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SUMMARY

This report presents results of a series of truss assembly tests conducted to evaluate a mobile work station concept intended to mechanically assist astronaut manual assembly of erectable space trusses. The tests involved assembly of a tetrahedral-truss beam by a pair of test subjects with and without pressure (space) suits, both in Earth gravity and in simulated zero gravity (neutral buoyancy in water). The beam was assembled from 38 identical graphite-epoxy nestable struts, 5.4 m in length with aluminum quick-attachment structural joints. Struts and joints were designed to closely simulate flight hardware. The assembled beam was approximately 16.5 m long and 4.5 m on each of the four sides of its diamond-shaped cross section. The results show that average in-space assembly rates of approximately 38 seconds per strut can be expected for struts of comparable size. This result is virtually independent of the overall size of the structure being assembled because translation of workers and equipment is limited to the length of a single strut. Movable platforms transport workers and material, so that workers are relieved of primary energy-expending tasks. Only simple, routine tasks of the assembly procedure are required of the workers. The mobile work station concept would improve astronaut assembly for on-orbit assembly of truss structures, and this assembly-line method is highly competitive with other construction methods being considered for large space structures.

INTRODUCTION

Previous studies (refs. 1, 2, 3, and 4) identified truss configurations such as those illustrated in figure 1 as prime candidates for low-mass, large-area space structures. Two approaches to the construction of such structures have led to two basic truss designs denoted "deployable" and "erectable." Deployable trusses are assembled on Earth, packaged by folding them for transportation to orbit in the Space Shuttle, and then automatically unfolded or deployed on-orbit. These trusses can become structurally complex and are difficult to package efficiently. In contrast, erectable trusses are assembled piece-by-piece on-orbit and are characterized by relative structural simplicity (ref. 5). In addition, erectable trusses assembled using nestable columns or "struts" are characterized by high packaging efficiency (ref. 6). Before these potential benefits of erectable trusses can be realized, however, efficient on-orbit assembly methods must be developed and demonstrated. Techniques for on-orbit automatic assembly of erectable structures have been devised (ref. 7). These techniques appear feasible and could lead to rapid assembly; however, they require development of complex and probably expensive equipment. On-orbit manual assembly, on the other hand, is an alternative which would have a high payoff potential. The manual assembly approach would exploit human capability and would avoid development costs and space testing of complex automated equipment.

Ground test programs (refs. 8, 9, and 10) have been conducted to assess the potential of manned extravehicular activity (EVA) for assembly of erectable trusses. These programs have examined a variety of quick joining methods and manual assembly procedures including some mechanically assisted modes of operation using a simulated remote manipulator arm. All have concluded that astronaut EVA assembly is well within human capabilities. Assembly tasks have been broken down into basic steps to obtain average elemental times of performance which can be used to predict assembly times for larger and more complex structures. These task element times are useful for strictly manual assembly rate predictions, but for assembly of larger structures involving astronaut and material translation, translational time must be considered. Totally manual assembly quickly becomes impractical as the size of the structure increases. Therefore, the concept of a mobile work station was developed. The mobile work station virtually eliminates the dependency of translational times on the size of the structure. It is an assembly-line method where translational requirements are limited to the length of a single strut. The construction tasks are simple and repetitive; many, if not all, struts can be identical, and quick-attachment joints can eliminate the need for tools.

The purpose of this report is to present a boiler-plate version of the mobile work station. It was fabricated and ground tested to demonstrate qualitatively and quantitatively the potential of mechanically aided astronaut assembly of space truss structures. To demonstrate the concept, a beamlike truss was assembled from prefabricated struts. A series of assembly tests was performed in both 1-g (Earth gravity in air) and simulated 0-g (neutral buoyancy in water) environments where $g = 9.8\ \mathrm{m/s^2}$. This report describes the mobile work station, truss hardware, and assembly tests. In addition, assembly rates obtained from the mobile work station tests are compared with results obtained from totally manual assembly tests and theoretical results for automated assembly. A motion-picture film supplement showing the simulated 0-g tests is available on loan. A request form and a description of the film (L-1289) are found in the back of this report on page 35.

APPARATUS

Truss Hardware

Struts.- Thirty-eight graphite-epoxy nestable struts, each approximately 5.4 m long with a mass of approximately 1.6 kg, were assembled to form a beamlike segment of a tetrahedral truss. This truss was 16.5 m long and 4.5 m on each of the four sides of its diamond-shaped cross section. (See fig. 1.) A typical full strut, shown in the lower photograph in figure 2, is formed from two conical half-struts joined at their larger ends (center photograph). The half-struts are shown nested for packaging in the upper photograph in figure 2. Aluminum quick-attachment end fittings were integrally bonded to the smaller ends of the half-struts during fabrication for precise fitting placement. Details of the half-strut manufacturing process are given in reference 11, and the half-strut dimensions are given in figure 3. The fittings at the small diameter end of the half-struts were threaded as shown in figure 3 to receive a quick-attachment joint half and facilitate final length adjustment. The final length was adjusted in a fixture with a reference half-strut that was fixed at one end and attached to a floating head at the other end as shown in figure 4. The floating head compensated for thermally induced length variations and thus permitted all half-struts to be set at ambient temperature to within ± 0.051 mm of the length of the reference half-strut. The full struts were then assembled prior to the tests by joining plus tolerance to minus tolerance half-struts. This method made it possible to maintain a length error for the full struts of less than one part in 100 000. (It was assumed that since all struts were manufactured identically, all had the same coefficient of thermal expansion.)

Strut center joint fittings.- Two half-struts were held together at their large diameter ends by interlocking spring latches of the strut center fittings shown unassembled in figure 5(a). The spring latches of the fittings were tapered to facilitate alignment of the joint halves (fig. 5(b)). Once the joint halves were aligned, only a short translational (axial) motion of a half-strut was required to latch the joint. Figure 5(c) shows the joint fully assembled.

Strut end joint fittings and nodal cluster.- A strut being attached to a nodal cluster fitting is shown in figure 6. The joint, which is designed for both quick attachment and quick release, has an internal spring-loaded latching pawl as shown in a longitudinal section of the joint in figure 7. The left-hand half of the joint shown in figure 7 is preattached to a nodal cluster (along with the proper number of other similar fittings) as shown in figure 6. The right-hand half of the joint shown in figure 7 is permanently attached to a strut. Transfer of load through the joint is accomplished by semicircular tongues and grooves as described in reference 9. A series of photographs presented in figure 8 shows the side installation feature which permits attachment of an undeformed strut between two fixed nodes. The joint is disassembled by pressing the latching pawl release lever as shown in the lower photograph in figure 8.

Neutral buoyancy compensators.- For the simulated 0-g assembly tests, neutral buoyancy of the struts was required. Neutral buoyancy compensators were used for this purpose as shown in figure 9. A neutral buoyancy compensator was inserted into the small diameter end of each half-strut; the threaded end fitting was then screwed on loosely and installed permanently with 1.59-mm-diameter roll pins during the final length setting operation in the length setting fixture. The compensator was made of stiff polycarbonate plastic and had two separate compartments. The larger compartment was a sealed (airtight) air chamber of a fixed volume, which provided positive buoyancy to the half-strut in water. The smaller compartment was not airtight and contained lead shot ballast, which was gradually added through a small orifice with a door to precisely trim the half-strut to a neutrally buoyant, vertically oriented condition at arbitrary water depth (0 to 12 m). When the half-struts were assembled, the full strut was neutrally buoyant in any orientation.

Strut retainer clips (1-g assembly tests).- As indicated earlier, assembly tests of the tetrahedral-truss beam were performed in both 1-g and simulated 0-g environments. Although two test subjects participated in each assembly test, only for the struts spanning the mobile work station (transverse struts) could both ends be connected simultaneously by the test subjects. All the other struts required installation by one test subject working alone. During these installations, the far end of the strut did not necessarily latch. Therefore, to conduct the 1-g tests, the retainer clip shown in figure 10 was devised to support the far end of the strut (simulating the 0-g condition) until the test subject could be translated to the opposite end to verify or latch the connection.

Mobile Work Station Hardware

A subscale model of the mobile work station developed for the ground tests in this study is shown in figure 11(a). The full-scale mobile work station hardware is shown in figure 11(b). The mobile work station consisted of pairs of four major components: (1) work platforms, (2) elevator towers, (3) trolley beds, and (4) conveyor rails. These components are shown in figure 11(a) attached to a model of the Shuttle orbiter cargo bay and supporting a tetrahedral-truss beam (black structure) which represents the truss structure assembled during this investigation. Note that one conveyor rail, shown in figure 11, was physically lower than the other so that during the 1-g tests, the test subjects could work in an upright position while assembling the tetrahedral-truss beam, which has a diamond-shaped cross section. The mass of the mobile work station hardware was about 1360 kg. This mass, as well as the volume of the structure, was required to react gravitational as well as inertial loads for the 1-g assembly operations and to meet the requirements of underwater operation for the simulated 0-g tests.

The mobile work station concept required two test subjects to use their eyes and hands to make the structural connections. Each subject worked from one of the movable platforms located on each side of the structure being assembled. The test subjects were secured by foot restraints on the work platforms at all times during the assembly and were moved within a prescribed planar work envelope as required. The platforms moved up and down on the towers, and the towers moved left and right on the trolley beds. These components and the assembled segments of the truss were moved by five air motors controlled by a third subject at a remote control console. The air motors and control system were not representative of flight hardware, but were used to facilitate underwater operation. In space, motors and controls would presumably be electrical, and the controls might be placed on each work platform; thus the need for a third astronaut and remote control console might be eliminated. For the present tests, the platforms were moved at approximately 0.333 m/s, although this speed varied somewhat because of hydrodynamic drag and deterioration of the hardware in the corrosive water environment.

TESTS

Test Setup

A series of 1-g and simulated 0-g assembly tests was performed. The 1-g tests were performed at the Langley Research Center with the test subjects in street clothes. The mobile work station was located inside a building and attached to a concrete floor as shown in figure 12. The simulated 0-g tests were performed underwater in the Neutral Buoyancy Simulator at the Marshall Space Flight Center (fig. 13) with the test subjects in NASA A7L-B Skylab pressure suits. (One test in this facility was performed with the test subjects in scuba gear.) For the simulated 0-g tests, the mobile work station was attached to the sills of a full-scale mock-up of the Shuttle cargo bay as shown in figure 13. The 38 struts used to assemble the beam were stored in racks located to the left and right of each test subject. The strut racks were mounted to the movable towers so that the stored struts were always within arm's reach of a test subject (fig. 14). Figure 12 shows the strut racks without the struts, and figure 13 shows the strut racks fully loaded. All the hoses shown in figures 12 and 13 are air supply lines to the air motors and would not be present in an actual flight version of this concept.

The lower nodal clusters, which were stored in the conveyor rail tracks, were equipped with teflon slider pads. A conveyor chain was located in the high-side conveyor rail and was equipped with fittings at one-strut-length spacings. With the conveyor chain operating, these fittings automatically picked up and slid the nodal clusters from the storage area along the tracks to the proper locations for receiving the struts. The nodal clusters that were stored in the low-side conveyor rail track were manually slid from the storage location to premarked positions for assembly by the test subject. The upper nodal clusters were stored on the tops of the strut racks (fig. 14) within arm's reach of the test subjects. The clusters were attached to the strut racks by quick-attachment, quick-release joints similar to those used in the truss structure. The upper nodal clusters used for the immediate beam segment being assembled were supported by vertical aluminum masts (fig. 12) that were clamped to the conveyor rails at the appropriate locations (one strut length apart on the low-side conveyor rail and one-half strut length apart on the high-side conveyor rail). The test subjects attached these upper nodal clusters to the masts at the proper height with quick-attachment, quick-release joints.

All simulated 0-g tests were recorded by five permanently mounted videotape cameras with different view angles. The videotapes included voice recordings of the test subjects during the assembly tests. In addition, 16-mm motion pictures and 35-mm still photographs were taken with portable underwater cameras. The 1-g tests were recorded by still photographs only.

Test Procedure

The assembly logistics for the 1-g (atmospheric) and 0-g (underwater) tests were identical. Five work positions were located on each side of the mobile work station. These work positions are designated by the double letters in the schematic shown in figure 15. Work positions A, B, and C were located on the conveyor rails, while positions D and E were located at the tops of the node holder masts. Work positions on the low-side conveyor rail were designated LA, LB, LC, LD, and LE, while those on the high-side conveyor rail were designated HA, HB, HC, HD, and HE. The tests were initiated with both test subjects secured by the foot restraints on the work platforms and the console operator in position. All systems were in operational readiness (two-way voice communication was established between the test subjects and the console operator), and the struts were stored in the strut racks adjacent to each work platform. The high-side platform was located at position HA and the low-side platform was located at position LE. The nodal cluster joint fittings, numbered from 1 to 14 (fig. 15), were located at the positions indicated in table I.

The same three subjects performed all timed tests - two test subjects located in the mobile platforms to actually assemble the truss structure and the third subject at the remote control console. The two basic tasks of the test subjects were to install a strut together by simultaneously attaching the two ends as shown in figure 16, or to install a strut alone by attaching one end as shown in figure 17, translating to the other end, and completing the installation. The fully assembled truss in the simulated 0-g environment is shown in figure 18.

