NASA Contractor Report 3285

EVA Manipulation and Assembly of Space Structure Columns

Tomas E. Loughead and Edwin C. Pruett

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FOREWORD

This report describes the large space structures (LSS) simulations conducted in Marshall Space Flight Center's (MSFC) Neutral Buoyancy Simulator between March 22 and September 20, 1979 in support of NB-18A, NB-18B and NB-18C. The work was performed to evaluate 5.48 m. (18 ft.) columns and snap joint/unions provided by Langley Research Center (LaRC), and 9.14 m. (30 ft.) columns and ball/socket joints provided by Rockwell International (RI).

Essex Corporation under Contract NAS8-32989 prepared the test procedures, conducted the tests, and prepared the test reports. The test series was a joint effort by NASA's MSFC, LaRC and Essex. The direction, support and assistance by MSFC's Jack Stokes, Harry Watters and Charlie Cooper and LaRC's Larry Bement, Harold Bush and Richard Wallsom are gratefully acknowledged.

Questions concerning either the LSS tests or this report should be addressed to Mr. Harry Watters, EL15, MSFC, at (205) 453-4430.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAA	Apex Assembly Aid
CRF	Column Restraint Fixture
EVA	Extravehicular Activity
LaRC	Langley Research Center
LSS	Large Space Structures
MMU	Manned Maneuvering Unit
MSFC	Marshall Space Flight Center
NB	Neutral Buoyancy
RI	Rockwell International
RMS	Remote Manipulator System
SEM	Simulated Equipment Module
STS	Space Transportation System

1.0 INTRODUCTION

One of the most valuable aspects of NASA's Space Transportation System (STS) is that it allows for the multiple launches of the space shuttle to support a single payload objective. The advent of this multilaunch mission system greatly expands the types and the scope of work that can be performed in space because it makes possible the piece by piece orbital erection of large space structures for use as platforms on which to attach various scientific or mission support modules. Such structures were not formerly feasible because they were too big for a single-launch mission configuration.

In making use of this new capability, a number of missions have been proposed by NASA and by various contractors which will require large space structures for a variety of long-term projects, such as solar, stellar and earth observations; life science investigations; materials processing; and the collection and transmission of solar energy to earth or to other orbital systems.

Neither the Apollo nor the Skylab programs included any large structure erection or deployment except for the deployment of the two Skylab solar shields. Hence, we are at the dawn of a new era of space structures, with demand for them already being felt and the ability to launch them already in existence. However, we are lacking in sufficient data regarding optimum hardware configurations for specific LSS applications and the techniques for assembling these structures in space.

2.0 EXECUTIVE SUMMARY

2.1 PURPOSE OF STUDY

The purpose of this study was to investigate extravehicular activity (EVA) assembly procedures and hardware configurations for orbital assembly of a single tetrahedral cell and to obtain task element time data used for the prediction of assembly times for larger, more complex structures.

2.2 TEST CONDITIONS

All tests were conducted in MSFC's Neutral Buoyancy Simulator using test subjects wearing A7LB pressure suits equipped with standard EVA chestpack and backpack mockups.

The basic test layout consisted of a cargo bay mockup which served as a support for stowed columns and crew aids such as handrails and foot restraints. An outrigger mounted on the sill of the cargo bay served as a mounting fixture for the triangular base of the tetrahedron and provided translation paths for crew members and a support for one of the workstations.

Data were collected through still and motion photography, recorded closed circuit television, recorded crew comments, oscillographic records of crew heart rates, and post-test debriefings.

Participants included personnel from MSFC, LaRC, RI, and Essex Corporation, as well as the standard complement of safety divers, utility divers, and various other support personnel.

2.2.1 Hardware Configurations

During the NB-18A, B and C test runs, the following hardware configurations were investigated:

- 5.48 m. (18 ft) graphite/epoxy columns equipped with snap joint/unions
- 5.48 m. (18 ft) graphite/epoxy columns equipped with ball/socket unions
- 9.14 m. (30 ft) tubular aluminum alloy columns equipped with ball/socket joints.

2.2.2 Assembly Procedures

Several assembly procedures were used throughout the test series to evaluate various EVA aids and assembly methods. The four basic procedural combinations were:

- EVA only - no manned maneuvering unit (MMU) or remote manipulator system (RMS)

- EVA only - with "MMU," but no "RMS"

- Augmented - EVA with "RMS" but no "MMU."

- Augmented - EVA with "RMS" and "MMU."

2.2.3 Contingency Column Removal and Folded Column Deployment

In addition to the tetrahedron assembly operations, two additional tests were conducted in which a single subject was required to release from an assembled structure a single 9.14 m.(30 ft) column equipped with ball/socket joints and to remove the column from the structure. Concommitant with these tests, two folded 9.14 m.(30 ft) columns equipped with two types of center hinge joints (latch lock and sleeve lock) were deployed by pressure suited subjects. The two deployment conditions were: (1) without deployment aids, and (2) with one end of the column anchored and a fulcrum point used to aid the crew member in rotating the column's free end to the latch position.

2.3 TEST RESULTS AND CONCLUSIONS

The time required to assemble the structure using columns equipped with the ball/socket joints was slightly less than the time required for columns with the snap joint/unions, although no difference was found statistically. The snap joint/union's tight alignment tolerances and susceptibility to damage and wear made the assembly task more difficult for the crew and resulted in the longer assembly times.

The greatest effect on assembly times was observed when the test subjects were assisted by the simulated RMS (RMS activities performed by a utility diver) during the augmented assembly sequences. The following mean assembly times were observed:

ASSEMBLY TIME (Min)

Augmented	Manual
14.9	25.4

This represents a mean assembly time of approximately 5 minutes per column with two unassisted crew members and approximately 2.5 minutes per column if a RMS is used, assuming utility diver performance was comparable to RMS.

Another factor that affected assembly time was the evolutionary design of crew workstations and the reduction in the number of translation tasks by crew members (both through the use of a RMS and the development of more efficient assembly procedures).

These test data indicate that the assembly of large space structures through the use of EVA is not only feasible but can also be done efficiently and within the physical limitations of the EVA crew members.

The contingency column removal tests resulted in a mean removal time of 3.1 minutes per column--slightly less than the unaided installation time of 5.1 minutes.

The folded column deployment tests demonstrated no significant differences in assembly times for the latch-lock or sleeve-lock configurations. When a fulcrum point was used to aid the crew member, deployment times were slightly longer (1.21 min. versus .67 min.) than when the crew member was operating unaided, although test subjects reported a preference for the assisted deployment over unassisted deployment.

Generally, it may be concluded that EVA assembly of large structures in space is feasible and assembly times can be minimized by

- The design of workstations which allow the majority of tasks to be completed within optimum reach envelopes of pressure suited subjects

- The design of structural hardware, crew aids, and assembly procedures (including the use of a RMS) such that the need for translation by crew members is minimized.

3.0 SCOPE

This project encompassed the neutral buoyancy investigation of the snap joint/union developed and provided by LaRC and the ball/socket joint developed and provided by RI. These two types of column end fittings and unions were attached to two types of columns--5.48 m. (18 ft.), tapered graphite/epoxy columns developed by LARC and 9.14 m. (30 ft.) aluminum columns developed by RI.

Three general procedures were utilized in assembly of the tetrahedral cell. These were: (1) EVA only, (2) EVA with a simulated RMS to assist the crew member, and (3) EVA with a simulated MMU.

In addition, tests were conducted involving the contingency removal of columns fitted with the ball/socket joint and the deployment of folded 9.14 m. (30 ft.) aluminum columns fitted with two types of hinged center joints--a latch lock configuration and a sleeve lock configuration, both developed and provided by RI. Table 1 provides an overview of the test configurations.

Table 1: Test Configurations, NB-18A, NB-18B, and NB-18C

TEST SERIES	TEST NUMBERS	ASSEMBLY PROCEDURE	COLUMN	JOINT
NB-18A	1 - 14	Manual - No MMU	5.48 m. (18 ft.)	Snap Joint/ Union
	15 - 17	Augmented - No MMU	5.48 m. (18 ft.)	Snap Joint/ Union
NB-18B	1,2,3,7	Manual With MMU	9.14 m. (30 ft.)	Ball/Socket Joint
	4,5,6,8	Augmented With MMU	9.14 m. (30 ft.)	Ball/Socket Joint
	9,10	Augmented With MMU	5.48 m. (18 ft)	Ball/Socket Joint
	11,12	Manual With MMU	5.48 m. (18 ft)	Ball/Socket Joint
NB-18C	1 - 4	Manual - No MMU	5.48 m. (18 ft)	Snap Joint/ Union
	5 - 8	Manual No MMU	5.48 m. (18 ft)	Ball/Socket Joint

After each test series, a quick-look test report was written describing major hardware and procedural changes, test data, and assembly procedures. These reports are available upon request from Mr. Harry Watters, EL15, George C. Marshall Space Flight Center, Alabama 35812.

4.0 METHOD

4.1 TEST SUBJECTS

The eleven subjects that participated in the tests were trained by NASA in the A7LB pressure suits and were experienced scuba divers. Experience in performing tasks while wearing the A7LB suit varied among the subjects and could be judged to range from novice to expert. No attempt was made to control for pressure suit experience in the experimental design, although as a general rule, more weight was given to comments and opinions of the more experienced test subjects.

4.2 TEST EQUIPMENT

All tests were conducted in the MSFC Neutral Buoyancy Simulator, Building 4706. The basic test layout consisted of a medium fidelity double pallet mockup (Figure 1) which served as the support for the six columns mounted in a column restraint fixture (CRF). Also housed in the pallets were the simulated equipment module (SEM), a container for stowage of unions, the apex assembly aid (AAA), and various crew aids such as foot restraints and handrails. An outrigger mounted on the sill of the cargo bay served as a mounting fixture for the three pedestals which secured the three columns forming the tetrahedron's base triangle. The outrigger also served as a translation path for the crew members and a support for the workstation at Position C. Although the basic layout remained static during the test series, the location of handrails and foot restraints was adjusted to improve the crew member's position at the various work sites.

In the test series NB-18B (Section 6.0), no AAA or outrigger was used. The tetrahedron was secured to the cargo bay by attaching the pedestals A and B to two short pieces of aluminum channel mounted on the sill (see Figure 6).

Tests were conducted with subjects in A7LB pressure suits fitted with standard EVA equipment including umbilicals and chestpack and backpack mockups. Helmet visors were not available for the tests.

4.3 GENERAL PROCEDURES

Although the assembly procedures and initial equipment arrangement varied from one test series to another, the general test procedures presented below represent the basic steps in all the test runs.

After pretest briefings and neutralization of pressure suits, the subjects were carried to the pallet mockup, and the test was started. During the test, the subjects were given real time assembly instructions (Appendices A, B, C and D) via in-suit intercoms by the test conductor throughout the cell assembly sequence. Instructions to the utility and safety divers were given through a hydrophone located near the mockup. A debriefing was held at the end of each test day to collect crew and observer comments and make plans for the next day's test(s).

