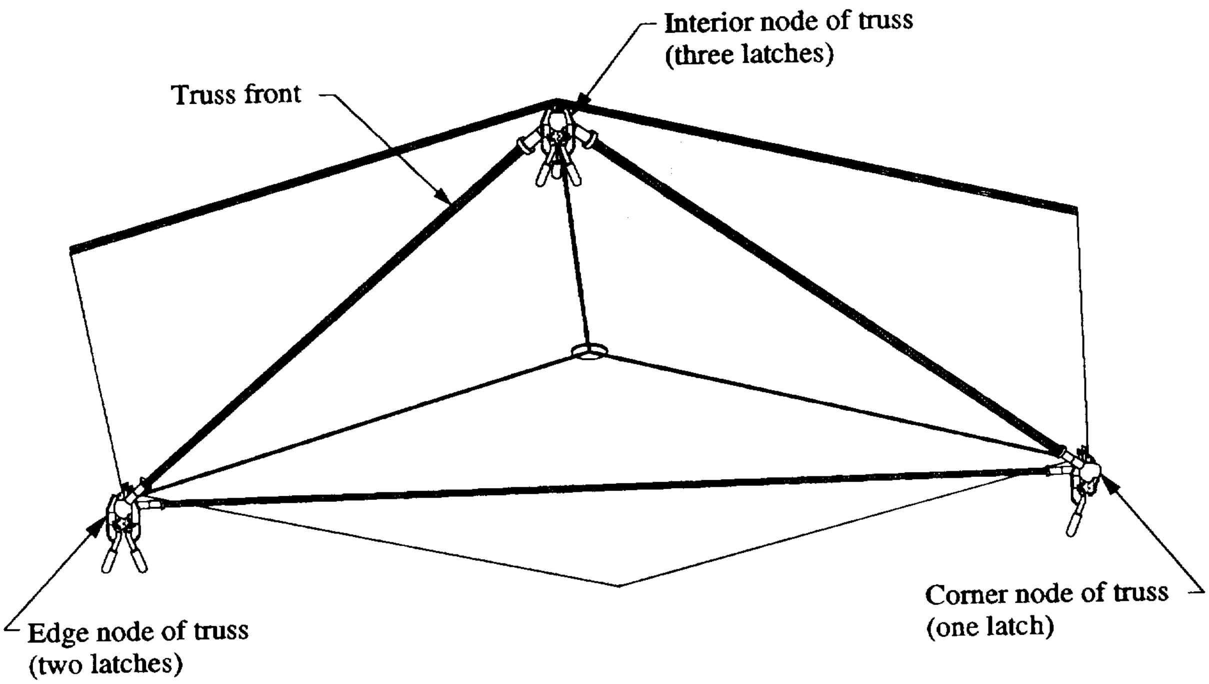
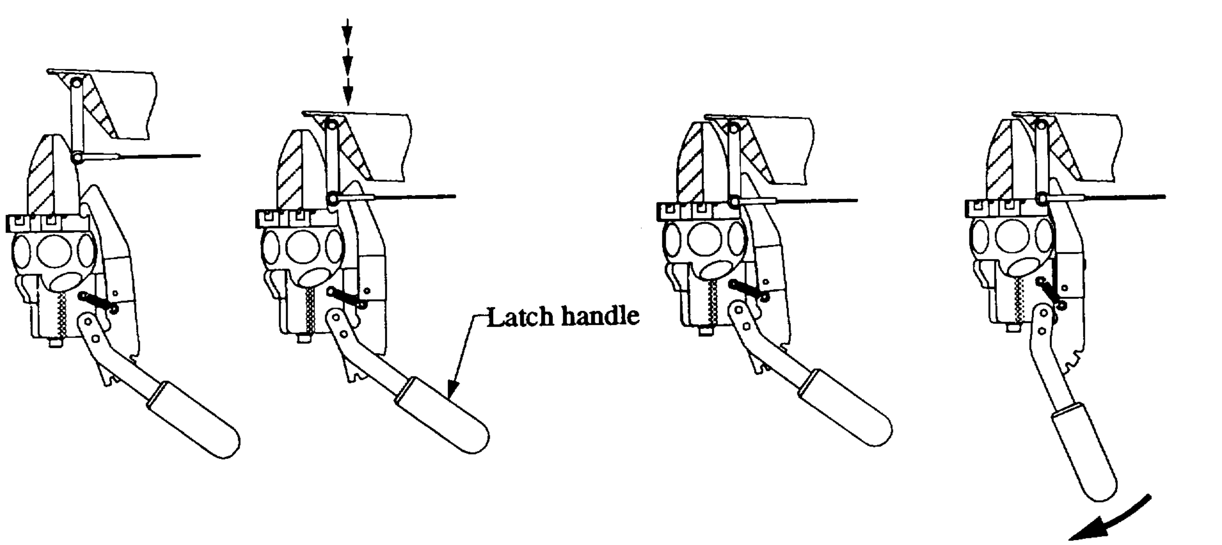
(b) Photograph of developmental hardware.

Figure 7. Design 1 panel attachment concept.



(a) Back of panel attached to triangle of struts on front of support truss.



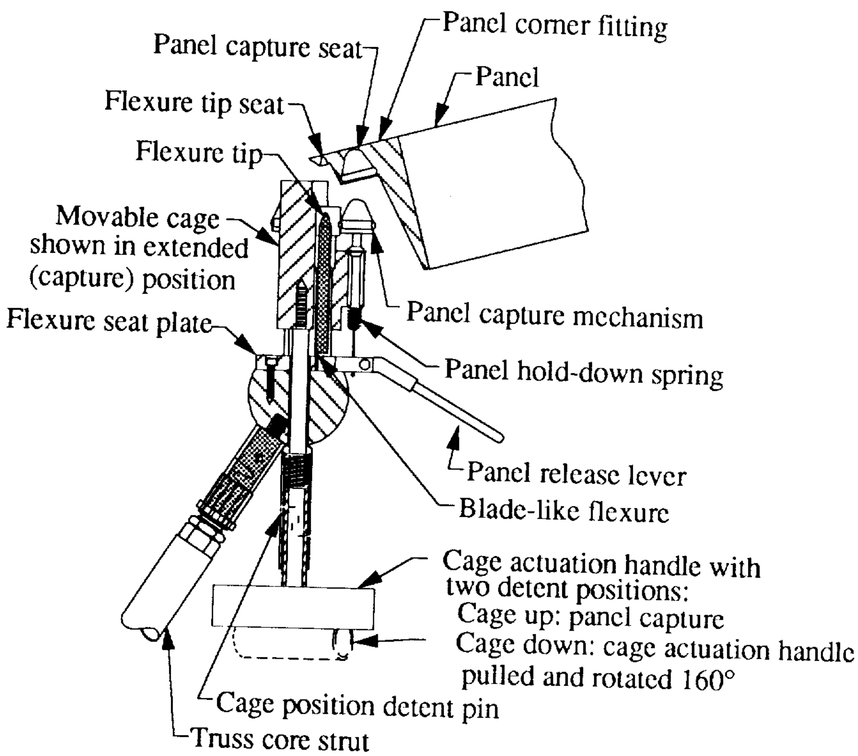
(b) Lower hinge pin placed on panel alignment guide.

(c) Panel pulled in on panel alignment guide toward latch.

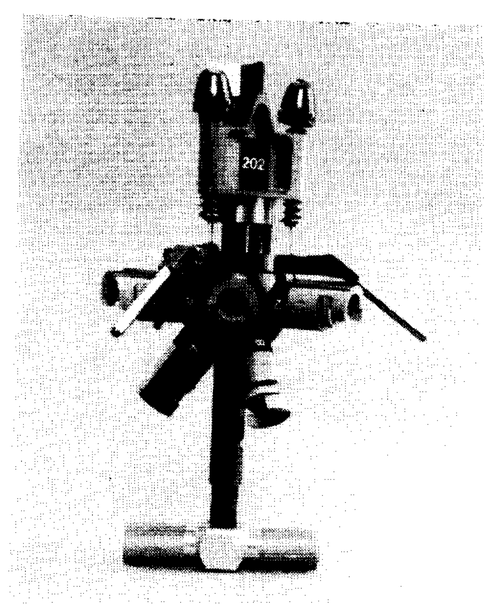
(d) Panel captured.

(e) Panel locked to node.

Figure 8. Design 1 panel attachment sequence.



(a) Schematic of developmental hardware.



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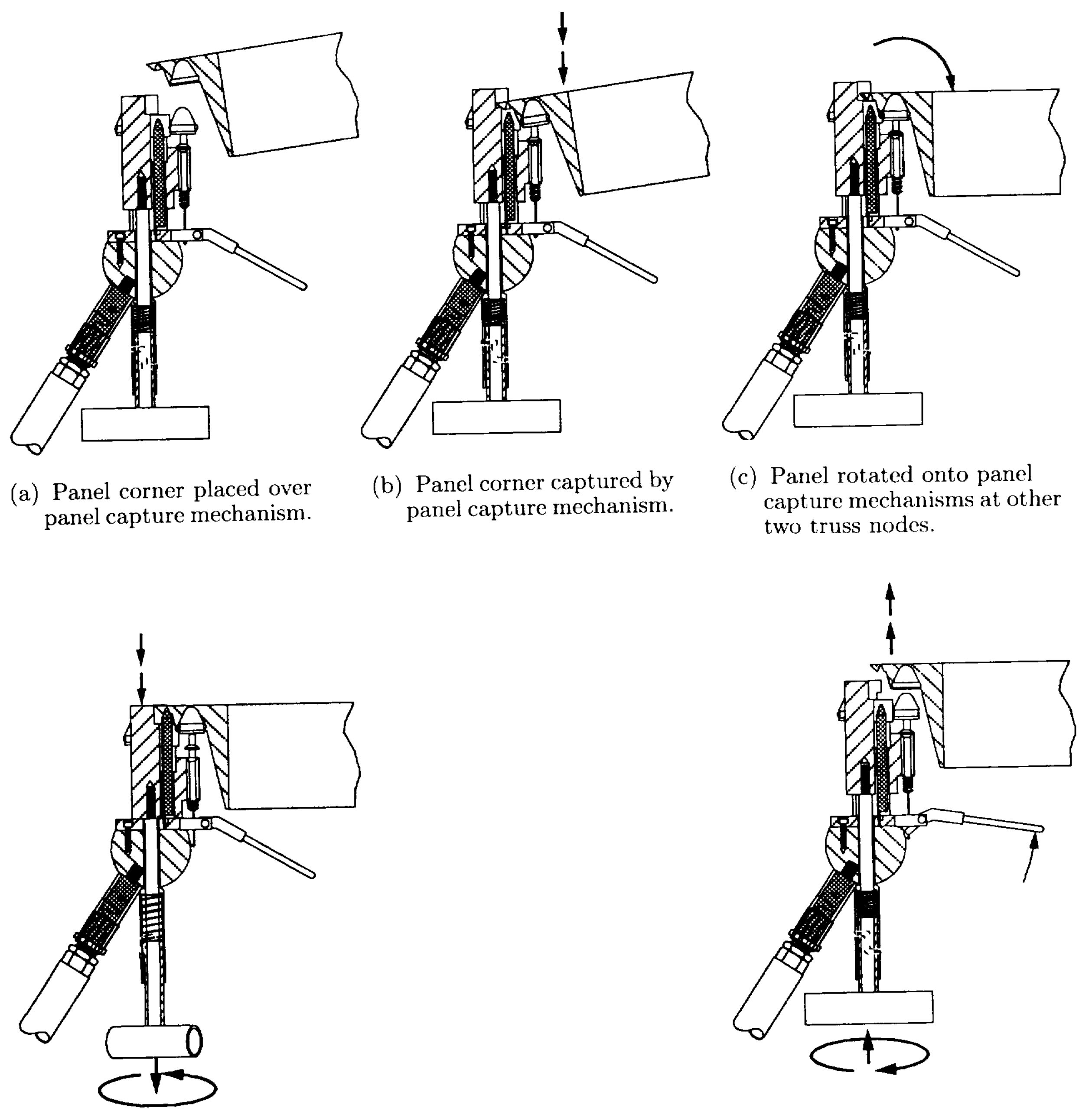
(b) Photograph of developmental hardware.

Figure 9. Design 2 panel attachment concept.



(a) Panel corner placed over panel capture mechanism.

(b) Panel corner captured by panel capture mechanism.

(c) Panel rotated onto panel capture mechanisms at other two truss nodes.

(d) Cage lowered with cage actuation handle to place panel corner on flexure tip.

(e) Cage raised with cage actuation handle and panel release lever depressed to release panel corner.

Figure 10. Design 2 panel attachment sequence.

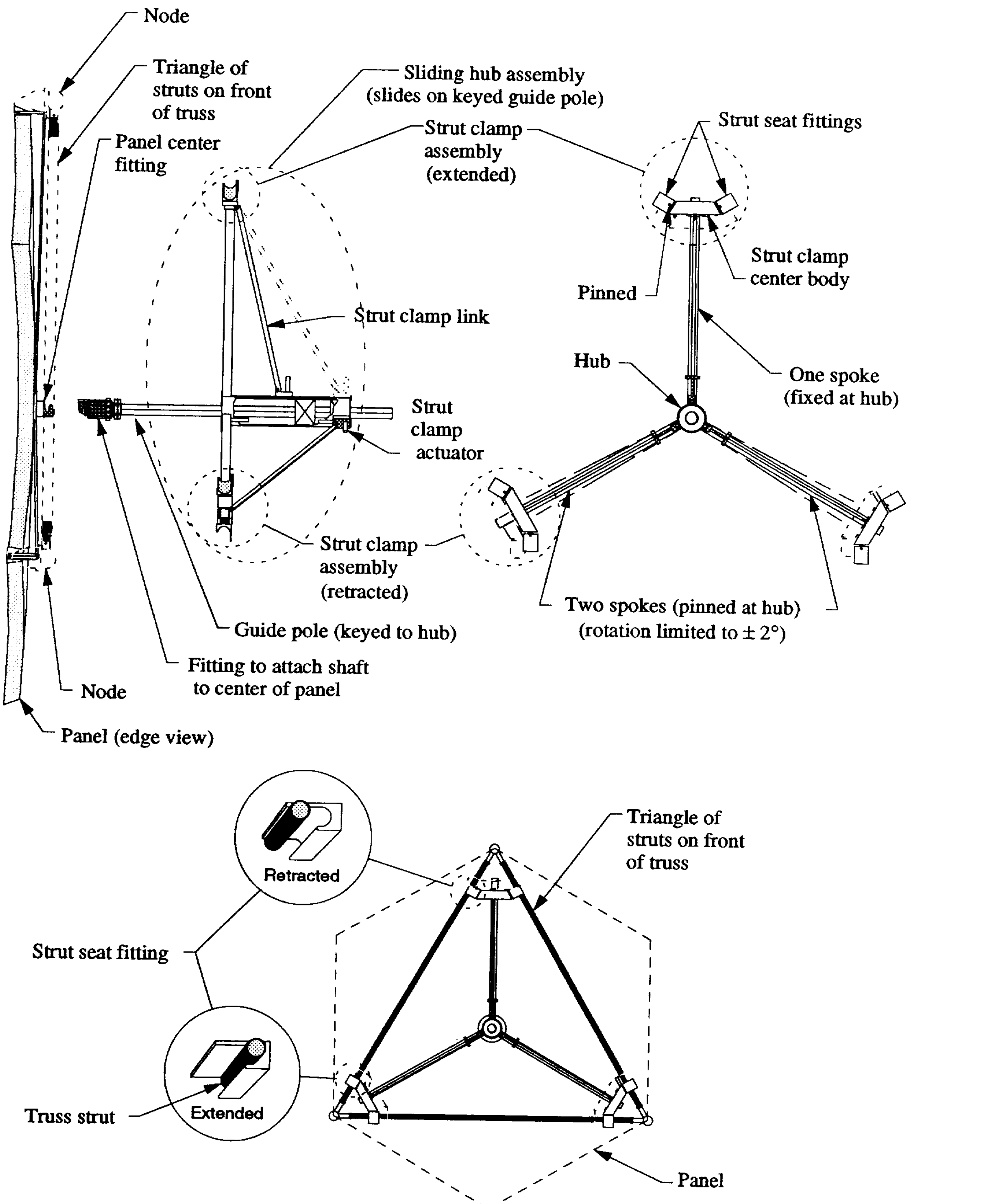


Figure 11. Panel replacement tool concept.

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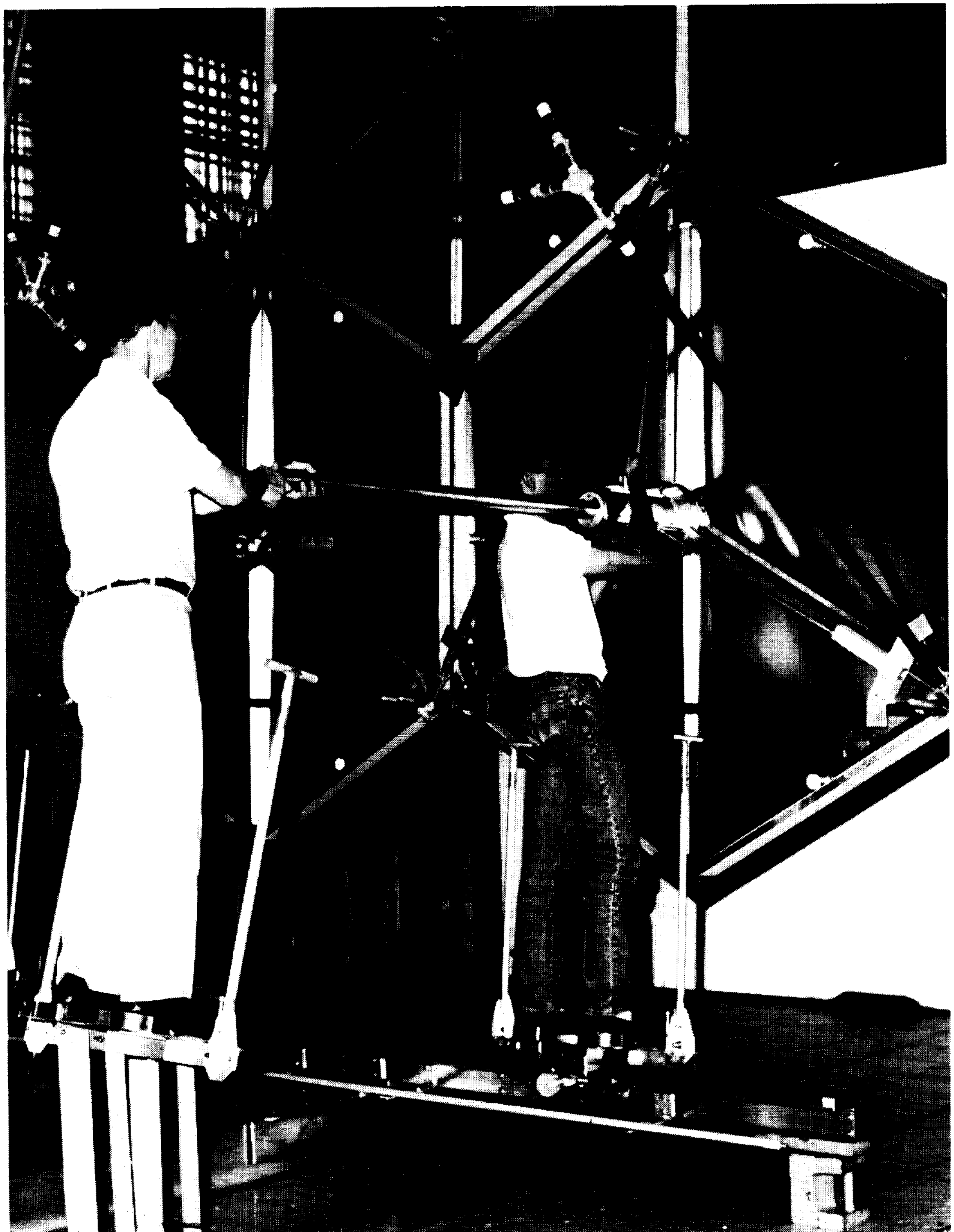

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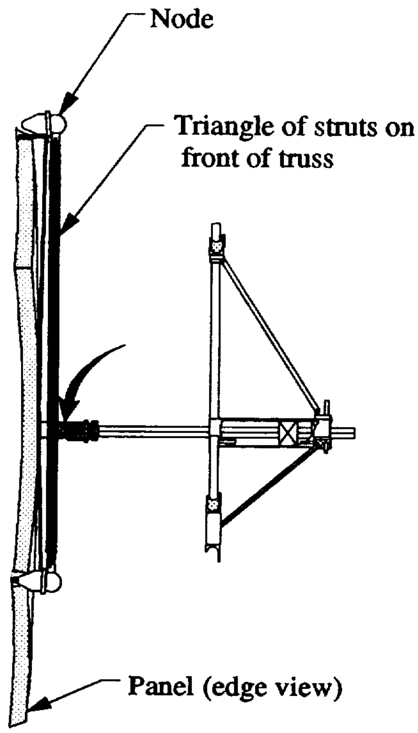
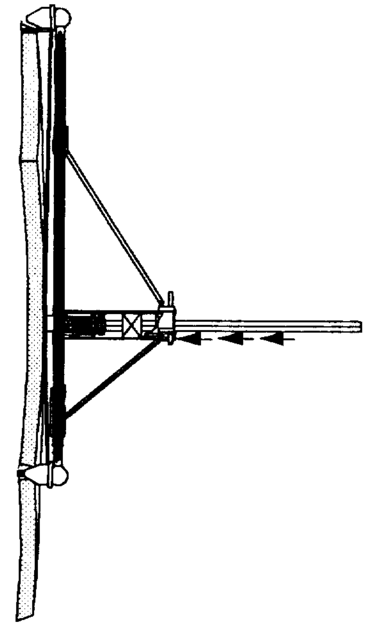
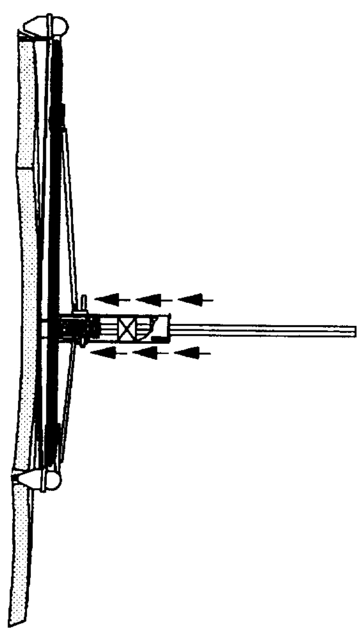
Figure 12. Photograph of panel replacement tool developmental hardware.



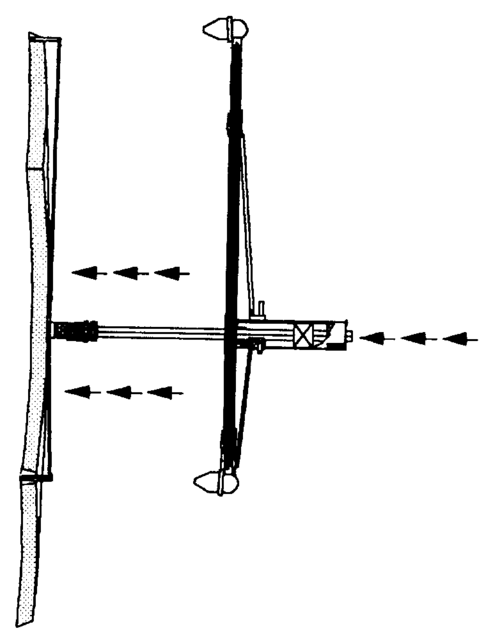
(a) Attach guide pole to center of panel.