A number of 1-g tests were performed to develop the assembly procedure, which is presented in the appendix of this paper. Once this procedure was developed, several 1-g tests were timed to establish assembly rates. For the 1-g tests, the subjects were randomly interchanged to become proficient in all aspects of the operation.

After an initial shakedown assembly test in the Neutral Buoyancy Simulator, five simulated 0-g tests (four with the test subjects in pressure suits and one with the test subjects in scuba gear) were conducted and timed. For these tests, there was no interchange of position among the test subjects. In all but the scuba gear test, the console operator controlled the tests by following the assembly procedure so that he could relay the correct instructions over the two-way voice communications system. The scuba gear test was conducted with no voice communications between the console operator and test subjects. Instead, hand signals were used to indicate to the console operator when a particular task was completed. In addition, following instructions from the console operator, two pairs of NASA astronauts who were unfamiliar with the mobile work station and the truss hardware performed two simulated 0-g partial assemblies. These subjects were given only a short pretest briefing on terminology and quick-attachment joints before each assembly.

RESULTS AND DISCUSSION

A 5-minute film supplement of the simulated 0-g tests is available upon request. A request form for this supplement appears at the back of this report (p. 35).

Assembly Logistics

Although an effective systematic assembly procedure was developed for these tests (see appendix), no attempt was made to determine the optimum method. Because of the repetitiveness of the steps, however, the test subjects quickly learned their respective tasks during the 1-g tests, and little voice communication was required for subsequent tests other than the voice signal "ready" by the test subjects when a particular task was completed. In fact, the one test that was performed in scuba gear was conducted without voice communications, with only hand signals and television monitors to aid the console operator. The two untimed, simulated 0-g assemblies by NASA astronauts who were inexperienced with the mobile work station were performed with little difficulty and no logistics confusion.

Although tethering of the men and struts may be a requirement in space, no tethers were used in the present tests. The test subjects were not required to leave their respective foot restraints at any time during the assembly tests; thus, man tethers were not necessary. Strut and joint tethers were not used nor were they needed. All struts, including those requiring one-man assembly, were easily installed without incident in both gravitational and neutral buoyancy tests. No climbing on the structure was required; thus the struts remained in place while the test subject was translated to make the opposite end connection.

The significant feature of the mobile work station concept is that large structures in space could be effectively assembled with a selected combination of human and mechanical operations. The mobile work station would relieve the workers of tedious tasks of manually moving themselves and the truss structural components over large distances. In addition, the mobile work station would position the workers at the correct location and orientation to locate and latch each strut element and would react all assembly task loads. A space version of the mobile work station may have a somewhat different configuration from the boiler-plate model used in this study because a space model would not have to operate under the restrictive conditions of gravity and drag experienced with operations in water. Even though the mobile work station is illustrated in this report attached to the Shuttle (fig. 11(a)), it could also be attached to a space operations center (space station) or be designed as a free flyer. In the present tests, a beamlike truss was assembled; however, the concept, with minor modifications, is also applicable to the construction of large platforms. A beam could be assembled in one direction, raised one bay width in the mobile work station, and translated in the opposite direction while assembly is continued underneath the structure. This process could be repeated until the desired platform is assembled. Auxiliary equipment or utilities could be attached during assembly as required.

Assembly Rates

Rates of assembly of the 38-strut truss using the mobile work station are shown in table II for three ground test conditions. Also shown is an estimated assembly rate for space operation of the mobile work station. The 1-g assembly in street clothes and air took an average of 24 seconds per strut. Maneuvering the struts in air is more realistic of space operation than in water because of water drag effects; however, the test subjects were not impeded by pressure suits for the 1-g tests. The effects of gravity were of little consequence because the struts had a mass of only 1.6 kg each and thus were easily handled by the test subjects in the 1-g environment. The assembly performed in neutral buoyancy in scuba gear averaged 39 seconds per strut. Thus, water drag added about 15 seconds per strut to the assembly rate in air. Finally, assembly in neutral buoyancy in a pressure suit required an average of 53 seconds per strut. Thus, the pressure suit encumbrance added another 14 seconds per strut to the neutral buoyancy assembly rate obtained in scuba gear. An assembly rate for space operation may be approximated as follows:

$$\begin{pmatrix}\text{Assembly rate}\\\text{in space}\end{pmatrix} \approx \overbrace{\begin{pmatrix}\text{0-g assembly}\\\text{rate in}\\\text{pressure suit}\end{pmatrix}}^{\text{Tank test}} - \overbrace{\left[\begin{pmatrix}\text{0-g assembly}\\\text{rate in}\\\text{scuba gear}\end{pmatrix} - \begin{pmatrix}\text{1-g assembly}\\\text{rate in}\\\text{street clothes}\end{pmatrix}\right]}^{\text{Water drag}}$$

Thus, the projected assembly rate in space appears to be about 38 seconds per strut. The identical result can also be obtained by adding the 14 seconds per strut due to pressure suit restrictions to the 1-g assembly rate obtained in street clothes, 24 seconds per strut.

Comparison of On-Orbit Assembly Methods

A preliminary indication of how the mobile work station assembly capability compares with other on-orbit assembly methods is given in figure 19. In this figure, the on-orbit assembly time in days is plotted as a function of assembly rate in struts per day for hexagonal planform tetrahedral-truss platforms of various sizes. All platforms are assumed to be assembled from struts 20 m long. The dashed line in figure 19 represents the present 5-day on-orbit operational limit of the Space Shuttle. The three shaded vertical bars represent ranges of assembly rates that may be expected for (1) strictly manual EVA assembly (rates based on data obtained from neutral buoyancy assembly tests of a six-strut tetrahedral-truss structure, refs. 8 and 9), (2) assembly with the mobile work station (data presented herein), and (3) automatic machine assembly (rates derived from theoretical time lines). For manual and mobile work station assembly, 8-hour workdays are assumed, for automatic assembly, 24-hour workdays are assumed (ref. 7). The mobile work station assembly rate is approximately a factor of 5 faster than strictly manual assembly and approaches predictions for automatic assembly. Note, however, that totally manual assembly requires manual translation of the astronauts and material and becomes increasingly prohibitive as the size of the structure increases. With the mobile work station, astronaut and material translation is performed mechanically and the distances depend only on the length of the struts and not on the size of the structure. Thus, long manual translation times, which can lead to early astronaut fatigue, are eliminated and extravehicular time is devoted primarily to structural assembly.

CONCLUDING REMARKS

Tests were conducted to evaluate a mobile work station concept that would enhance astronaut capability for on-orbit assembly of erectable space trusses. A tetrahedral-truss beam was assembled by a pair of test subjects with and without pressure (space) suits, both in Earth gravity and in simulated zero gravity (neutral buoyancy in water). The beam was assembled from 38 identical graphite-epoxy nestable struts, 5.4 m long, with aluminum quick-attachment structural joints. The struts were preset to precision lengths at ambient temperature in a length setting fixture, so that assembly of the structurally redundant truss was relatively easy. Struts and joints were designed to closely simulate flight hardware. The assembled beam was approximately 16.5 m long and 4.5 m on each of the four sides of its diamond-shaped cross section.

It was found that the assembly-line techniques which required only limited, simple, routine tasks of the test subjects lead to rapid assembly of truss structures in the mobile work station. Movable work platforms used to transport workers and material eliminated primary energy-expending tasks that would fatigue the workers; thus, they could concentrate on the less demanding tasks of installing struts. The test subjects remained attached by foot restraints to these platforms at all times during the assembly and were thus always in position to react assembly task loads. All assembly operations required of the test subjects were effectively performed in Skylab space suits. The routine tasks of the assembly procedure were quickly learned and were amenable to general truss structure. In fact, it was observed that the repetitive nature of the assembly tasks could lend themselves to preprogramming or electronic sequencing of the platform positions, with the assembly workers controlling the rate of the assembly sequence. Although a beamlike truss was assembled, the concept could be applicable to the construction of large platforms. A beam could be assembled in one direction, raised one bay width in the mobile work station, and translated in the opposite direction while assembly is continued underneath the structure. This process could be repeated until the desired platform is assembled.

The data showed that average in-space assembly rates of approximaely 38 seconds per strut can be expected for struts comparable in size to those used in the present tests. This result was virtually independent of the overall size of the structure being assembled. The mobile work station concept would improve astronaut efficiency for on-orbit assembly of truss structures, and the assembly-line method is highly competitive with other construction methods being considered for large space trusses.

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ASSEMBLY PROCEDURE

During the present tests, two test subjects assembled a tetrahedral-truss beam from 38 struts. The tests were initiated with the struts stored in strut racks adjacent to each work platform and with the nodal cluster joint fittings (numbered 1 to 14 in fig. 15) located as indicated in table I. Both test subjects were secured by foot restraints to the work platforms located at positions HA and LE (fig. 15). A console operator controlled the movement of the work platforms according to the following commands:

Down	Translate test subject vertically downward
Left	Translate test subject to his left one full strut length
Left 1/2	Translate test subject to his left one-half strut length
Right	Translate test subject to his right one full strut length
Right 1/2	Translate test subject to his right one-half strut length
Up	Translate test subject vertically upward

The following terms are used to describe the assembly tasks performed by the test subjects:

Pass	Pass one end of strut to other test subject
Perm. attach	Make permanent attachment
Receive	Receive one end of strut being passed by other test subject
Temp. attach	Make temporary attachment

A step-by-step listing of the assembly procedure follows:

Step	Low-side test subject	High-side test subject
1	Receive and perm. attach transverse strut	Pass and perm. attach transverse strut
2	Pass and perm. attach transverse strut	<u>Left 1/2, up</u>;* receive and perm. attach transverse strut
3	<u>Right</u>; receive and perm. attach transverse strut	Pass and perm. attach transverse strut
4	Pass and perm. attach transverse strut	<u>Left 1/2, down</u>; receive and perm. attach transverse strut

*Commands requiring translation are underlined.

Step	Low-side test subject	High-side test subject
5	Left 1/2, down;* receive and perm. attach transverse strut	Pass and perm. attach transverse strut
6	Pass and perm. attach transverse strut	Right; receive and perm. attach transverse strut
7	Perm. and temp. attach diagonal strut	Perm. and temp. attach diagonal strut
8	Left 1/2, up; perm. attach transverse strut	Left 1/2, up; perm. attach transverse strut
9	Perm. and temp. attach horizontal strut	Perm. and temp. attach diagonal strut
10	Right; perm. attach transverse strut	Left, down; perm. attach transverse strut
11	Perm. and temp. attach diagonal strut	Perm. and temp. attach horizontal strut
12	Left 1/2, down; perm. attach transverse strut	Right; perm. attach transverse strut
13	Left, up; release node 2	Left 1/2, up; release node 1
14	Right; release node 5	
Operate conveyor 1/2 strut length		
15	Install node 9	
16	Left 1/2; pass and perm. attach transverse strut	Left 1/2; receive and perm. attach transverse strut
17	Right, down; pass and perm. attach transverse strut	Perm. and temp. attach diagonal strut; Right 1/2 down; receive and perm. attach transverse strut; perm. attach transverse strut
18	Perm. and temp. attach horizontal strut	Left, up; perm. and temp. attach horizontal strut
19	Left; perm. attach transverse strut	Right; perm. attach transverse strut
20	Right; perm. and temp. attach diagonal strut	Left; release node 6
21	Left 1/2, up; perm. attach transverse strut	

*Commands requiring translation are underlined.

Step	Low-side test subject	High-side test subject
	Operate conveyor 1/2 strut length	
22	Down;* pass and perm. attach transverse strut	Down; insert node 14; receive and perm. attach transverse strut
23	Right, up; receive and perm. attach transverse strut	Pass and perm. attach transverse strut
24	Perm. and temp. attach diagonal strut	Perm. and temp. attach horizontal strut
25	Left 1/2, down; perm. attach transverse strut	Perm. and temp. attach diagonal strut
26	Right, up; perm. and temp. attach horizontal strut	Right; perm. attach transverse strut
27	Left; perm. attach transverse strut	Left 1/2, up; perm. attach transverse strut
28	Right; receive and perm. attach transverse strut; release node 9	Pass and perm. attach transverse strut; left 1/2
	Operate conveyor 1/2 strut length	
29	Install node 13	Install node 10
30	Left 1/2; receive and perm. attach transverse strut	Pass and perm. attach transverse strut
31	Right, down; pass and perm. attach transverse strut	Perm. and temp. attach diagonal strut; right 1/2, down; receive and perm. attach transverse strut; perm. attach transverse strut
32	Perm. and temp. attach horizontal strut	Left, up; perm. and temp. attach horizontal strut
33	Left; perm. attach transverse strut	Right; perm. attach transverse strut
34	Right; perm. and temp. attach diagonal strut	Left; release node 10
35	Left 1/2 up; perm. attach transverse strut	
	Operate conveyor 1/2 strut length	
36	Down; pass and perm. attach transverse strut	Down; receive and perm. attach transverse strut

*Commands requiring translation are underlined.