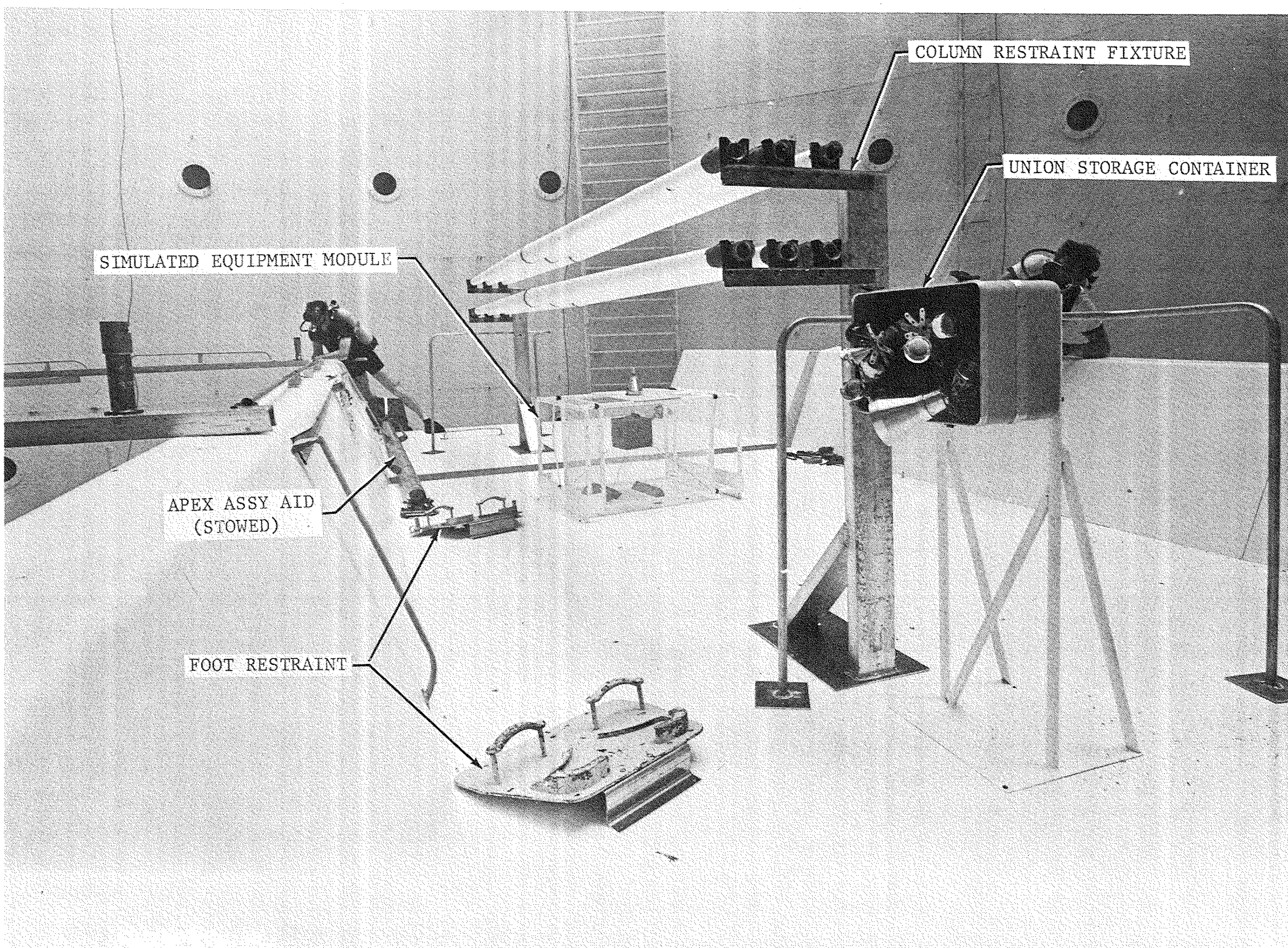


Figure 1: Dismantled Tetrahedral Cell and Associated Equipment Prior to Assembly

Data were collected through still and motion photography, recorded closed circuit television, recorded crew comments, oscillographic records of crew heart rates (originating from ear lobe transducers), and the post-test debriefings.

Participants included engineering personnel from MSFC, LaRC, RI, and Essex Corporation as well as the standard complement of safety divers, utility divers, and various other support personnel.

5.0 NB-18A, EVA MANIPULATION AND ASSEMBLY OF SPACE STRUCTURE COLUMNS - 5.48 m.(18 ft.) LENGTH

5.1 TEST SERIES 1 - MANUAL ASSEMBLY SEQUENCE (Tests 1 Through 14)

This section addresses the first 14 pressure suited tests conducted during the period of March 22 through September 12, 1979 which utilized the snap joint/union attached to 5.48 m.(18 ft.) graphite/epoxy columns developed and furnished by LaRC. Prior to the first suited test on March 22, three swim-through exercises were conducted with scuba-equipped subjects in order to facilitate the development of procedures and to test the hardware. It was during this period that the decision was made to omit installation of the seventh, horizontal column as outlined in the original NB-18A test plan (January 8, 1979). It was also during this period that the initial AAA was fabricated.

5.1.1 Purpose

The purpose of this test series was to investigate assembly procedures and hardware configurations for manual assembly of the tetrahedral cell with 5.48 m. (18 ft.) tapered, graphite/epoxy columns and snap joint/unions provided by LaRC.

5.1.2 Test Conditions

The following test conditions were utilized during the first test series:

- 5.48 m.(18 ft.) graphite/epoxy column fitted with snap joint/unions
- Manual assembly sequence (without RMS or MMU).

5.1.3 Test Procedures

The test began with both subjects located near Position B (Figure 2) and the AAA secured in the cargo bay in the undeployed position. Upon a signal from the test conductor, both subjects installed the three base columns on the outrigger, followed by deployment of the AAA. Subject 2 then translated to the top of the AAA and installed the ends of the three upper columns while Subject 1 installed the lower ends of the columns on the base unions. After completion of the tetrahedron, Subject 2 installed the SEM on the apex union of the structure. The Manual Assembly Sequence presented in Appendix A defines the initial condition and step-by-step crew tasks.

5.1.4 Test Results

The most beneficial results obtained were the evolution of better hardware configurations and procedures. Table 2 summarizes the changes brought about as the result of each test and the elapsed times recorded for assembly of the tetrahedral cell.

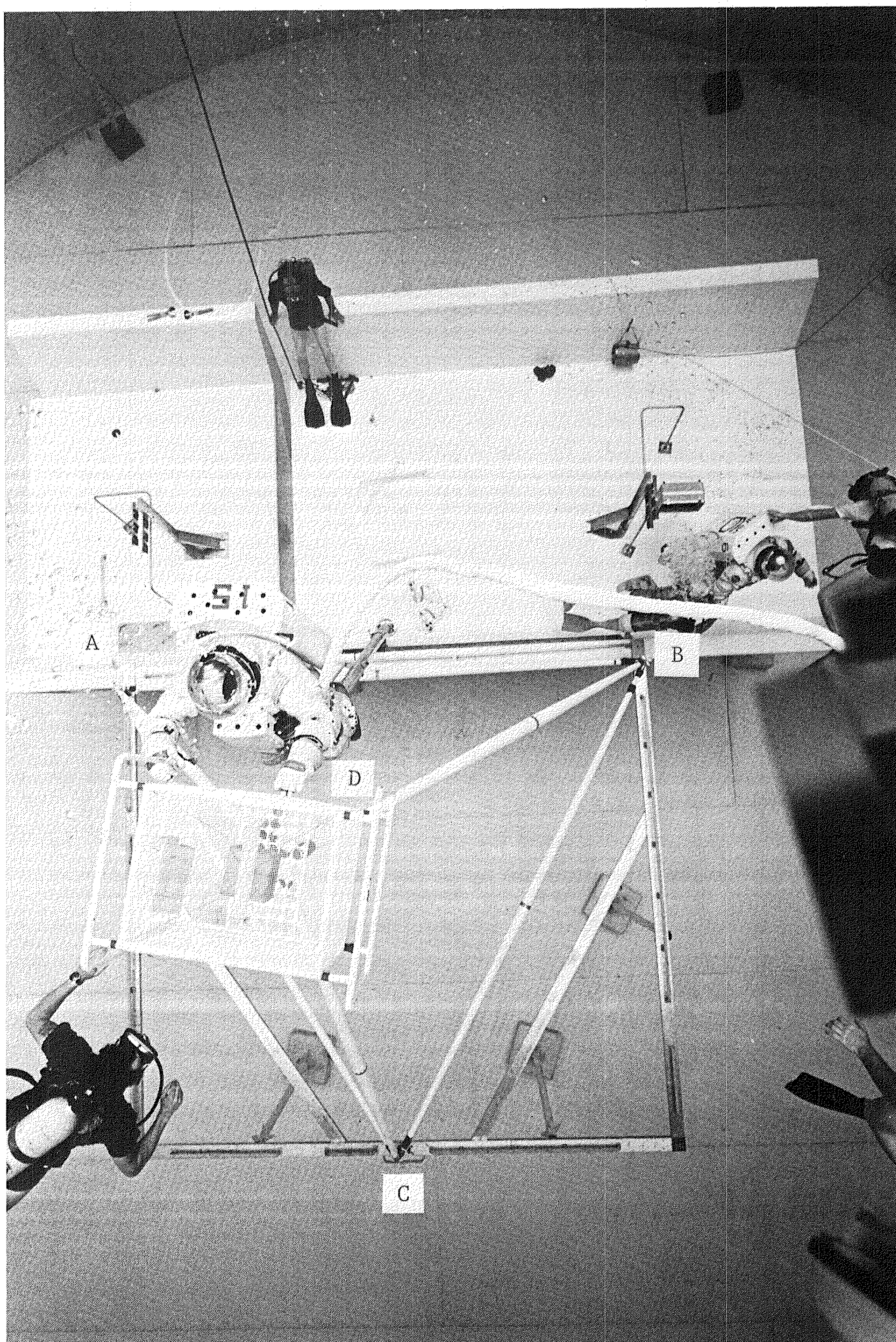


Figure 2: Assembled Tetrahedral Cell Showing Work Station Locations

Table 2: Summary of Changes in Hardware/Procedures Resulting from Test Series 1

TEST NO.	DATE	ASSY TIME (minutes)	HARDWARE/PROCEDURES IMPACT AFFECTING NEXT TEST
1	3/22/79	87.0	• AAA redesigned - diameter enlarged, foot restraint replaced leg loop restraints • CRF redesigned to hold columns in two rows of three columns each • Relocated AAA to more vertical position • Dive bag for translation of unions discarded for wire loop tether • Redesigned SEM attachment mechanism from snap joint/union to threaded configuration • Relocated SEM stowage area from near Position B to near base of AAA
2	4/16/79	54.37	• Relocated AAA foot restraint • Indexed AAA base clamp • Added leg restraint at Position C
3	4/17/79	56.95	• Loosened union mounting pedestals on outrigger
4	4/17/79	58.80	• Enlarged knobs on AAA base clamp • Added foot restraint at Position A
5	4/18/79	33.33	• Added alignment pins at base of AAA • Modified AAA deployment procedure
6	4/19/79	45.75	• Added foot restraint at Position C • Added handrails on diagonal braces of outrigger • Reoriented AAA in stowed position
7* 8*	9/10/79 9/10/79	42.37 40.52	• Repositioned AAA foot restraint • Modified procedure to install Column 4 in Union D • Repositioned foot restraints at Positions A, B and C
9* 10*	9/11/79 9/11/79	54.58 40.18	• Realigned outrigger, pedestals, etc. • Rotating (self aligning) joints oriented toward base of cell instead of at apex union
11* 12*	9/12/79 9/12/79	26.80 29.18	• Placed Apex (Union D) on Column 4 prior to start of test
13* 14*	9/12/79 9/12/79	29.42 29.32	

*More than one assembly was performed during testing session.

Most of the changes occurred after Test 1 (March 22, 1979), which was terminated following damage to two of the vertical columns after being struck by a subject's chestpack. This resulted in the redesign of the AAA which included a larger vertical member (from 2.0 in. to 4.5 in. outside diameter, see Figures 3 and 4) as well as replacement of the AAA loop leg restraints with foot restraints to provide a more stable workstation. Subsequent tests resulted in numerous minor adjustments to the workstations (many of which were unique to that testing situation) with the final configuration utilizing foot restraints at all four workstations.

5.2 TEST SERIES 2 - AUGMENTED ASSEMBLY SEQUENCE (Tests 15 Through 17)

5.2.1 Purpose

The purpose of this test series conducted on September 14, 1979 was to compare assembly operations using EVA crewmen only and EVA crewmen with a RMS for assistance.

5.2.2 Test Conditions

The following test conditions were utilized during the second test series:

- 5.48 m. (18 ft.) graphite/epoxy columns fitted with snap joint/unions
- Augmented assembly sequence.

5.2.3 Test Procedures

The test began with both subjects ready to enter the foot restraints at their workstations (Crewman 1 at Position B and Crewman 2 at Position A). The AAA was in the deployed position; Crewman 2 was holding Union A and had Union C fastened to his wrist tether. Union D had been installed on Column 4 prior to the start of the test.

Upon instruction from the test conductor, the subjects began the assembly task according to the Augmented Assembly Sequence (Appendix B), and two utility divers simulated the RMS by translating the columns and SEM into position. During the pre-test briefing, the utility divers had been instructed to simulate the movements of the RMS by translating the equipment at a low rate of speed and avoiding translation paths near the AAA.