(b) Slide hub assembly along guide pole until strut seat fittings contact struts.



(c) Extend strut clamps by sliding clamp actuators along hub. Lock in place when struts are seated in strut seat fittings.



(d) Unlatch panel corners from truss nodes and slide guide pole and panel out of hub assembly.

Figure 13. Panel removal procedure. Replacement procedure is a reversal of removal procedure.

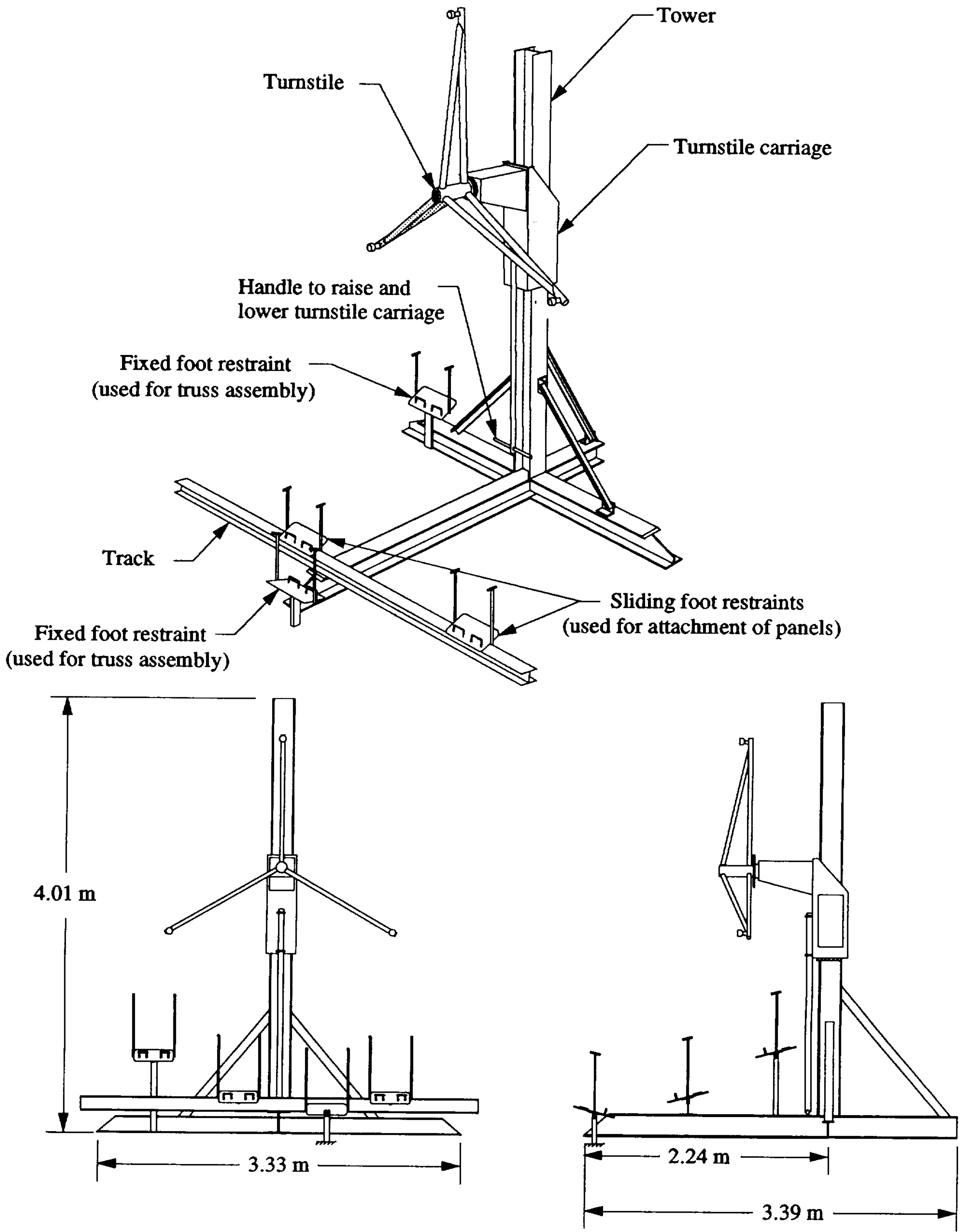


Figure 14 . Assembly fixture.

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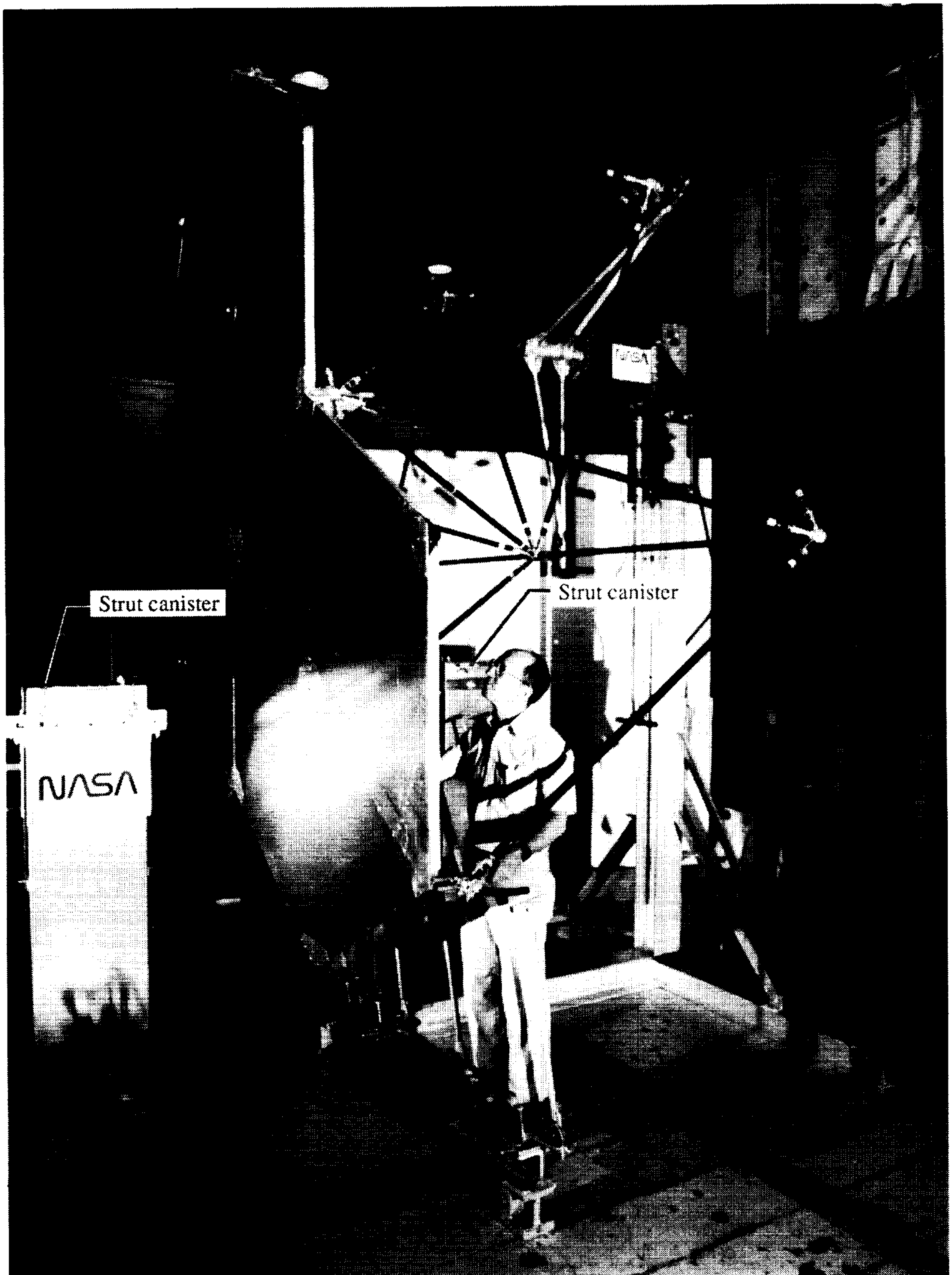

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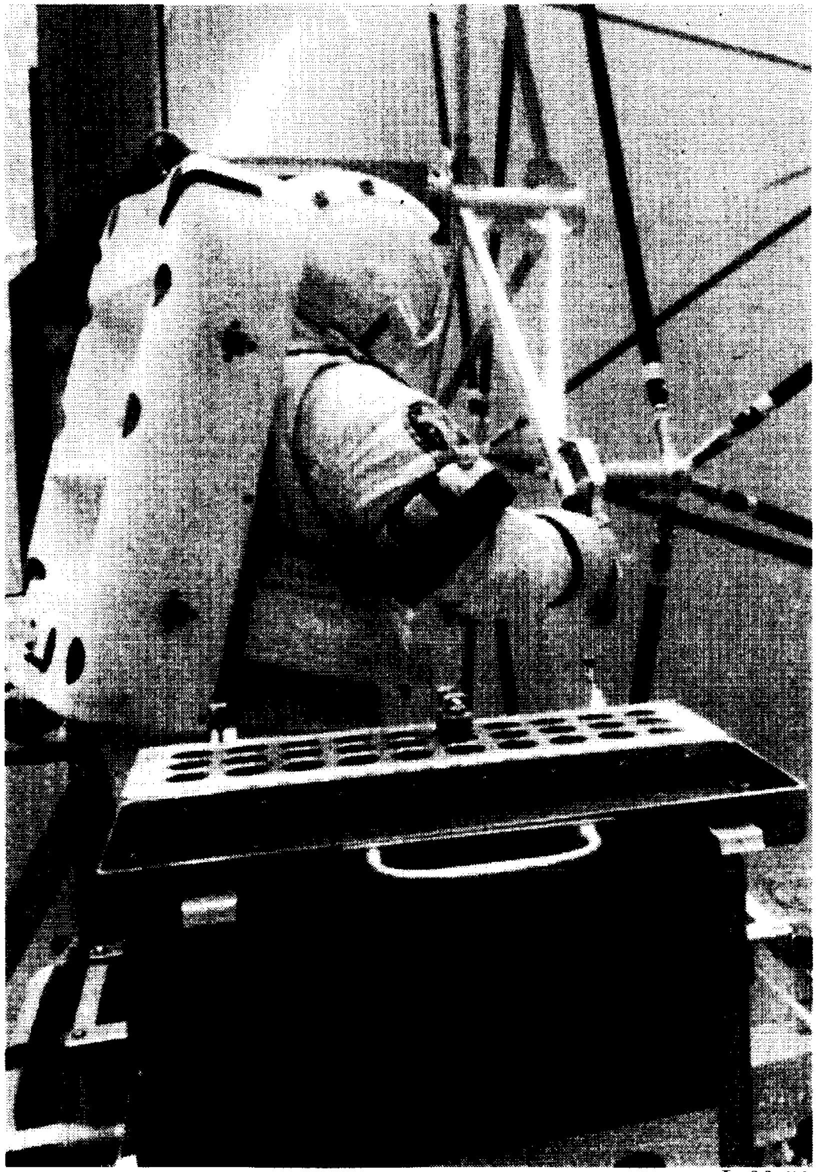
Figure 15. Photograph of assembly fixture.



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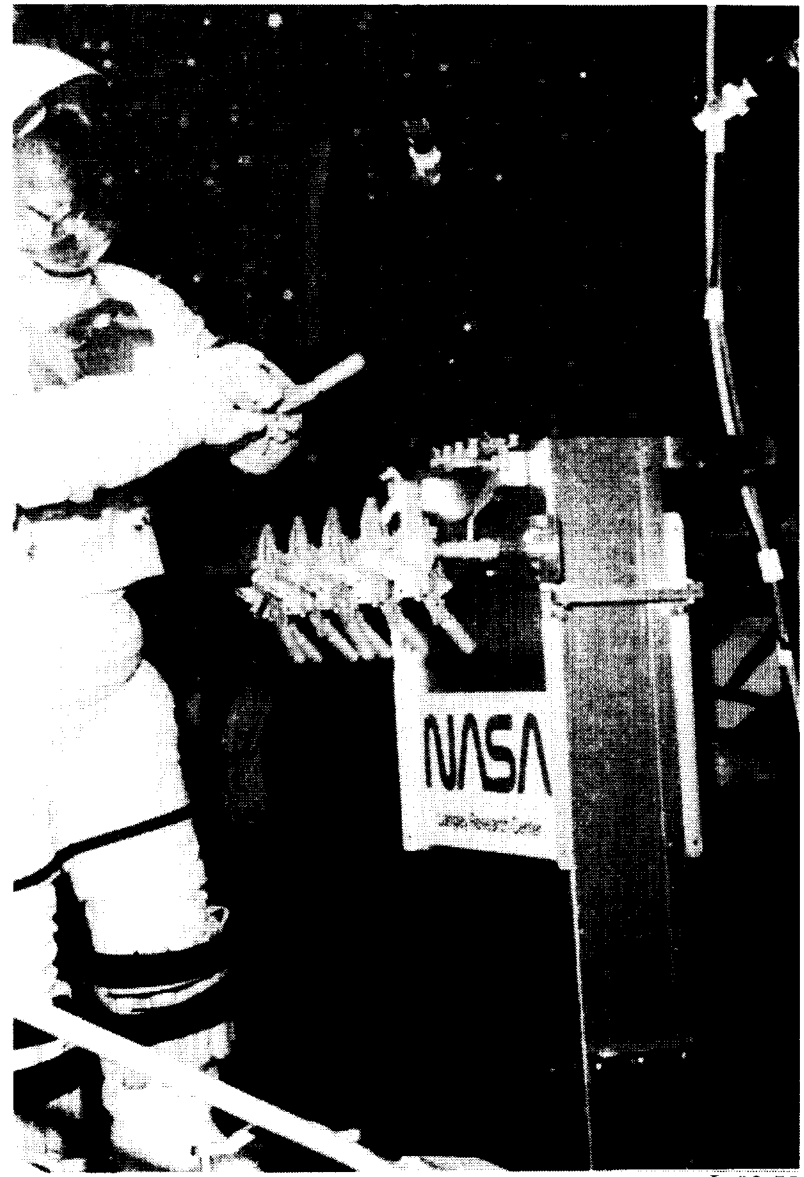
(a) Strut stowage.



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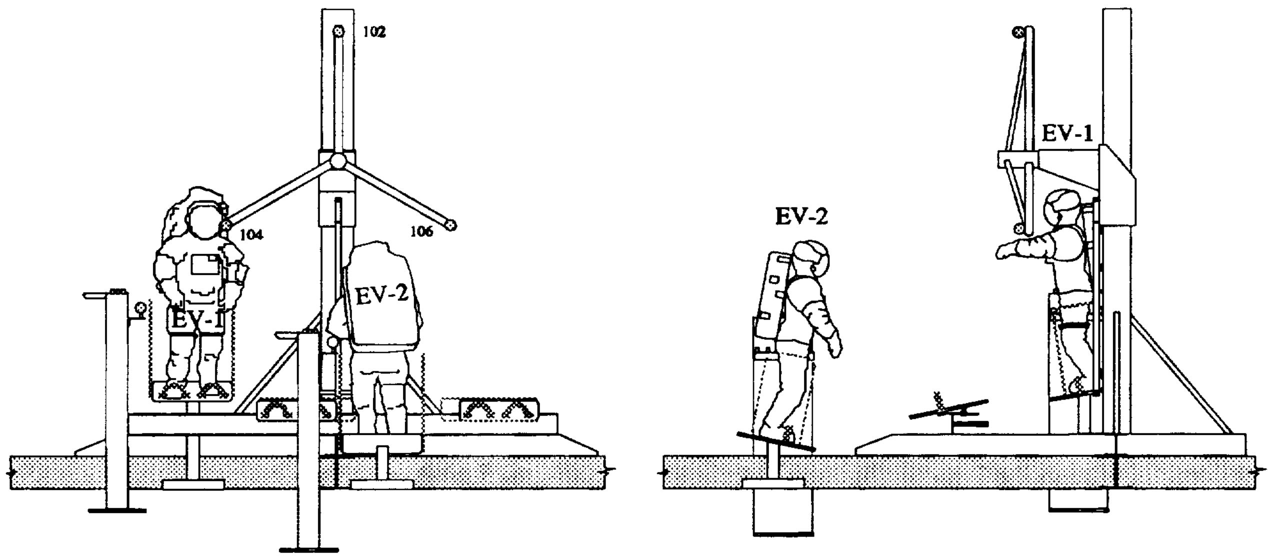
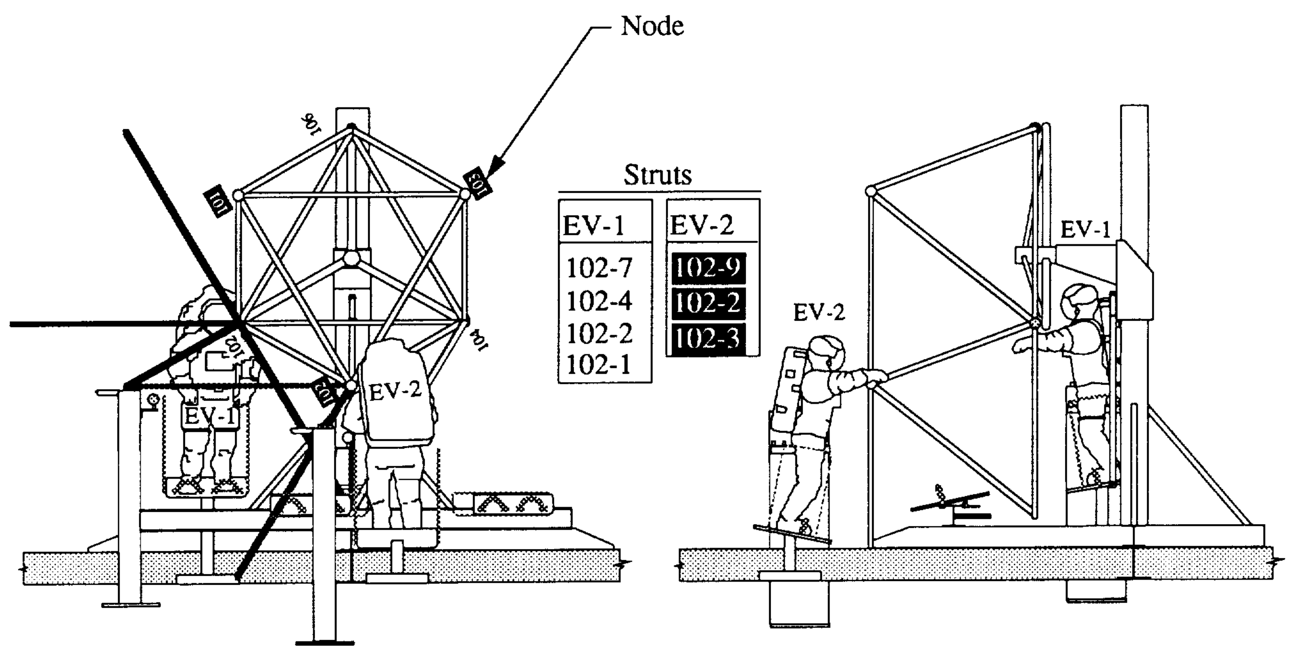
(b) Node stowage.

Figure 16. Strut and node stowage canisters.

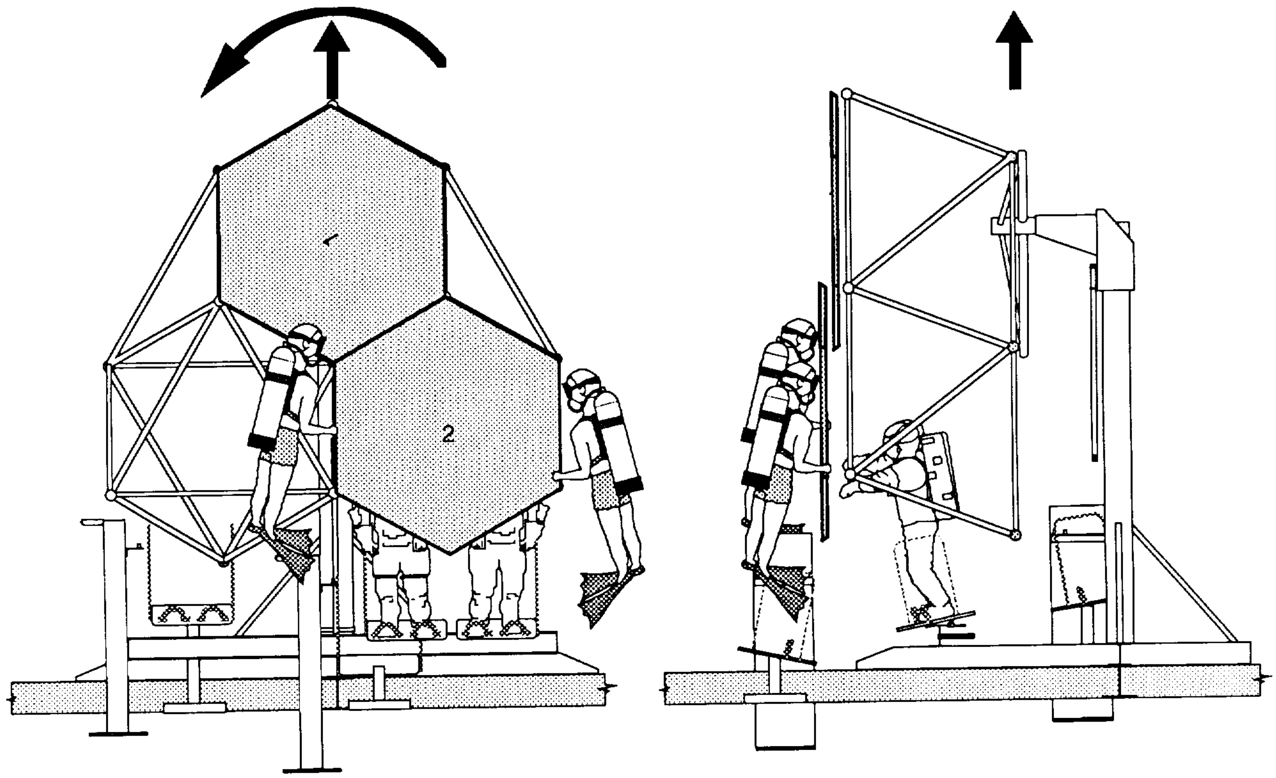


(a) Assembly fixture configuration and location of test subjects at start of test.

