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MARTIN MARIETTA

Advanced Servomanipulator Remote Maintenance Demonstration

T. L. Ray
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CONSOLIDATED FUEL REPROCESSING PROGRAM

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Consolidated Fuel Reprocessing Program

ADVANCED SERVOMANIPULATOR REMOTE MAINTENANCE DEMONSTRATION

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NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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ABSTRACT

The advanced servomanipulator (ASM) is a dual-arm, force-reflecting, master/slave servomanipulator that was designed for remote maintenance applications and is digitally controlled. The ASM is installed in the Maintenance Systems Test Area (MSTA) of the Fuel Recycle Division at the Oak Ridge National Laboratory. The unique aspect of ASM is that the slave arms were designed to be remotely maintainable, using a similar remote manipulator system, to maximize availability and minimize downtime. This test report describes the results of the maintenance testing conducted on ASM. Demonstration of the ability to maintain ASM remotely is an important precursor to the ultimate application of ASM in a totally remote facility.

The approach taken in the design of ASM was for the manipulator slave arms to be composed of modules capable of being removed and replaced by another manipulator system of similar capabilities. The ASM incorporates gear and torque tube drives with drive couplings that facilitate remote maintenance. Although the use of special fixtures is normally discouraged for remote maintenance, special fixtures were required for this demonstration due to the complex nature of the slave arms.

This test was performed to demonstrate that the ASM slave arms could be completely disassembled and reassembled remotely. Demonstrating recovery from failures was not an objective of this test. Also, specific maintenance tasks could vary somewhat from the sequence tested, depending on which component failed. Complete arm disassembly would not be required for maintenance or replacement of most individual modules.

The remote maintenance demonstration was performed on ASM using the Central Research Laboratory's model M-2 servomanipulator with an auxiliary hoist and a remote viewing system. The key component of the M-2 maintenance system is the dual-arm, bilateral force-reflecting, 6 D.F. master/slave servomanipulator. The M-2 is mounted on a bridge in an area adjacent to MSTA, and it can access the modules on the ASM slave arms.

Maintenance of ASM was successfully demonstrated using the M-2 servomanipulator and special fixtures. The entire disassembly process took about 4 h, and the assembly took about 3 1/2 h. Although there were some problems, in general, the arm modules were adequately designed for remote removal and replacement. Recommendations, which are documented in this report, have been made for improvements.

1. INTRODUCTION AND PURPOSE

The Fuel Recycle Division of the Oak Ridge National Laboratory (ORNL) is developing remote equipment for applications in future nuclear fuel cycle facilities as part of the Department of Energy's Consolidated Fuel Reprocessing Program (CFRP). This equipment must operate in a hazardous operating environment including exposure to ionizing radiation and corrosive chemicals. One goal of this development work is to reduce exposure of personnel to the hazardous operating environment. To accomplish this goal, this hot-cell equipment is designed to be maintained with remote equipment, including the use of remote servomanipulators. Since this maintenance equipment is also installed in the hazardous environment, it must also be maintained remotely.

The remote servomanipulator system developed at ORNL, the advanced servomanipulator (ASM), was designed for the slave arms to be remotely maintained. The primary purpose of the remote maintenance test on ASM was to demonstrate that the ASM slave arms could be remotely maintained.

This test was performed to demonstrate that the ASM slave arms could be completely disassembled and reassembled remotely. Demonstration of the ability to maintain ASM remotely is an important precursor to the ultimate application of ASM in a totally remote facility. It is recognized that this test does not demonstrate recovery from potential failures in all arm positions; however, this was not an objective of this test. Also, specific maintenance tasks could vary somewhat from the sequence tested, depending on which component failed. Complete arm disassembly would not be required for maintenance or replacement of many components individually.