5.2.4 Test Results

Three successful assemblies of the tetrahedral cell were accomplished during the one test session on September 14. Table 3 summarizes the assembly times for the three assembly operations. An analysis of the data obtained from Tests 15, 16 and 17 is available in Sections 8.1.2 and 9.2.

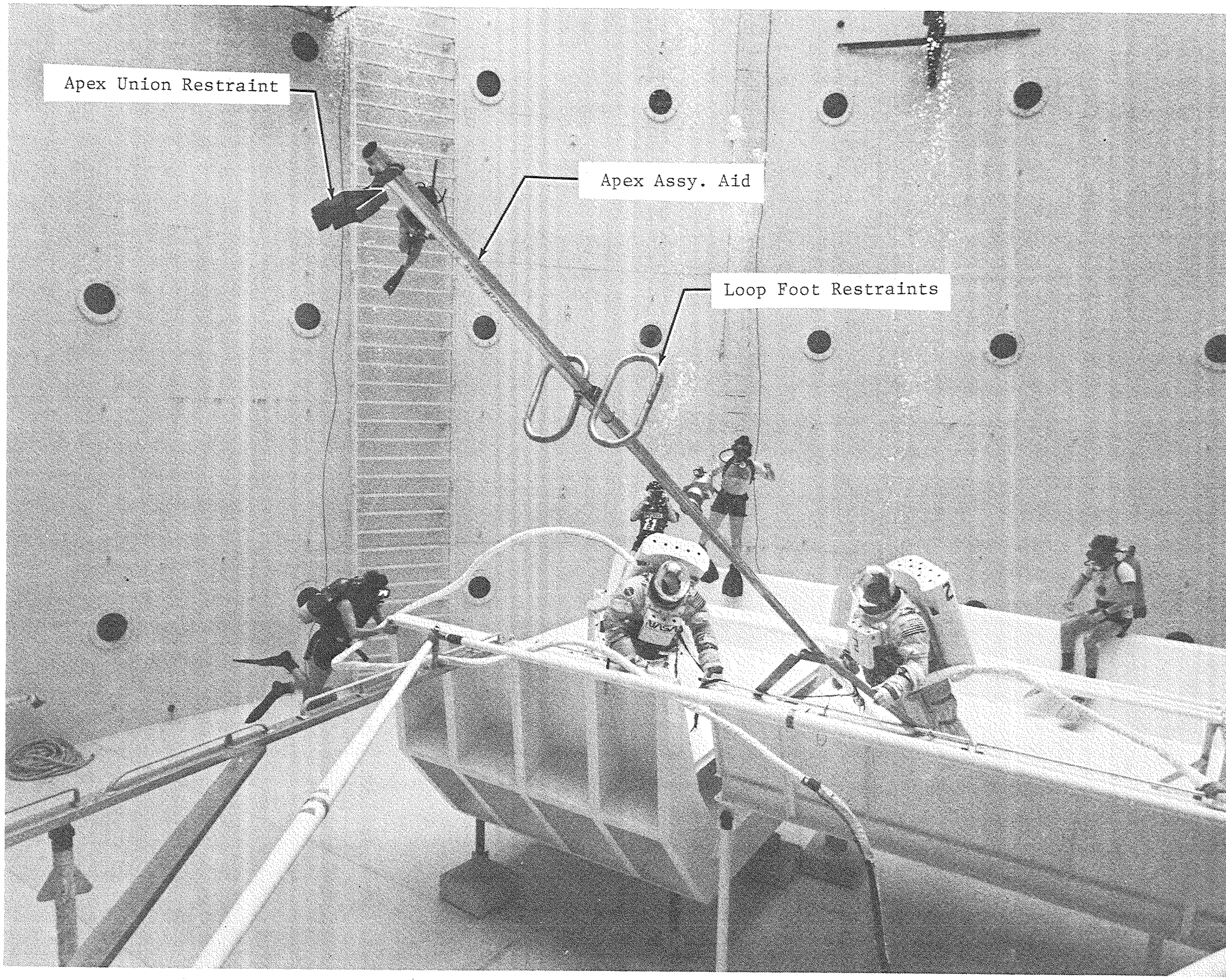


Figure 3: Erected Apex Assembly Aid

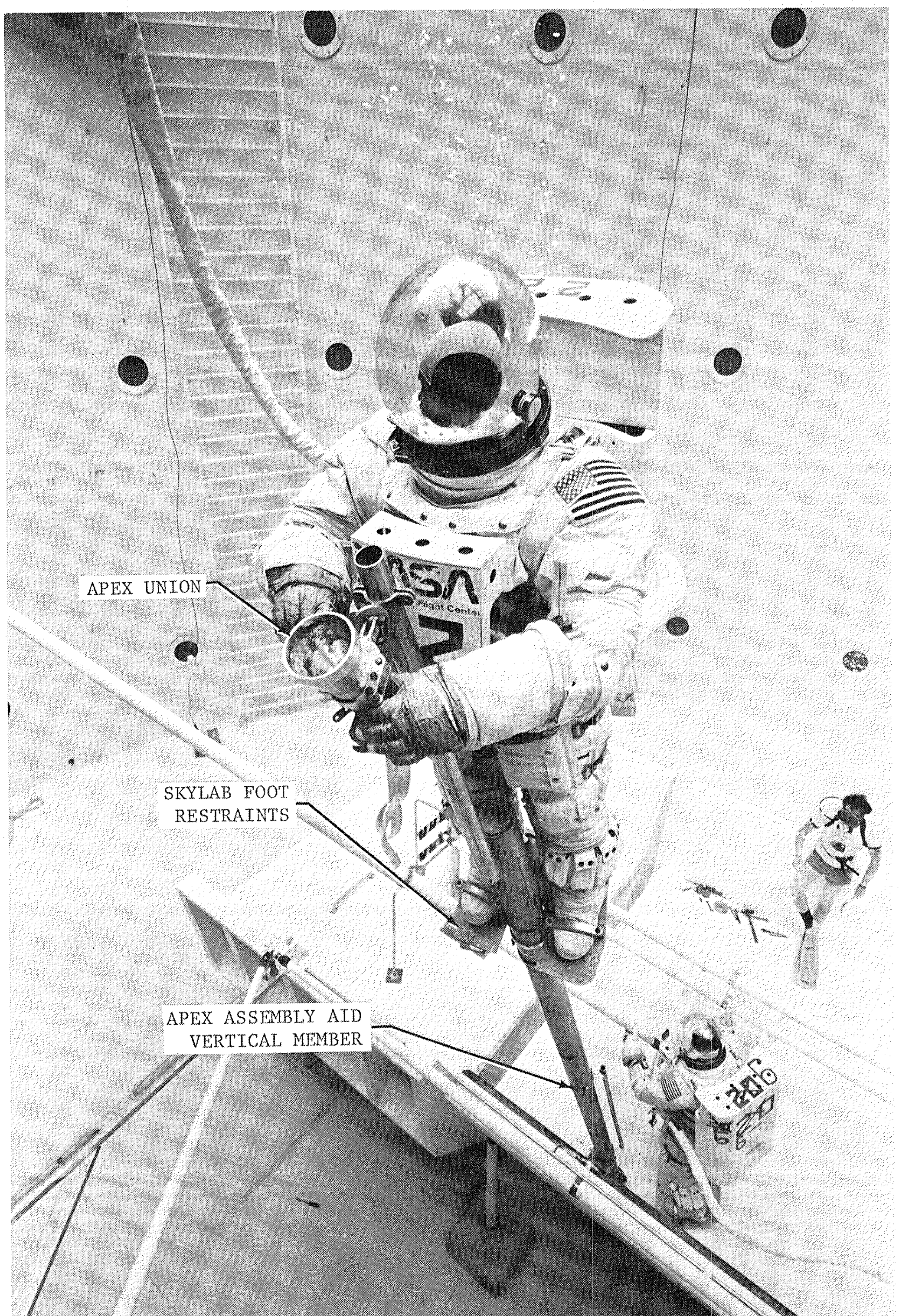


Figure 4: Erected Apex Assembly Aid Final Configuration

Table 3: Assembly Times for Augmented Assembly Sequence (Tests 15, 16 and 17, NB-18A)

TEST NO.	DATE	ASSEMBLY TIME (minutes)
15	9-14-79	16.55
16	9-14-79	14.50
17	9-14-79	15.08

6.0 NB-18B, EVA MANIPULATION AND ASSEMBLY OF SPACE STRUCTURE COLUMNS - 9.14 m. (30 ft) LENGTH

6.1 MANUAL AND AUGMENTED ASSEMBLY SEQUENCE (Tests 1 Through 8)

This section addresses the eight pressure-suited tests conducted during the period of June 19-28, 1979 which utilized 9.14 m.(30 ft) aluminum columns fitted at the ends with a rigid ball and lock nut developed and furnished by RI (Figures 5 and 6). The SEM was the same unit used in the NB-18A test series (Section 5.0, above) with modifications made to accommodate the self-actuating attachment mechanism (also developed by RI) which secured the SEM to the apex union of the completed tetrahedral cell.

Prior to the first suited test on June 19, 1979, modifications were made to the cargo bay mockup and related equipment to accommodate the longer columns and different column end fittings used in the test series.

On June 14 and 15, 1979, three swim-through tests were conducted by subjects equipped with scuba gear in order to facilitate the development of procedures and to test the hardware.

6.1.1 Purpose

The purpose of this test series was to investigate assembly procedures and hardware configurations for manual and augmented assembly sequences of the tetrahedral cell with 9.14 m.(30 ft) aluminum columns and ball/socket joints provided by RI.

6.1.2 Test Conditions

The following test conditions were utilized during this test series:

- 9.14 m.(30 ft) aluminum colums fitted with ball/socket joints
- Manual assembly sequence (with MMU only) - Tests 1, 2, 3 and 7
- Augmented assembly sequence (with RMS and MMU) - Tests 4, 5, 6 and 8.

6.1.3 Test Procedures

Each test began with Subject 1 near Position B and Subject 2 near Position A (Figure 2, above).

During Test 1, Subject 1 was equipped with a battery powered MMU simulator which was inadequate to translate the subject and column. The use of this device was discontinued during subsequent tests with utility divers translating the subjects between workstations (Figures 7 and 8).