Step	Low-side test subject	High-side test subject
37	Right, up;* receive and perm. attach transverse strut	Pass and perm. attach transverse strut
38	Perm. and temp. attach diagonal strut	Perm. and temp. attach horizontal strut
39	Left 1/2, down; perm. attach transverse strut	Perm. and temp. attach diagonal strut
40	Right, up; Perm. and temp. attach hori-zontal strut	Right; perm. attach transverse strut
41	Left; perm. attach transverse strut	Left 1/2, up; perm. attach transverse strut
42	Right; receive and perm. attach trans-verse strut; release node 13	Pass and perm. attach transverse strut
43	Down	Left 1/2, down

*Commands requiring translation are underlined.

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TABLE I.- NODAL CLUSTER JOINT LOCATIONS AT START OF ASSEMBLY TESTS

Nodal cluster number*	Location*
1	Station HE; ready for assembly
2	Station LE; ready for assembly
3	Station LB; ready for assembly
4	Station HA; ready for assembly
5	Station LD; ready for assembly
6	Station HD; ready for assembly
7	Stored in low-side conveyor rail track
8	Station HC; ready for assembly
9	Stored on top of low-side strut storage rack
10	Stored on top of high-side strut storage rack
11	Stored in high-side conveyor rail track
12	Stored in low-side conveyor rail track
13	Stored on top of low-side strut storage rack
14	Stored in high-side conveyor rail track

*Node numbers and location designations are defined in figure 15.

TABLE II.- ASSEMBLY RATES BASED ON ASSEMBLY TESTS OF A 38-STRUT TRUSS USING THE MOBILE WORK STATION

Test conditions	Assembly rate, s/strut
Experimental:	
1g; street clothes; air	24
0g; scuba gear; water	39
0g; pressure suit; water	53
Estimated:	
0g; pressure suit; space	38

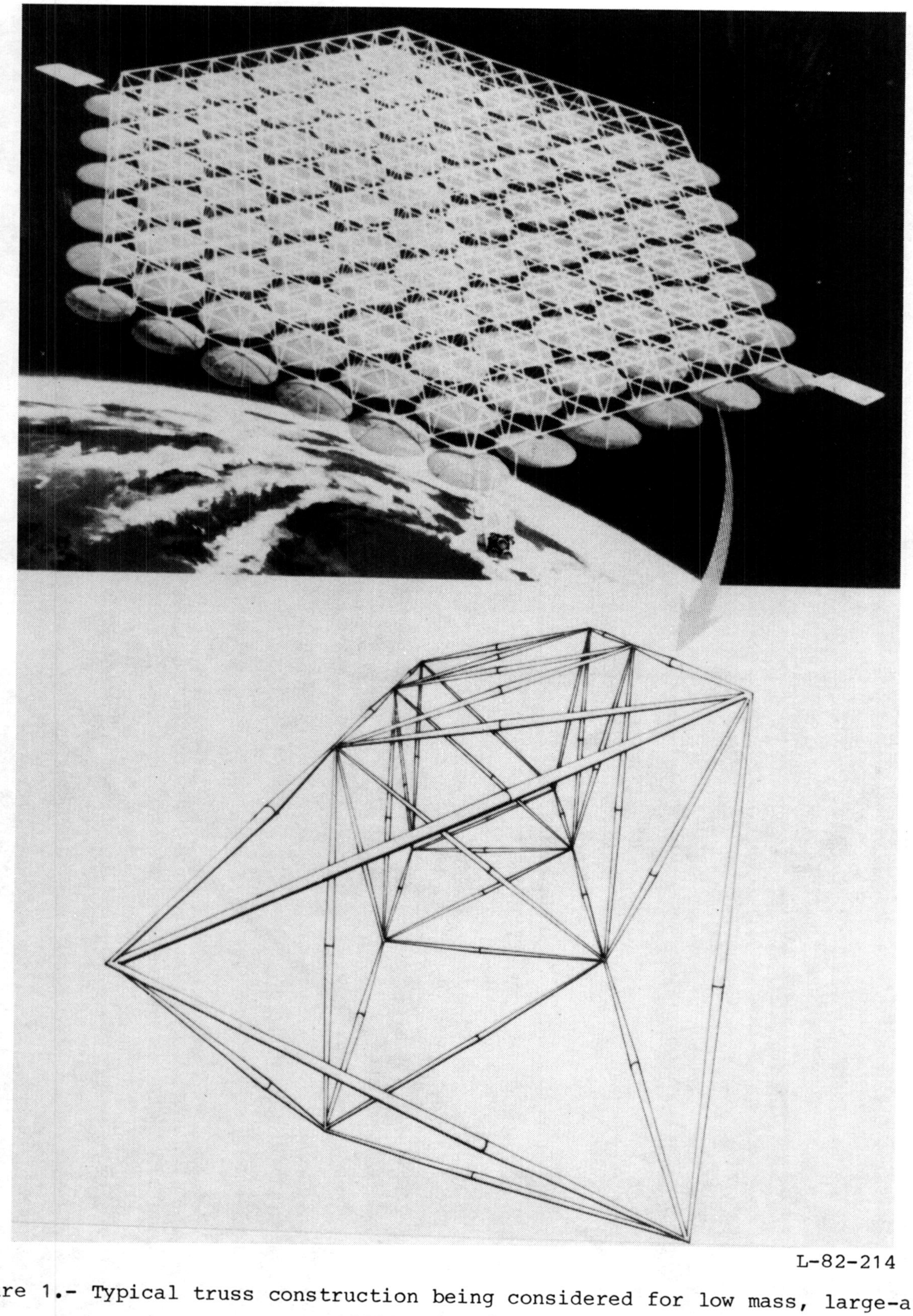

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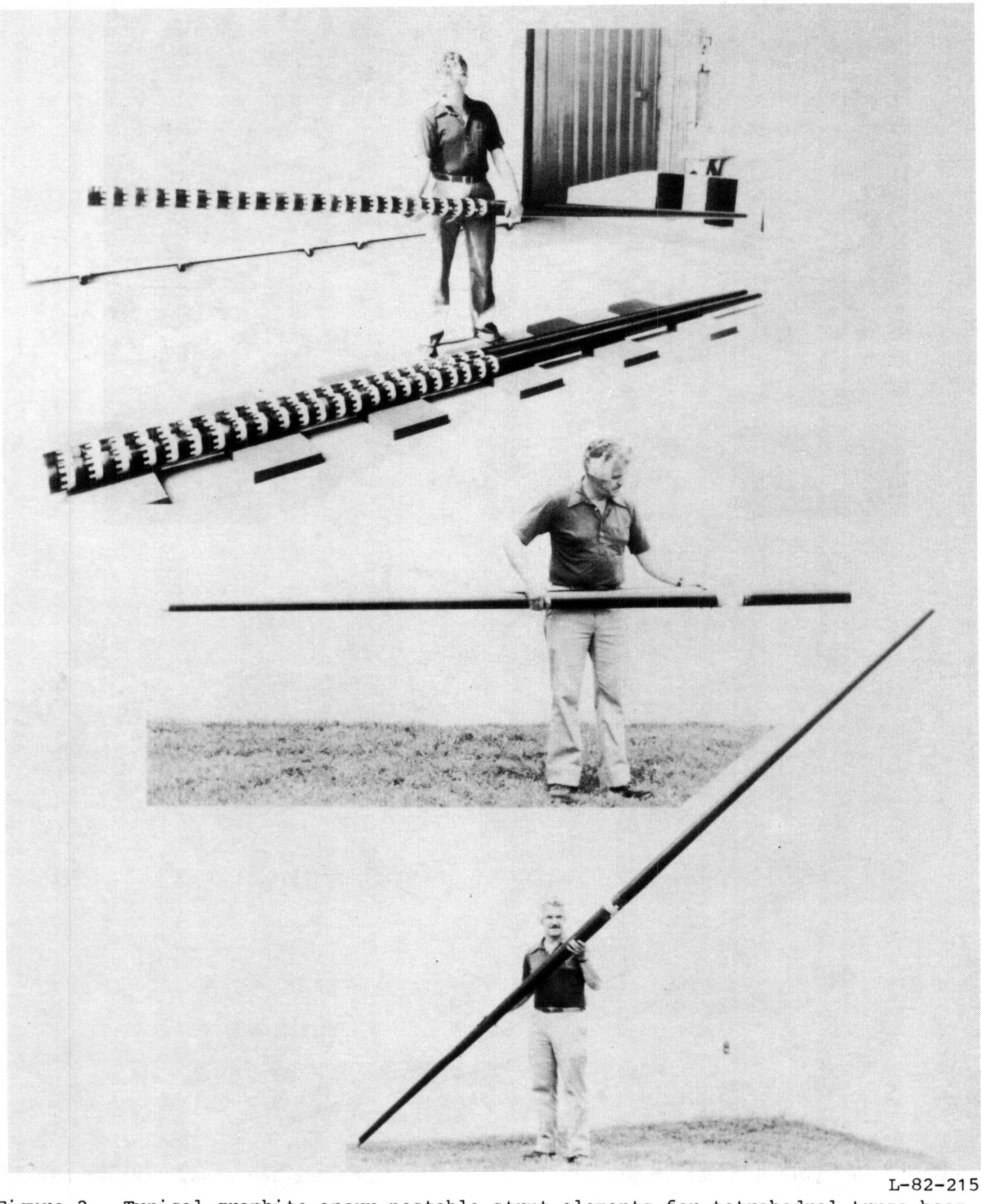
Figure 1.- Typical truss construction being considered for low mass, large-area space structures.



L-82-215
Figure 2.- Typical graphite-epoxy nestable strut elements for tetrahedral truss beam.

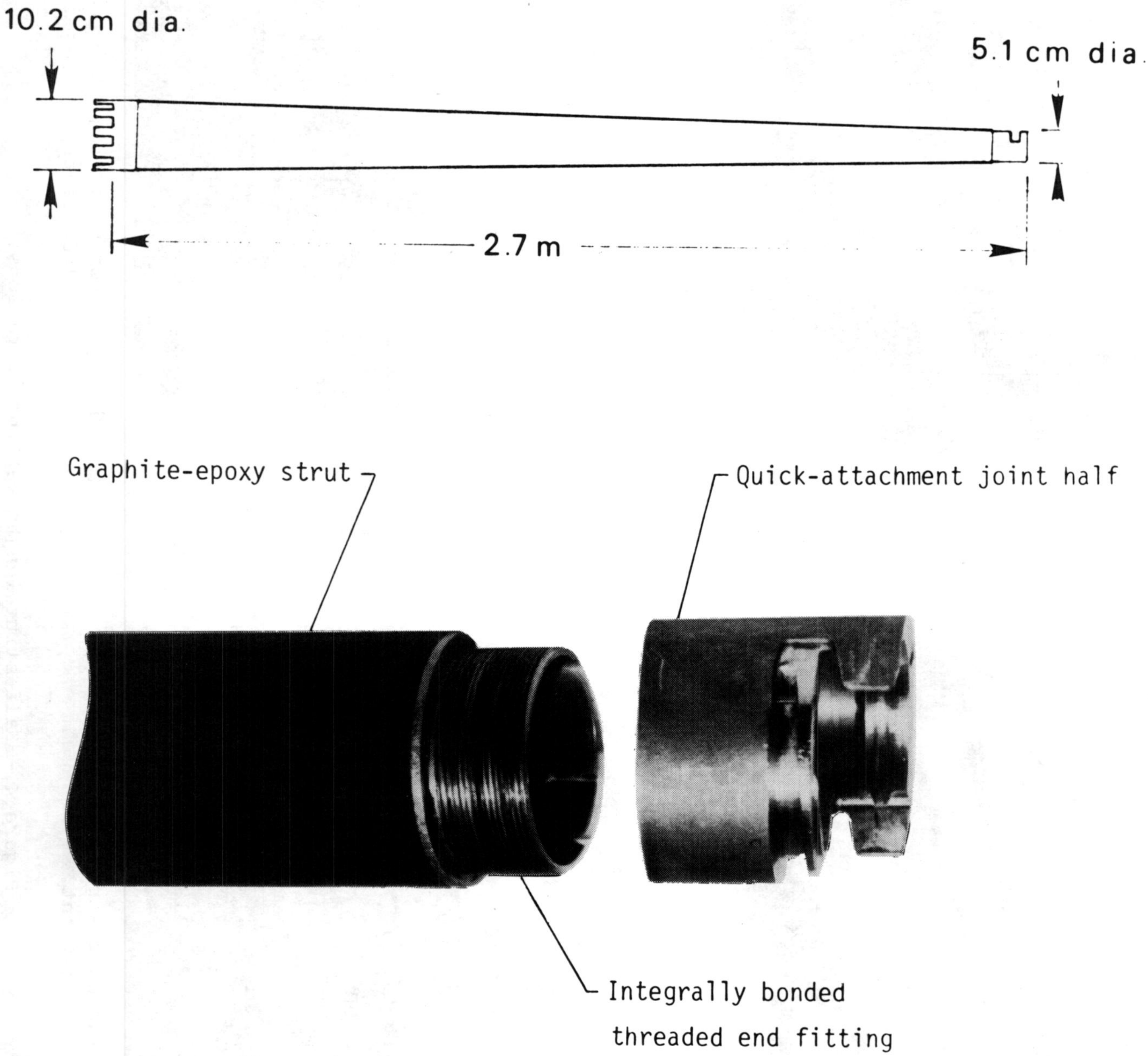
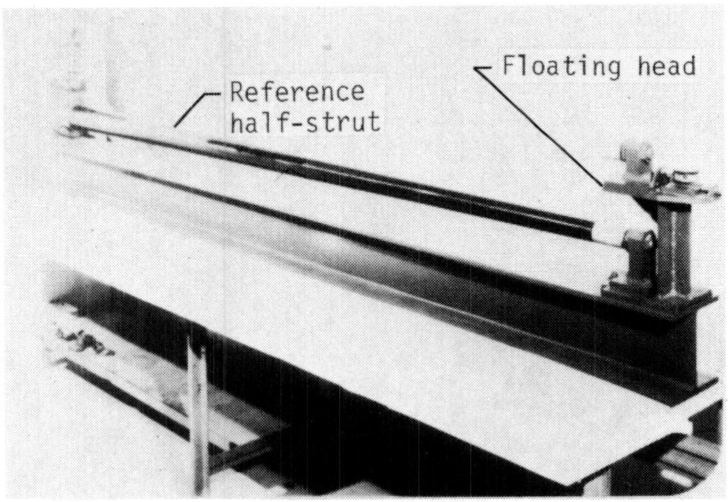
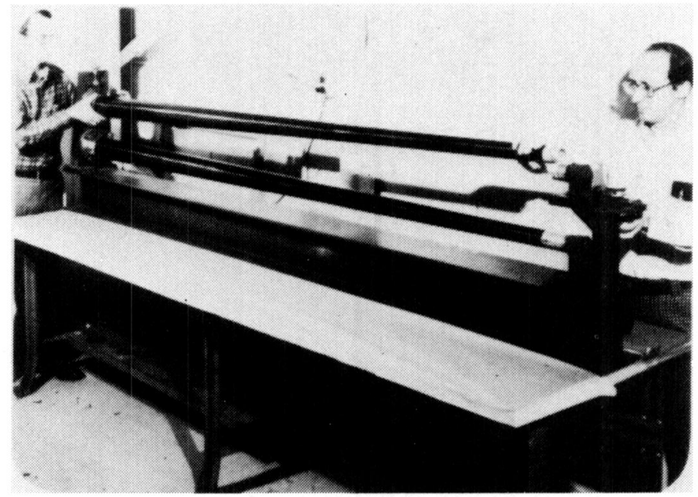