This report presents the conditions and summarizes the results of this maintenance demonstration. Other reports have been prepared which summarize the information in general terms,[1] or which focus on specific aspects of the demonstration.[2]

2. ASM DESCRIPTION

The ASM is a force-reflecting, dual-arm master/slave servomanipulator that is digitally controlled and designed to be remotely maintainable.[3] This remote maintenance demonstration was conducted on the ASM slave arms as shown in Fig. 1. Each ASM arm has 6 D.F. and a maximum capacity of 23 kg (50 lb). The ASM design facilitates remote maintenance by its modularity. The modular design was made possible with the use of gear and torque tube force transmission drives, which separate at gear or spline interfaces. This maintenance concept allows replacement of failed ASM modules, using another remote manipulator, and return to operation relatively quickly. The ASM consists of 15 mechanical modules (including 8 motor modules) and a modularized cable harness. These modules are shown in Fig. 2 and are described briefly in the following paragraphs.

The shoulder pitch axis is made up of four modules: the shoulder pitch sleeve, the shoulder gear box, and two standard motor modules. The shoulder pitch sleeve is fixed to the transporter interface package and is not remotely replaceable by itself; however, the other three modules are. The shoulder gear box module transmits power from two motors to the shoulder pitch sleeve through gear reducers. The shoulder gear box module mounts on the shoulder pitch sleeve with two captive remote bolts.

The standard motor modules are identical for all joints and have an integral brake, position sensor, and tachometer. Each motor module attaches to the gear box with a single remote bolt on a special motor mount. Motor replacement is facilitated by a special split-face-type drive coupling and an AMP quick disconnect electrical connector on the housing.

The roll sleeve module provides the shoulder roll axis of motion. This module supports the gear pod and the elbow modules and attaches to the shoulder pitch sleeve module with four captive remote bolts.

The gear pod module provides the motor mounts for the six arm drive motors and the appropriate gear reduction for each of those six drives. This module mounts on top of the roll sleeve, attached by three captive bolts around the periphery of the roll sleeve. Six motor modules must be removed before the gear pod can be removed.

The elbow module includes the upper arm, elbow joint, and lower arm. The elbow module contains the torque tubes which transmit power to drive the four lower degrees of freedom. The upper arm is attached by three captive capscrews in an attachment ring at the bottom of the roll sleeve. The lower arm provides the remote coupling for the wrist module.

The ASM wrist module provides 4 D.F., has the highest number of parts, and is expected to have the highest maintenance requirements. For this reason, the wrist was designed to be relatively easy to replace. This module attaches to the lower arm by four captive bolts located around the periphery of the wrist.

The tong module is based on a Central Research Laboratory's (CRL) rotary drive, two finger tong. Although not replaced separately in this demonstration, the tongs can be replaced remotely using a special tool.