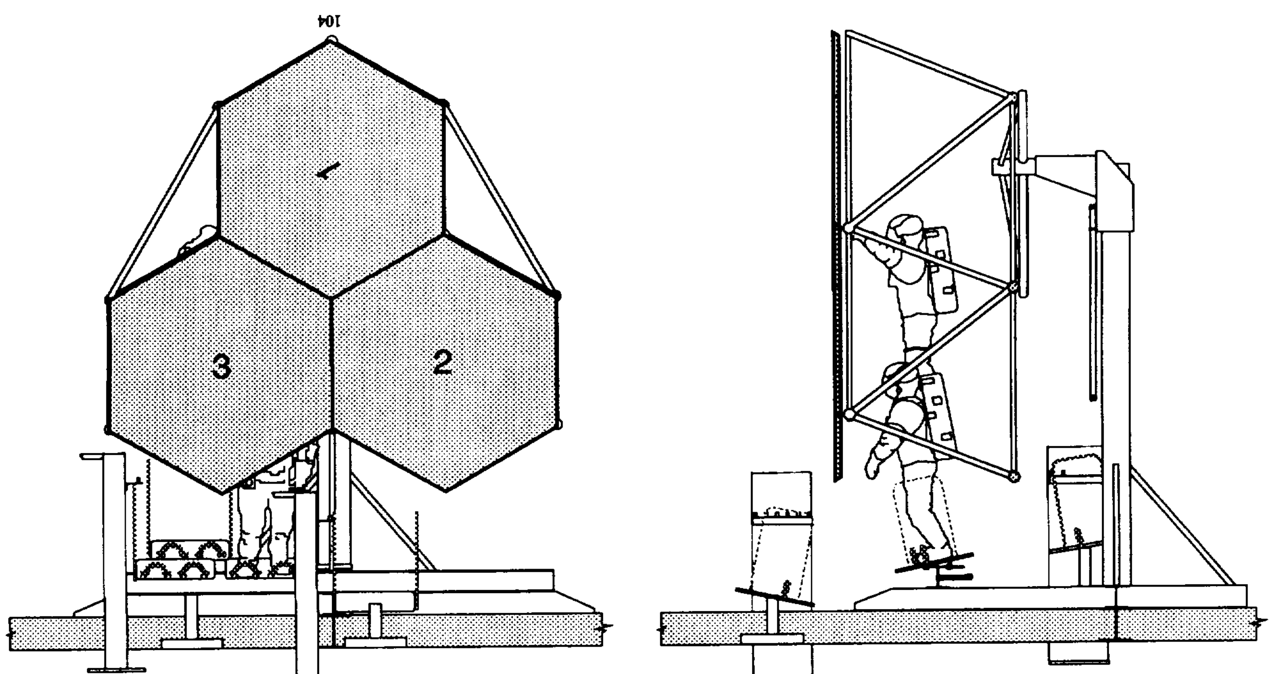


(b) Typical step in assembly procedure. EV-1 connects struts to ports 7, 4, 2, and 1 of node 102 (back) and EV-2 connects struts to ports 9, 2, and 3 of node 102 (front).

Figure 17. Assembly procedure for test article. (Nodes 102, 104, and 106 are preattached to turnstile; white numbers on black background indicate front surface struts and nodes; black numbers indicate back surface struts and nodes.)



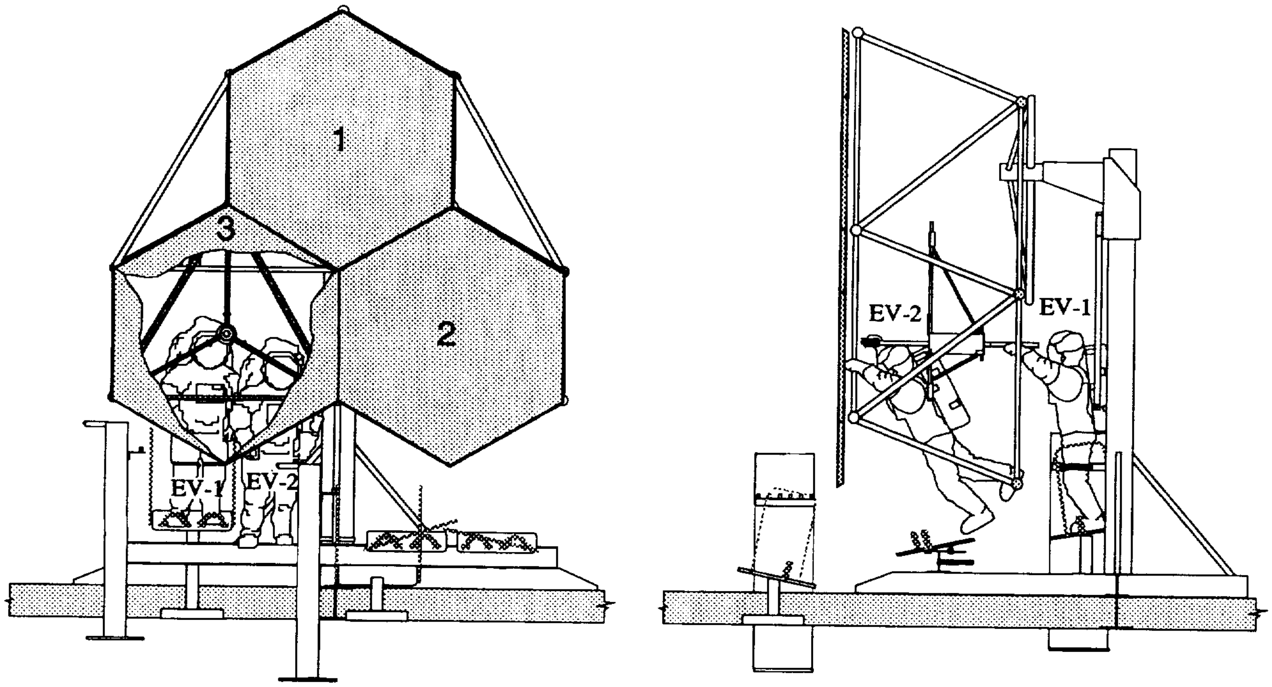
(c) Scuba divers simulate function of remote manipulator system to bring panel within reach of test subjects.



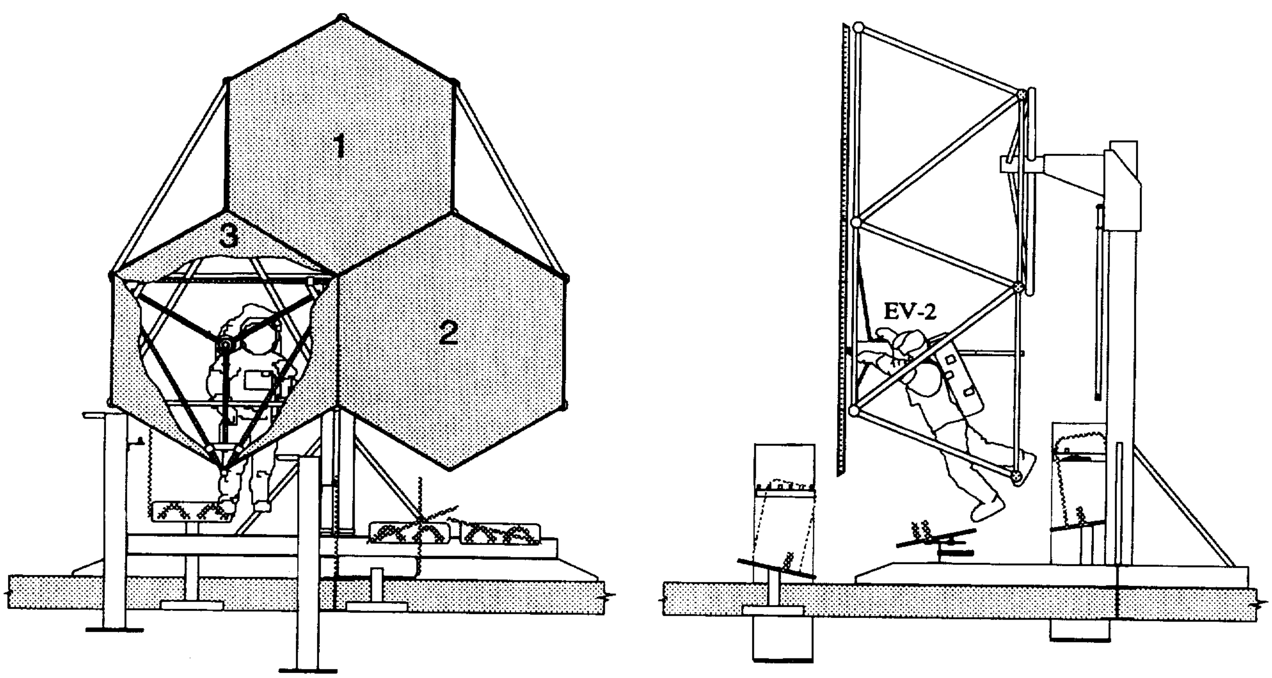
End of assembly test

(d) Test subject leaves foot restraint to make final panel connection to truss node.

Figure 17. Concluded.

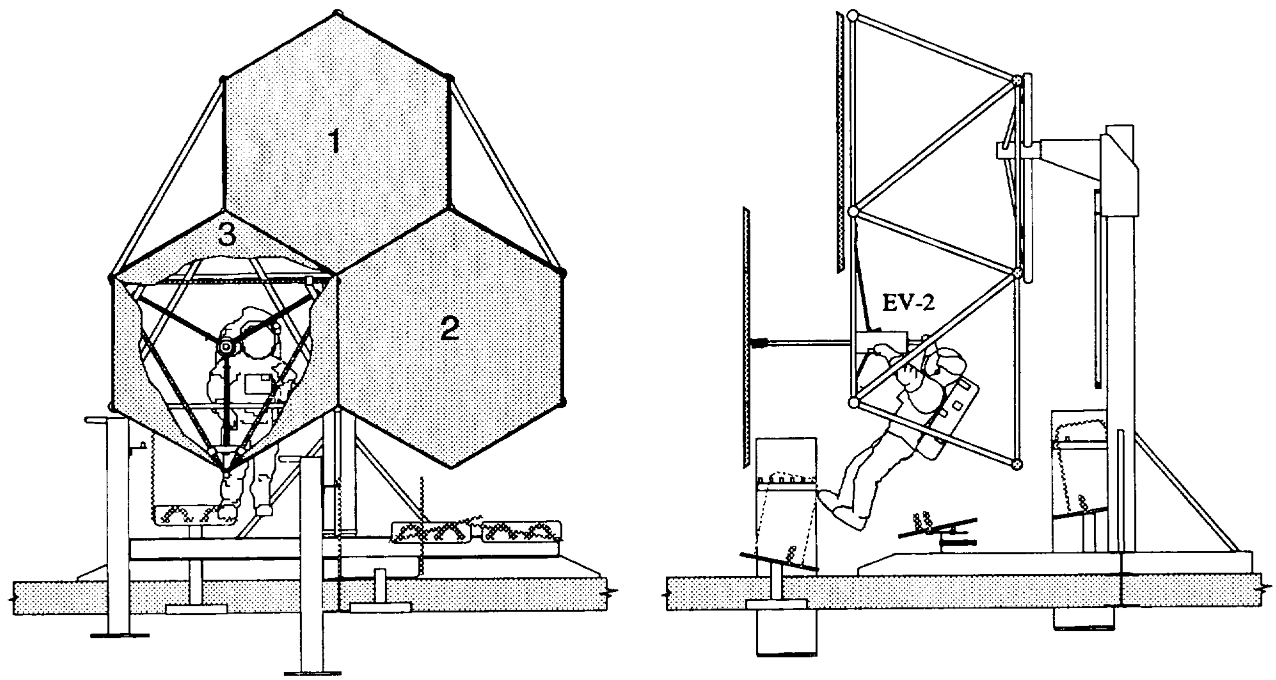


(a) EV-1 passes panel replacement tool through truss to EV-2.

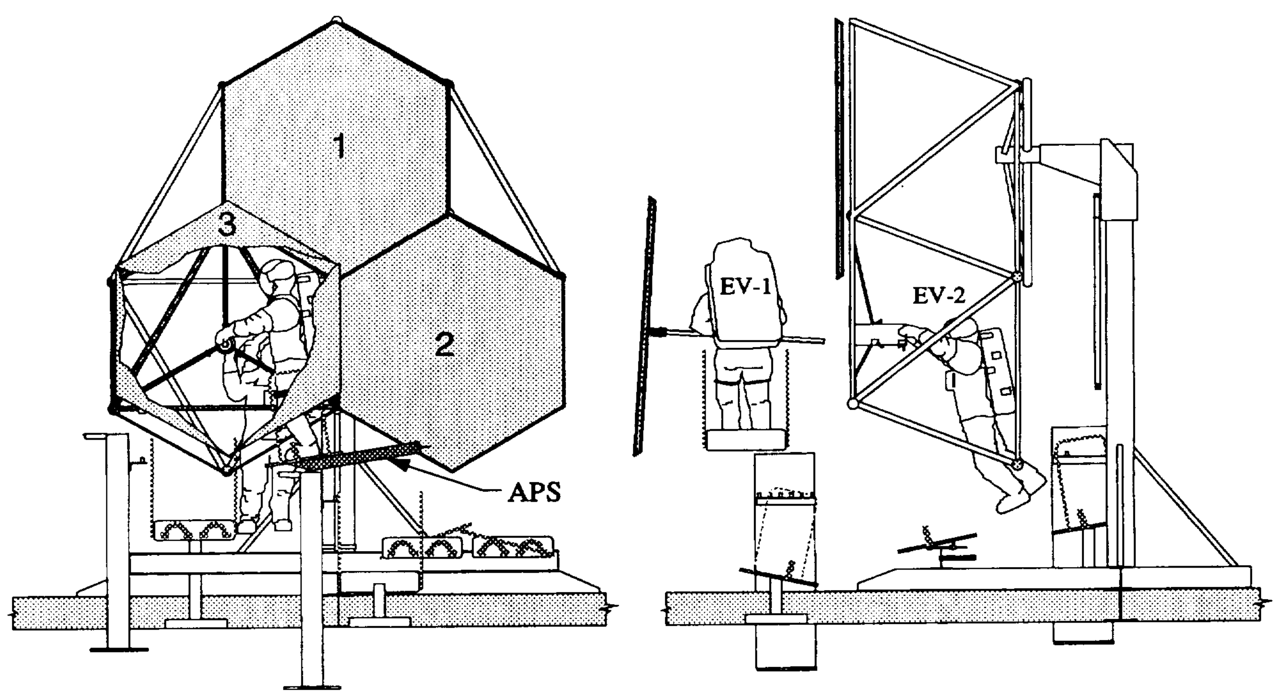


(b) EV-2 attaches guide pole to center of panel then attaches panel replacement tool to truss. During these activities, EV-1 is being moved by astronaut positioning system (not shown) to a position in front of truss.

Figure 18. Damaged panel removal procedure. Replacement procedure is reversal of removal procedure.



(c) EV-2 slides panel (with attached guide pole) away from truss.



(d) EV-1 in astronaut positioning system (APS) foot restraint removes guide pole with attached panel from truss.

Figure 18. Concluded.

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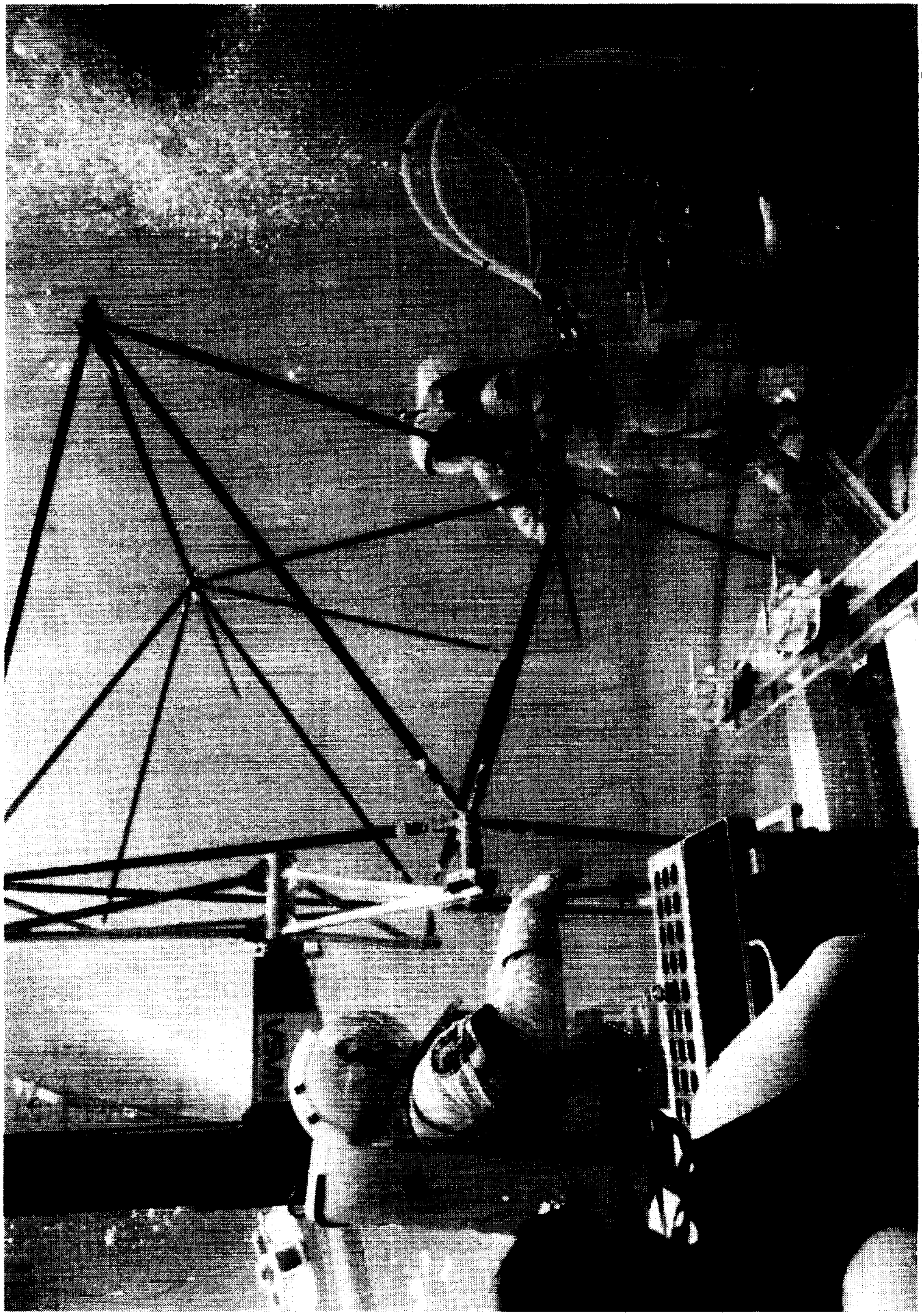


L-92-54

Figure 19. Truss assembly.

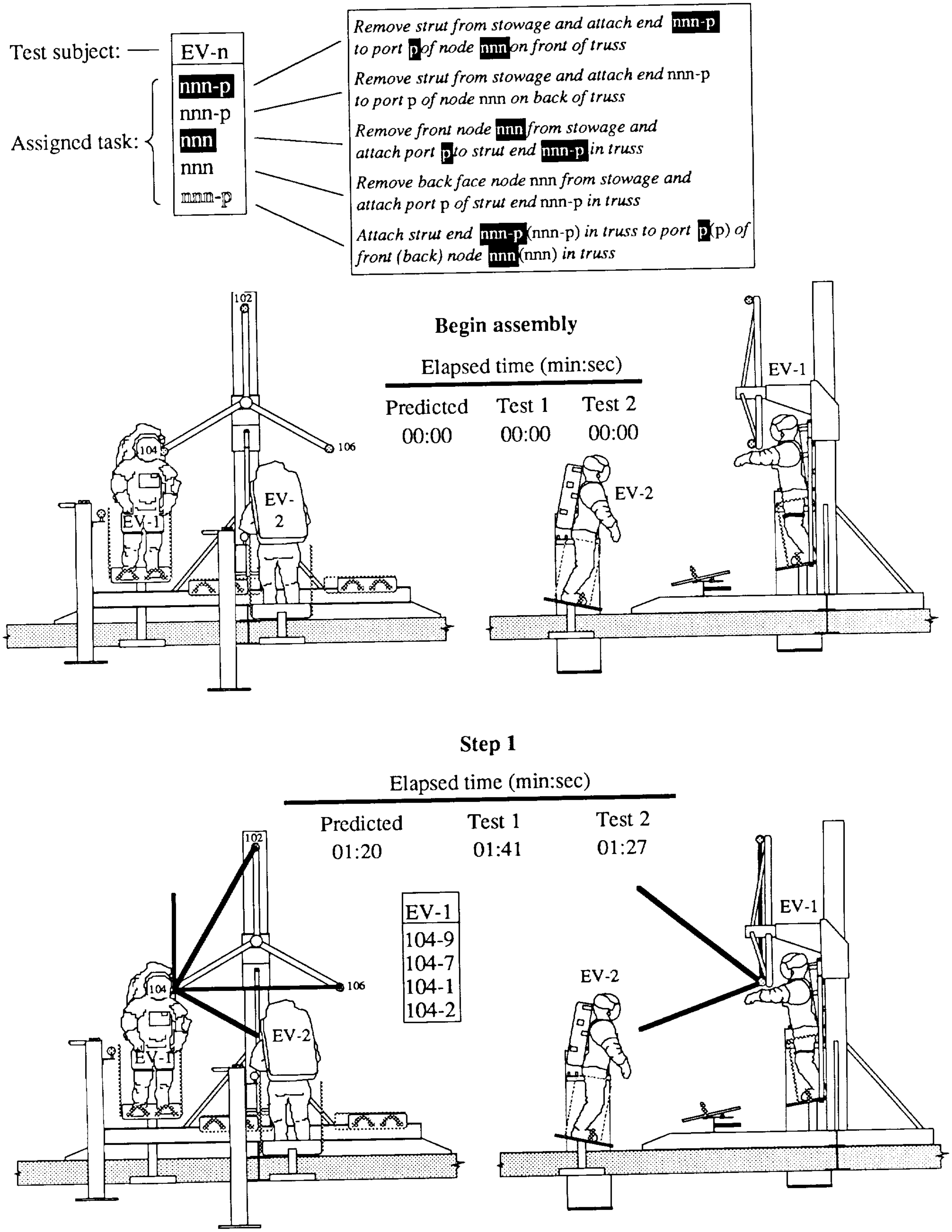
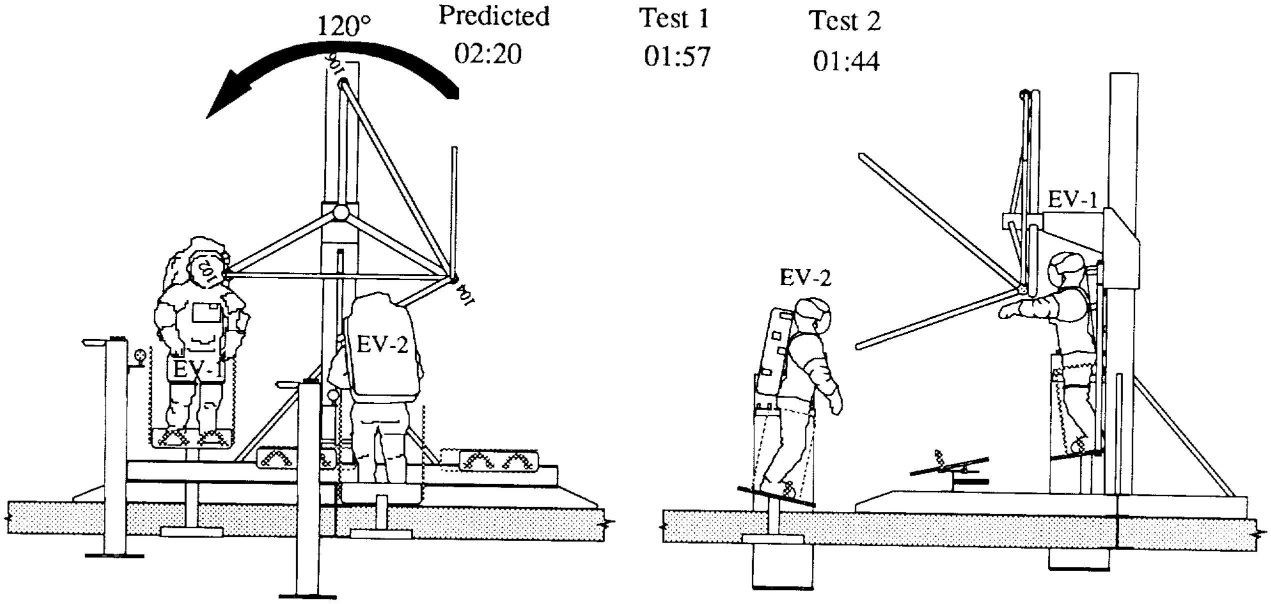


Figure 20. Comparison of predicted assembly time with test results.