Figure 3.- Graphite-epoxy nestable half-strut.

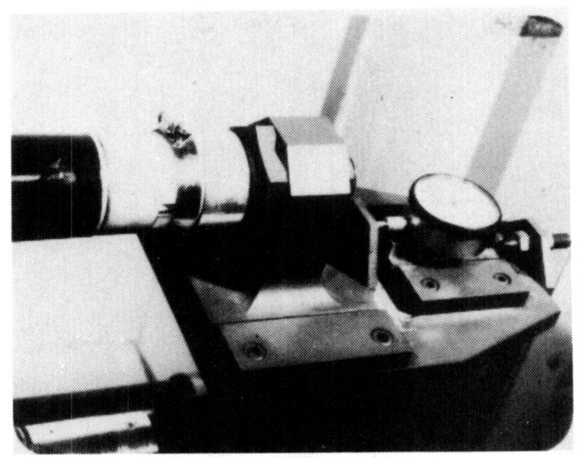


(a) Fixture with reference half-strut.



(b) Installing half-strut for length adjustment.

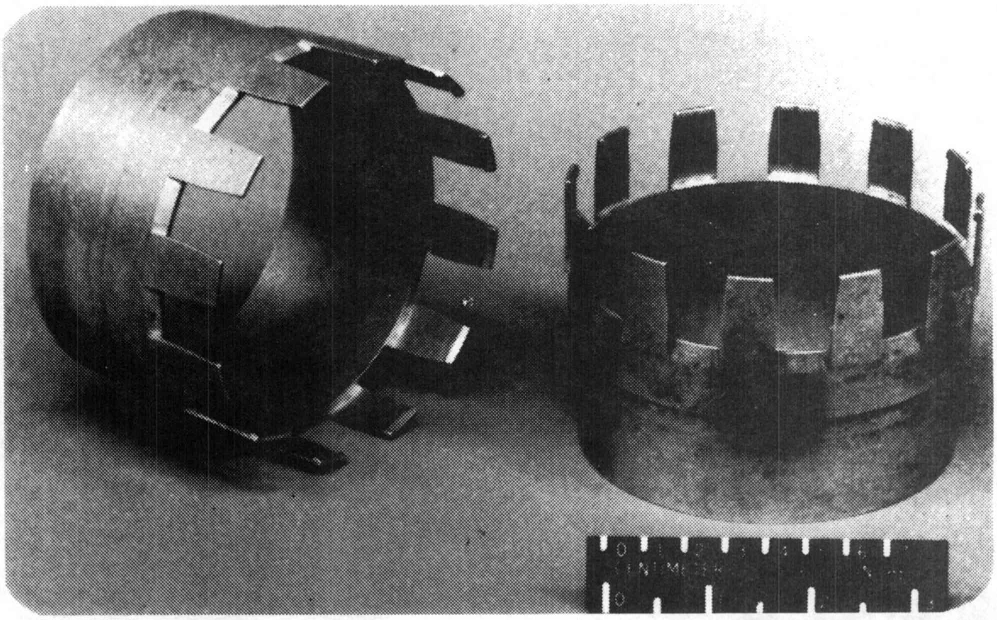
(c) Rotating half-strut for length adjustment.



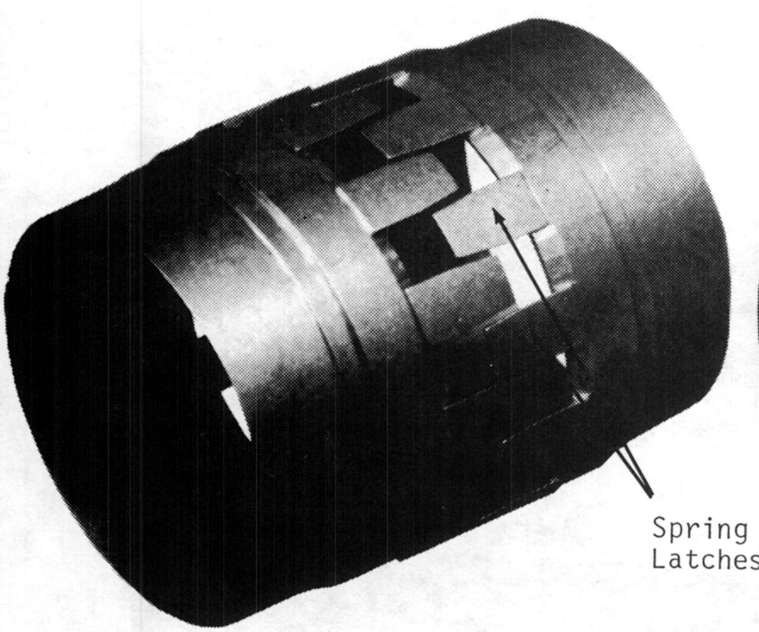
(d) Dial gage for measuring half-strut length differential.

L-82-216

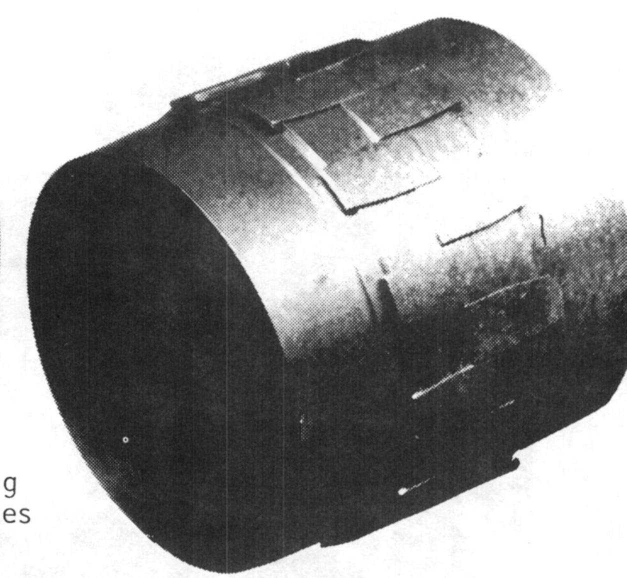
Figure 4.- Half-strut length setting operations.



(a) Center joint halves.



(b) Aligned for latching.



(c) Fully latched.

Figure 5.- Strut center joint fittings.

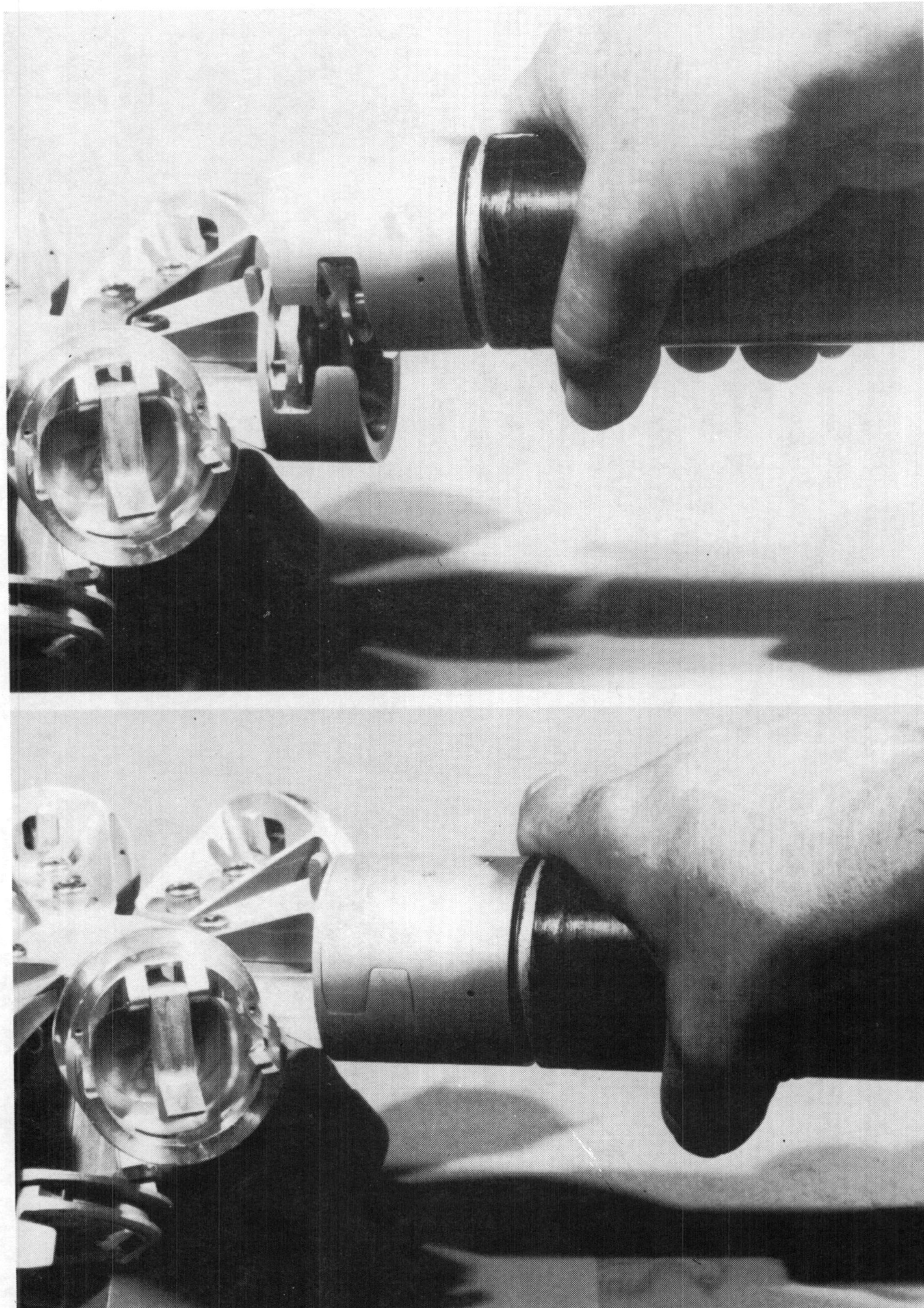


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Figure 6.- Strut end joint and nodal cluster.