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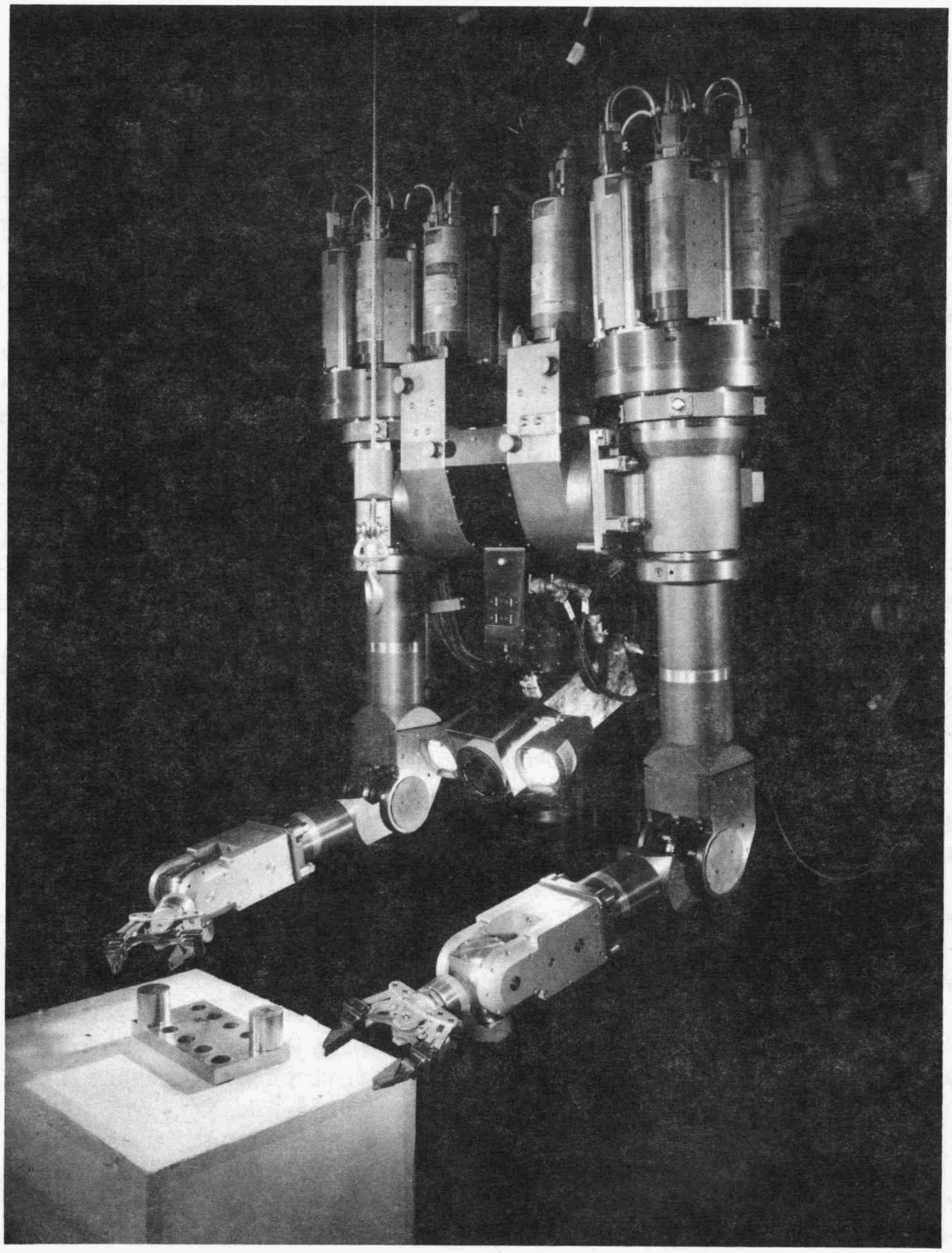

Fig. 1. Advanced servomanipulator.