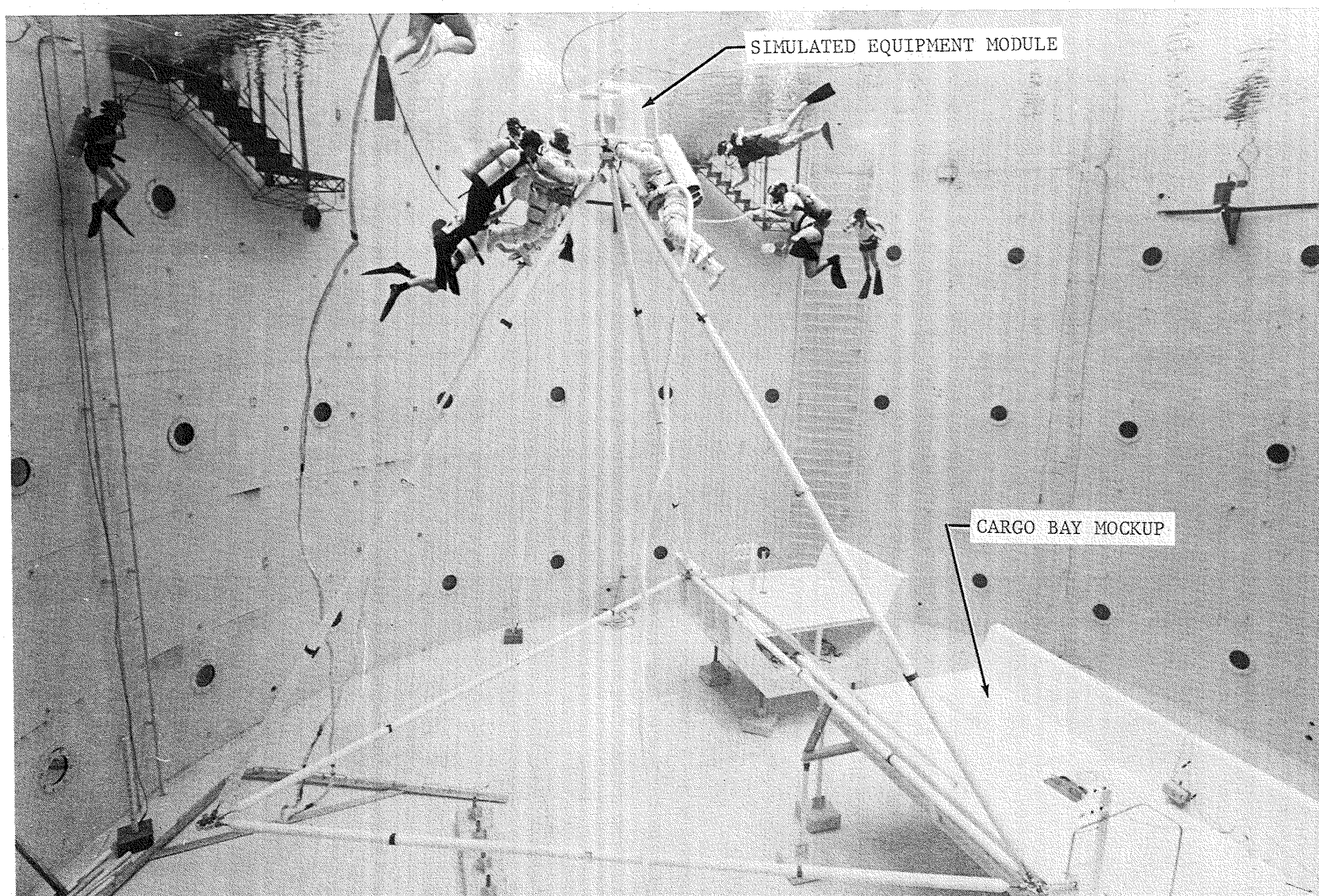


Figure 5: Assembled Tetrahedral Cell - 9.14 m (30 ft) Columns

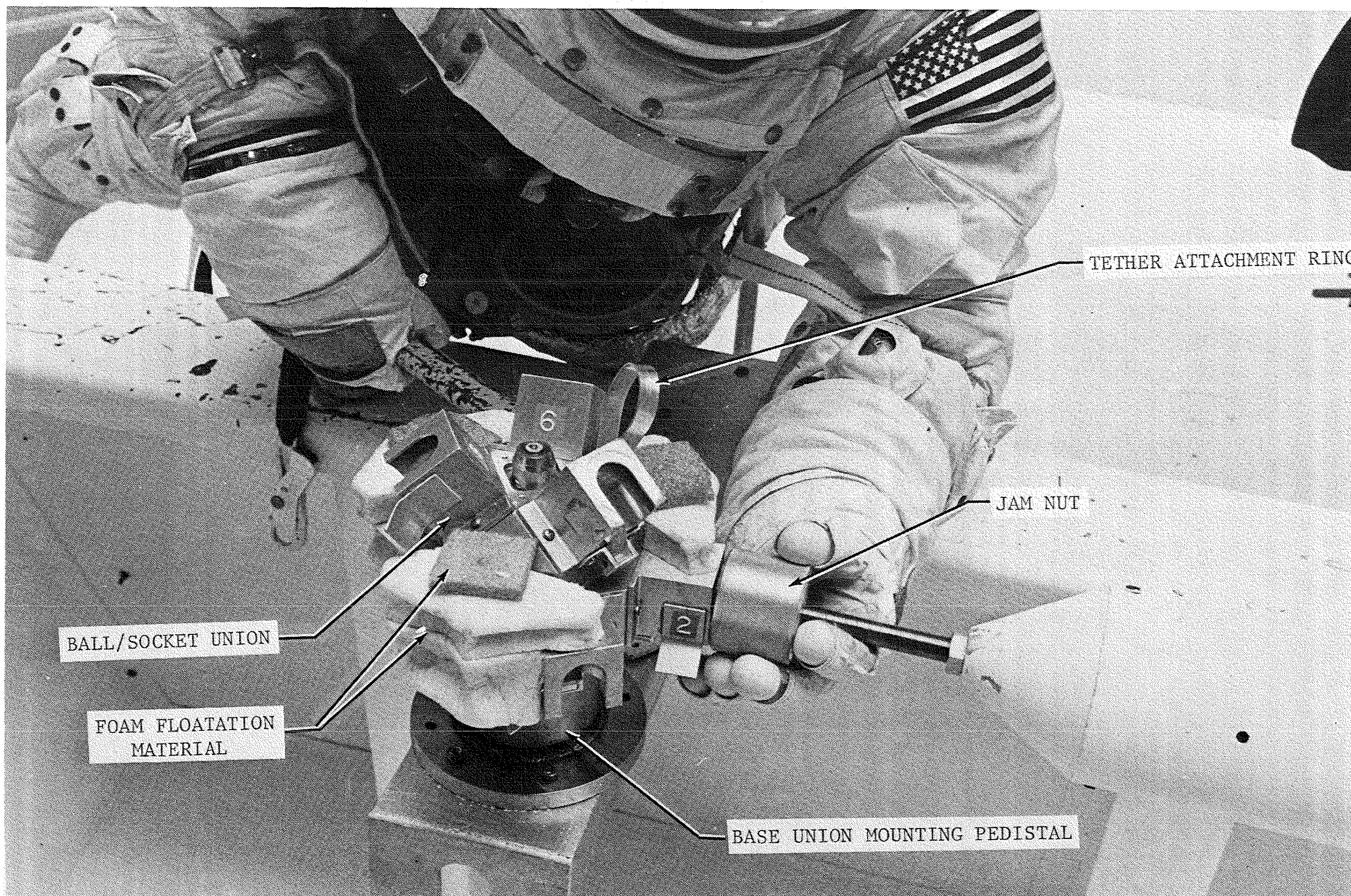


Figure 6: Ball/Socket Union Configuration

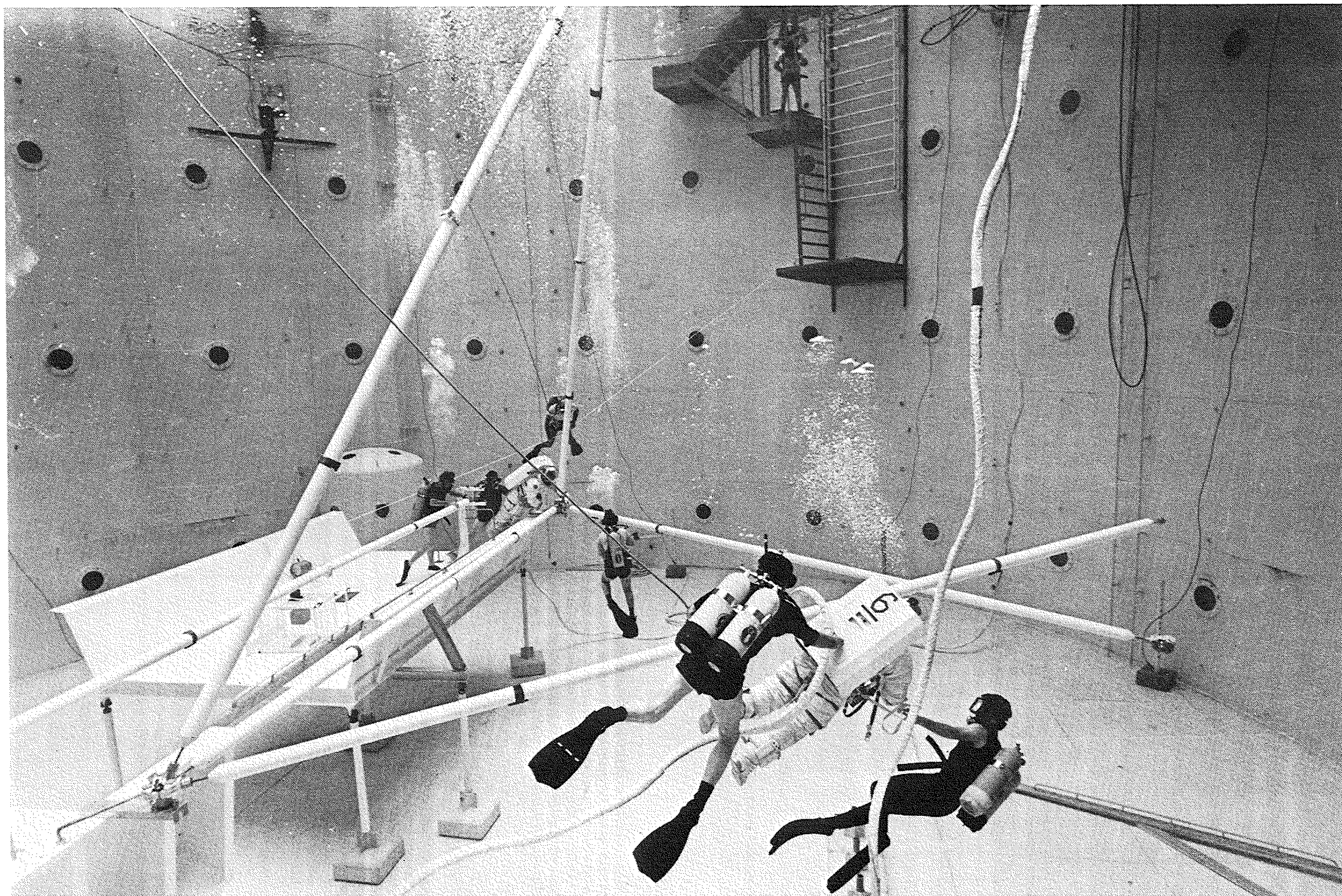


Figure 7: Translation of Pressure Suited Subject by Divers Simulating MMU

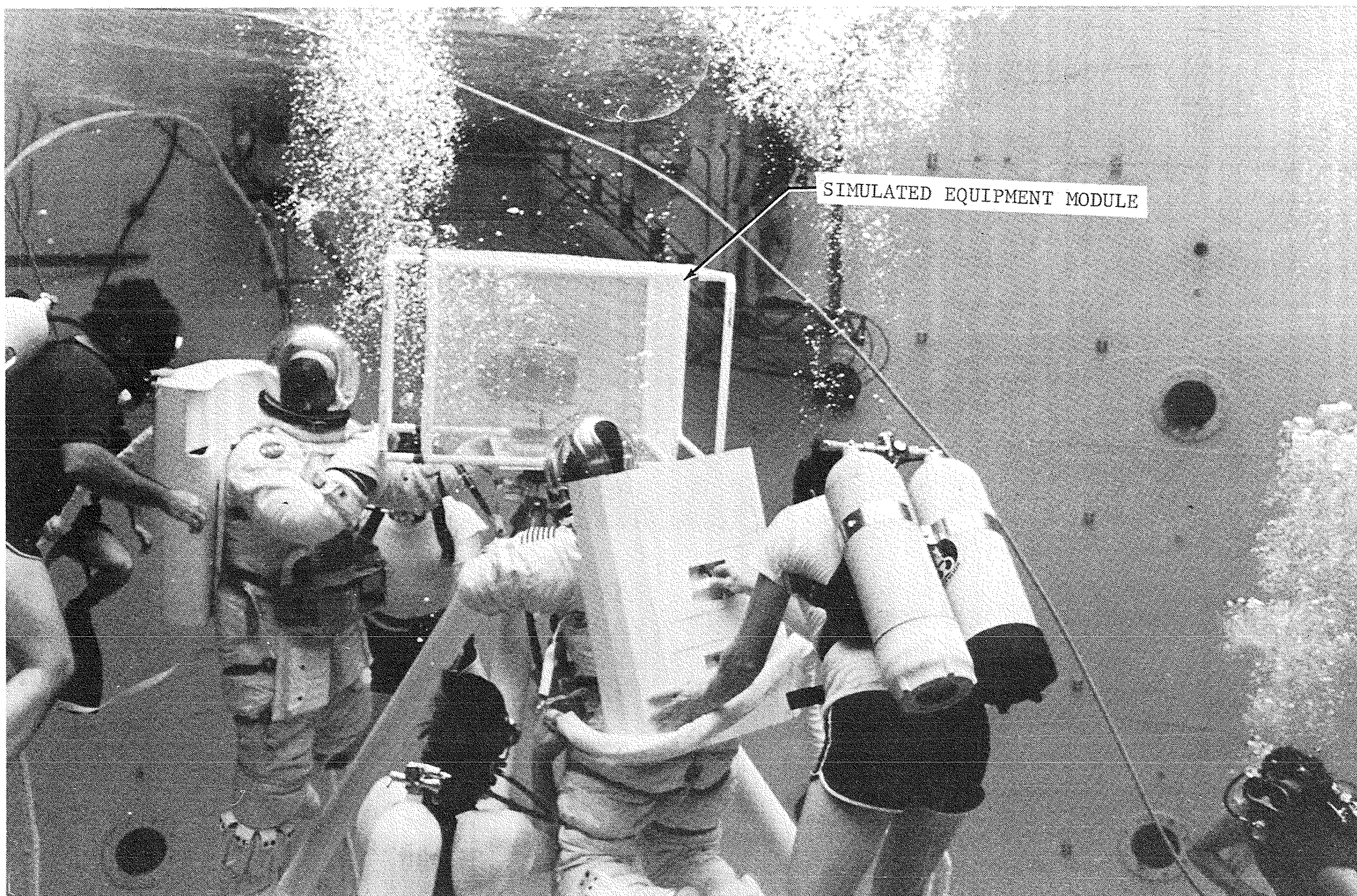


Figure 8: Pressure Suited Subjects Being Held in Position by Divers Simulating MMUs

Due to the highly viscous drag encountered in translating and rotating the 9.14 m.(30 ft.) aluminum columns under water, utility divers assisted the test subjects when these activities were required.