Step 2

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
02:20	01:57	01:44



Step 3

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
03:20	03:38	03:14

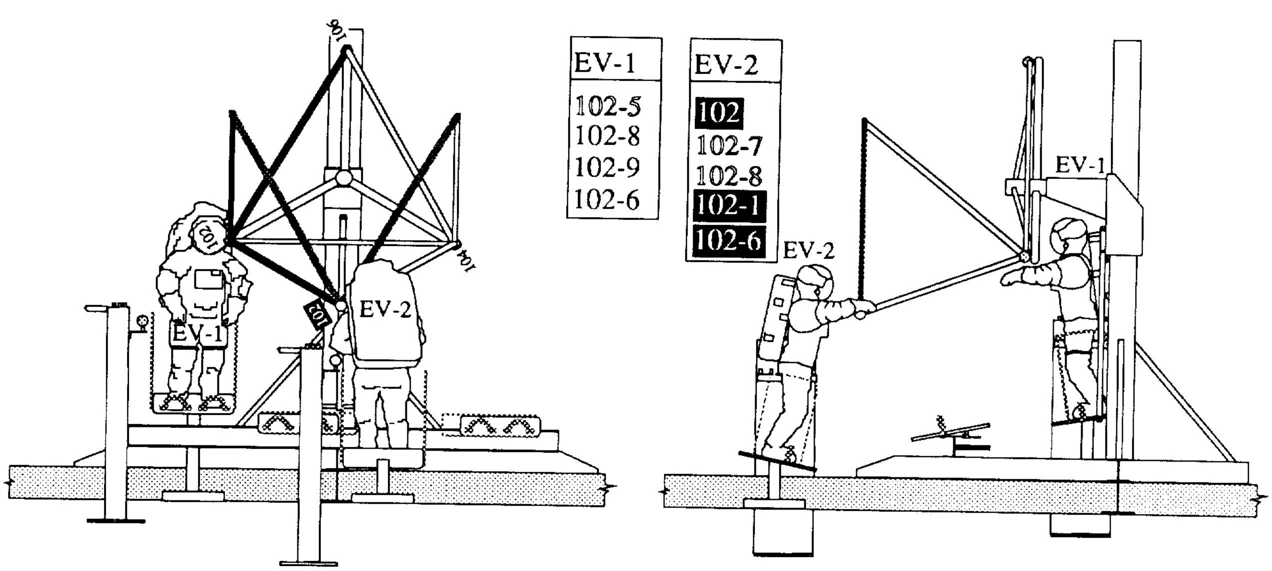
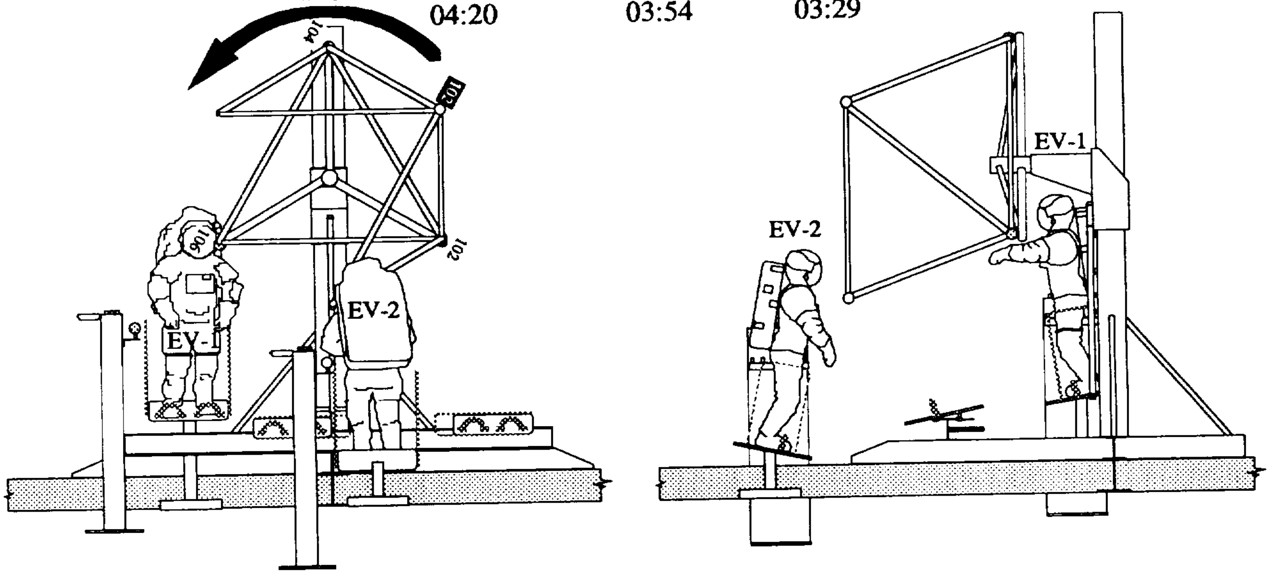


Figure 20. Continued.

Step 4

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
04:20	03:54	03:29



Step 5

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
05:00	05:09	05:15

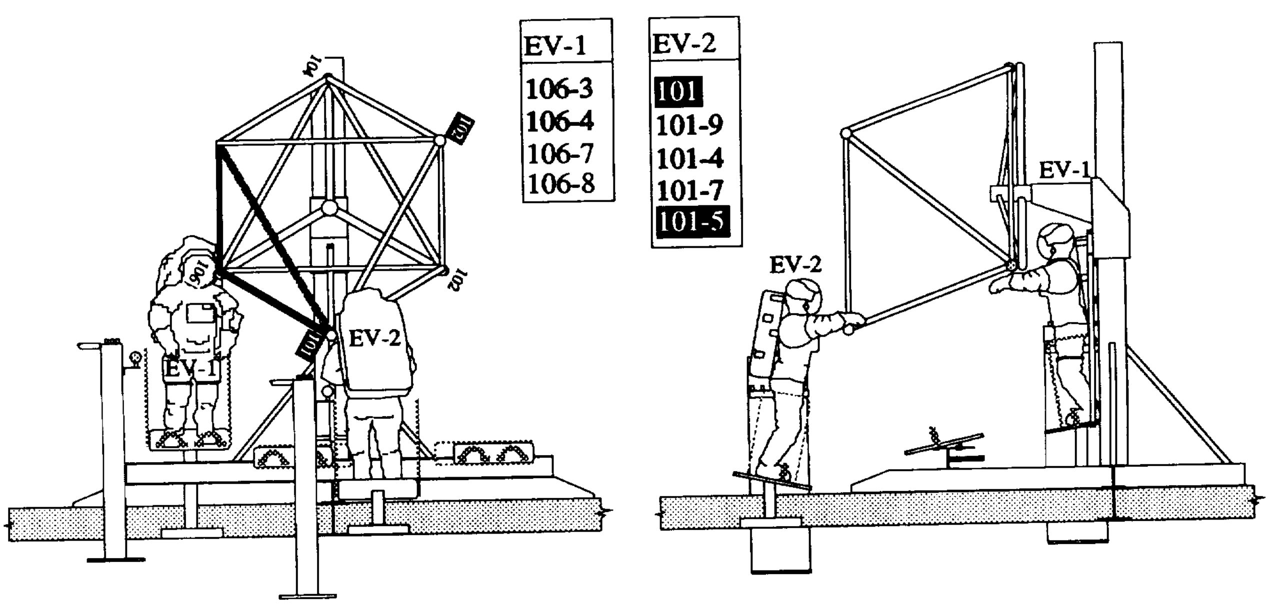
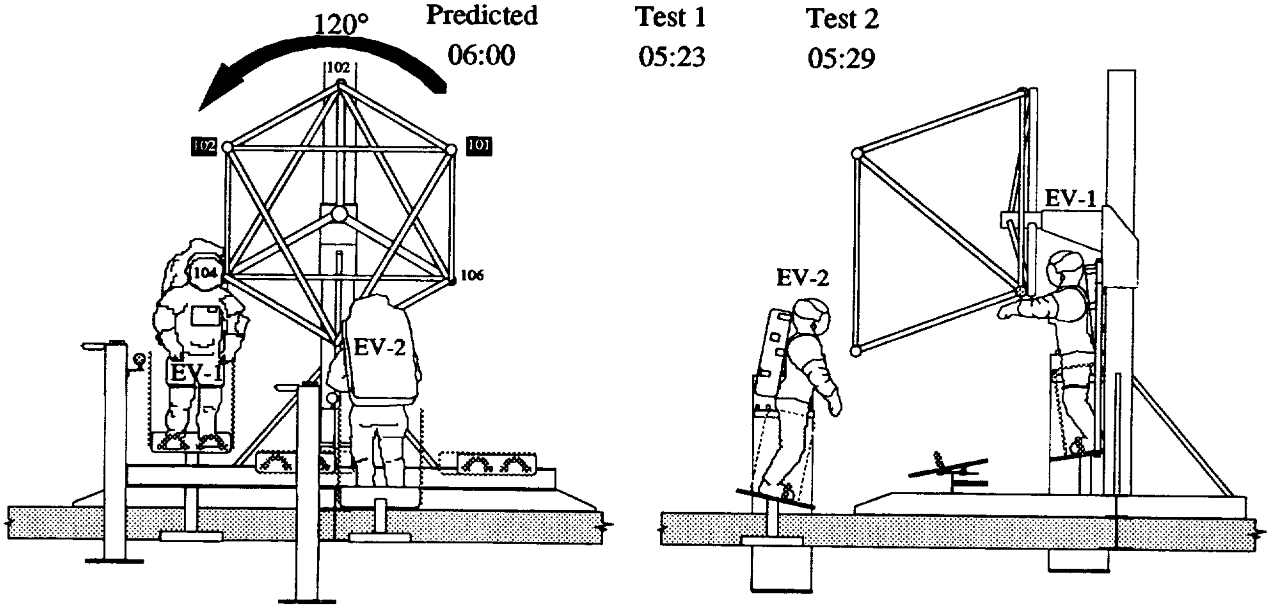


Figure 20. Continued.

Step 6

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
06:00	05:23	05:29



Step 7

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
06:20	06:13	06:19

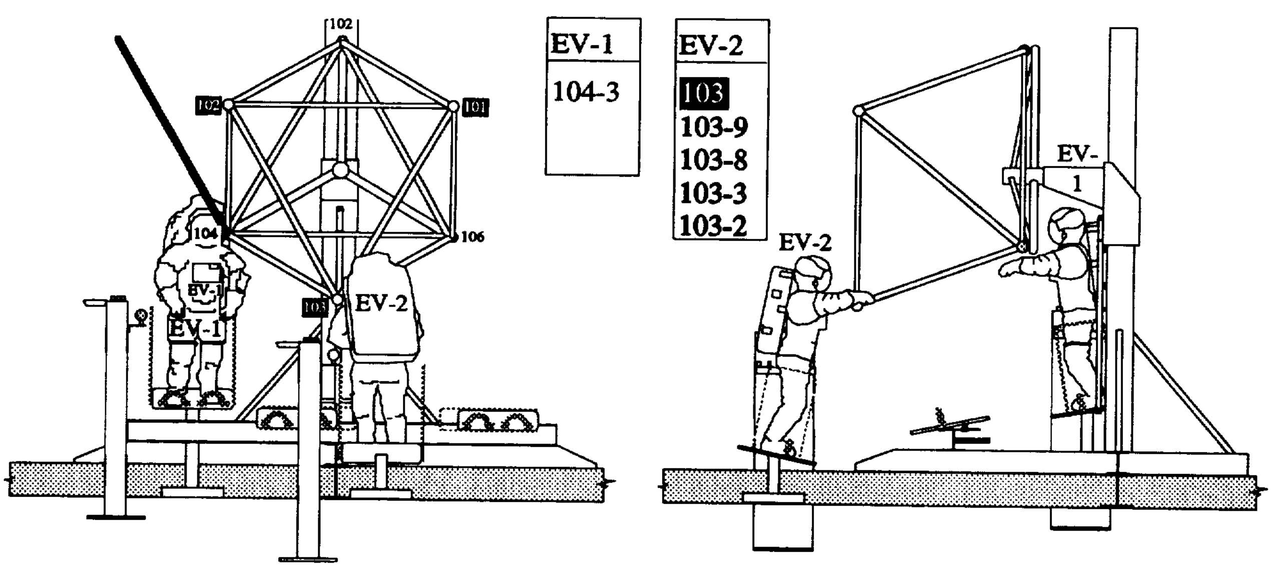
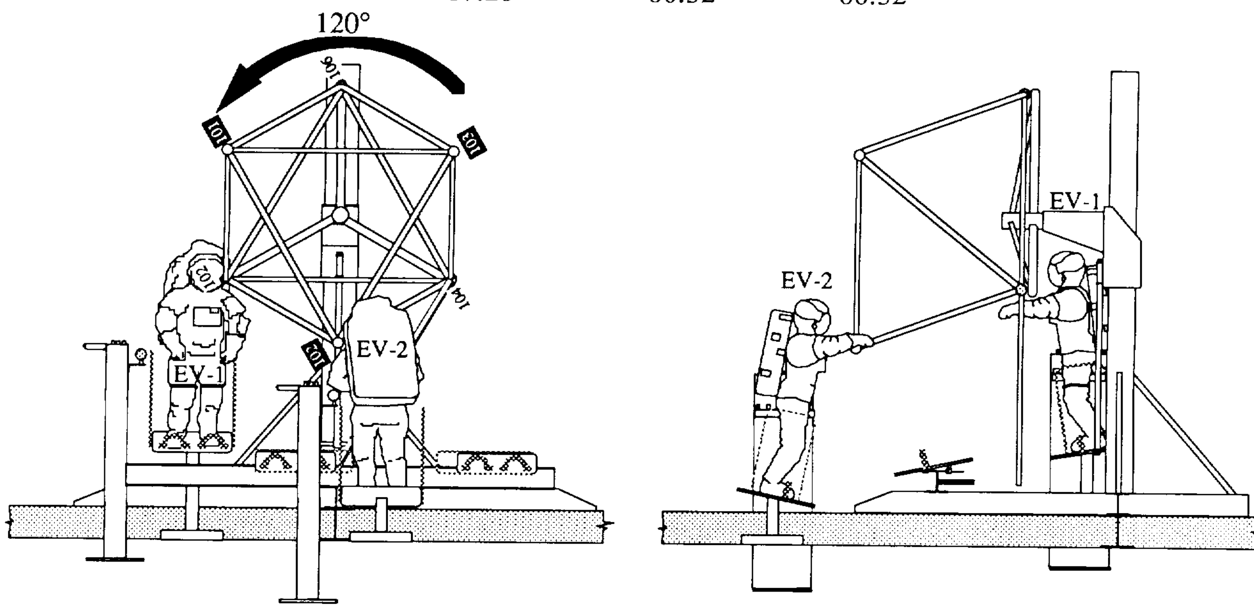


Figure 20. Continued.

Step 8

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
07:20	06:32	06:32



Step 9

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
08:20	08:46	09:06

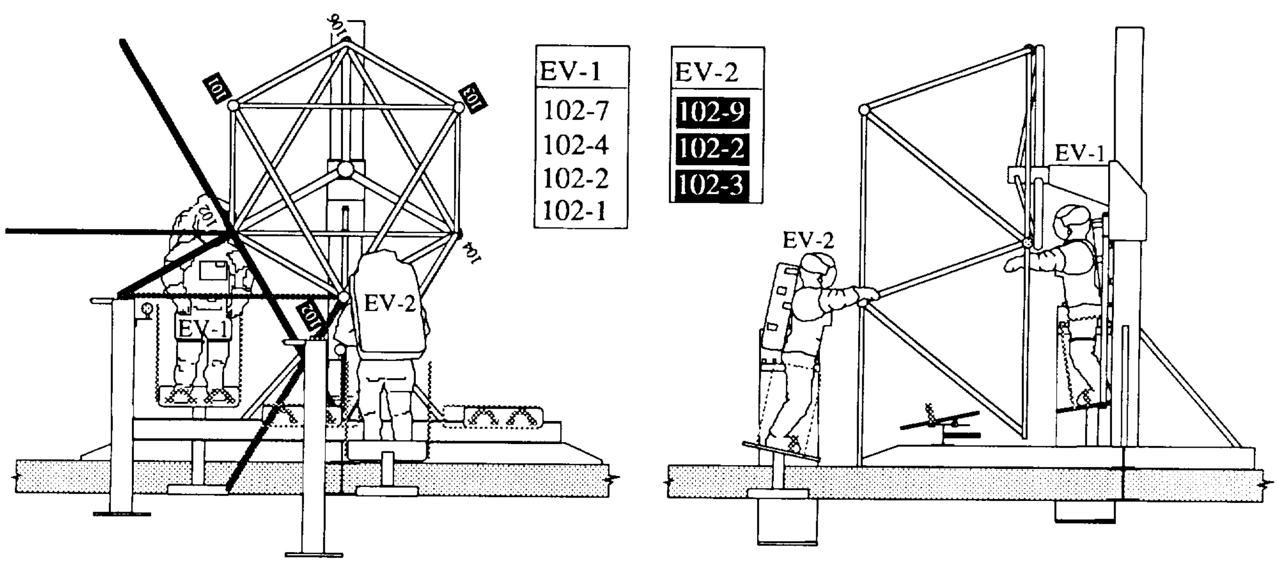
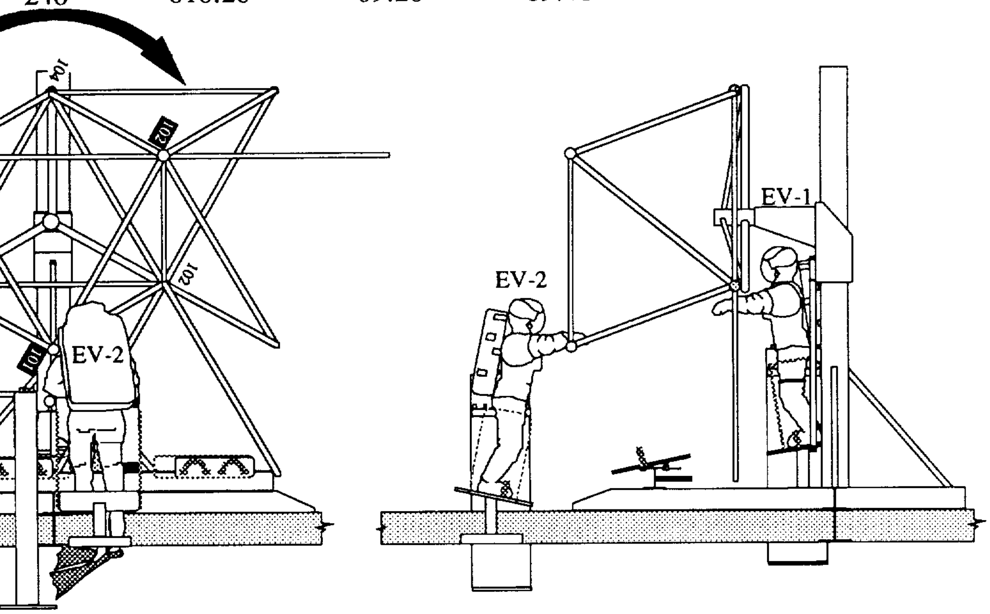


Figure 20. Continued.

Step 10

Elapsed time (min:sec)

Predicted	Test 1	Test 2
010:20	09:20	09:41



Step 11

Elapsed time (min:sec)

Predicted	Test 1	Test 2
11:20	11:30	11:34

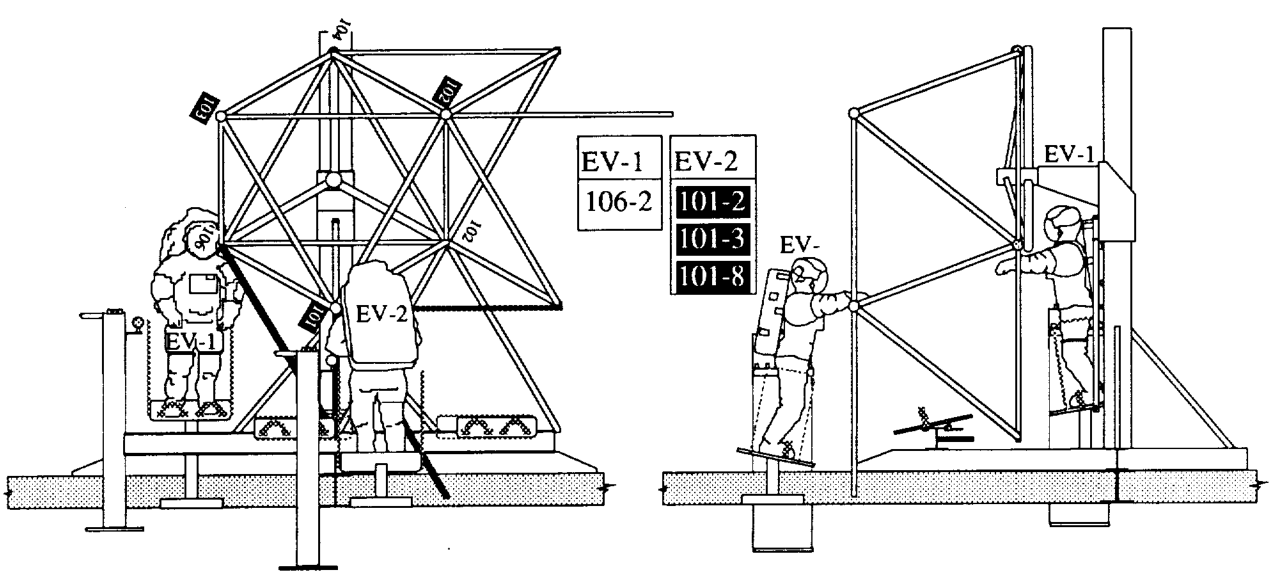
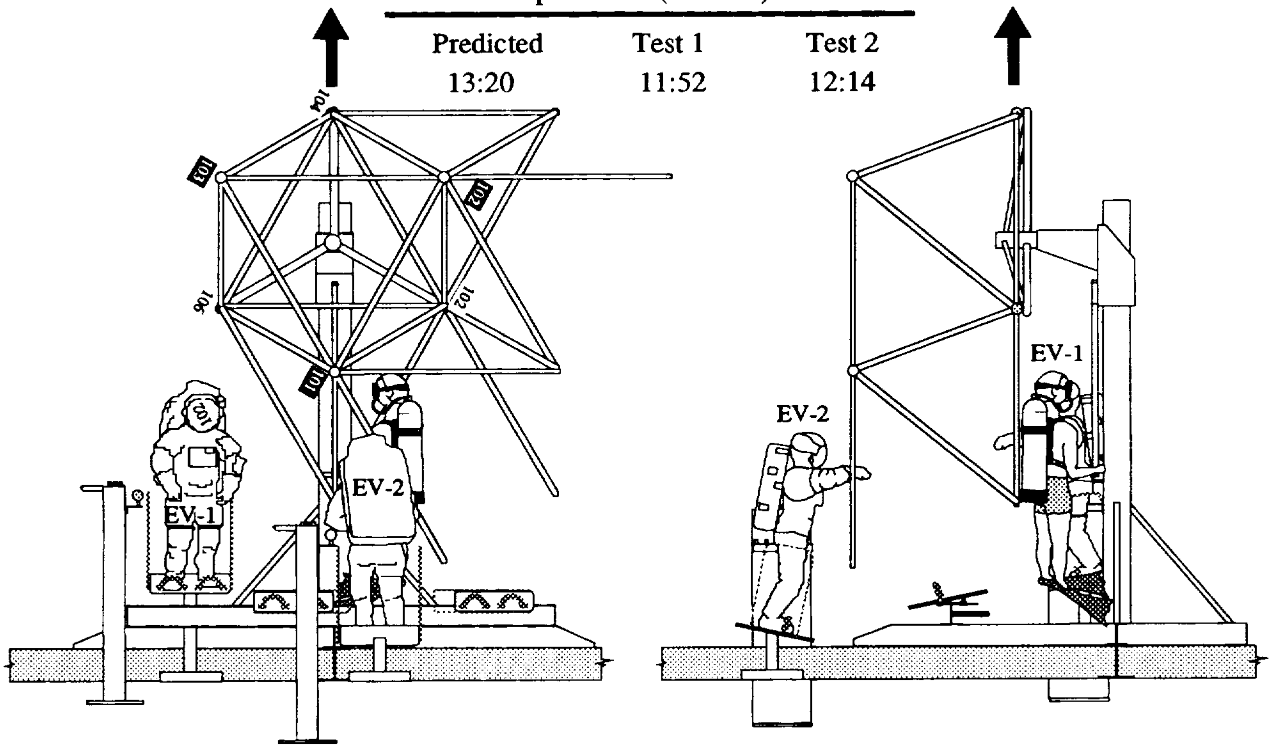


Figure 20. Continued.