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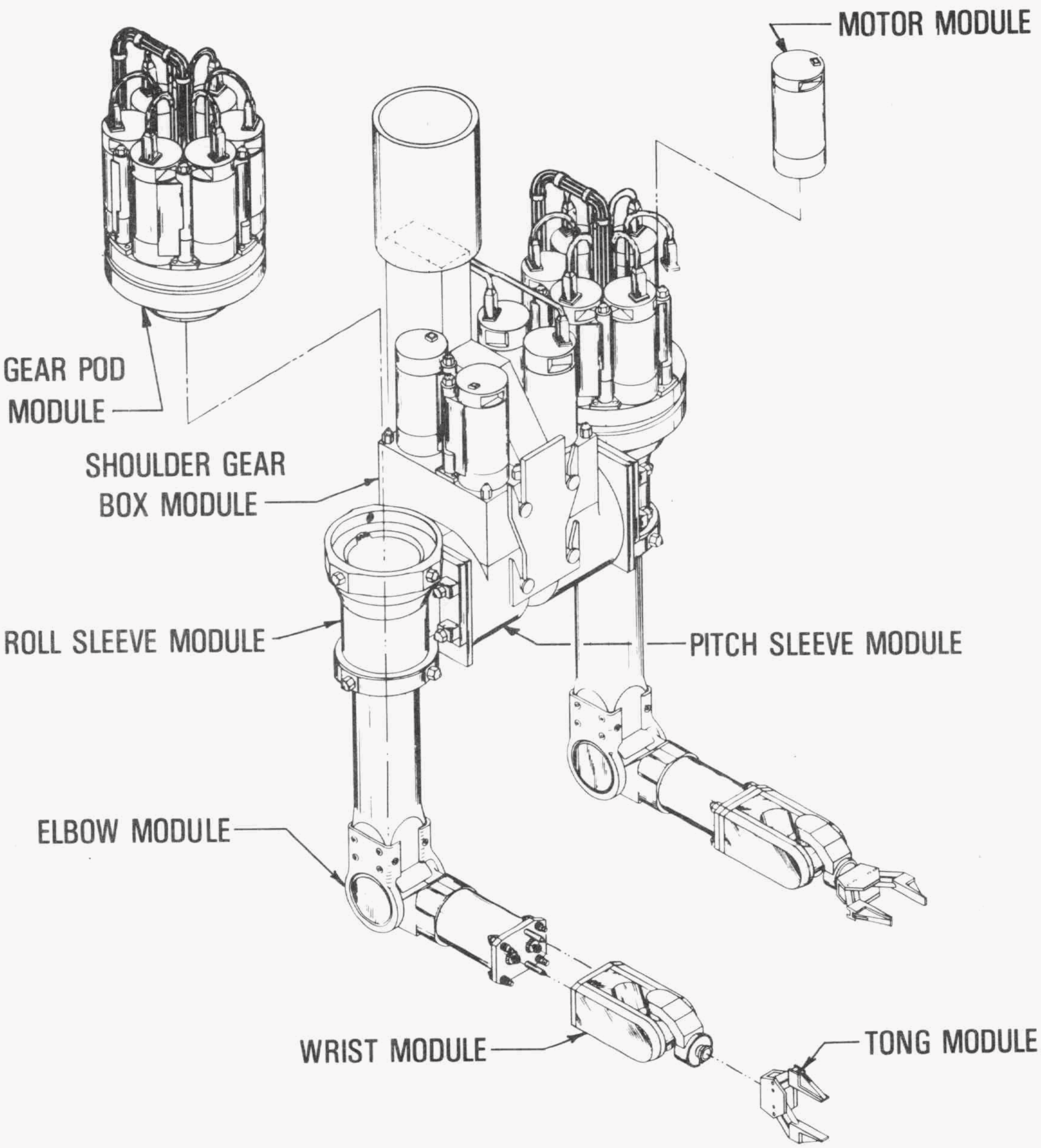

Fig. 2. ASM remotely replaceable modules.

The cable harness provides signal and power conductors from the motor modules to the transporter interface package. The harness includes cabling and electrical connectors. The motor end is an AMP connector, and the interface package end is a LEMO connector. Mechanical support blocks are provided at two locations on the cable harness. The mechanical supports have alignment guides and are attached with two captive remote bolts.

3. MAINTENANCE EQUIPMENT AND TOOLS

The remote maintenance demonstration was performed on ASM using the Remote Operations and Maintenance Demonstration (ROMD) facility remote maintenance and remote viewing system. The key component of the maintenance system is the M-2, a dual-arm, bilateral, force-reflecting master/slave servomanipulator that was jointly developed by CRL and ORNL. The M-2 is mounted on a bridge in the ROMD facility[4] adjacent to ASM, where it can access the modules on ASM. The M-2 servomanipulator incorporates a distributed, microprocessor-based digital control system. The M-2 servomanipulator system consists of two major assemblies: the slave package (shown in Fig. 3) and the master control station (shown in Fig. 4). The M-2 slave is positioned at the work site by means of an overhead transporter consisting of a gantry bridge and a telescoping tube trolley assembly. The M-2 transporter runs on the same bridge rails as the ASM transporter. A control room adjacent to the facility houses the control station.

3.1 MODEL M-2 SLAVE

The slave package consists of a pair of servomanipulator arms, three television viewing cameras, lights, and a 230-kg (500-lb) capacity auxiliary hoist. Each slave arm has a 23-kg (50-lb) continuous capacity, a 46-kg (100-lb) time-limited (peak) capacity, and 6 D.F. (joints), plus tong grasp.