Four of the tests (Tests 1, 2, 3 and 7) employed a manual assembly sequence (Appendix C) in which the subjects manually translated the columns and SEM into position. The remaining four tests (Tests 4, 5, 6 and 8) employed an augmented assembly sequence (Appendix D) in which translation of the columns and SEM was accomplished through divers simulating the use of a RMS.

6.1.4 Test Results

Table 4 summarizes the assembly times and test conditions for tests 1 through 8. The use of a RMS simulator resulted in a shorter mean assembly time (14.54 min. versus 22.06 min.) than when manual translation of structural members was employed. The test subjects reported no difficulty in assembling the tetrahedral cell with the exception of the installation of the SEM. The primary problem encountered in this task was the lack of indexing aids and visual feedback indicating mating of the SEM to the apex union.

Table 4: Assembly Times for Manual and Augmented Assembly Sequence (Tests 1 Through 8, NB-18B)

TEST NO.	DATE	ASSEMBLY SEQUENCE	ASSEMBLY TIME (Minutes)
1	6-19-79	Manual	29.58
2	6-25-79	Manual	23.77
3	6-25-79	Manual	15.45
7	6-28-79	Manual	19.42
4	6-26-79	Augmented	19.63
5	6-27-79	Augmented	15.07
6	6-27-79	Augmented	10.98
8	6-28-79	Augmented	12.48

6.2 MANUAL AND AUGMENTED ASSEMBLY SEQUENCE (Tests 9 Through 12)

This section addresses the four pressure suited tests conducted on July 10, 1979, in which the 5.48 m.(18 ft.) graphite/epoxy columns used in the NB-18A tests were mated with the rigid ball/joint used in the previous test series (Section 5.1, above).

Prior to the tests, changes were made in the location of the attachment points on the cargo bay, the CRF, and the workstations near base unions A and B to accommodate the shorter columns used in this test series.

Although the hardware configuration was the same as for the comparison study (NB-18C, Section 7.0 of this report), the assembly procedures and initial conditions warrant the separate treatment of these tests from those of the comparison study.

6.2.1 Purpose

The purpose of this test series was to investigate assembly times for manual and augmented assembly sequences of the tetrahedral cell when utilizing the 5.48 m. (18 ft) graphite/epoxy columns fitted with the rigid ball/socket.

6.2.2 Test Conditions

The following test conditions were utilized in this test series:

- 5.48 m. (18 ft) graphite/epoxy columns fitted with ball/socket joints
- Augmented assembly sequence (with RMS and MMU) - Tests 1 and 2
- Manual assembly sequence (with MMU only) - Tests 3 and 4.

6.2.3 Test Procedures

The same test procedures were used as in Section 6.1 with the augmented assembly sequence (Appendix D) employed for Tests 1 and 2, and the manual assembly sequence (Appendix C) employed for Tests 3 and 4. As in the previous test series, utility and safety divers fulfilled the function of the RMS and MMUs.

6.2.4 Test Results

Table 5 summarizes the assembly times and test conditions for Tests 9 through 12. As in the previous test series (Paragraph 5.1, above), the use of a RMS to augment the tetrahedral assembly resulted in somewhat lower mean assembly times when compared with the manual assembly sequence (10.74 min. versus 13.60 min.).

In general, no difficulties were encountered with either the procedures or hardware with the exception of installation of the SEM as in previous tests. One failure did occur when the ball end fitting of one of the columns became dislodged after a fracture of the graphite/epoxy column during Test 1. The column was replaced without interruption of the test.

Table 5: Assembly Times for Augmented and Manual Assembly Sequences (Tests 9 Through 12, NB-18B)

TEST NO.	DATE	ASSEMBLY SEQUENCE	ASSEMBLY TIME (Minutes)
9	7-10-79	Augmented	11.28
10	7-10-79	Augmented	10.20
11	7-10-79	Manual	14.18
12	7-10-79	Manual	13.05

6.3 CONTINGENCY REMOVAL OF A COLUMN AND DEPLOYMENT OF A FOLDED COLUMN

This section addresses the contingency removal of a column and deployment of a folded 9.14 m.(30 ft.) column tests conducted concurrently with the tests described in Section 6.1, above.

6.3.1 Purpose

The purposes of these tests were to investigate and determine task element times concerning contingency removal of one column from a tetrahedral cell by a pressure-suited subject, and to investigate and compare two types of center hinge joints--a latch lock configuration and a sleeve lock configuration. These two types of joints were deployed under two conditions: (1) unassisted, and (2) assisted by the use of a fulcrum point.

6.3.2 Test Conditions

The following test conditions were utilized in this test series:

- Contingency Removal of a Column
  - Assembled tetrahedral cell with 9.14 m. (30 ft.) aluminum columns fitted with ball/socket joints
  - Subject at apex of assembly with tool attached to wrist tether
- Unassisted Deployment of a Column
  - Subject in foot restraints in center of cargo bay
  - 9.14 m. (30 ft.) folded column with latch lock or sleeve lock center hinge joint (see Table 6)
- Assisted Deployment of a Column
  - Subject in foot restraints near fulcrum point on sill of cargo bay

- o Assisted Deployment of a Column (continued)
  - 9.14 m. (30 ft.) folded column with latch lock or sleeve lock center hinge joint (see Table 6).

6.3.3 Test Procedures

The column contingency removal tests consisted of the removal of a vertical column by a test subject from a pre-assembled tetrahedral cell (see Figure 9). The tasks consisted of the subject loosening the jam nut, depressing the latching mechanism of the union with a tethered tool, translating to the lower end of the column, and repeating the same tasks. As in other tests in Section 6, translation of the pressure-suited subject was accomplished through the use of a diver simulating a MMU.

The tests involving deployment of folded 9.14 m. (30 ft.) columns investigated two types of center hinge joints--a sleeve lock and a latch lock. These were employed under two conditions: (1) the test subject in foot restraints using no deployment aids (Figure 10), and (2) the test subject in foot restraints with one end of the column anchored in a union with a fulcrum point near the center hinge joint (Figure 11).

6.3.4 Test Results

6.3.4.1 Contingency Removal of a Column

The two tests of column contingency removal resulted in a mean task time of 3.08 minutes (3.20 min. and 2.95 min.). Both test subjects reported no difficulty in any of the steps required to remove the column and stated that the removal tool worked satisfactorily.

6.3.4.2 Deployment of a Folded Column

Table 6 presents the mean deployment times (in minutes) for both test subjects for deployment of the folded columns with and without the use of a fulcrum point. Each test subject participated in the column deployment test once for each test condition.

Table 6: Mean Column Deployment Times (In Minutes)

	Center Hinge Joint	
Deployment Method	Sleeve Lock	Latch Lock
With Fulcrum	1.34	1.08
Without Fulcrum	.64	.70