Step 12

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
13:20	11:52	12:14



Step 13

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
14:20	12:04	12:20

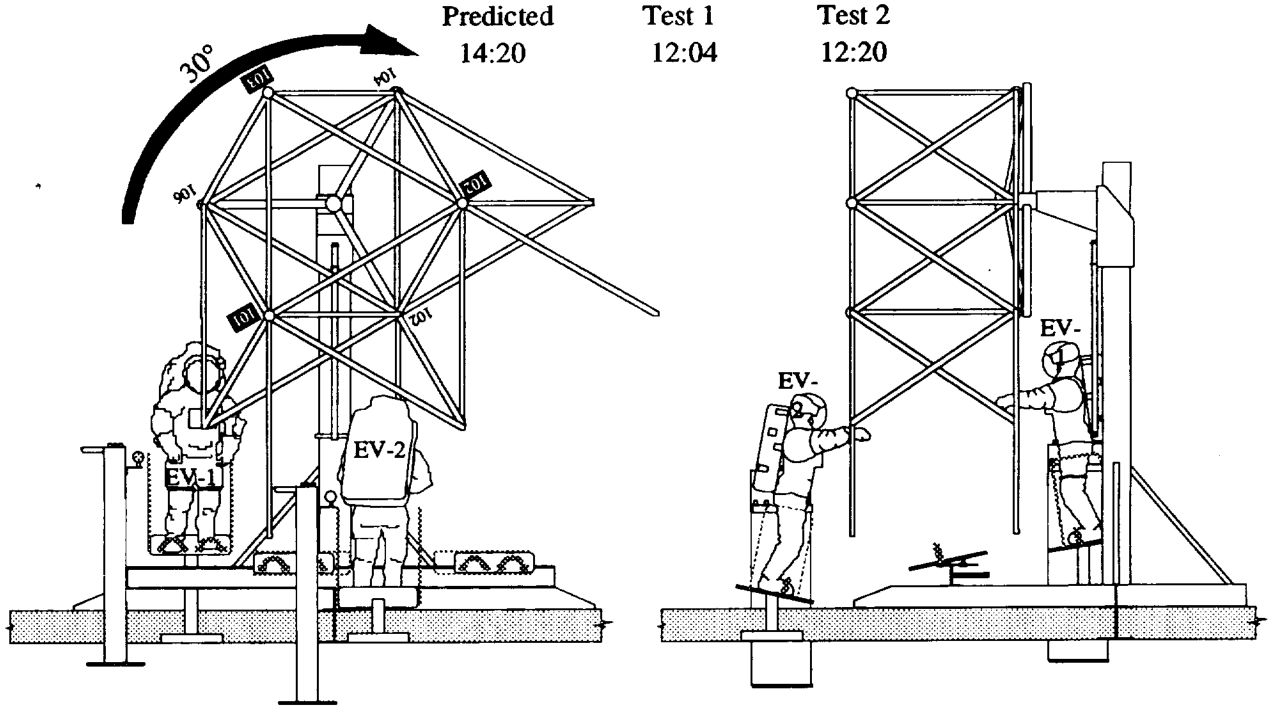
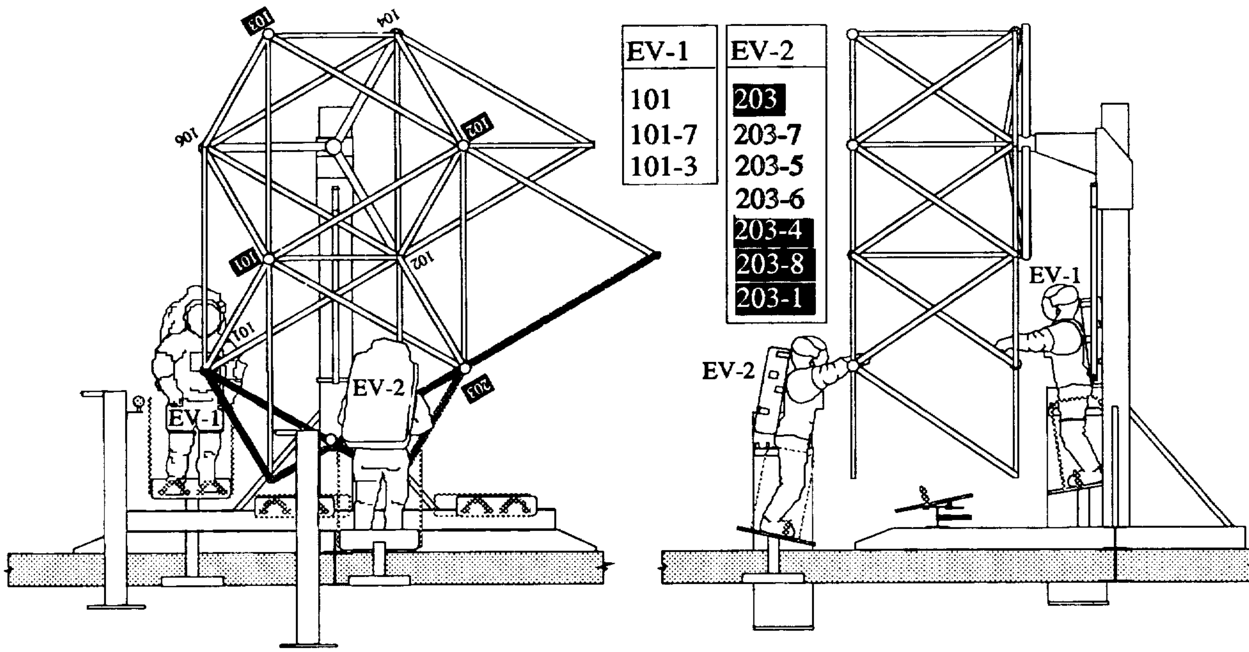


Figure 20. Continued.

Step 14

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
16:20	16:26	17:33



Step 15

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
18:20	16:26	17:42

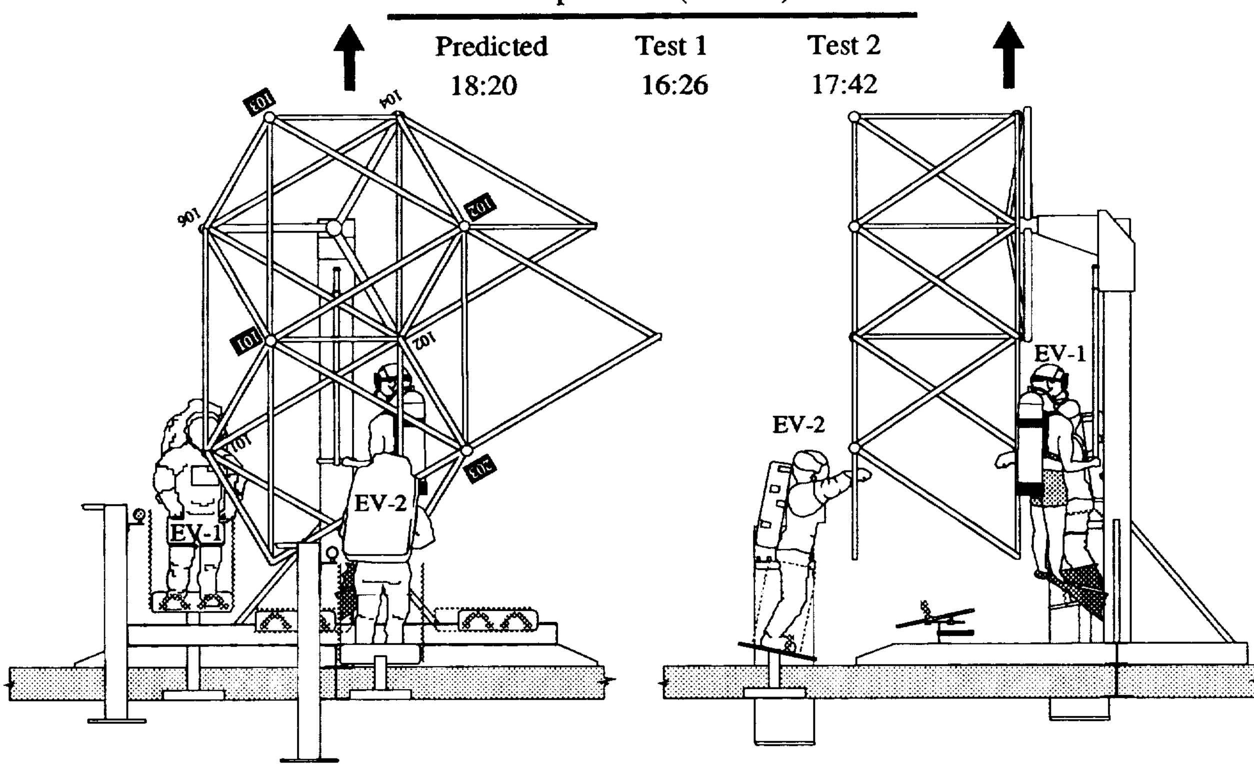
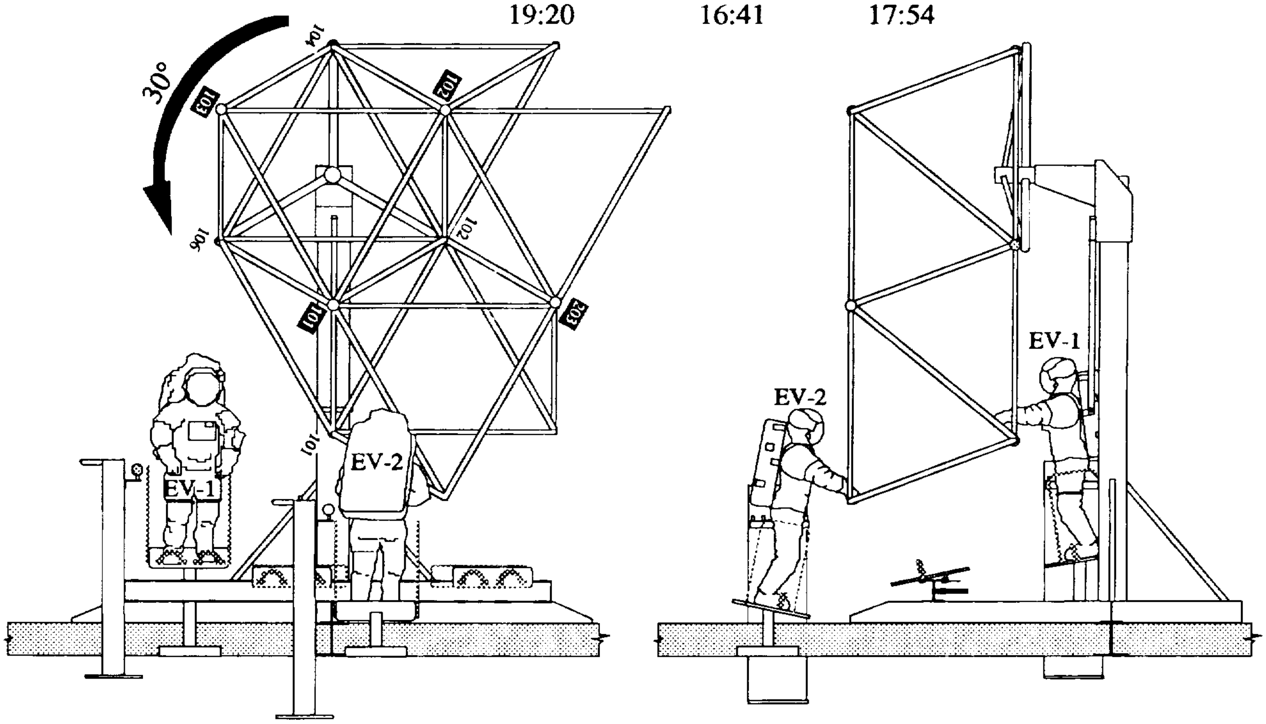


Figure 20. Continued.

Step 16

Elapsed time (min:sec)

Predicted	Test 1	Test 2
19:20	16:41	17:54



Step 17

Elapsed time (min:sec)

Predicted	Test 1	Test 2
20:20	19:57	20:01

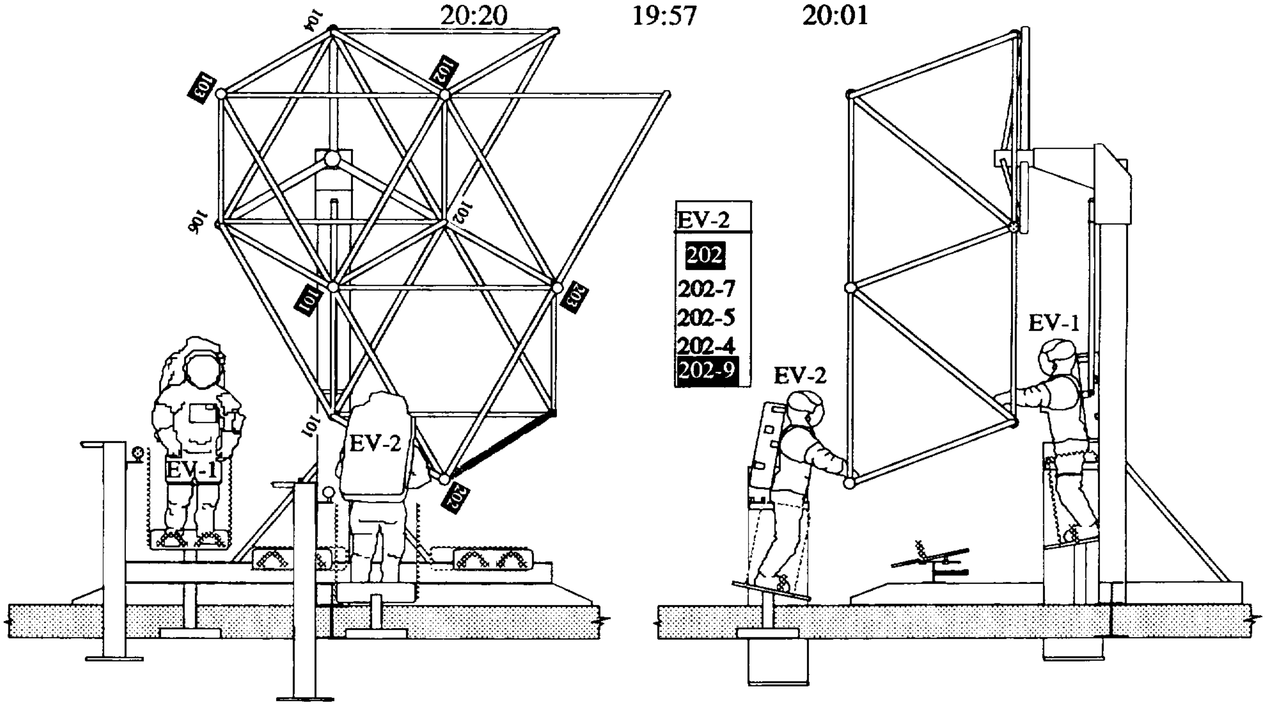
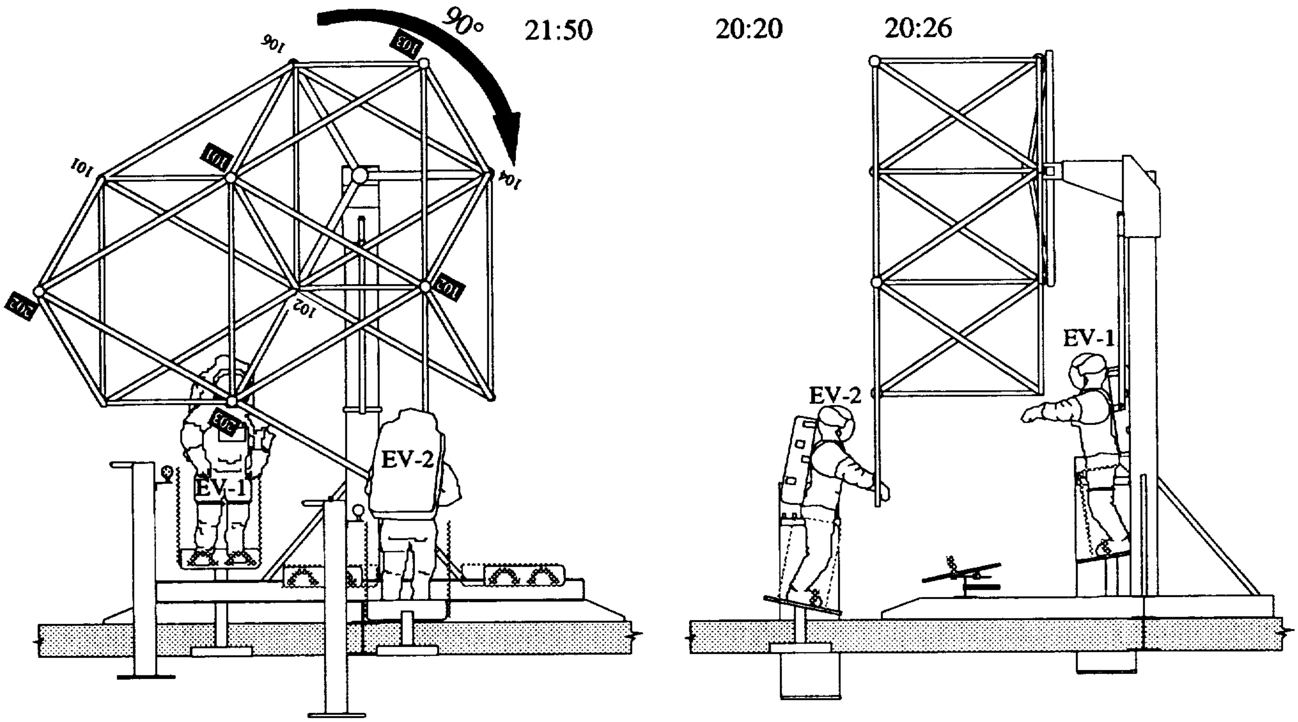


Figure 20. Continued.

Step 18

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
21:50	20:20	20:26



Step 19

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
22:50	24:25	23:03

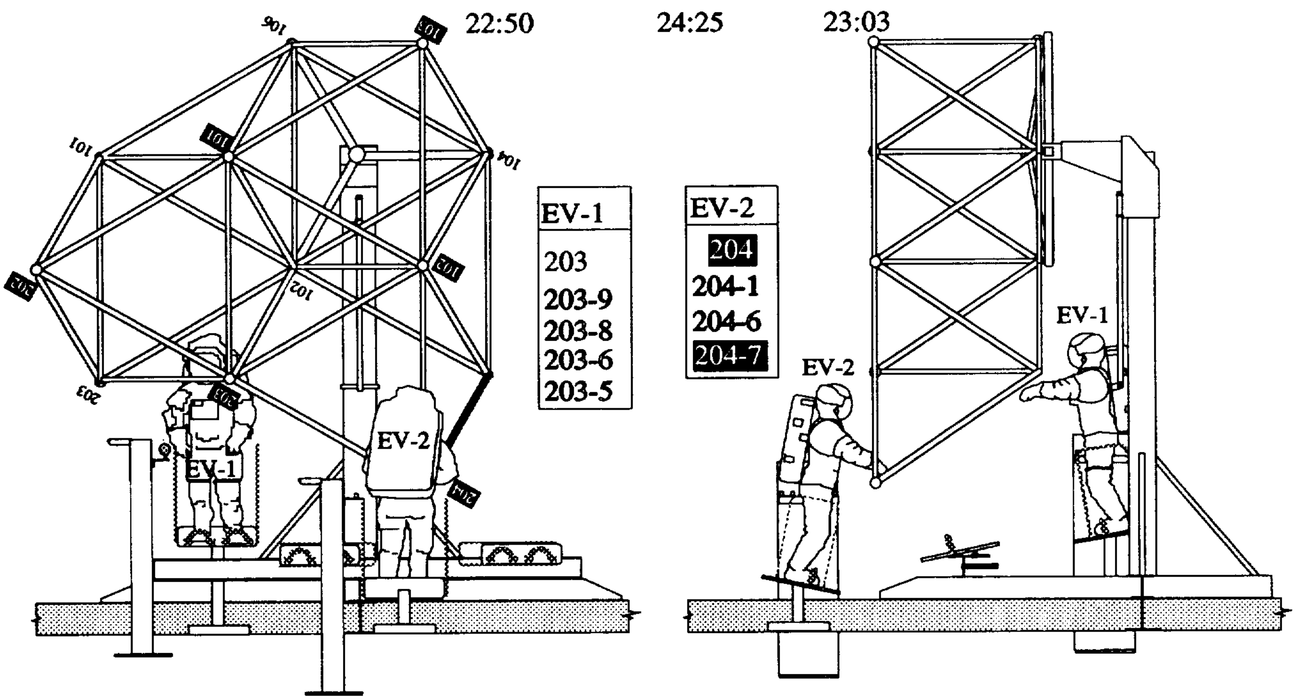
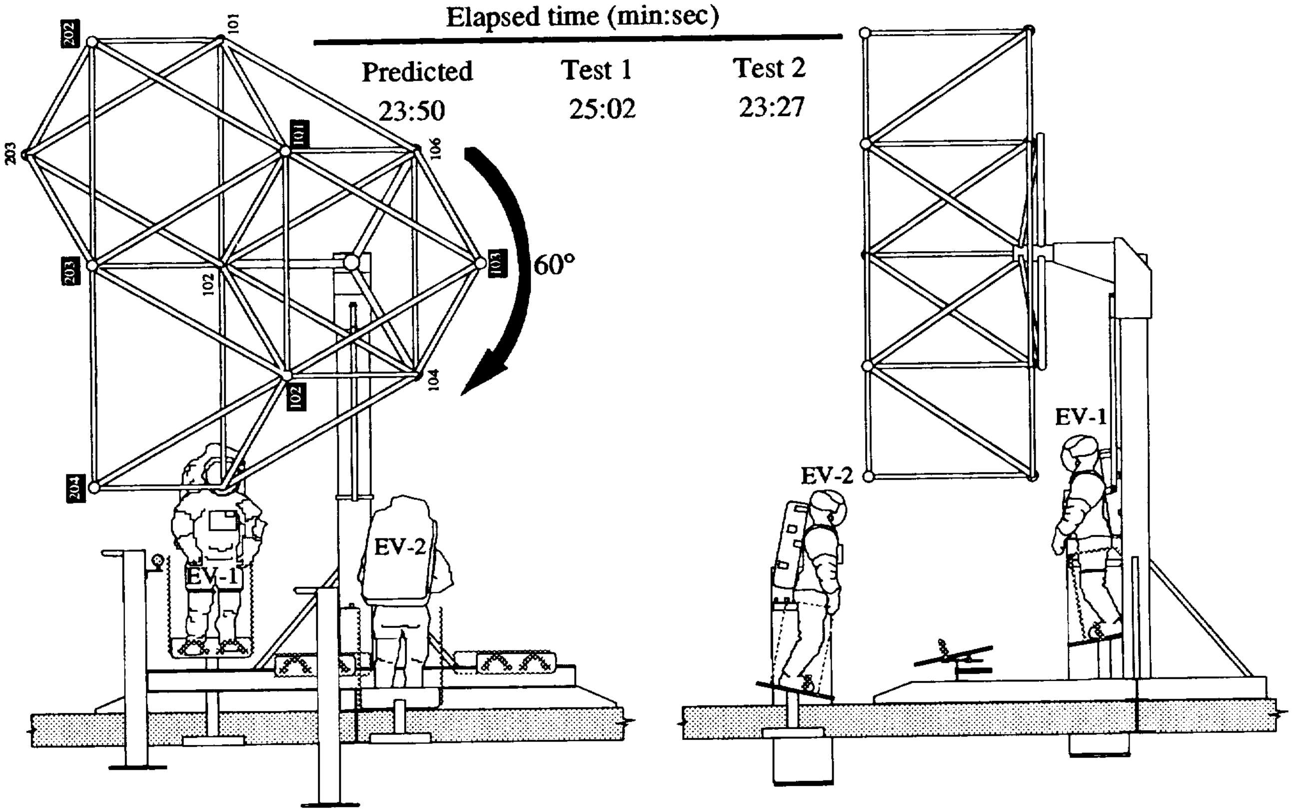


Figure 20. Continued.