Operator viewing of the remote work site is provided by closed-circuit television cameras mounted on shoulder booms. Each camera has 4 D.F. (pan, tilt, boom extend-retract, and boom pivot) and motorized lens controls (zoom, focus, and iris). In addition, one fixed camera is mounted between the slave arms. The two overhead cameras provide views in an orthogonal fashion to effect depth perception and viewing flexibility. The lower camera produces a wide angle view of the work site from a fixed position to provide additional viewing.

3.2 MODEL M-2 MASTER CONTROL STATION

Control of the model M-2 slave is performed by a single operator from the master control station. The master control station consists of a pair of master control arms, three 19-in. color television monitors, and an operator console.

The master control arms are kinematic replicas of the slave arms with 6 D.F. plus tong grip. Each master arm has an 11-kg (25-lb) peak capacity. The minimum slave loading detected or "felt" at the master arm is on the order of 0.45 kg (1 lb) or 1% of the peak capacity.

The operator can interface with the control system through a CRT and touchscreen system mounted in the operator console. Operating mode selection, force-reflection ratio selection, camera/lighting control, and system status diagnostics are examples of features provided by this operator interface.

Camera and auxiliary hoist controls are also located on the operator console and can be utilized by the operator. However, during this demonstration, a secondary operator was used to accomplish camera, hoist, and transporter positioning. This left the primary operator free to use both arms of the M-2.

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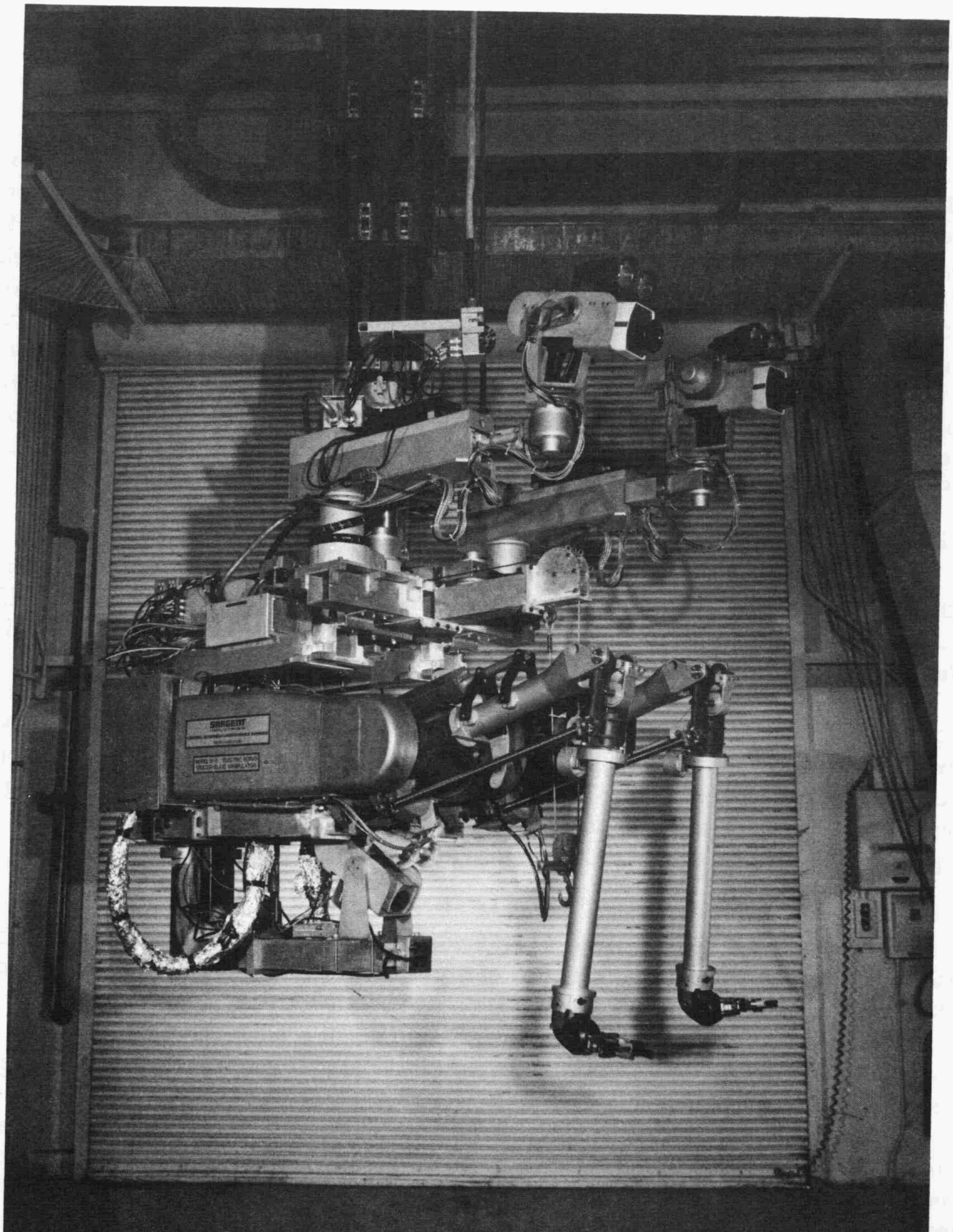