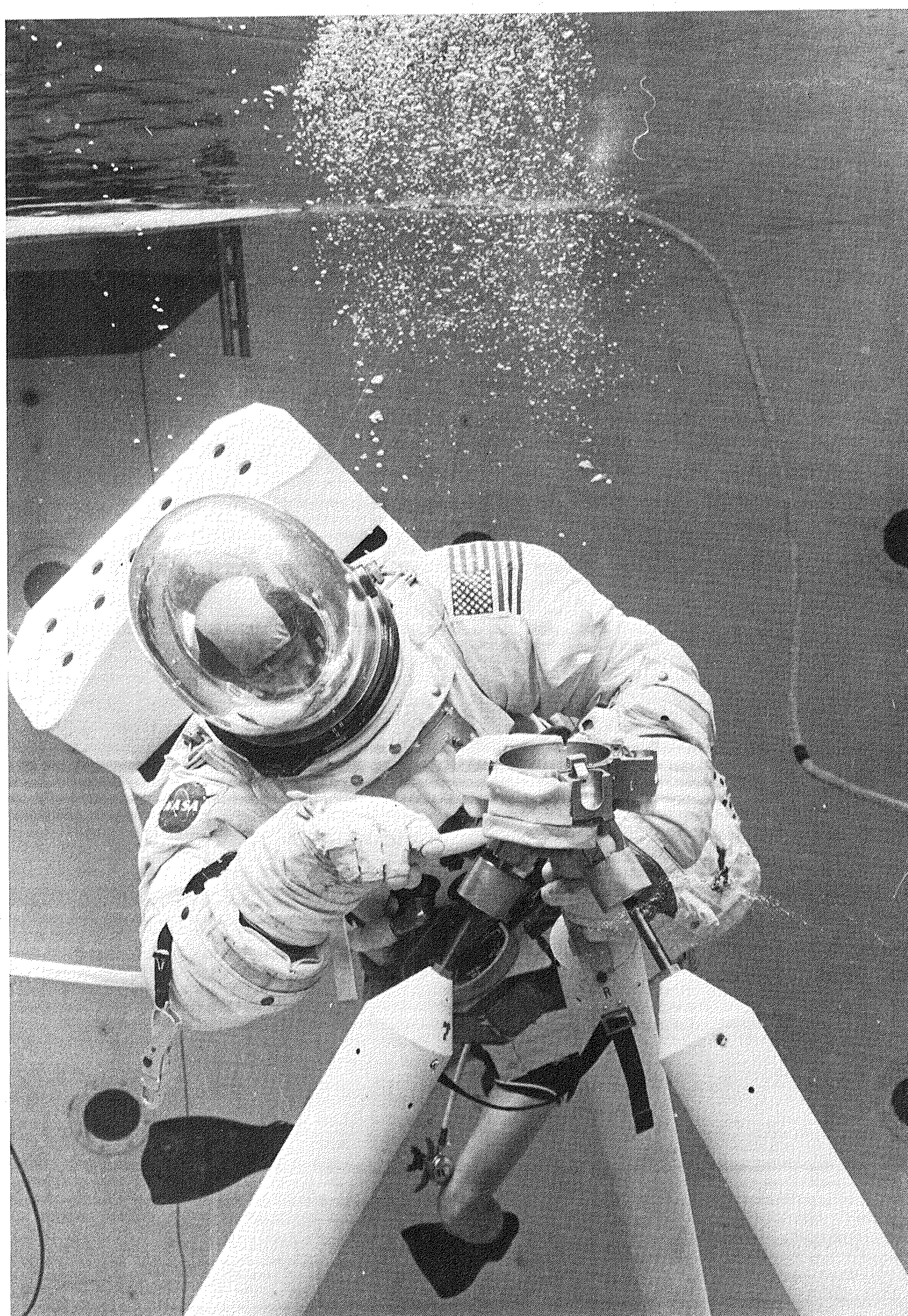


Figure 9: Removal of Column During Contingency Test

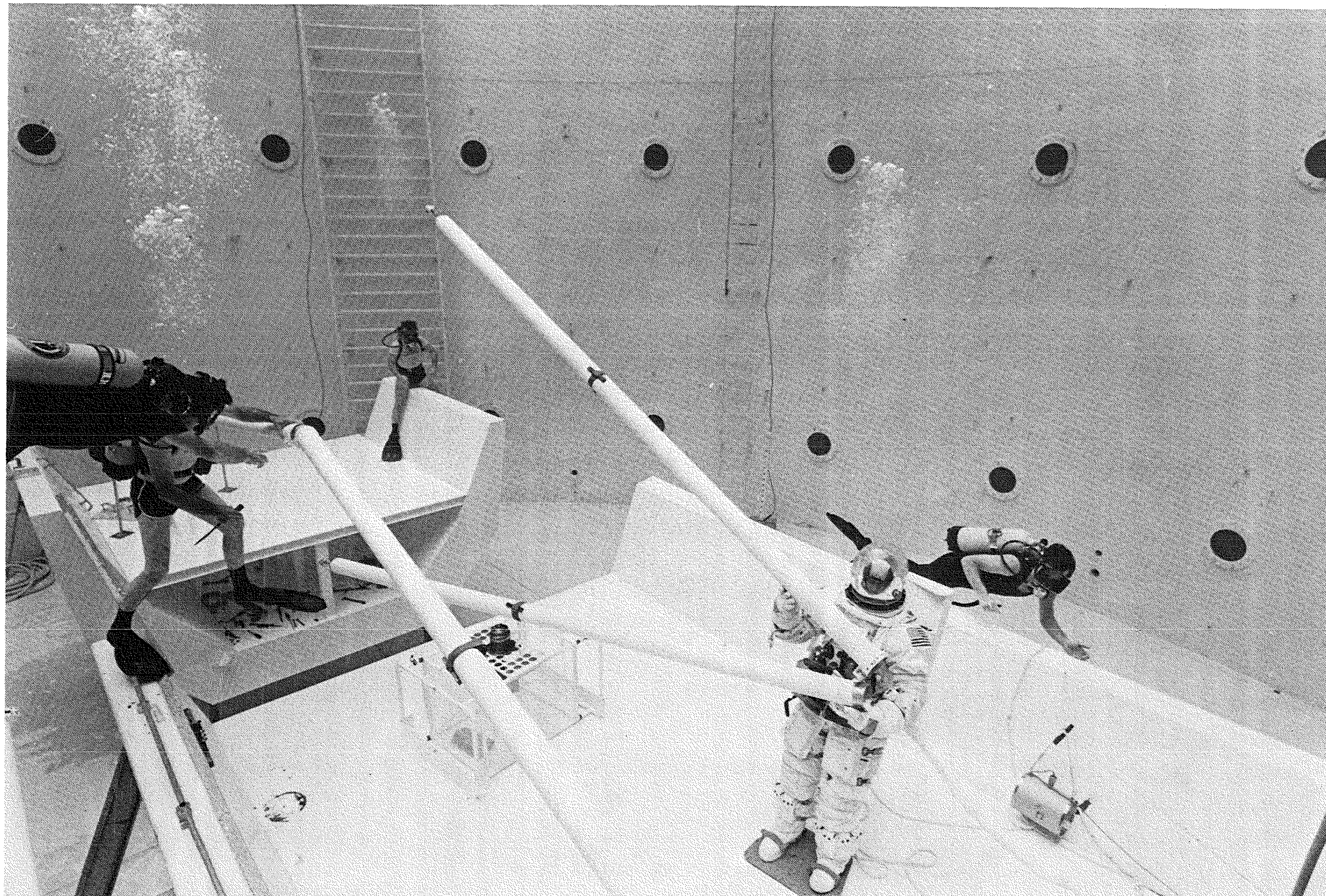


Figure 10: Unassisted Deployment of Folded 9.14 m.Column

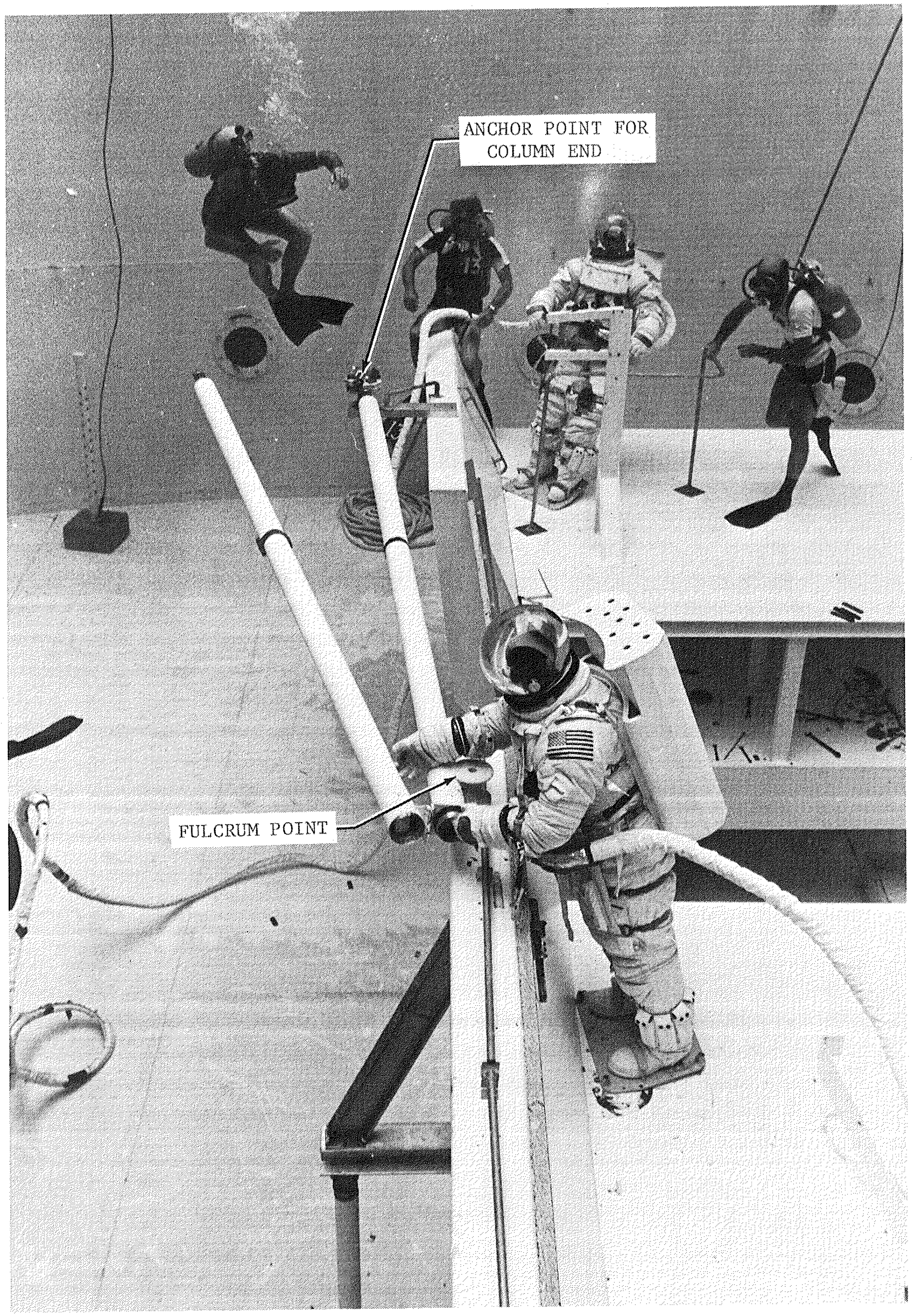


Figure 11: Deploying Folded 9.14 m. Column with End Anchored and Utilizing A Fulcrum Point

The use of a fulcrum point resulted in somewhat longer deployment times using both types of center hinge joints. Both subjects stated that they preferred the use of a fulcrum point but suggested that the fulcrum be mounted horizontally rather than vertically (see Figure 8, above).

Both types of center hinge joints operated with some difficulty with the most frequent problem being the failure of the locking mechanism to engage fully.

7.0 NB-18C, SNAP JOINT/UNION AND BALL/SOCKET JOINT COMPARISON STUDY

This section describes the eight tests conducted during the period of September 17-20, 1979 in which two types of column end fittings were compared.

7.1 PURPOSE

The purpose of this test series was to investigate the effect of two different types of column end fittings on assembly time.

7.2 TEST CONDITIONS

The following test conditions were utilized during the third test series:

- 5.48 m. (18 ft.) graphite/epoxy columns fitted with snap/joint unions (Tests 1-4) or ball/socket joints (Tests 5-8)
- Manual assembly sequence
- AAA in deployed position throughout test.

7.3 TEST PROCEDURES

The test began as in Test Series 2 with both subjects ready to enter the foot restraints at their workstations (Crewman 1 at Position B and Crewman 2 at Position A). The AAA was in the deployed position and Crewman 2 had Union A in his hand and Union C attached to his wrist tether. Union D was installed on Column 4 prior to the test.

Upon instruction from the test conductor, the subjects began the assembly task according to the Manual Assembly Sequence for the NB-18A/NB-18C Comparison Study. (Appendix E). Modification to the assembly procedure was necessitated by pre-test deployment of the AAA which eliminated tasks not directly related to the cell assembly, but which could introduce unwanted variance into the assembly time comparisons.

A counterbalanced design was used with two sets of subjects, each set performing two assembly operations utilizing both types of column end fittings. In addition, each subject performed in both crew positions in order to correct for any variation in individual subject performance.

After the last assembly was completed, all four test subjects attended a debriefing and were asked to comment on any facets of the tests, hardware, or procedures which they considered important.

7.4 RESULTS

Table 7 summarizes the assembly times, subject numbers, and test conditions for this test series. Tests 1 and 2 (NB-18A hardware) were both hampered by hardware components which had become fatigued through the previous assembly and disassembly operations. The primary difficulty centered about the locking tabs on the snap joint/unions, many of which had become bent or broken. These problems were overcome during Tests 3 and 4 by having utility divers inspect the mated joints and make repairs and secure the hardware with tape. It was also discovered that the SEM had an interference fit with the AAA. The difficulty with the SEM-AAA interference was overcome by a minor adjustment to the clamp at the upper end of the AAA.

Likewise, the assembly times for Tests 5 and 6 (NB-18C) increased because of an incorrectly installed SEM attachment mechanism. These tests were terminated when this was noticed.

The primary source of data for this test series, therefore, was derived from Tests 3, 4, 7 and 8. An analysis of these data is reported in Sections 8.1.3 and 8.2.2.

Table 7: Summary of Test Conditions, Subjects and Assembly Times for the Comparison Study (Tests 1 Through 8, NB-18C)

TEST	DATE	HARDWARE	CREWMAN 1 (Subject No.)	CREWMAN 2 (Subject No.)	ASSEMBLY TIME (Minutes)
1	9-17-79	Snap Joint	15	24	27.17*
2	9-17-79	Snap Joint	24	15	31.03*
3	9-18-79	Snap Joint	14	13	15.62
4	9-18-79	Snap Joint	13	14	15.32
5	9-19-79	Ball/Socket	15	24	16.15+
6	9-19-79	Ball/Socket	24	15	15.17+
7	9-20-79	Ball/Socket	14	13	12.92
8	9-20-79	Ball/Socket	13	14	11.07

*Crew experienced difficulty with fatigued column end attachments.
+Test terminated after difficulty with incorrectly installed SEM attachment hardware.

8.0 SUMMARY OF RESULTS

This section presents the results of statistical tests on assembly time and heart rate data. Crew and observer comments about the LSS columns and joints are presented in the discussion of conclusions in Section 9.0.

8.1 ASSEMBLY TIME COMPARISONS

Several comparisons were made of the various assembly times for the different test conditions. An analysis of variance was performed on the mean assembly times of five groups of data in order to determine whether significant relationships existed between apparent differences in assembly times under different test conditions. Table 8 presents the grouping of these data. The assembly times are shown in Figure 12. The times recorded during 20 tests were used in the analysis. Data for the five tests (NB-18A, Test 1; NB-18C, Tests 1, 2, 5 and 6) which were terminated prior to completion of the tetrahedron assembly were not included.