Step 20

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
23:50	25:02	23:27



Step 21

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
24:30	25:48	24:02

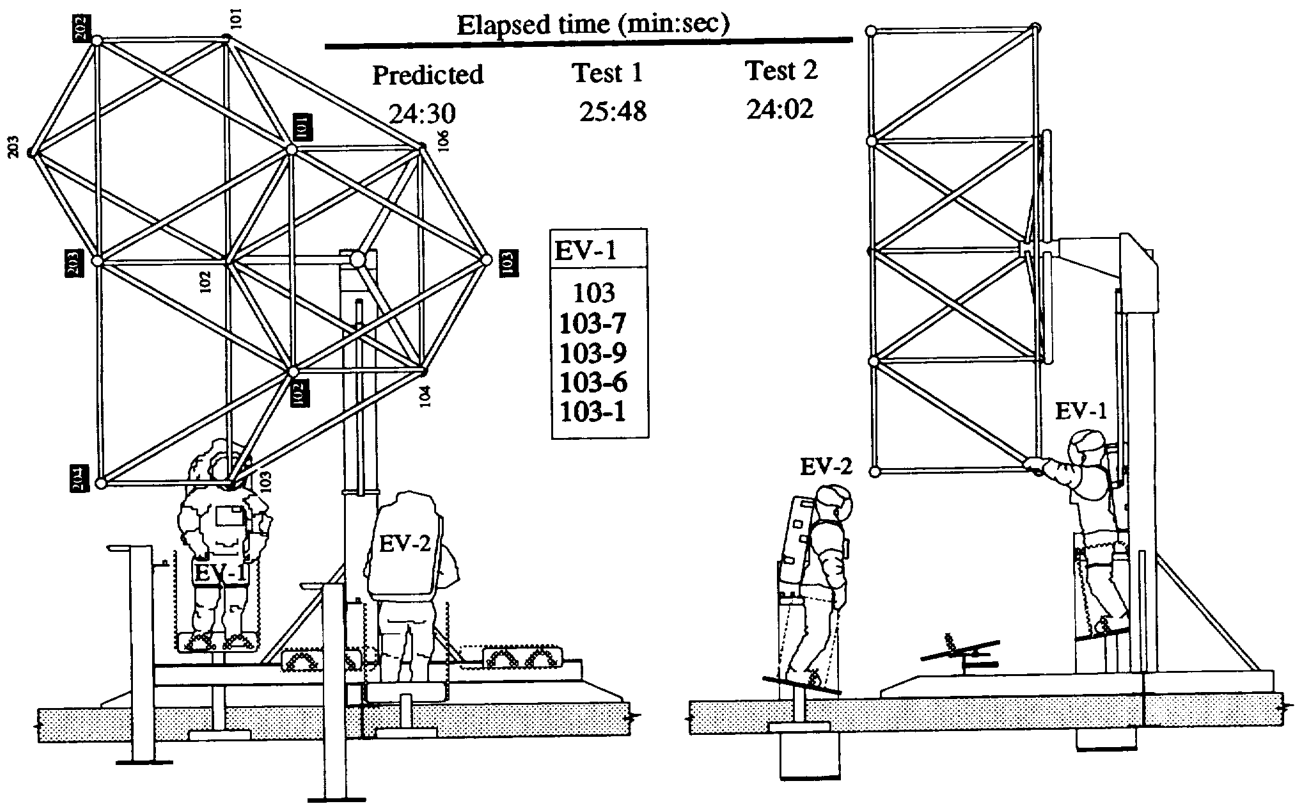
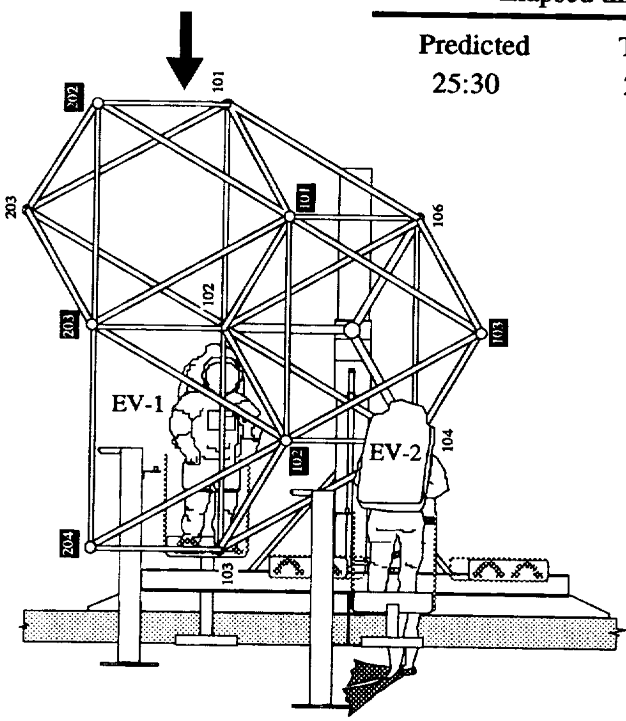


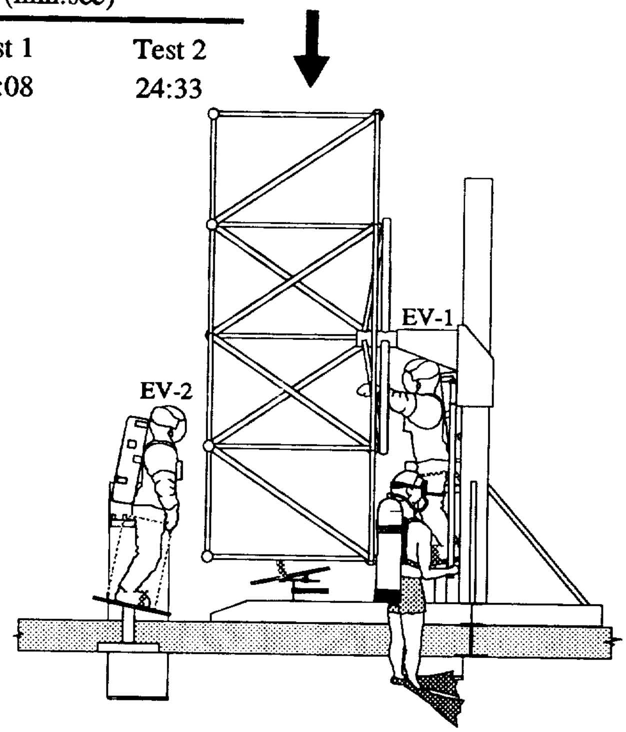
Figure 20. Continued.

Step 22

Elapsed time (min:sec)

Predicted	Test 1	Test 2
25:30	26:08	24:33

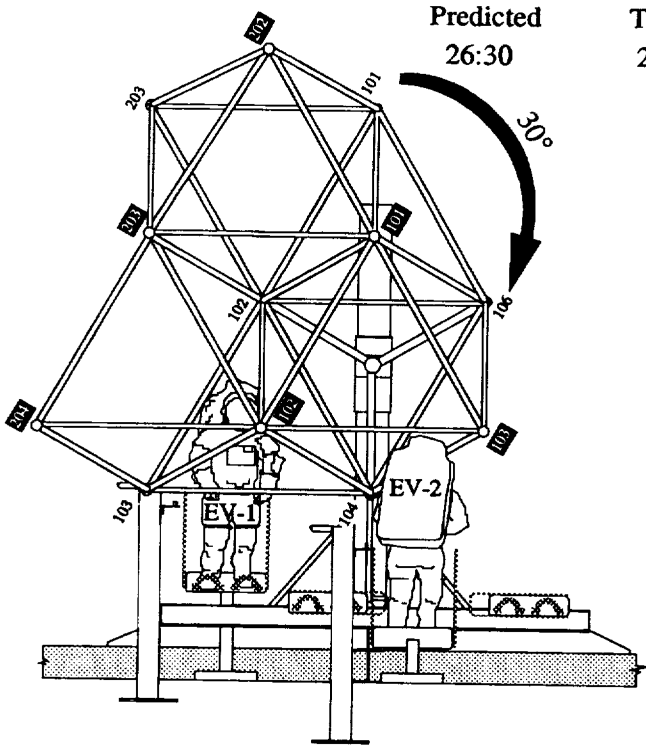




Step 23

Elapsed time (min:sec)

Predicted	Test 1	Test 2
26:30	26:21	24:45



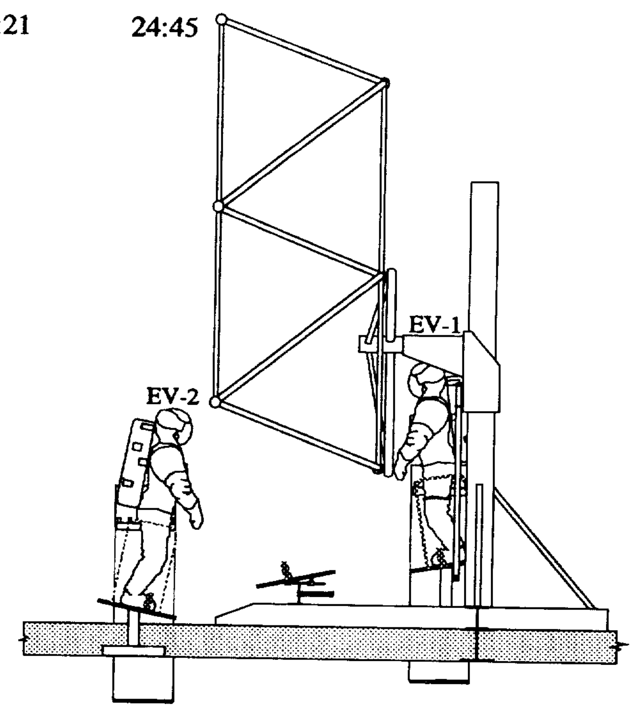
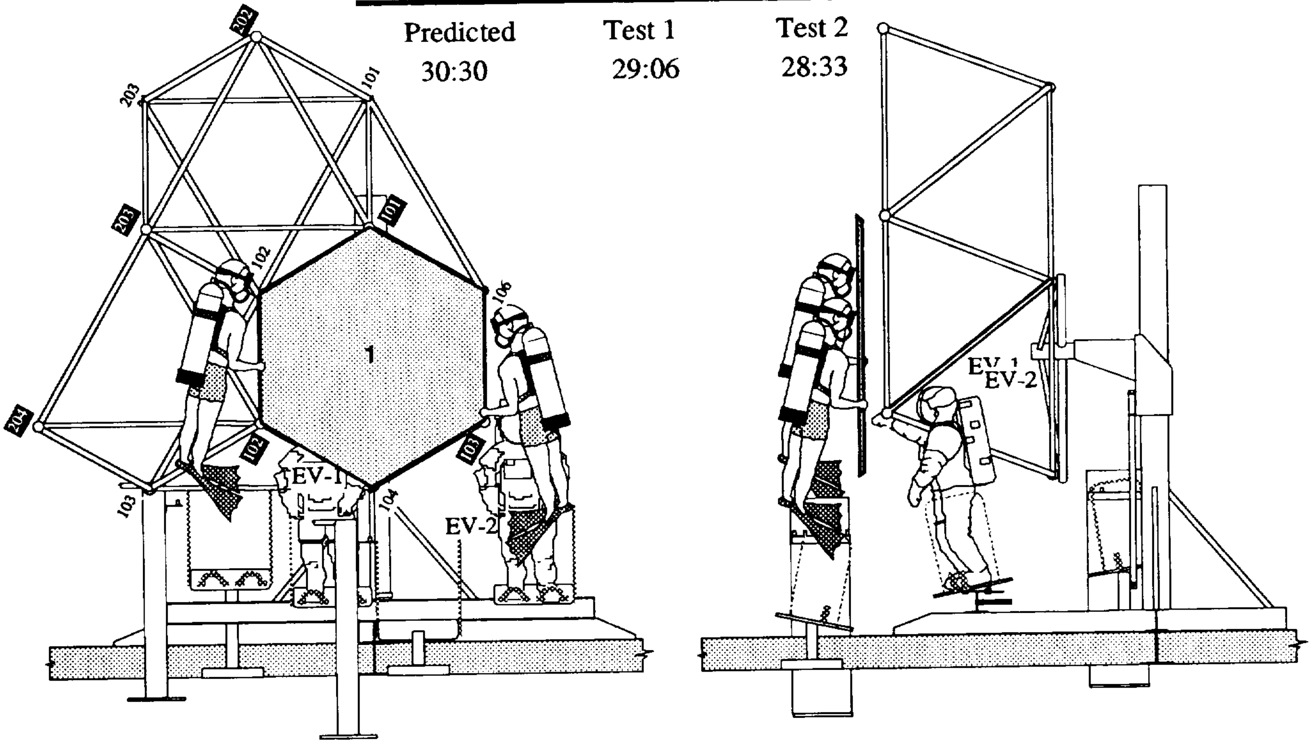


Figure 20. Continued.

Step 24

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
30:30	29:06	28:33



Step 25

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
31:30	30:08	28:58

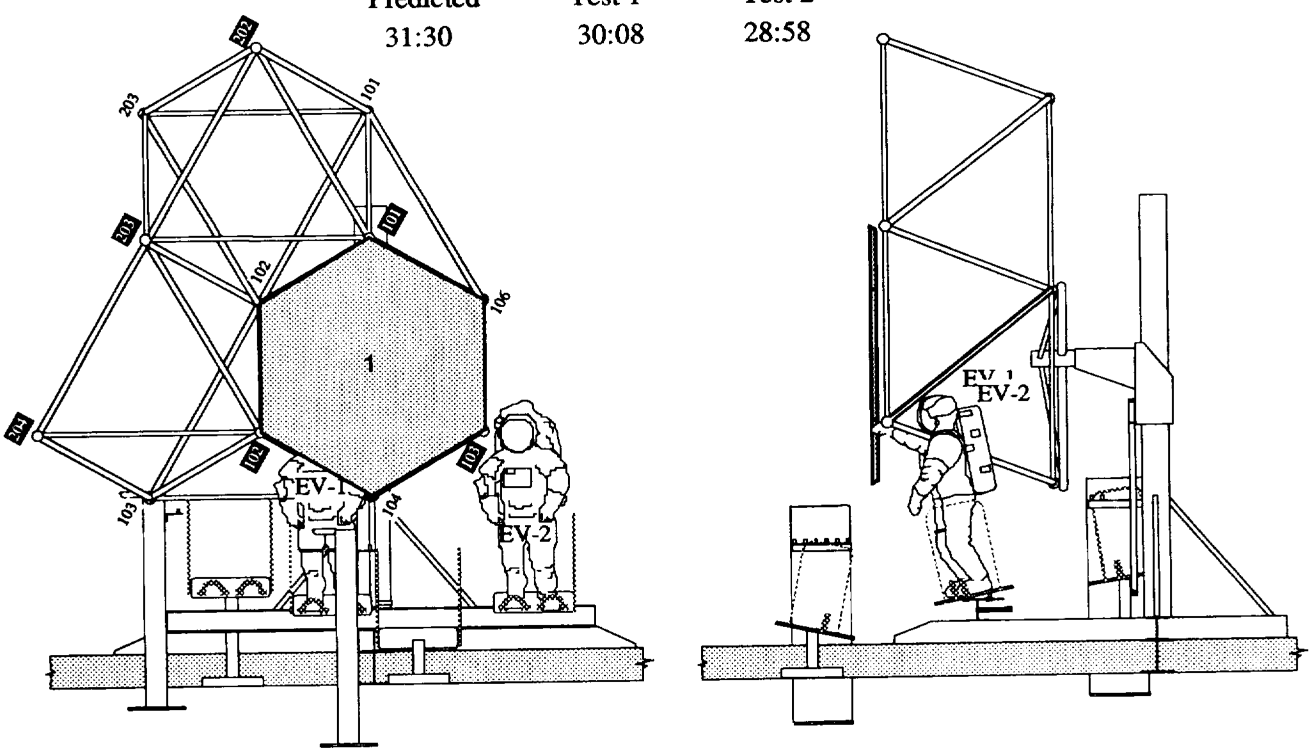
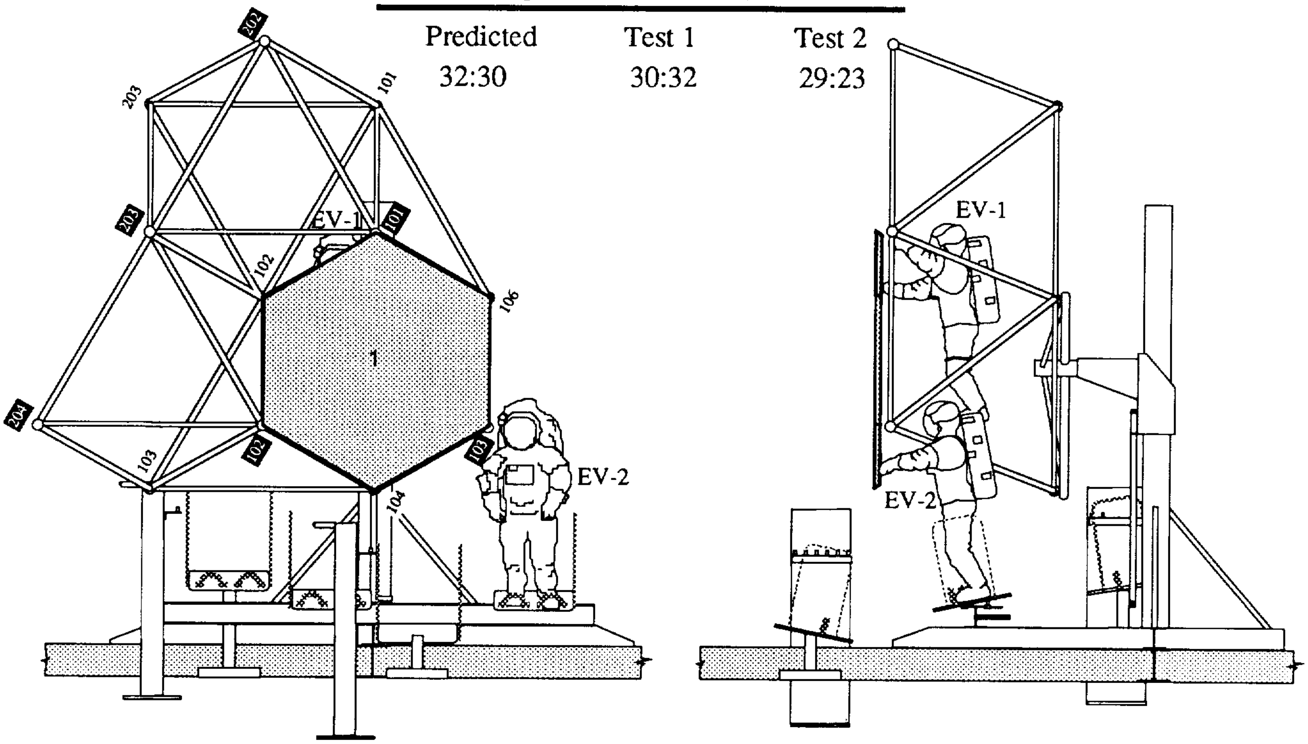


Figure 20. Continued.