Fig. 3. M-2 servomanipulator system.

ORNL-PHOTO 8489-86

Fig. 4. ROMD facility control room and M-2 master controller.

3.3 MAINTENANCE TOOLS

An effort was made to minimize the number of different bolt sizes required for the disassembly of the ASM arms. All tools that were used were of standard design and are shown in Fig. 5. The following tools were used in the remote disassembly.

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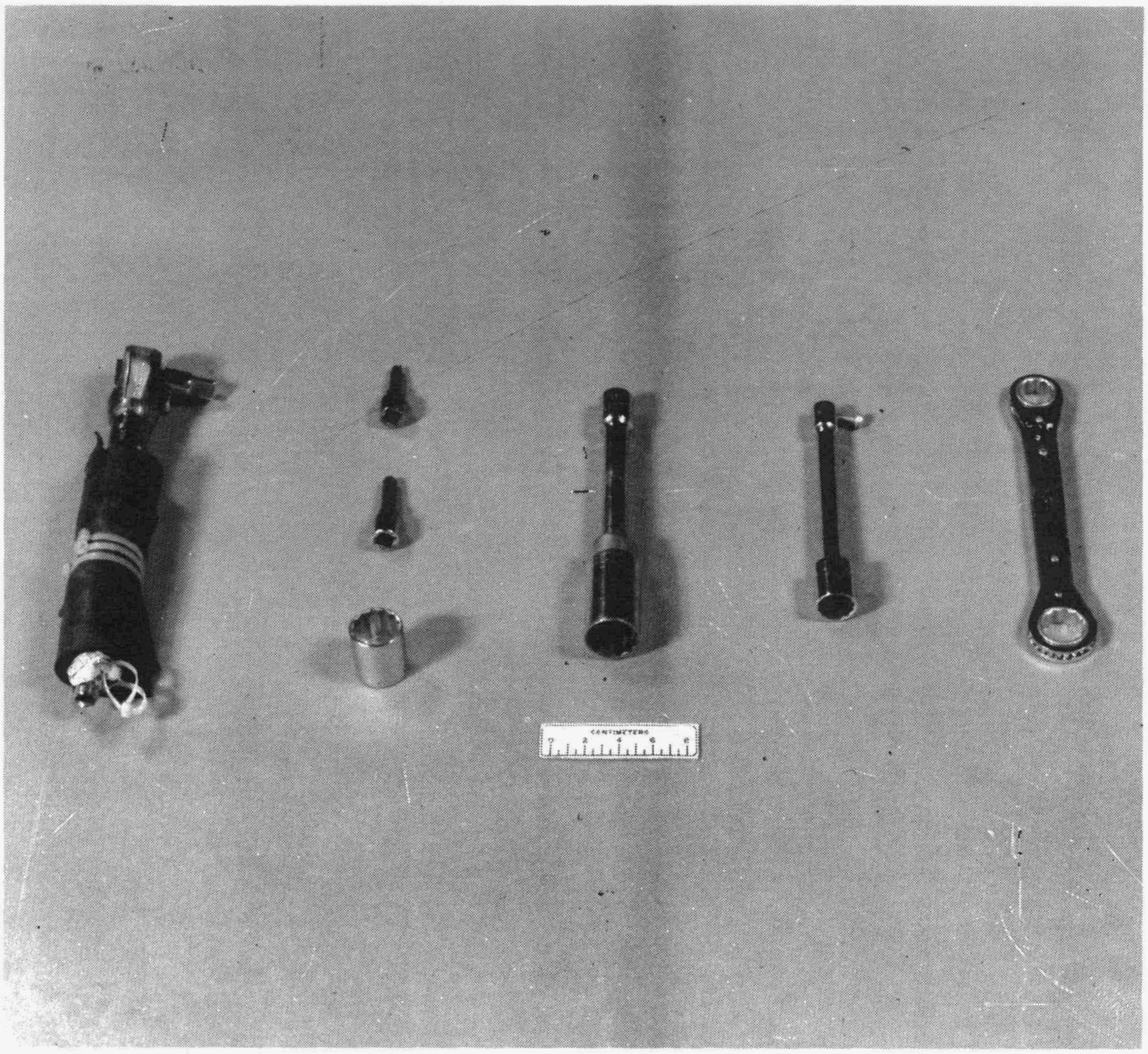