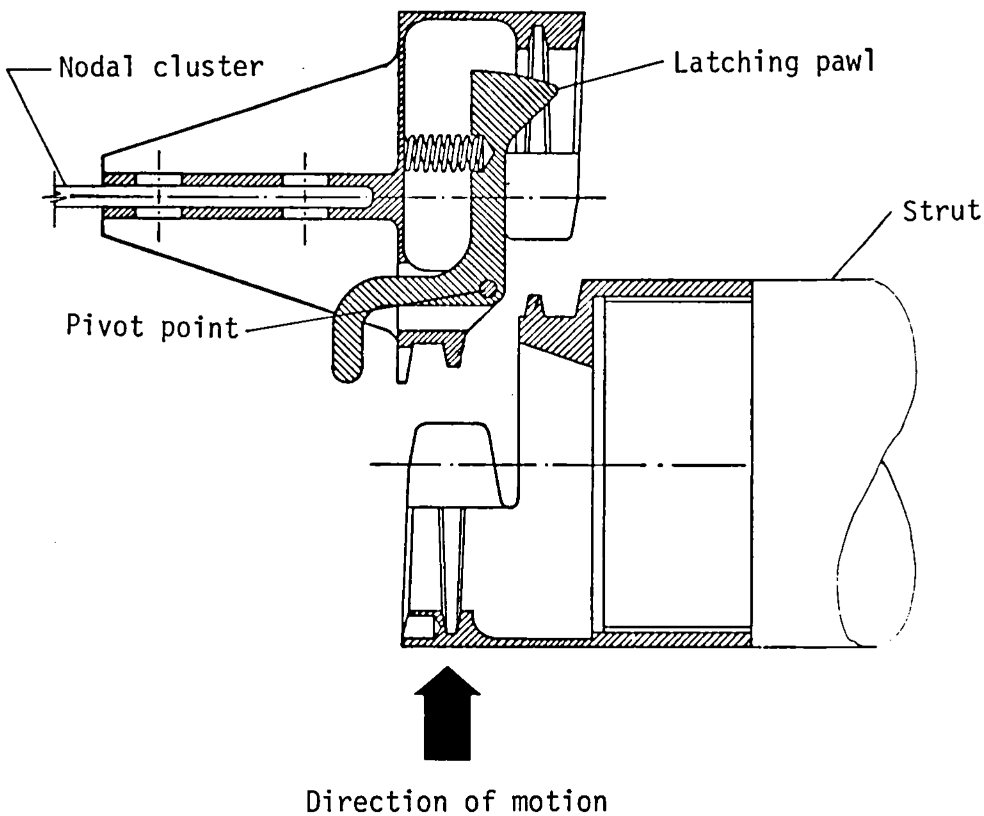

Figure 7.- Longitudinal section of cylindrical quick-attachment, quick-release joint.

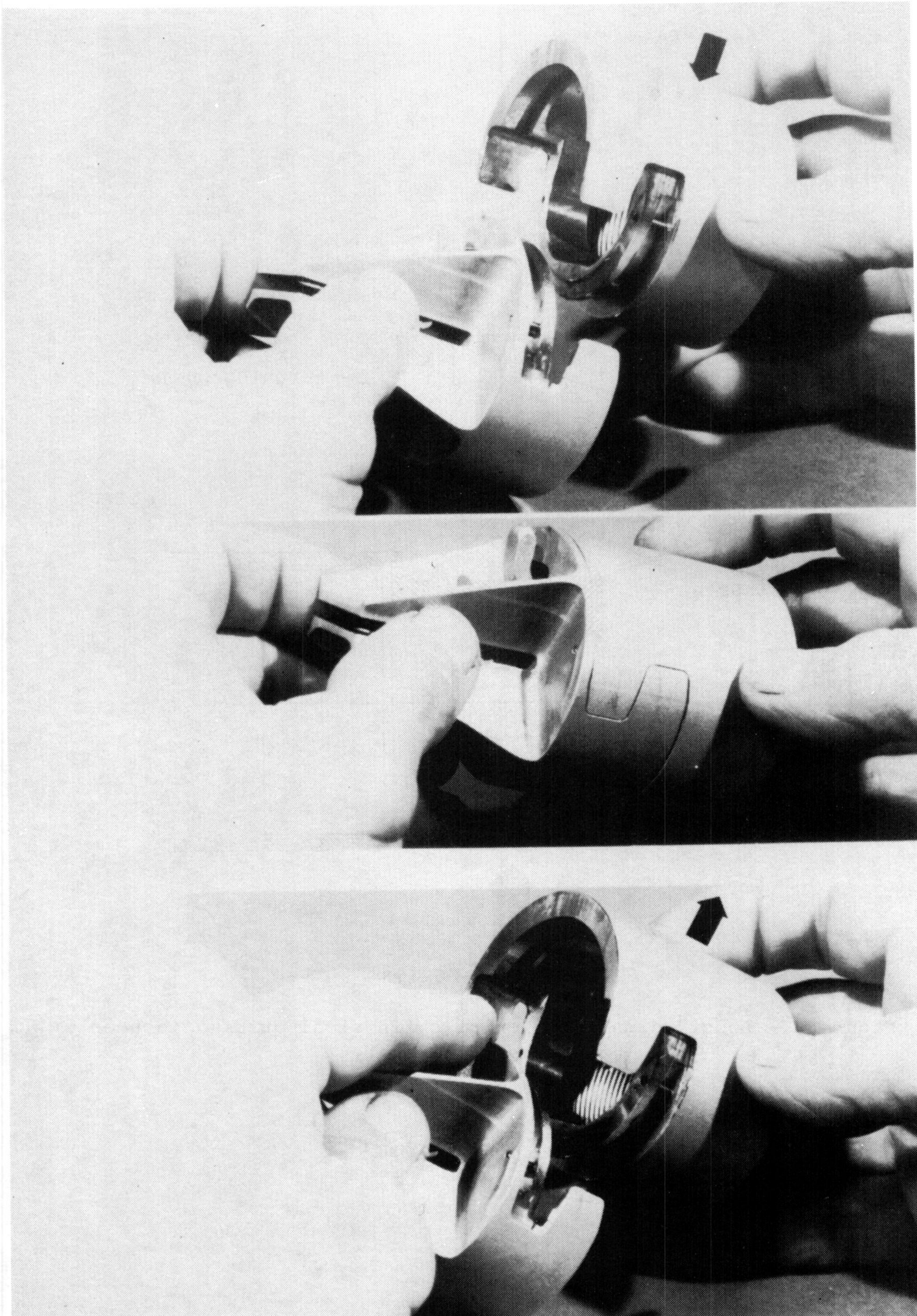

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Figure 8.- Assembly and disassembly of quick-attachment, quick-release strut end joint.

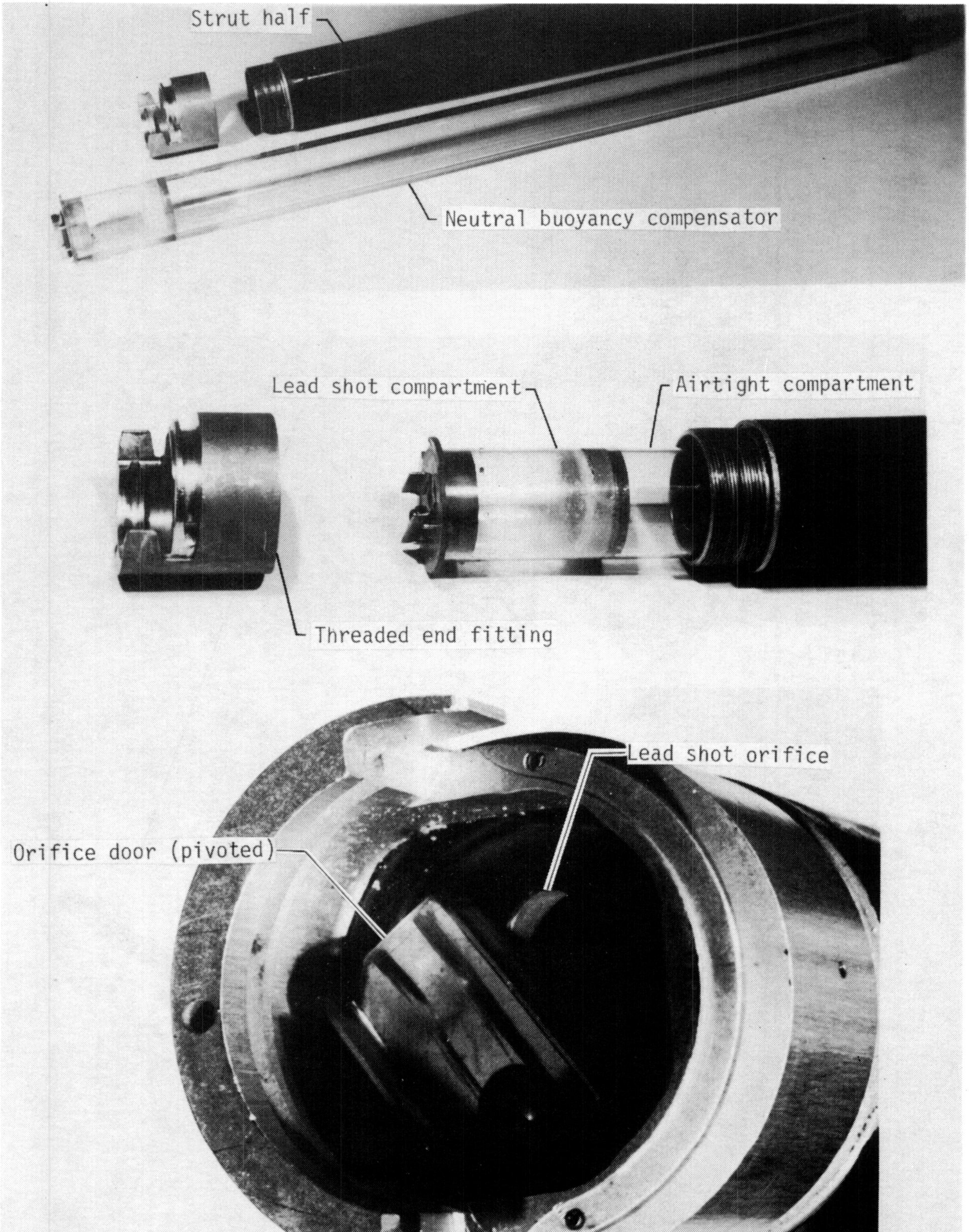

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Figure 9.- Neutral buoyancy compensator.