Step 26

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
32:30	30:32	29:23



Step 27

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
36:50	36:28	35:05

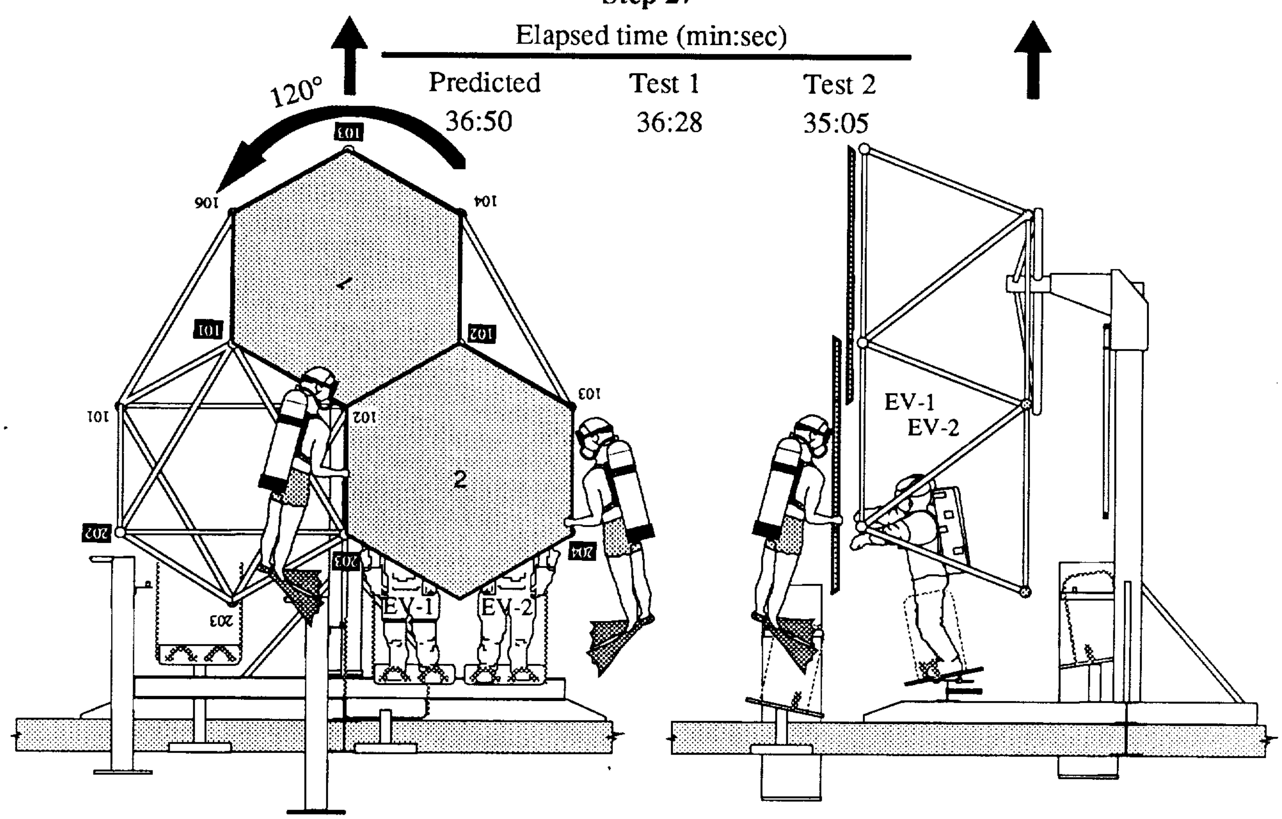
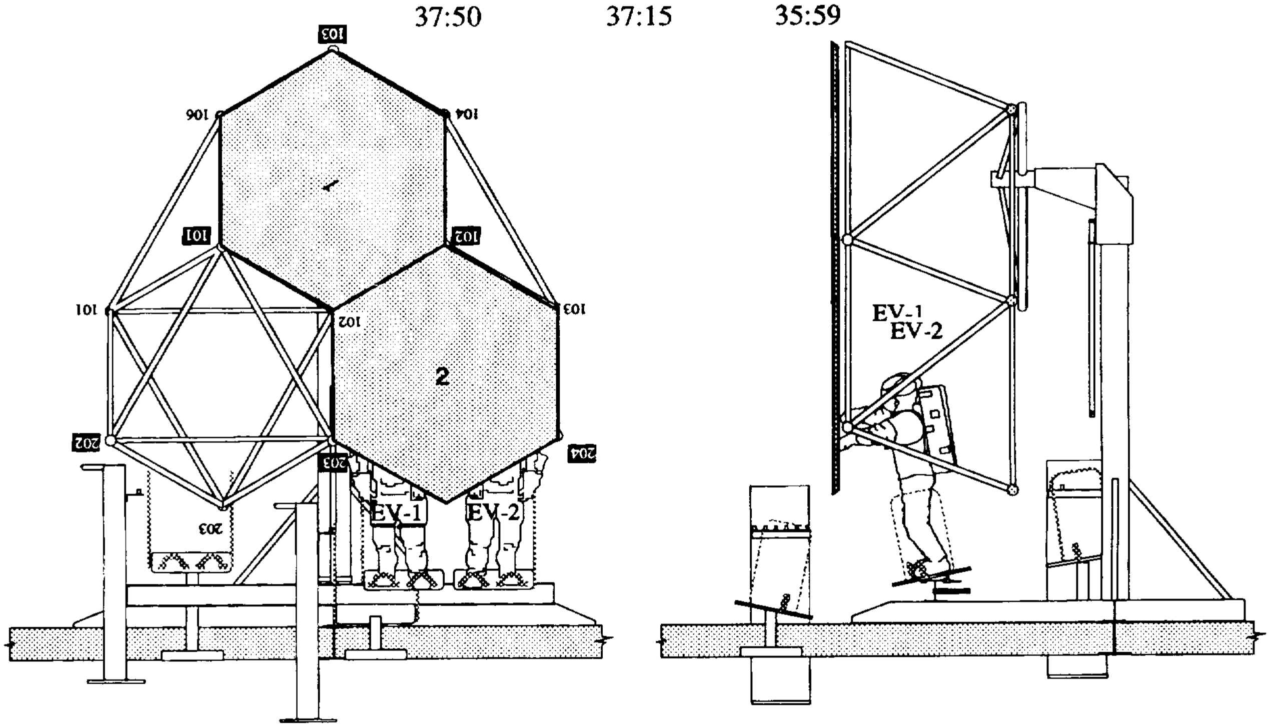


Figure 20. Continued.

Step 28

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
37:50	37:15	35:59



Step 29

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
38:50	37:39	36:45

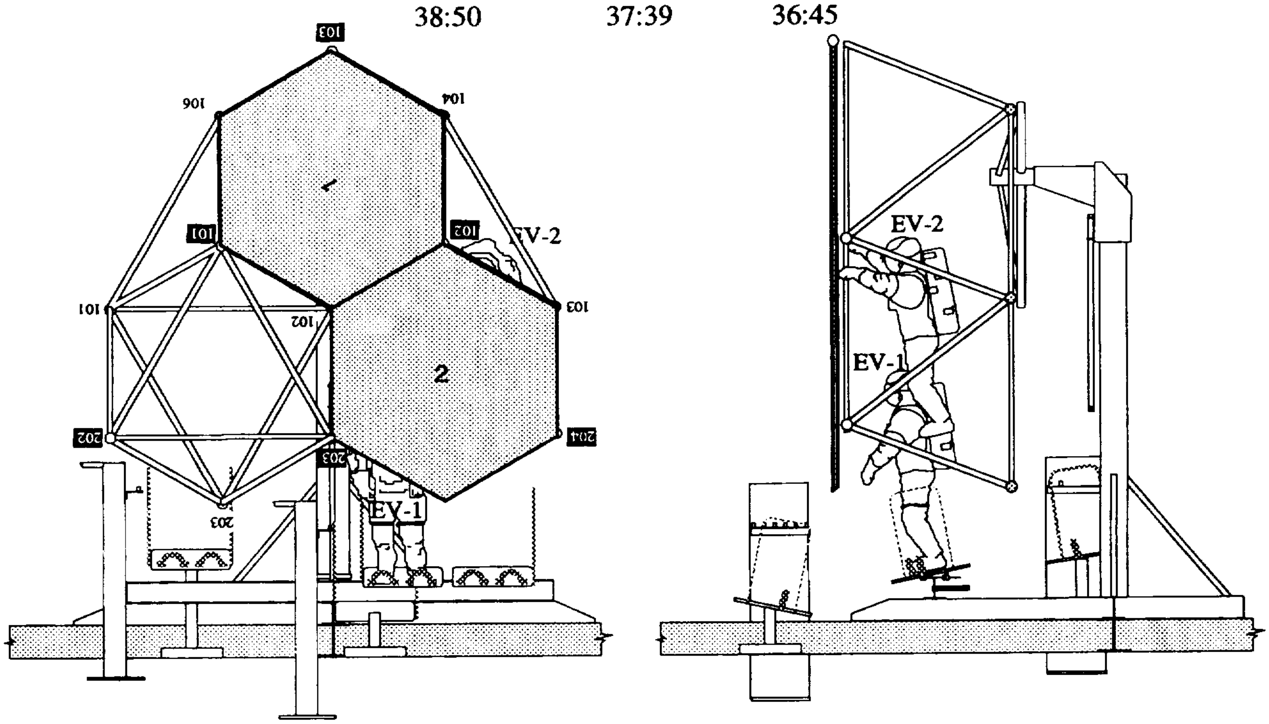
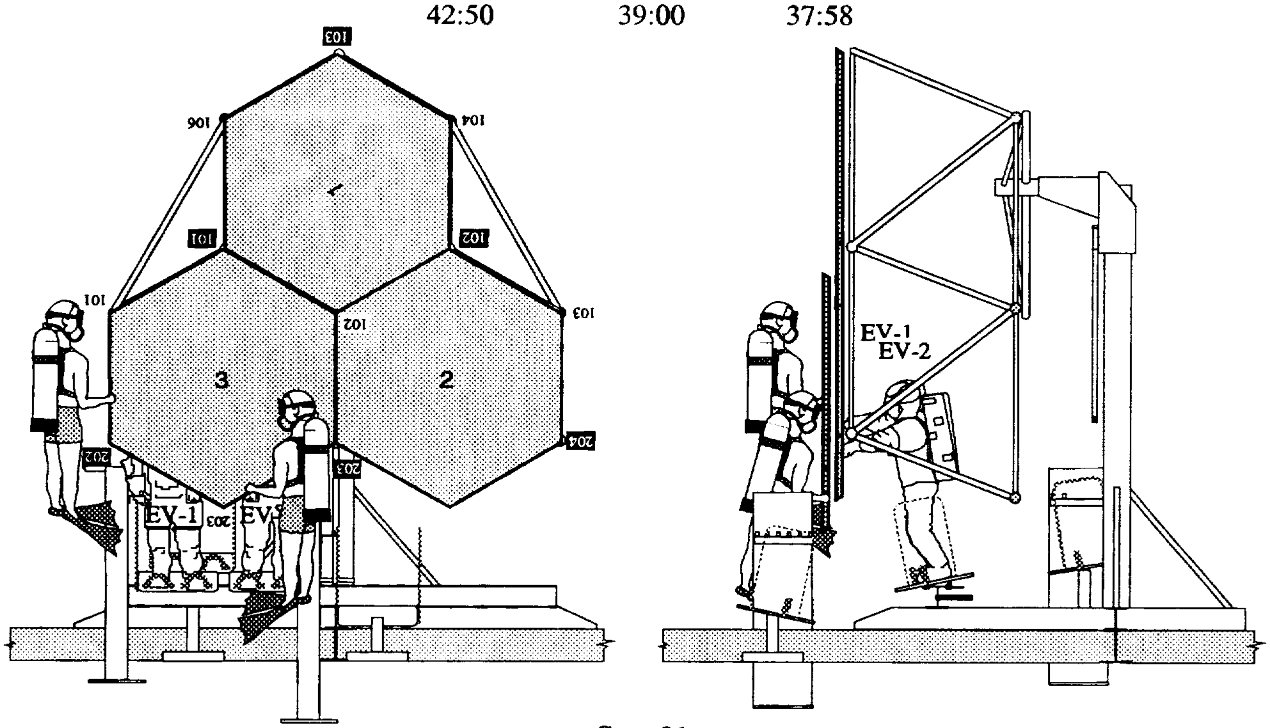


Figure 20. Continued.

Step 30

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
42:50	39:00	37:58



Step 31

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
43:50	39:36	38:21

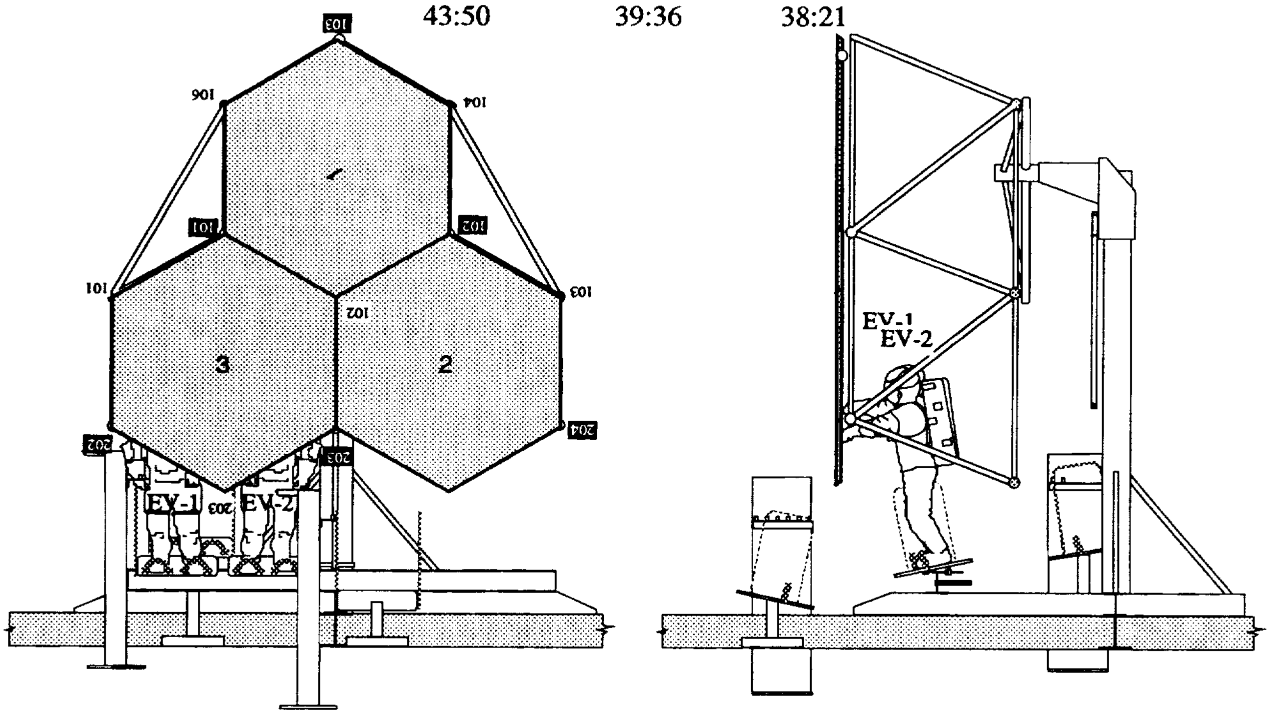
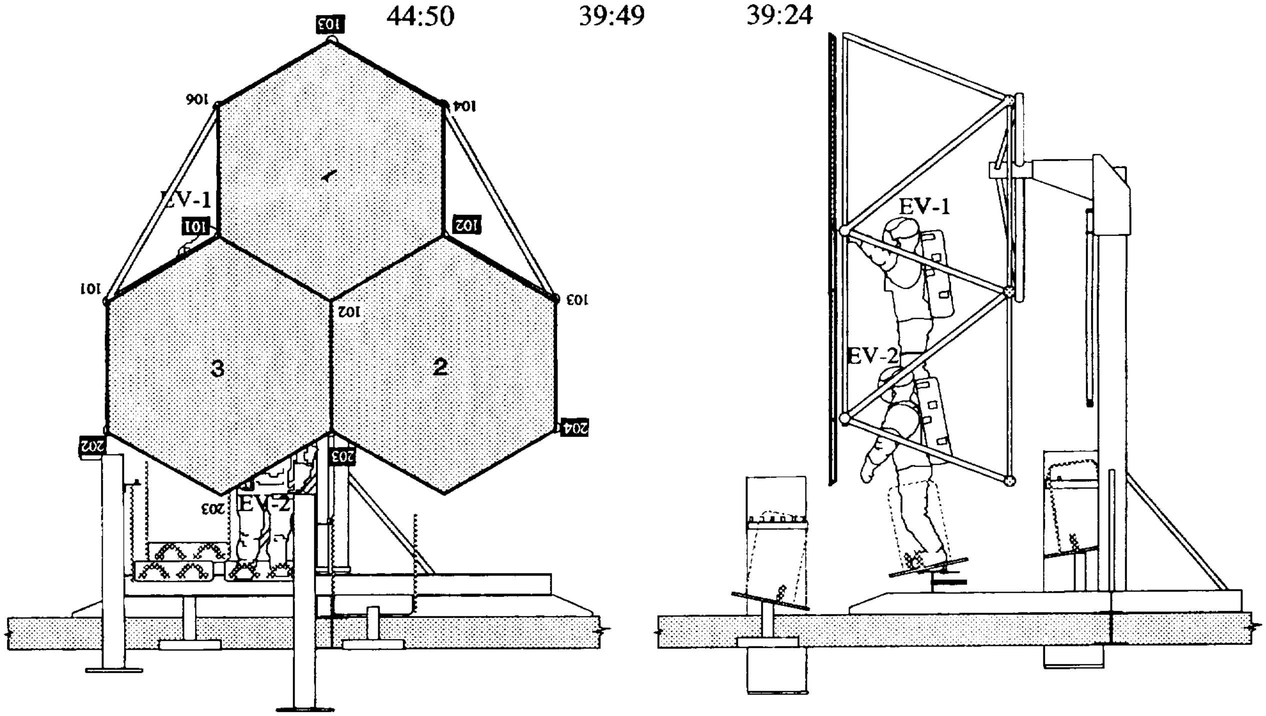


Figure 20. Continued.

Step 32

Elapsed time (min:sec)		
Predicted	Test 1	Test 2
44:50	39:49	39:24



End assembly

Figure 20. Concluded.

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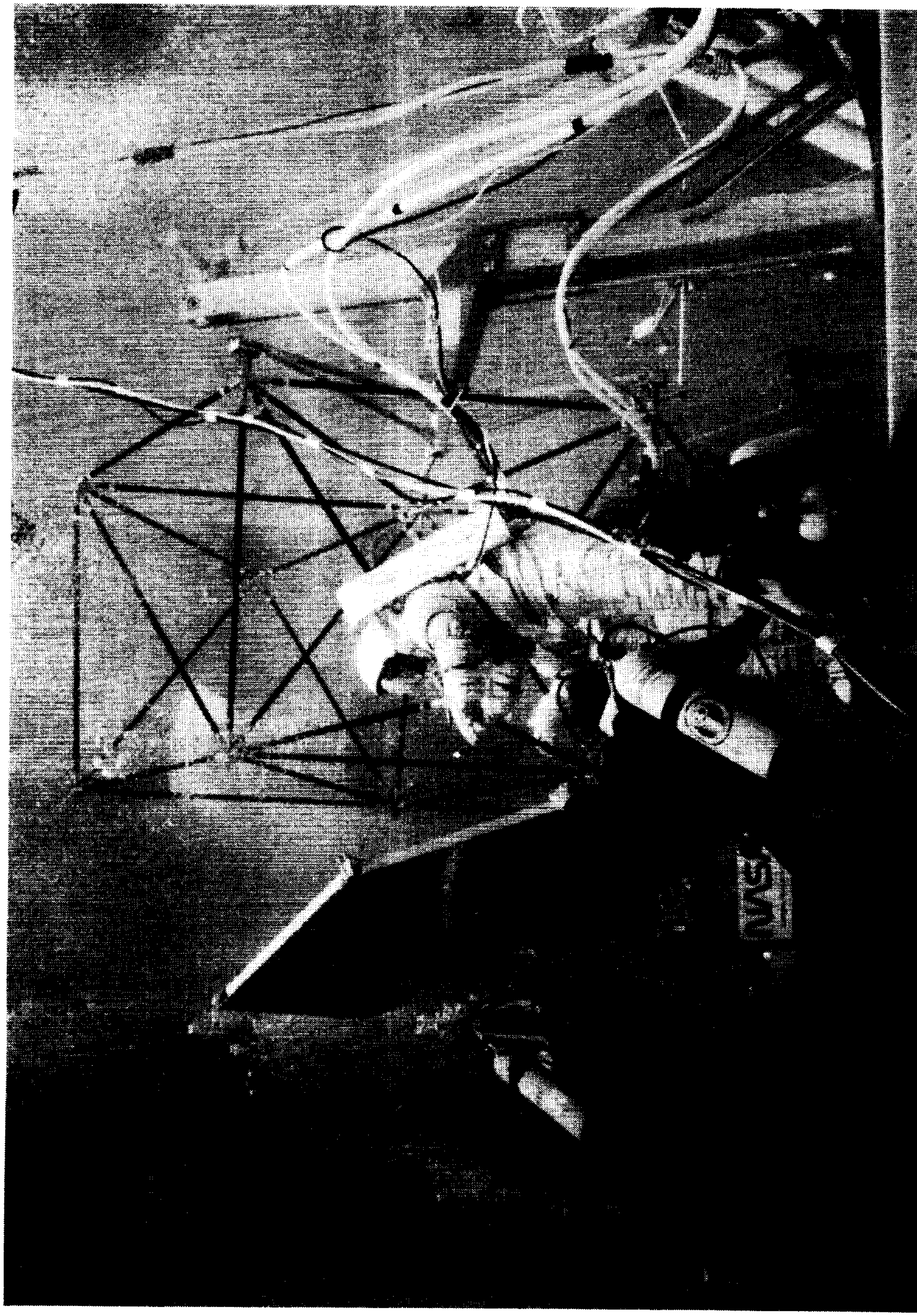
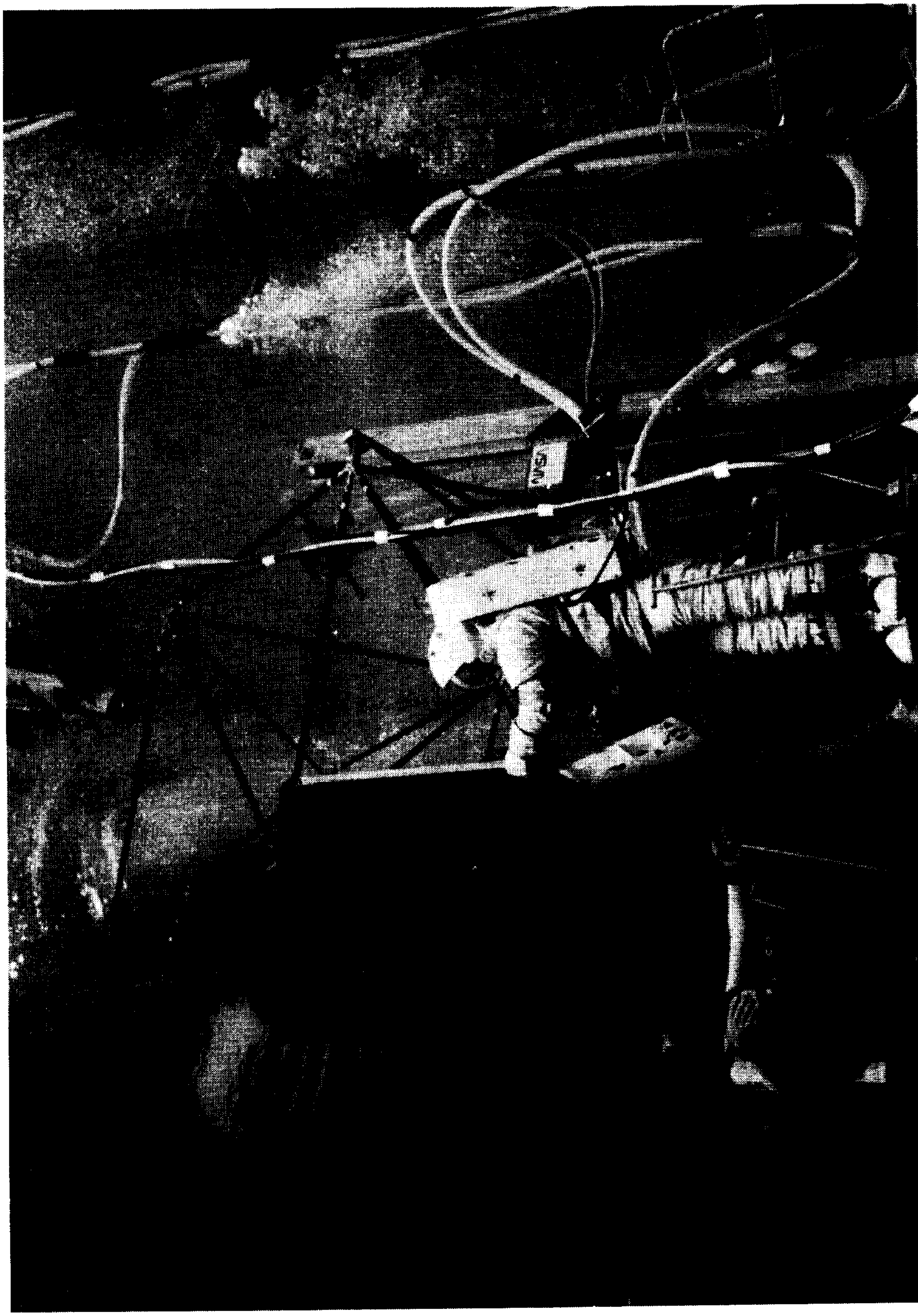