Table 8: Assembly Time Data Grouping for Analysis of Variance

TEST NO.	CONDITION
2-10	Manual Assy Sequence (NB-18A)
11-14	Manual Assy Sequence (NB-18A)
15-17	Augmented Assy Sequence (NB-18A)
3,4	Manual Assy Sequence (Snap Joint)
7,8	Manual Assy Sequence (Ball/Socket)

8.1.1 <u>Comparison of Assembly Times of Tests in Test Series 1 (Tests 2-14)</u>

A significant reduction of assembly time was observed in Tests 11-14 when compared with Tests 2-10 ($F=22.27$, $df=1, 15$, $p\leq.01$). This result is somewhat difficult to interpret, although the likely contributing factors were: (1) the installation of Union D on Column 4 prior to insertion in the AAA clamp, (2) the realignment of the outrigger and the associated pedestals, and (3) the procedural change in orienting the three upper columns so the self-aligning (rotating) unions were at the base. All three of these changes, aimed at facilitating the installation of the column end fittings in the unions through improved alignment of the test equipment, illustrate the need for fairly accurate alignment aids when this type of joint is used.

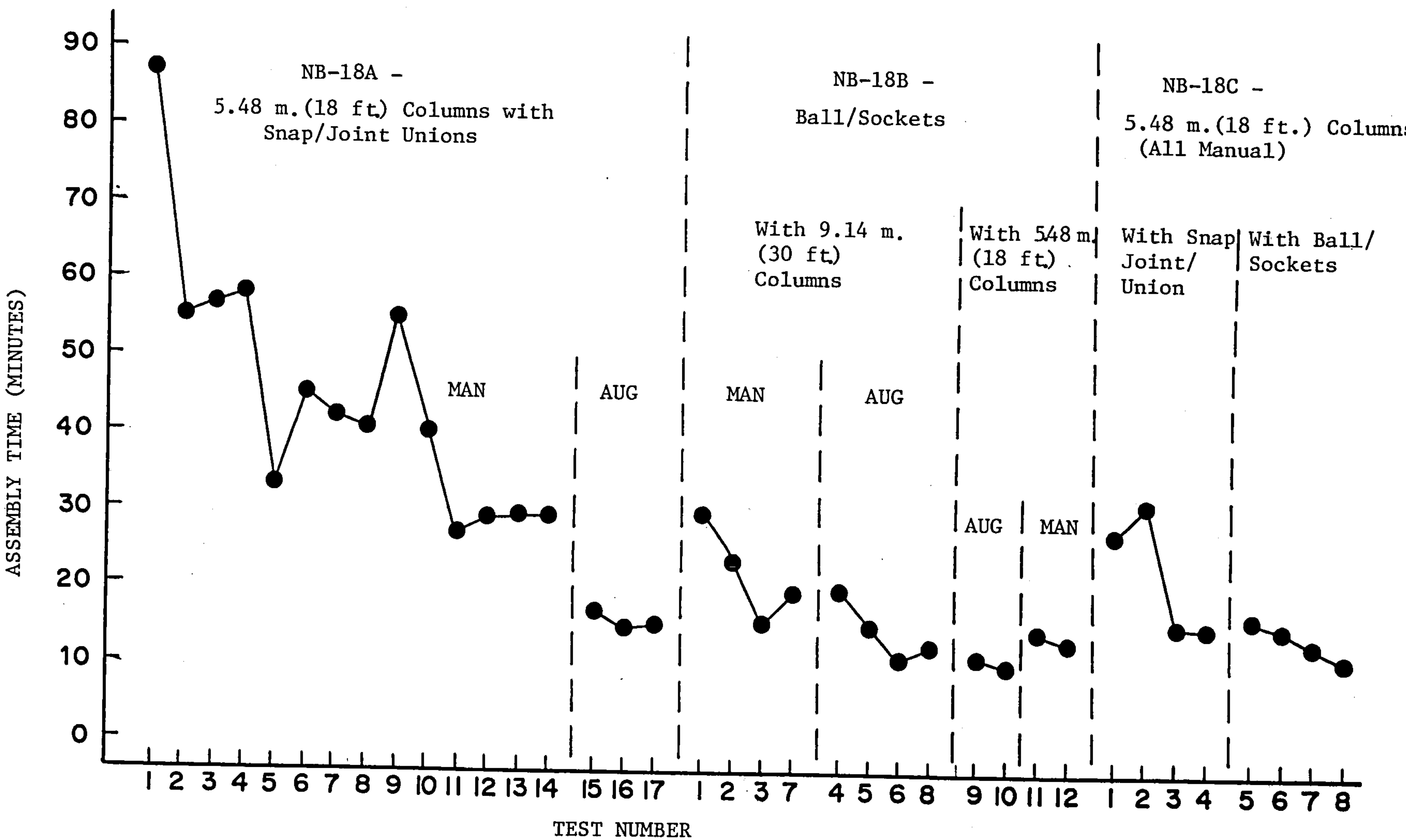


Figure 12: Assembly Times for NB-18A, NB-18B, and NB-18C

8.1.2 Comparison of Assembly Times of Manual and Augmented Assembly Sequences (Tests 11-14 and 15-17, NB-18A)

A comparison of assembly times recorded when the Manual Assembly Sequence (Tests 11-14) was compared with the Augmented Assembly Sequence (Tests 15-17) surprisingly revealed no significant difference. It must be remembered, though, that the analysis of variance test employed was very conservative when using such a small sample size. Sources of variance which could be considered "experimental noise" possibly diminish experimental effects which might be observed had these sources of noise not been present.

8.1.3 Comparison of Assembly Times When Using Two Types of Hardware: Snap Joint/Union (NB-18A, Tests 20, 21) and Ball/Socket Joint (NB-18C, Tests 24, 25)

Although a difference in mean assembly time was observed when the two types of hardware were utilized, statistical significance was not achieved. One interpretation may be that under similar testing conditions, when work stations are adequate and time consuming activities such as crew translation are minimized, differences in total assembly times are also minimized when different types of column end fittings are used.

8.2 HEART RATE COMPARISONS

Comparisons of heart rate data as a function of crew member position and as a function of the two types of column end fittings were performed. The results are discussed below.

8.2.1 Comparison of Heart Rates Between Crew Member Positions

An analysis of the heart rate data obtained from a strip chart recorded through a six seconds per minute time sampling technique revealed no significant difference in heart rates for each test subject when performing in the Crew Member 1 or Crew Member 2 position. This analysis was performed in order to determine whether significant differences existed in the amount of work required of each crew member. The lack of difference was interpreted as indicating that the assembly procedures resulted in a fairly well balanced effort between the two crewmen.

8.2.2 Comparison of Heart Rates Between Crew Members When Using Two Types of Column End Fittings

The test subjects also exhibited no significant difference in heart rate when utilizing the snap joint/union or the ball/socket joint column end fittings. It might be added, however, that heart rate data are somewhat difficult to interpret and, of all the data collected in the test series, these data are probably most susceptible to influences beyond the control of the test conductor. Factors such as the fit of the suit, relative position of the test subject, etc., all contribute to changes in heart rate which may mask changes brought about through the amount of work the test subject was doing.

9.0 CONCLUSIONS

9.1 TEST SERIES 1 - MANUAL ASSEMBLY SEQUENCE

The results from Test Series 1 support the proposition that EVA manual assembly of LSS is feasible and can also be done fairly efficiently with relatively low assembly times per tetrahedral cell. This statement is true if the following conditions are met:

- Assembly procedures are such that crew translation is minimized.
- Work stations are provided at critical assembly locations. Each should have a foot restraint and locate the crew member so as to optimize assembly operations.
- Assembly aids which hold partially assembled structures should provide alignment within the tolerances of the unions.

The present study was somewhat limited in that only one tetrahedral cell was assembled. Additional studies need to be performed which investigate assembly procedures and crew aid configurations on assemblies of more than one tetrahedral cell. The objectives of these studies should be to:

- Define elemental assembly tasks
- Provide additional normative data on task element times
- Develop assembly fixtures which optimize crew assembly performance
- Develop and quantify the design of work stations and crew aids
- Investigate the cost effectiveness of additional crew members and/or assembly machines for specific assembly activities.

9.2 TEST SERIES 2 - AUGMENTED ASSEMBLY SEQUENCE (Simulated RMS)

Although the data comparing manual and augmented assembly sequences show no statistically significant differences in assembly times, additional data probably would demonstrate that the use of the remote manipulator system would facilitate assembly. The primary effect of using a RMS would be to reduce the number of crew translations and allow the storage container for columns and unions to be located in an area outside the reach envelope of the assembly crew. The latter effect is especially important when more than one cell is being assembled. This would have to be traded against RMS operational constraints, such as arm oscillation, difficulty in capturing columns or unions, and capability of positioning columns within a cell.

It was the concensus of those involved in the present study that use of utility divers in the role of the RMS probably resulted in unrealistic translation times in that the divers probably moved faster and with more a agility than the RMS. It is recommended that when the RMS becomes available, further tests be conducted in order to determine the following:

- RMS task element time involving capture, translation, and positioning of columns
- Design of a column stowage fixture which is optimal for use with the RMS
- The development of assembly procedures which optimally utilize the RMS.

9.3 TEST SERIES 3 - SNAP JOINT/UNION (NB-18A) AND BALL/SOCKET JOINT (NB-18C) COMPARISON STUDY

Data, including crew comments, indicate that a comparison of the two types of column end fittings and associated hardware allow the following conclusions to be drawn:

- The ball/socket joint is less sensitive to structural alignment and crew training effects and, therefore, initially would be shown to result in somewhat lower assembly times.
- After adequate experience with both types of hardware, this difference should decrease to the point where any differences in terms of task element times would be negligible, as long as optimal workstations are provided for assembly crews.
- Decisions regarding the form of attachment hardware would probably hinge more on structural considerations (involving such factors as mass, packagability, cycle sensitivity to assembly and disassembly, and strength) than on ease of assembly, provided the above two factors are taken into account.
- It is conceivable that both types of hardware would prove useful in specific applications (i.e., a ball/socket configuration used in working contingencies where adequate workstations are not available).

9.4 SUMMARY OF TASK ELEMENT TIMES

Appendix F presents the task element times obtained from this test series. These data were obtained from a review of video tapes recorded during the tests.

Of particular interest, other than a quantification of assembly behaviors, is the finding that the individual task elements were relatively insensitive to the total assembly time of the tests from which they were obtained. That is, task element times from earlier tests were nearly equal to those obtained from later tests in which the assembly times were much shorter. An explanation of this apparent incongruity can be found in observing the time the subjects spent in non-assembly activities such as requesting instructions, making suggestions, etc.

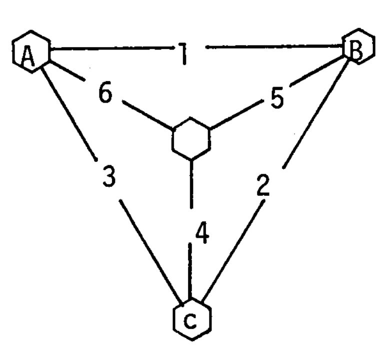
In planning assembly scenarios, it is best to include, over and above the totaled task element times, some additional time factor for conversation, rest, etc. Test results indicate that this additional time factor approximates 12% of the total task element time.