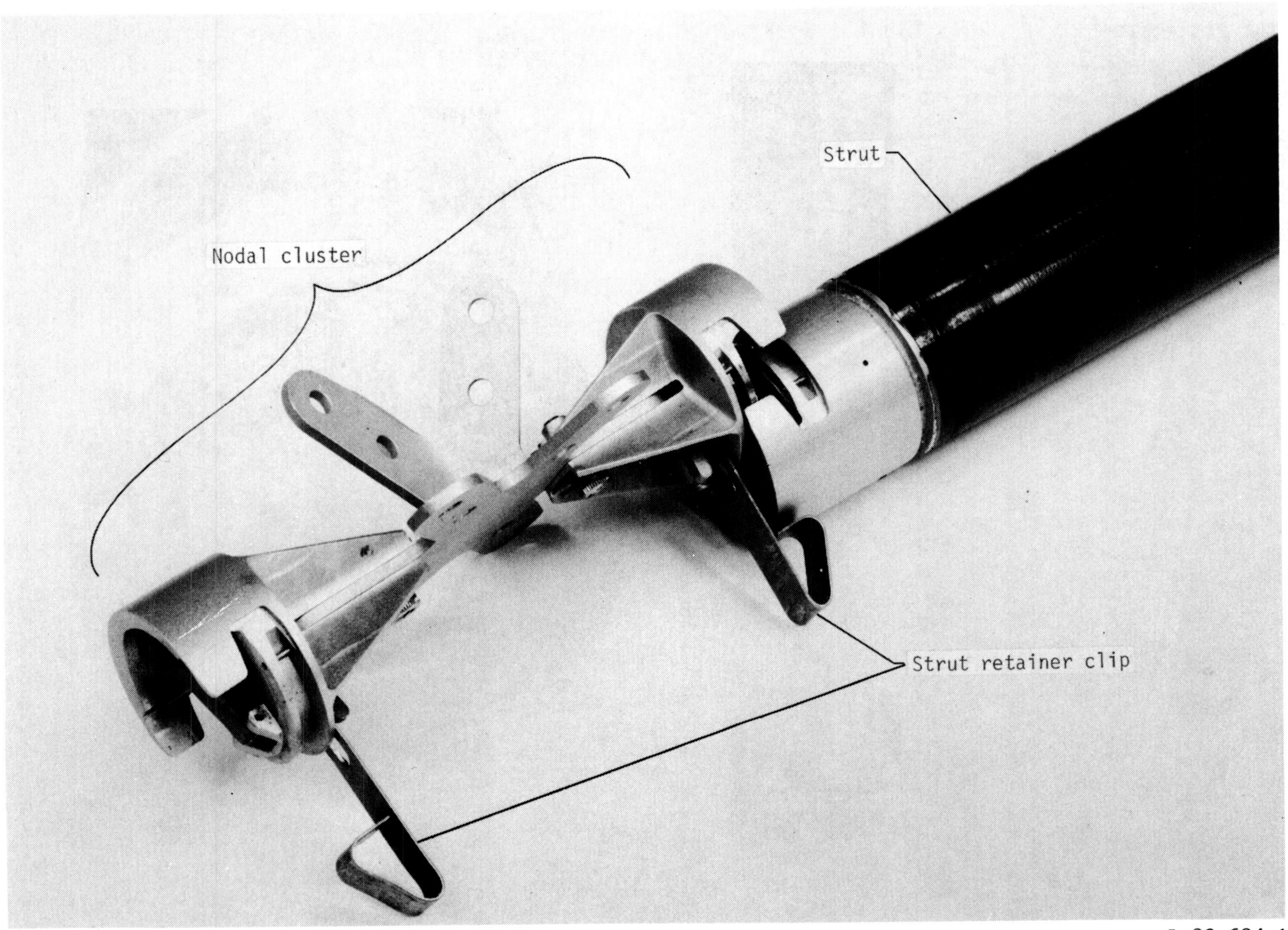

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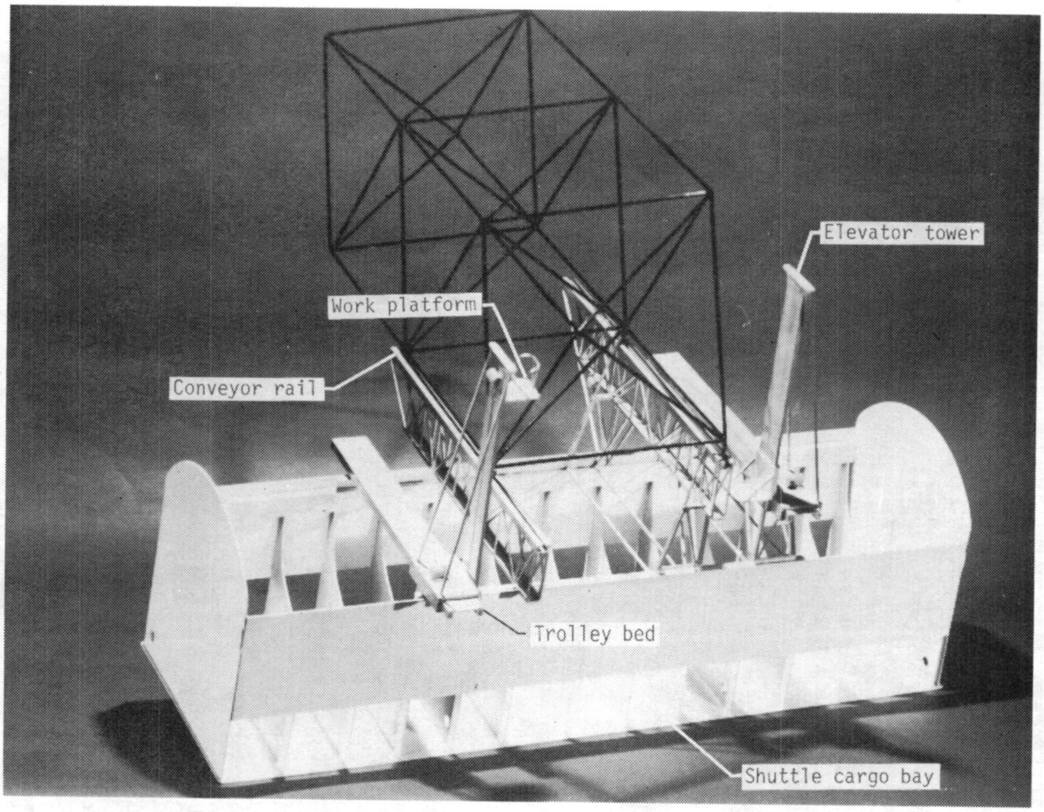
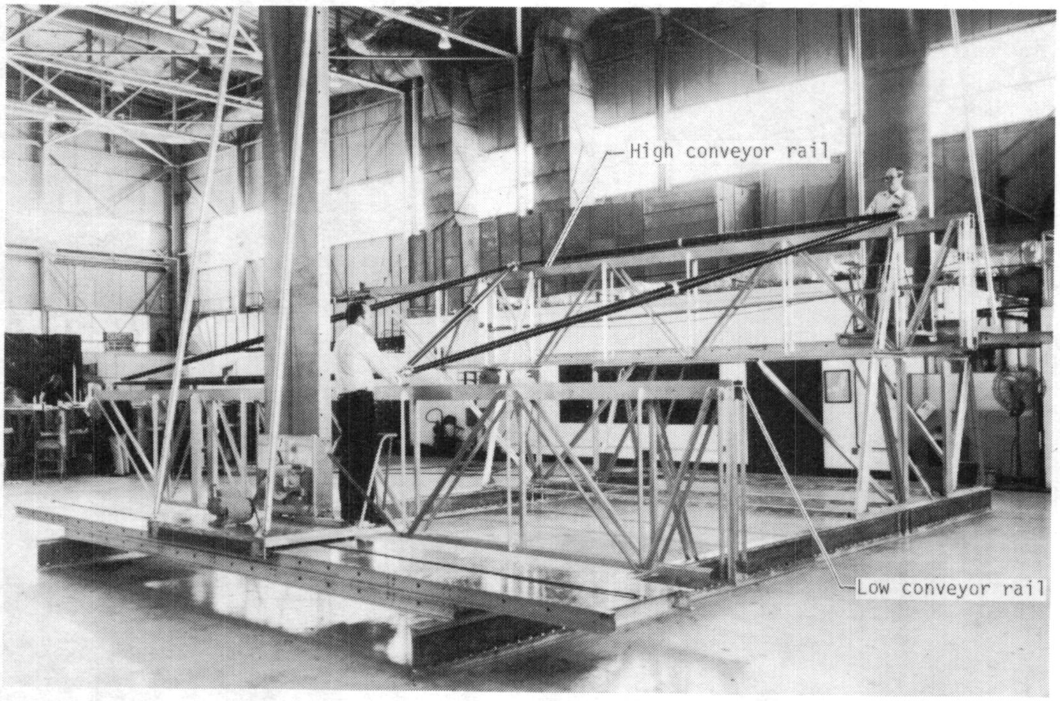
Figure 10.- Strut retainer clips for 1-g assembly tests.



(a) Subscale model.



(b) Full-scale hardware.

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Figure 11.- Mobile work station.

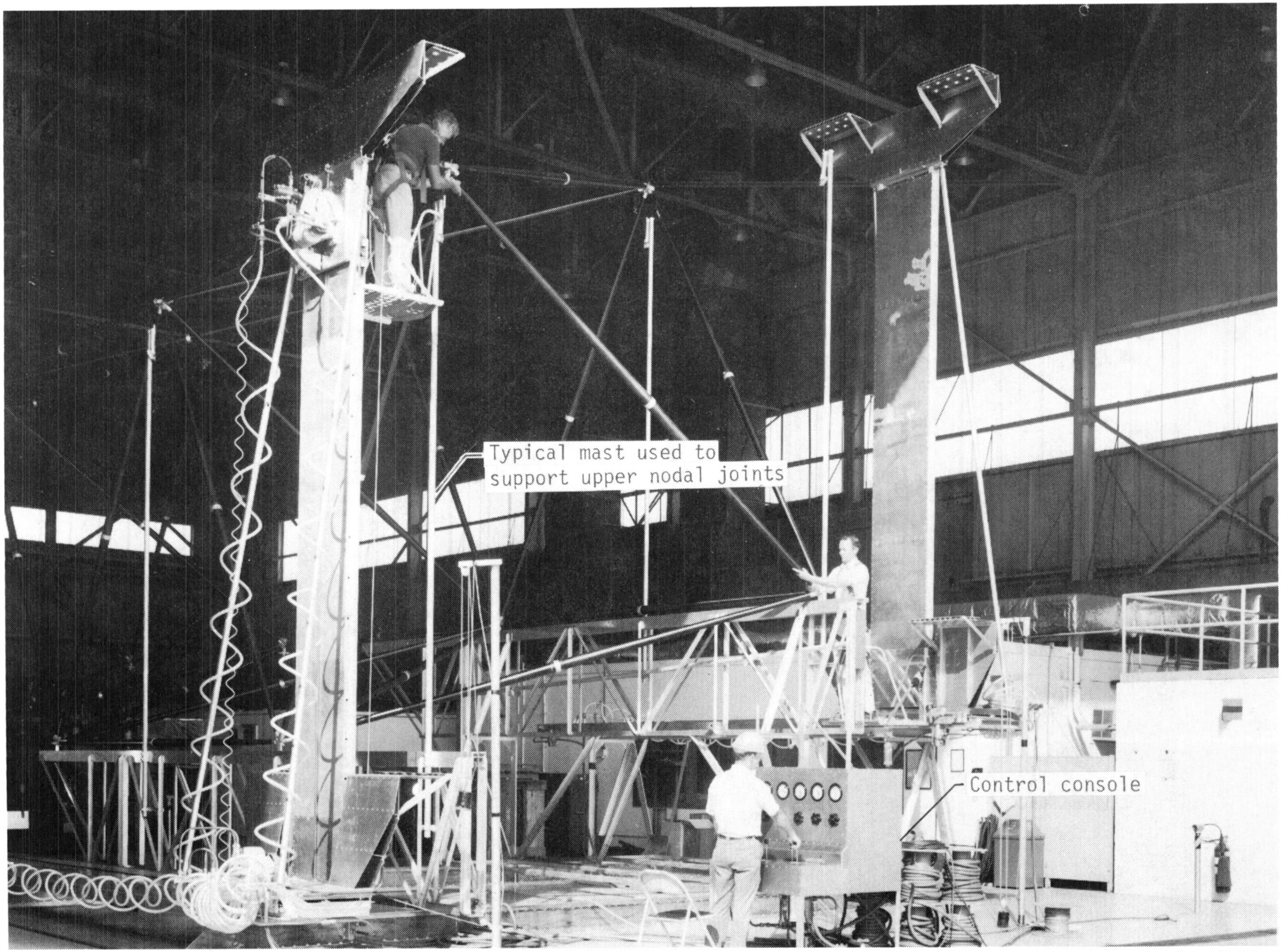

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Figure 12.- Setup for 1-g assembly test.

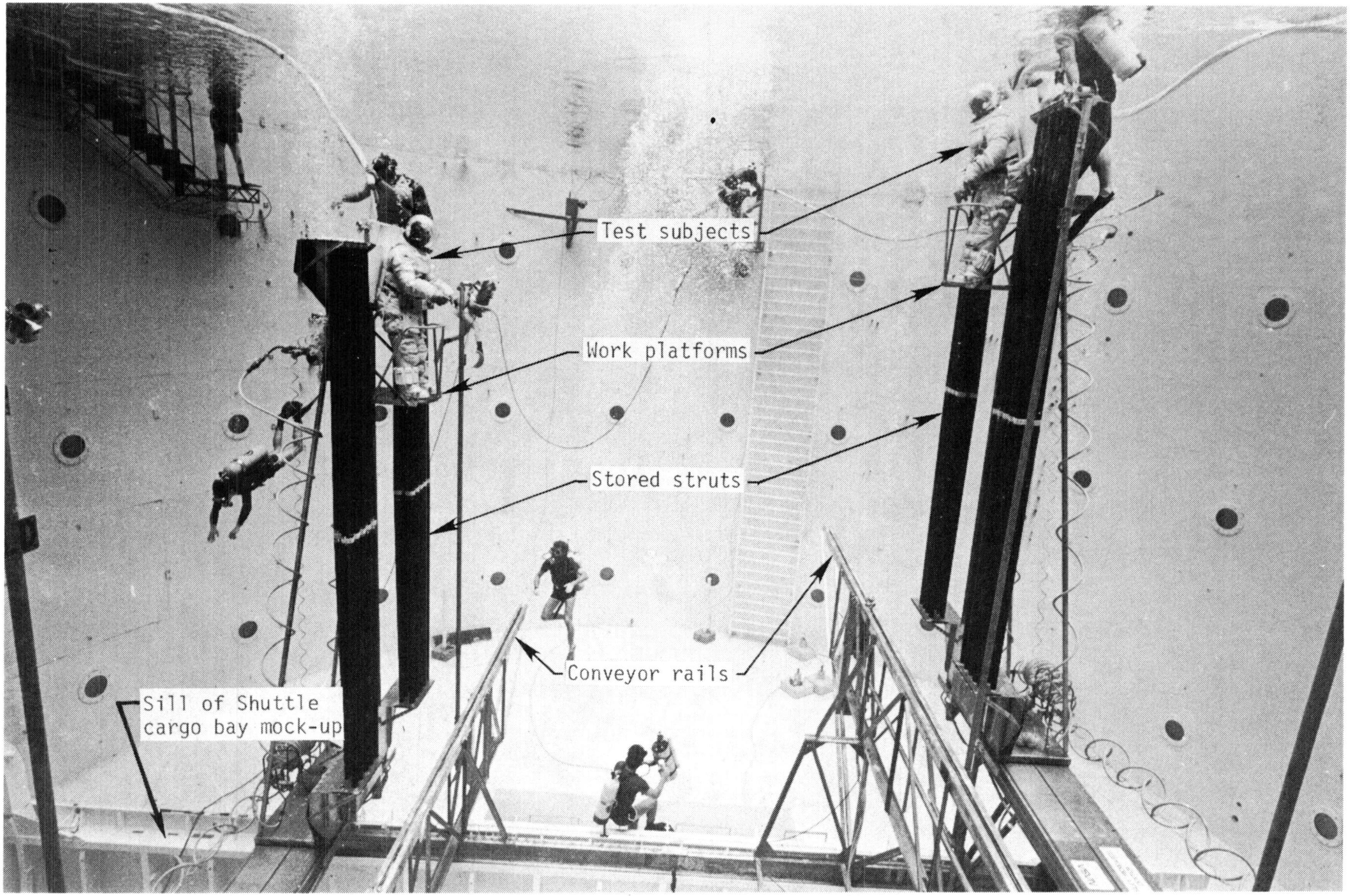

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Figure 13.- Setup for neutral buoyancy test.