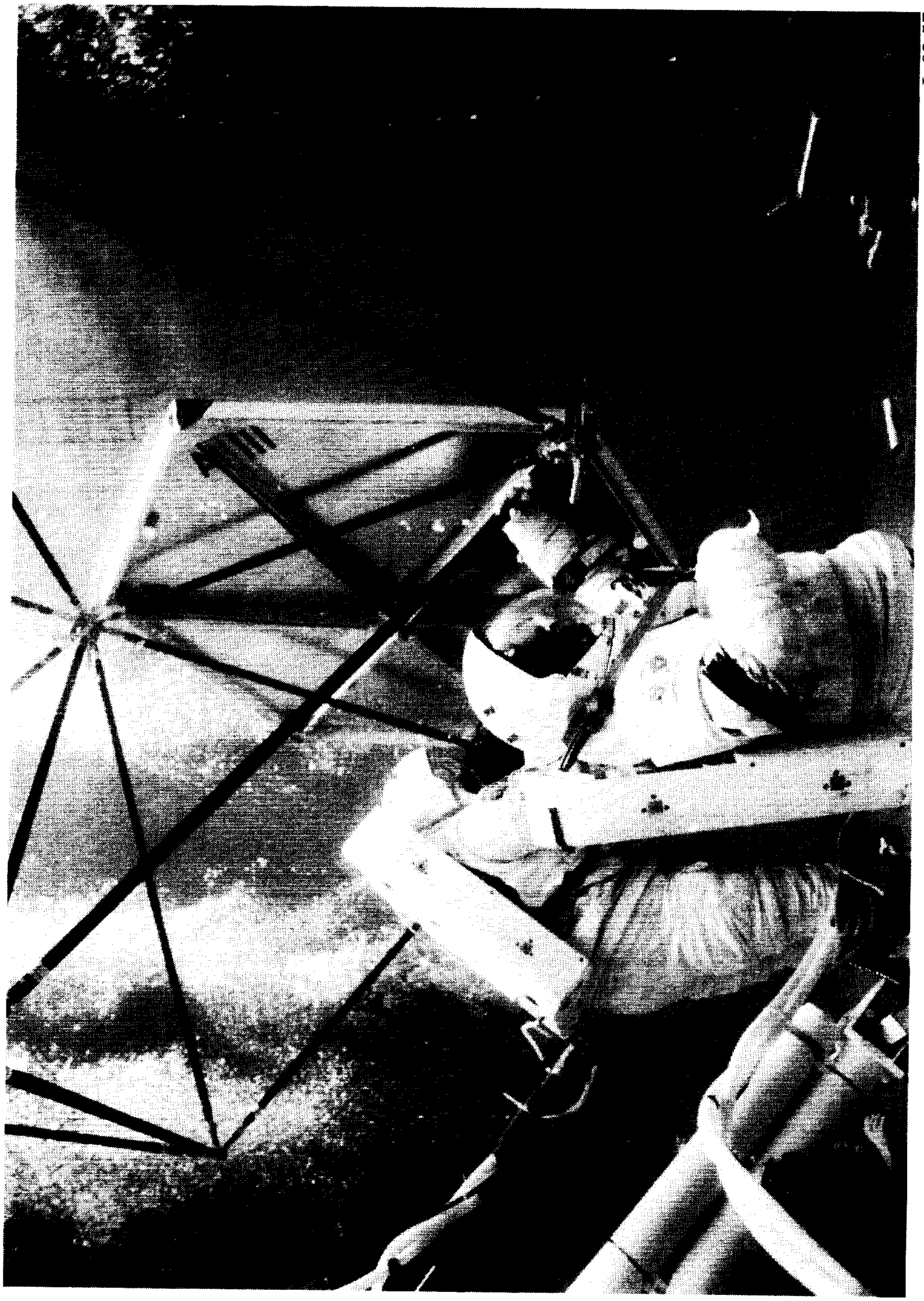
L-92-55

Figure 21. Positioning of panel by utility divers.



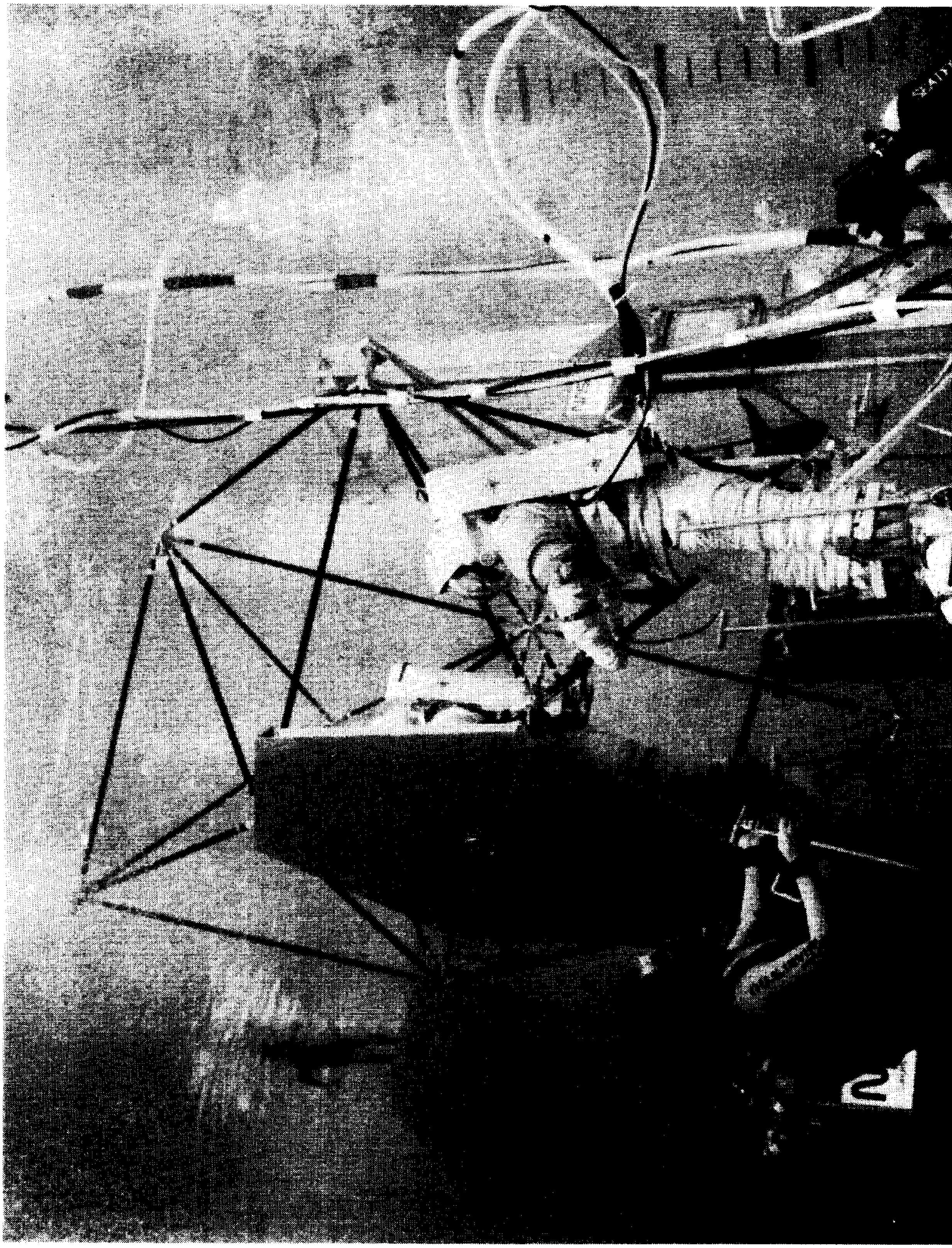
L-92-56

Figure 22. Attachment of panel to truss (front view).



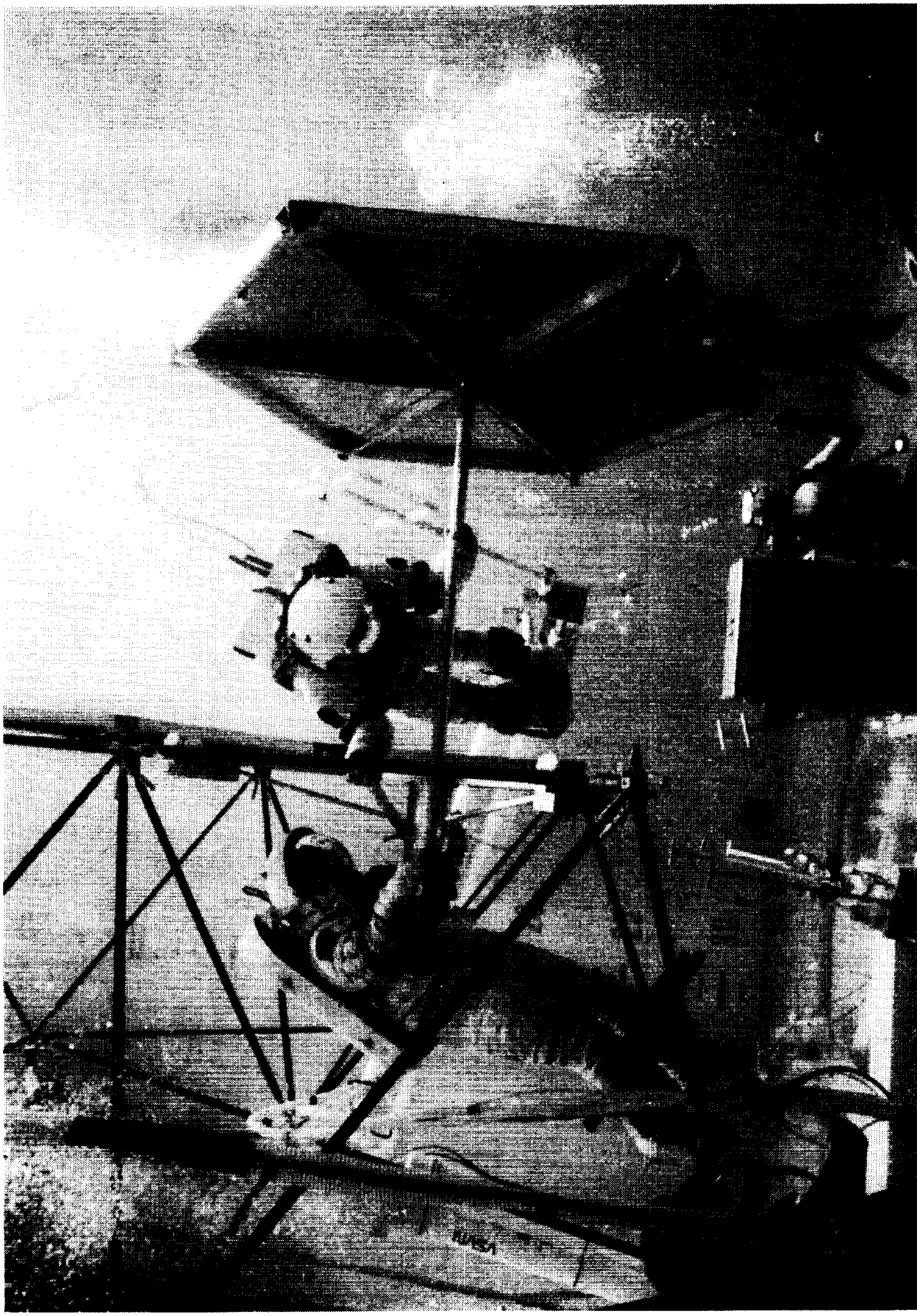
L-92-57

Figure 23. Attachment of panel to truss (back view).



L-92-58

Figure 24. Attachment of third panel-to-truss connection point.



L-92-59

Figure 25. Panel replacement activity.

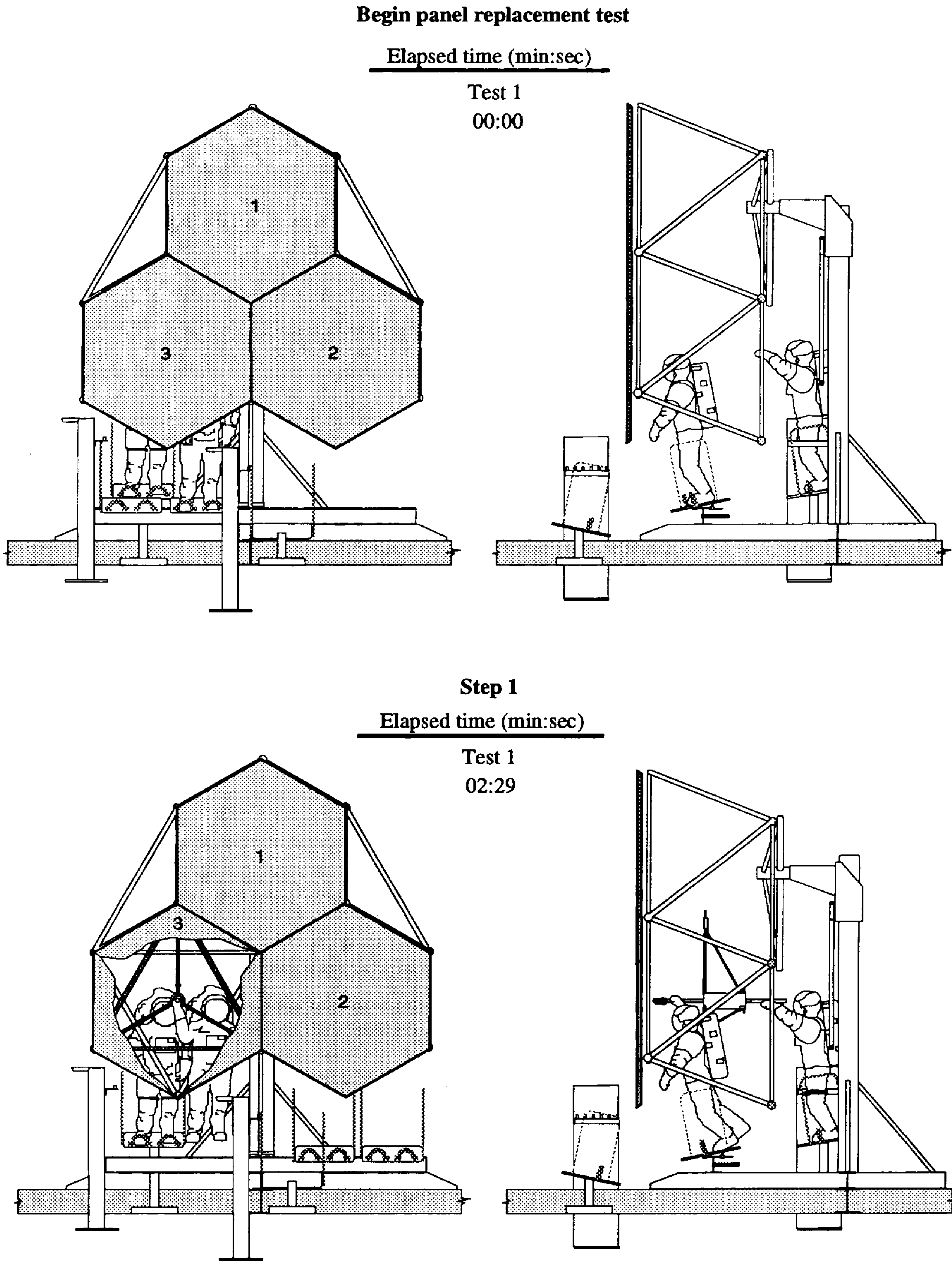


Figure 26. Panel replacement task times with design 1 panel attachment hardware.

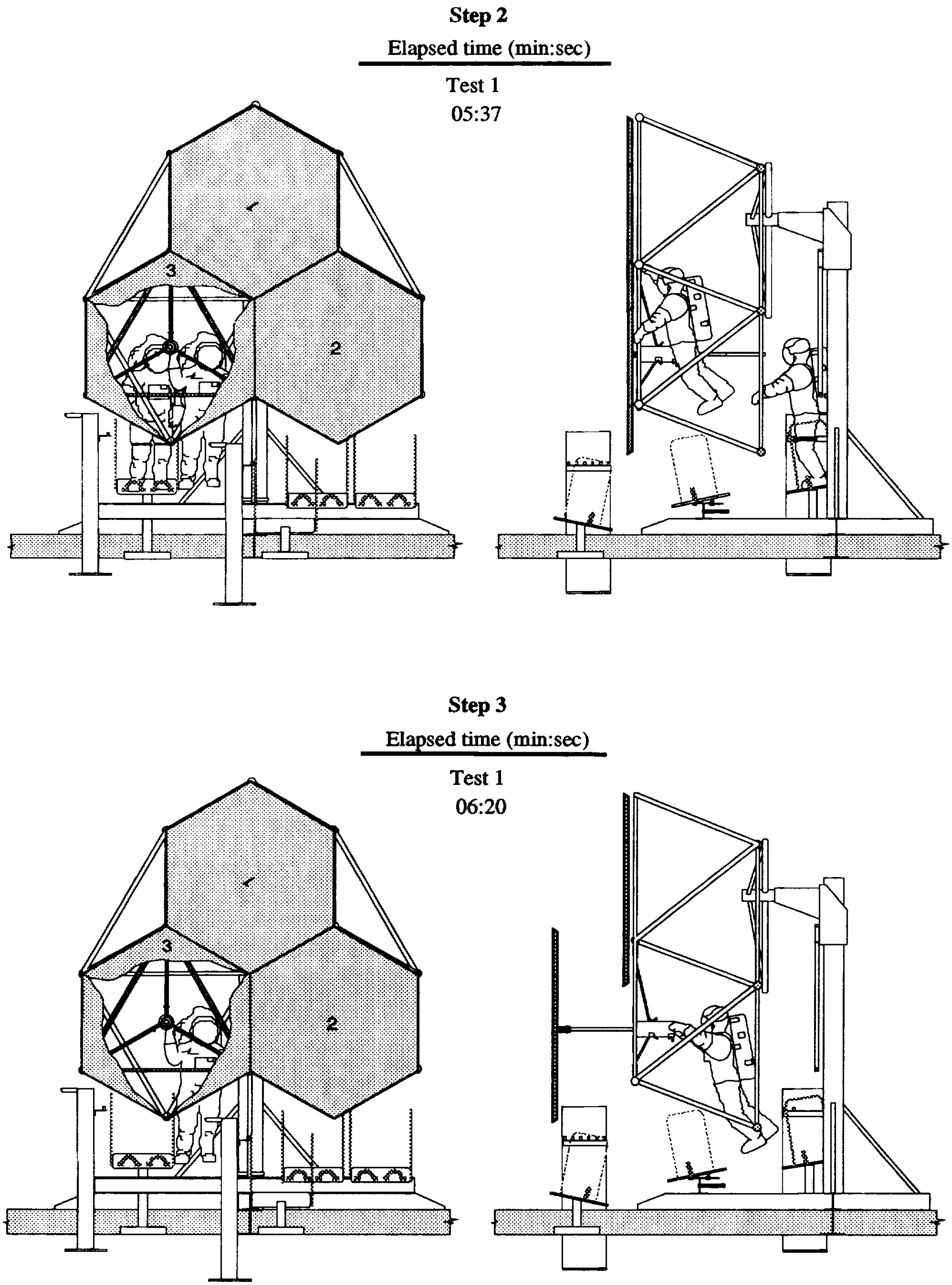


Figure 26. Continued.

Step 4

Elapsed time (min:sec)

Test 1

06:32

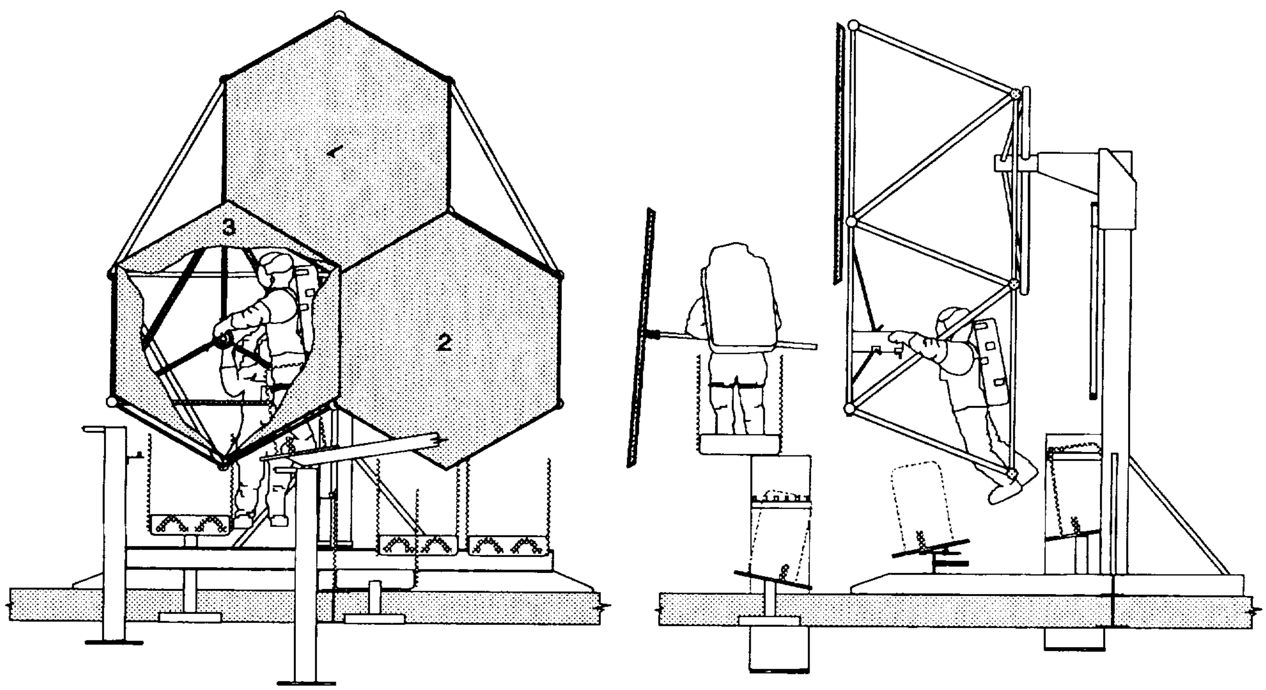


Figure 26. Concluded.

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13. ABSTRACT *(Maximum 200 words)*
This report presents results of tests performed in neutral buoyancy by two pressure-suited test subjects to simulate EVA tasks associated with the on-orbit construction and repair of a precision reflector spacecraft. Two complete neutral buoyancy assemblies of the test article (tetrahedral truss with three attached reflector panels) were performed. Truss joint hardware, two different panel attachment hardware concepts, and a panel replacement tool were evaluated. The test subjects found the operation and size of the truss joint hardware to be acceptable. Both panel attachment concepts were found to be EVA compatible, although one concept was judged by the test subjects to be considerably easier to operate. The average time to install a panel from a position within arm's reach of the test subjects was 1 min 14 sec. The panel replacement tool was used successfully to demonstrate the removal and replacement of a damaged reflector panel in 10 min 25 sec.

14. SUBJECT TERMS
EVA compatibility; Precision reflectors; Tetrahedral truss; Truss assembly; Simulated EVA assembly

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