APPENDIX A

MANUAL ASSEMBLY SEQUENCE (NB-18A)

MANUAL ASSEMBLY SEQUENCE - NB/18A

STEP	SUBJECT 1	SUBJECT 2
1	Install Union B at Pos B Install Col 1 in Union B	Install Union A at Pos A Install Col 1 in Union A
2	Rotate Col 2 toward S 2 Install Col 2 in Union B	Translate to Pos C Install Union C at Pos C Install Col 2 in Union C
3	Translate to Pos A Rotate Col 3 toward S 2 Install Col 3 in Union A	Receive Col 3 Install Col 3 in Union C
4	Translate to AAA Rotate AAA into erect pos Install Index Pin at base of AAA	Translate to AAA base Receive AAA Secure Clamp on AAA
5	Translate to Pos B Transfer Col 4 to S 2 Translate to Pos C Install Col 4 in Union C	Translate to top of AAA Receive Col 4 Rotate Col 4 toward Pos C Install Union D (installed on Col 4) in clamp on AAA
6	Translate to Pos B Rotate Col 5 toward S 2 Install Col 5 in Union B	Install Col 5 in Union D
7	Translate to Pos A Rotate Col 6 toward S 2 Install Col 6 in Union A	Install Col 6 in Union D
8	Translate to SEM Tether SEM Translate SEM to S 2	Receive SEM from S 1 Install SEM in Union D



APPENDIX B

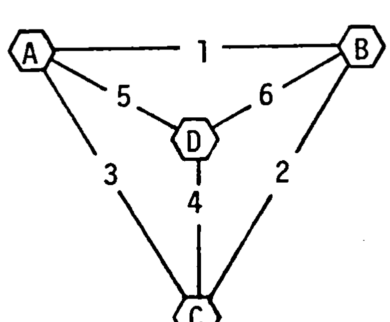
AUGMENTED ASSEMBLY SEQUENCE (NB-18A)

AUGMENTED ASSEMBLY SEQUENCE - NB/18A

ESSEX

Initial Conditions: (1) AAA in position
(2) Subject 1 at Position B
Subject 2 at Position A
(3) Subject 1 has Union B tethered
Subject 2 has Unions C then A tethered
(4) Union D mounted on Col 4 at Pos B end

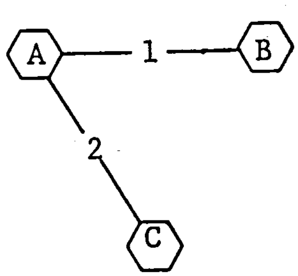
STEP	SUBJECT 1	SUBJECT 2
1	Install Union B at Pos B (RMS xlates Col 1 into pos) Install Col 1 in Union B	Install Union A at Pos A Install Col 1 in Union A
2	(RMS xlates Col 2 into pos)	Egress Foot Restraints Translate to Pos C Ingress Foot Restraints Install Union C at Pos C
3	Install Col 2 in Union B Egress Foot Restraints Translate to Pos A Ingress Foot Restraints	Install Col 2 in Union C
4	(RMS xlates Col 3 into pos) Install Col 3 in Union A Egress Foot Restraints Translate to Pos D Ingress Foot Restraints	Install Col 3 in Union C
5	(RMS xlates Col 4 into pos) Install Union D in AAA clamp (RMS xlates Col 5 into pos)	Install Col 4 in Union C Egress Foot Restraints Translate to Pos A Ingress Foot Restraints
6	Install Col 5 in Union D (RMS xlates Col 6 into pos)	Install Col 5 in Union A Egress Foot Restraints Translate to Pos B Ingress Foot Restraints
7	Install Col 6 in Union D (RMS xlates SEM into pos) Install SEM at Pos D	Install Col 6 in Union B



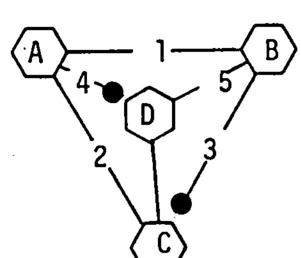
APPENDIX C

MANUAL ASSEMBLY SEQUENCE (NB-18B)

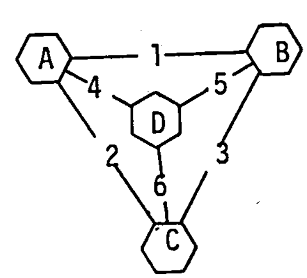
STEP	SUBJECT 1	SUBJECT 2
1	Ingress Foot Restraint Remove Union B Install Union B at Pos B	Ingress Foot Restraint Remove Union A Install Union A at Position A
2	Remove Column 1 Install Col. 1 in B1	Remove Column 1 Install Col 1 in A2
3	Remove Union C Install C2 on Column 2 Transfer Column 2 to S2	Receive Column 2 Install Column 2 in A1
4	Remove Column 3 Install Column 3 in B2	Remove Union D Install Union D on Col 5 (D8)
5	Remove Column 5 Install Col 5 into B7	Remove Column 4 Install Column 4 into A7
6	Remove Column 6 Tether Col 6 Egress Foot Restraints Translate to Position D Install Col 6 into D7	Remove Column 6 Tether Col 6 Egress Foot Restraints Translate to Position C Install Col 6 into C7
7	Install Col 4 into D9	Install Col 3 into C1 Translate to SEM Tether SEM Translate SEM to Postion D
8	Receive SEM from S2 Install SEM in Union D	Transfer SEM to S1 Install SEM in Union D



Steps 1 - 3



Steps 4 - 6



Steps 7, 8

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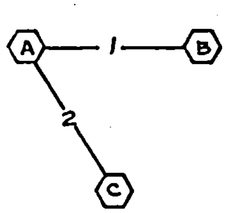
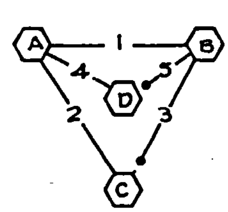
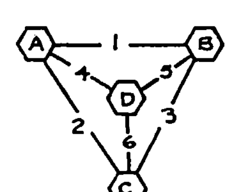
APPENDIX D

AUGMENTED ASSEMBLY SEQUENCE (NB-18B)

STEP	RMS	SUBJECT 1	SUBJECT 2
1		Install U B1 on Col.1 Install U D9 on Col 4 Egress Foot Rest. Translate to Pos B	Install U A2 on Col 1 Install U C1 on Col 3 Egress Foot Rest. Translate to Pos A
2	Remove Col 1 from Rack Translate Col 1 into Pos Release Col 1	Receive Col 1 Install Col 1 at Pos B	Receive Col 1 Install Col 1 at Pos A
3	Remove Col 2 from Rack Translate Col 2 into Pos (Inboard end toward Pos A, Outboard end toward Pos C) Release Col 2		Receive Col 2 Install Col 2 in U A1
4	Remove Col 3 from Rack Translate Col 3 into Pos (Ball end to Pos B, Union end to Pos C) Release Col 3	Receive Col 3 Install Col 3 in U B2	
5	Remove Col 4 from Rack Translate Col 4 into Pos (Ball end to Pos A, Union end to Pos D) Release Col 4		Receive Col 4 Install Col 4 in U A7
6	Remove Col 5 from Rack Translate Col 5 into Pos (Between Pos B and Pos D Release Col 5	Receive Col 5 Install Col 5 in U B7	Translate to Pos C Install Col 3 in U C7
7	Remove Col 6 from Rack Translate Col 6 into Pos (between Pos C and Pos D) Release Col 6	Translate to Pos D Install Col 5 in U D8 Receive Col 6 Install Col 6 in U D7	Receive Col 6 Install Col 6 in U C7
8	Translate Sem to Pos D Release SEM	Receive SEM Install SEM at U D	Receive SEM Install SEM at U D







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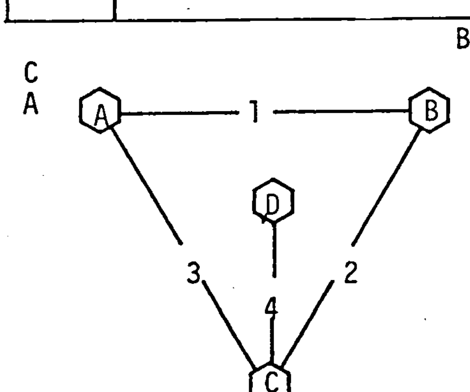
APPENDIX E

MANUAL ASSEMBLY SEQUENCE FOR NB-18A/NB-18B COMPARISON STUDY (NB-18C)

MANUAL ASSEMBLY SEQUENCE
FOR
NB-18A / NB-18B COMPARISON STUDY

ESSEX

STEP	SUBJECT 1	SUBJECT 2
1	Ingress Foot Restraints Install Union B at Pos B	Ingress Foot Restraints Install Union A at Pos A
2	Remove Column 1 Rotate Column 1 around AAA Install Column 1 in Union B	Install Column 1 in Union A
3		Egress Foot Restraints Translate to Pos C Ingress Foot Restraints Install Union C at Pos C
4	Remove Column 2 Rotate Column 2 around AAA Transfer Column 2 to S2 Install Column 2 in Union B	Receive Column 2 Install Column 2 in Union C
5	Remove Column 3 Transfer Column 3 to S2 Egress Foot Restraints	Receive Column 3 Rotate Column 3 toward Pos A
6	Translate to Pos A Ingress Foot Restraints Install Column 3 in Union A	Install Column 3 in Union C
7	Remove Column 4 Transfer Column 4 to S2 Egress Foot Restraints Translate to Pos D via AAA	Receive Column 4 Rotate Column 4 toward Pos D
8	Install Union D at Pos D	Install Column 4 in Union C



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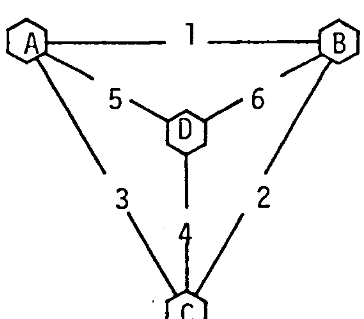
SUBJECT 1:____________________

SUBJECT 2:____________________

RUN No:__________ ET:__________

STEP	SUBJECT 1	SUBJECT 2
9	Install Column 5 in Union D	Egress Foot Restraints Translate to Pos A Ingress Foot Restraints Remove Column 5 Transfer Column 5 to S1 Install Column 5 in Union A
10	Receive Column 6 Install Column 6 in Union D	Egress Foot Restraints Translate to Pos B Ingress Foot Restraints Remove Column 6 Transfer Column 6 to S1 Install Column 6 in Union B
11	Receive SEM from S2 Install SEM on Union D	Egress Foot Restraints Translate to SEM Tether SEM Translate SEM to S1 via AAA Return to Cargo Bay



APPENDIX F

LSS ASSEMBLY TASK ELEMENT TIMES

LSS ASSEMBLY TASK ELEMENT TIMES

TASK ELEMENT	TIME (sec)
1.0 REMOVE	
1.1 Union from Box	7
1.2 Column from Rack	8
1.3 Union from Wrist Tether	18
1.4 Waist Tether from Handrail	10
1.5 SEM from Stowage	20
2.0 TRANSLATE	
2.1 Along Sill 10 ft	24
2.2 Along Sill 20 ft	43
2.3 Over edge of Sill from Outrigger	18
2.4 Over Sill from Cargo Bay	10
2.5 Up AAA 15 ft	33
2.6 Down AAA 15 ft	22
2.7 Up AAA with SEM	44
3.0 POSITION BODY	
3.1 To Ingress Foot Restraint	16
3.2 To Ingress Leg Restraint	29
3.3 To Receive Column W/O Leg Restraint	13
4.0 INGRESS	
4.1 Foot Restraint (1 handrail)	20
4.2 Foot Restraint (2 handrails)	13
4.3 Leg Restraint (1 handrail)	37

TASK ELEMENT	TIME (sec)
5.0 EGRESS	
5.1 Foot Restraint (1 handrail)	7
5.2 Foot Restraint (2 handrails)	5
5.3 Leg Restraint (1 handrail)	14
6.0 ATTACH	
6.1 Waist Tether to Handrail with Restraint	16
6.2 Waist Tether to Handrail without Restraint	21
6.3 Union to Own Wrist Tether	17
7.0 TRANSFER	
7.1 AAA to Vertical Position	33
7.2 AAA to Locked Position	26
7.3 Column 10° Using Foot Restraint	12
7.4 Column 60° Using Foot Restraint	44
7.5 Column 60° Without Foot Restraint	44

TASK ELEMENT	TIME (sec)
8.0 MATE	
8.1 Union to Pedestal (NB-18A)	28
8.2 Union to Pedestal (NB-18C)	23
8.3 Column to Union (NB-18A)	25
8.4 Column to Union (NB-18C)	9
8.5 SEM to Union (NB-18A)	95
8.6 SEM to Union (NB-18C)	34
8.7 (Tighten) Jam Nut (NB-18C)	12
8.8 AAA Clamp to Pole	56
8.9 Union to AAA Pole Clamp	55
9.0 VERIFY	
9.1 Union Mated	20
9.2 Column End Mated	36
9.3 AAA Clamp Secure	30
9.4 AAA Union Clamp Secure	35

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