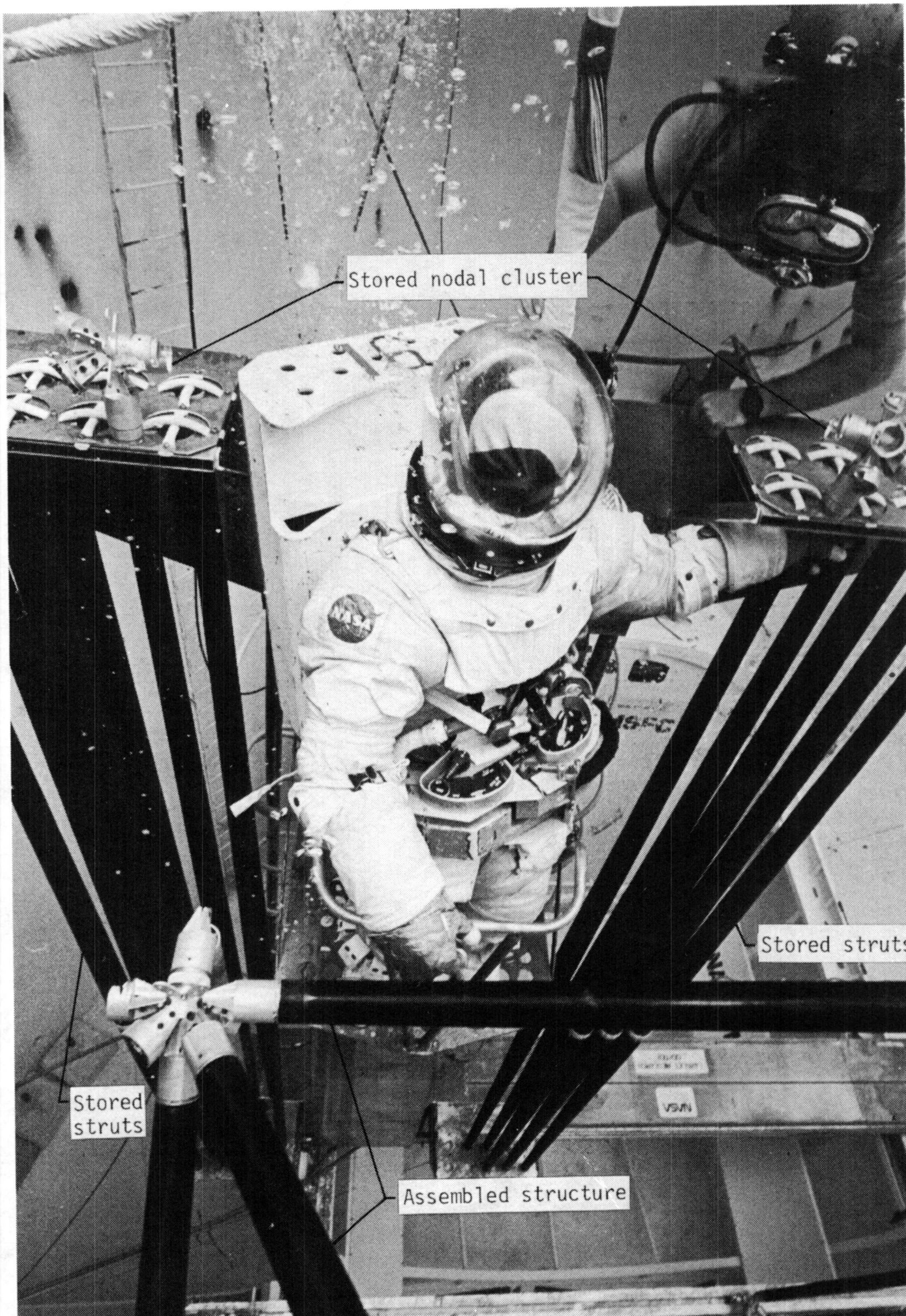

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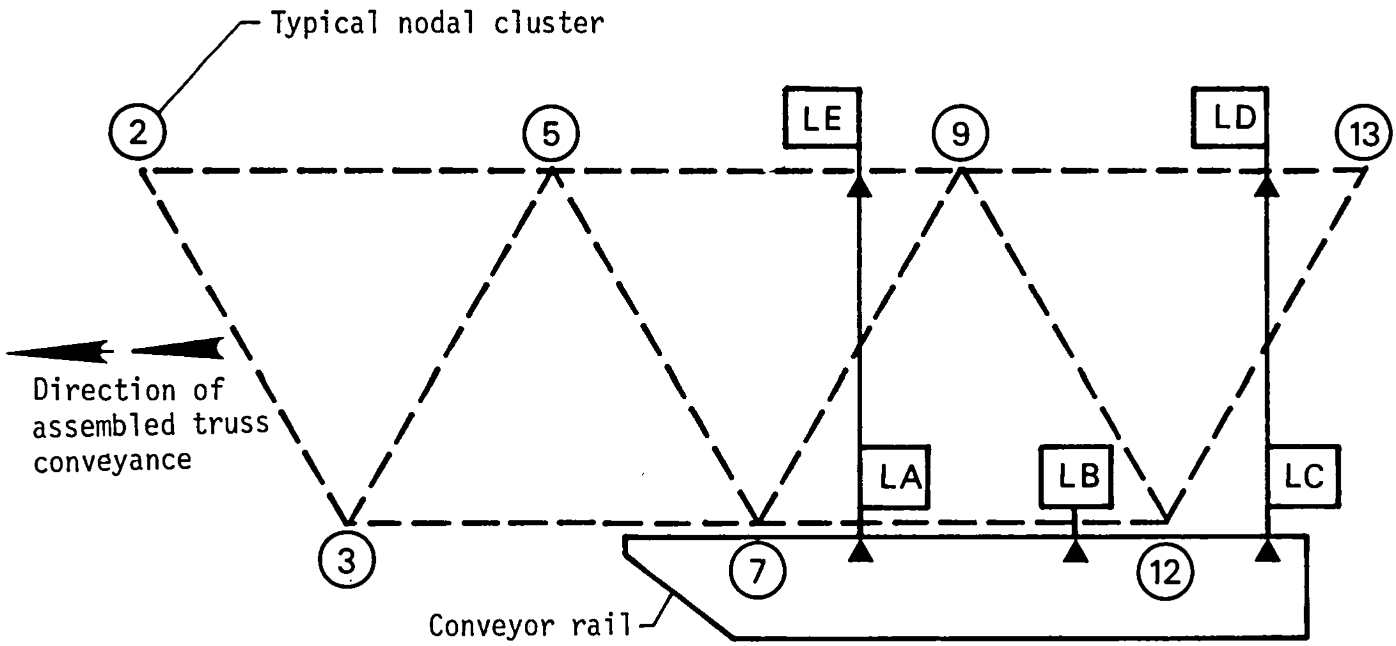
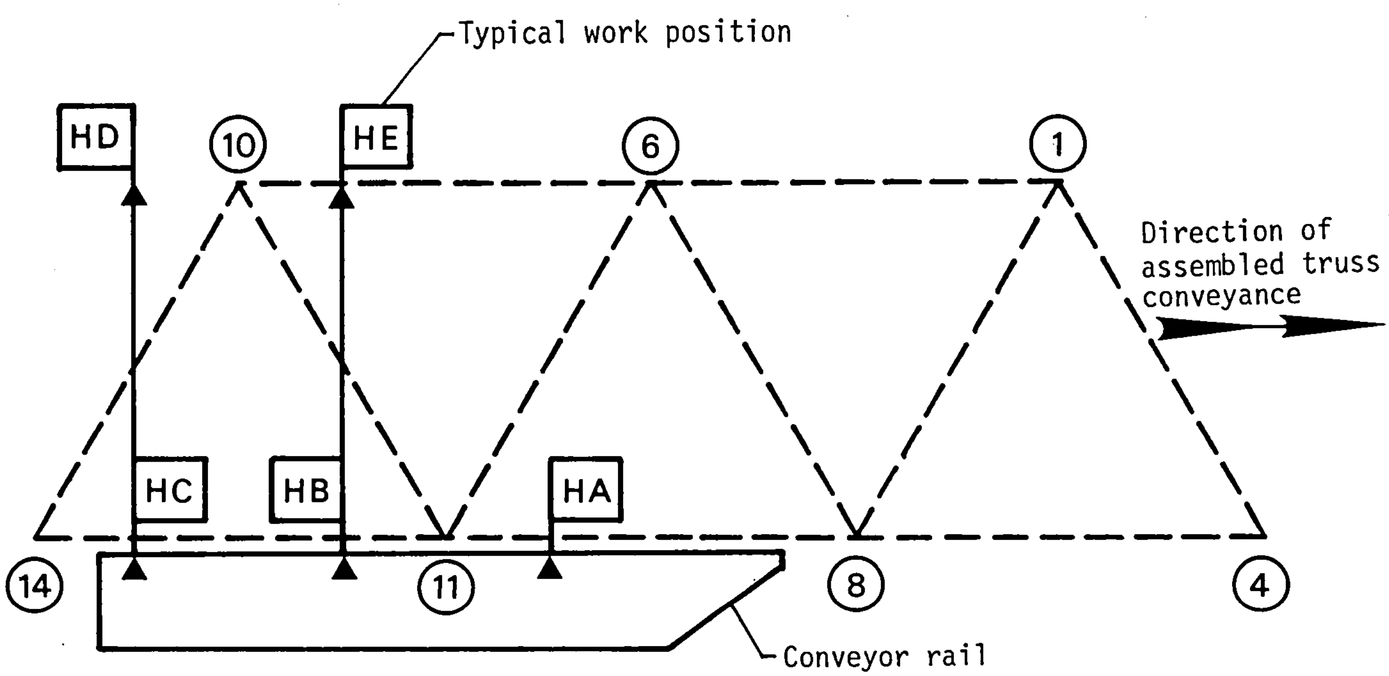
Figure 14.- Removal of strut from strut rack during simulated 0-g assembly test.



(a) View from low-side work platform.



(b) View from high-side work platform.

Figure 15.- Schematic showing work station locations, positions of nodal cluster joints, and direction of conveyance of assembled structure.

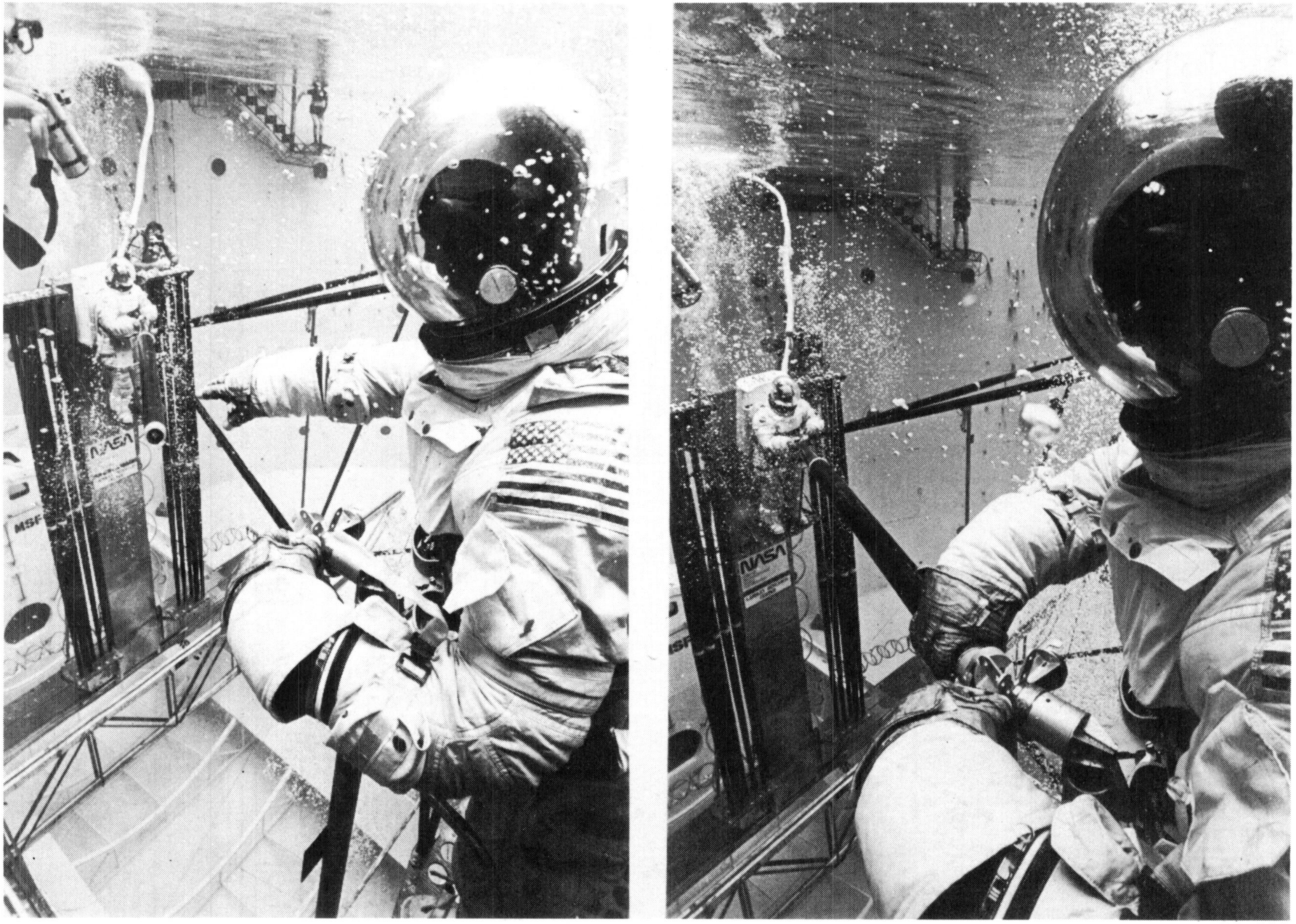


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Figure 16.- Installation of strut by two test subjects.

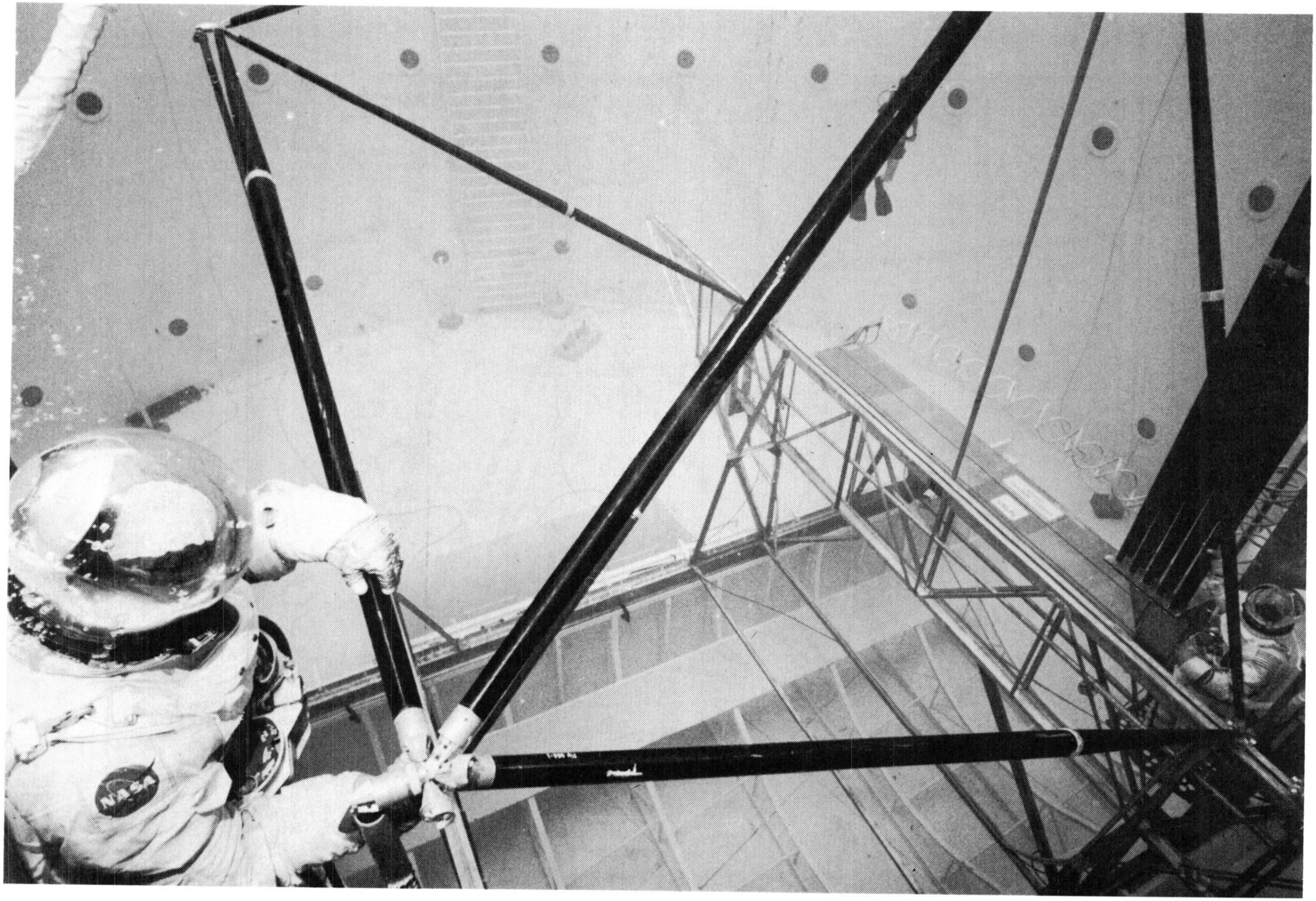

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Figure 17.- Installation of strut by one test subject.

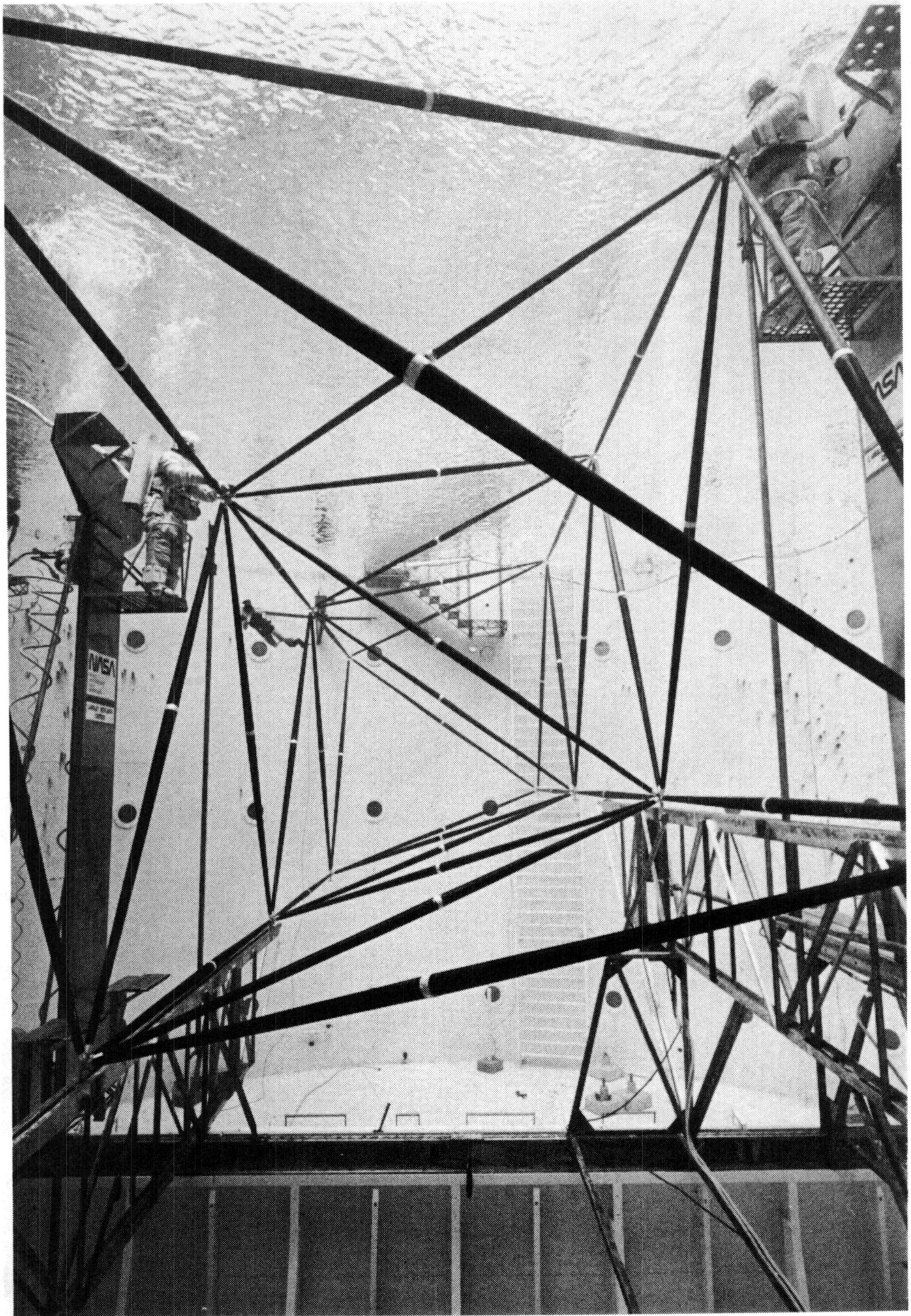

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Figure 18.- Assembled truss in the Neutral Buoyancy Simulator.

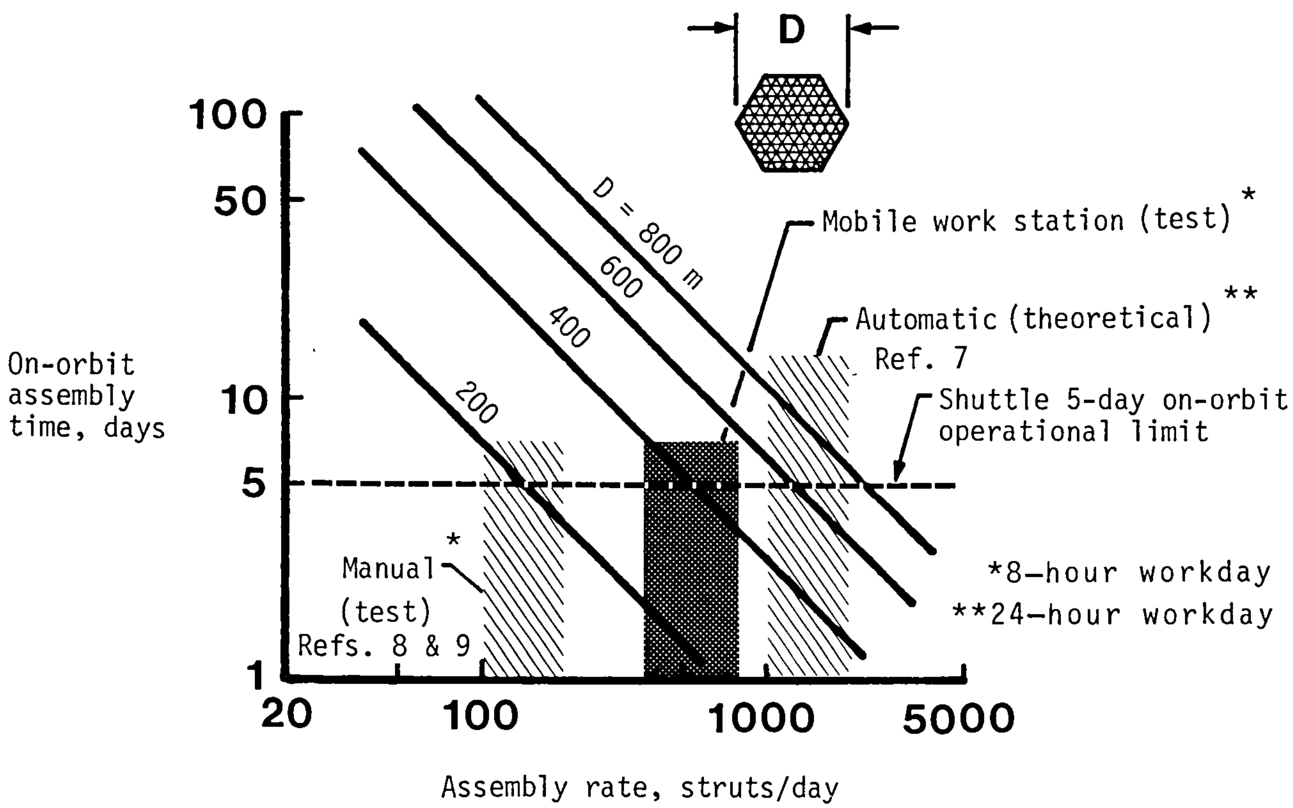

Figure 19.- Comparison of assembly rates for tetrahedral truss platform of various sizes (Strut length = 20 m).

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The film (16 mm, 5 min, color, silent) shows selected segments of simulated EVA (neutral buoyancy in water) assembly of a 38-strut tetrahedral-truss beam by two space-suited test subjects.

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16. Abstract
This report presents results of a series of truss assembly tests conducted to evaluate a mobile work station concept intended to mechanically assist astronaut manual assembly of erectable space trusses. The tests involved assembly of a tetrahedral-truss beam by a pair of test subjects with and without pressure (space) suits, both in Earth gravity and in simulated zero gravity (neutral buoyancy in water). The beam was assembled from 38 identical graphite-epoxy nestable struts, 5.4 m in length with aluminum quick-attachment structural joints. Struts and joints were designed to closely simulate flight hardware. The assembled beam was approximately 16.5 m long and 4.5 m on each of the four sides of its diamond-shaped cross section. The results show that average in-space assembly rates of approximately 38 seconds per strut can be expected for struts of comparable size. This result is virtually independent of the overall size of the structure being assembled. The mobile work station concept would improve astronaut efficiency for on-orbit manual assembly of truss structures, and also this assembly-line method is highly competitive with other construction methods being considered for large space structures.

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