Fig. 5. Maintenance tools.

Wrenches	3/8-in. drive pneumatic air wrench
	3/4-in. single ratchet box end wrench
Sockets and Extensions	5/16-in. Allen wrench
	1/4-in. Allen wrench
	1-in. socket with extension
	15/16-in. socket
	3/4-in. socket
	5-in. extension
	1/2-in. adapter

4. SPECIAL FIXTURES

Although the use of special fixtures is normally discouraged for remote applications, special fixtures were required for this demonstration due to the complex nature of the slave arms and maintenance requirements. Special fixtures were fabricated and used to maintain proper positioning of the ASM arms and also to provide lift points so that the modules could be removed. The need for maintaining proper positioning comes from the use of absolute position encoders integral with the ASM motors. These encoders are fixed range potentiometers, and for most joints, full joint travel uses full potentiometer range. If the potentiometer range is not matched to joint travel on reassembly, then the potentiometers could be driven past their limit, and the system would not be operational. Thus, fixtures are needed that will match the module joints to the position encoders. Also, the fixtures provide balanced lifting points for the arm modules. Integral lift fixtures were not provided on ASM due to the desire to minimize the size envelope and improve the appearance of the ASM arms. Seven fixtures were fabricated, and each is discussed in detail in the following sections. Design drawings for the fixtures can be found in the Engineering drawing series X3E - 12774 - 2000–8000.

4.1 POSITIONING HOIST

The positioning hoist shown in Fig. 6 was the largest fixture that was fabricated. This hoist was used when the M-2 hoist was unable to give the fixture and module a straight vertical lift. The hoist was also equipped with a pivoting turntable that allowed orientation in any working position in a 360° circle. The hoist itself could also be moved horizontally along the 3-ft dual tracks mounted under the turntable. It was equipped with reversible, variable speed controls that could be operated by the M-2 servomanipulator. The maximum capacity of the hoist was 68 kg (150 lb).

4.2 ARM HANDLING FIXTURE

Once the motors are removed from the gear pod, the arm is free to move. To prevent this movement and retain original positioning, an arm handling fixture (shown in Fig. 7) was fabricated. This fixture has been equipped to retain the arm's original position of 45° below horizontal and to provide a lifting point for handling the arm module. The fixture is installed vertically and is retained in place by two U-shaped frames. The upper portion of the fixture has an integral jack screw that lengthens the fixture to remove the arm module. Two clamshell devices, which attach to the lower portion of the roll sleeve, are used during this removal and for replacement.

4.3 WRIST/TONG FIXTURE

The wrist/tong module must also be kept in its original position because it will move once the motors are removed, thus the need for a wrist/tong fixture (Fig. 8). This fixture fits over the wrist module and is held in place by one U-shaped frame. It holds the tongs in a fixed position and provides a lift point for the module.

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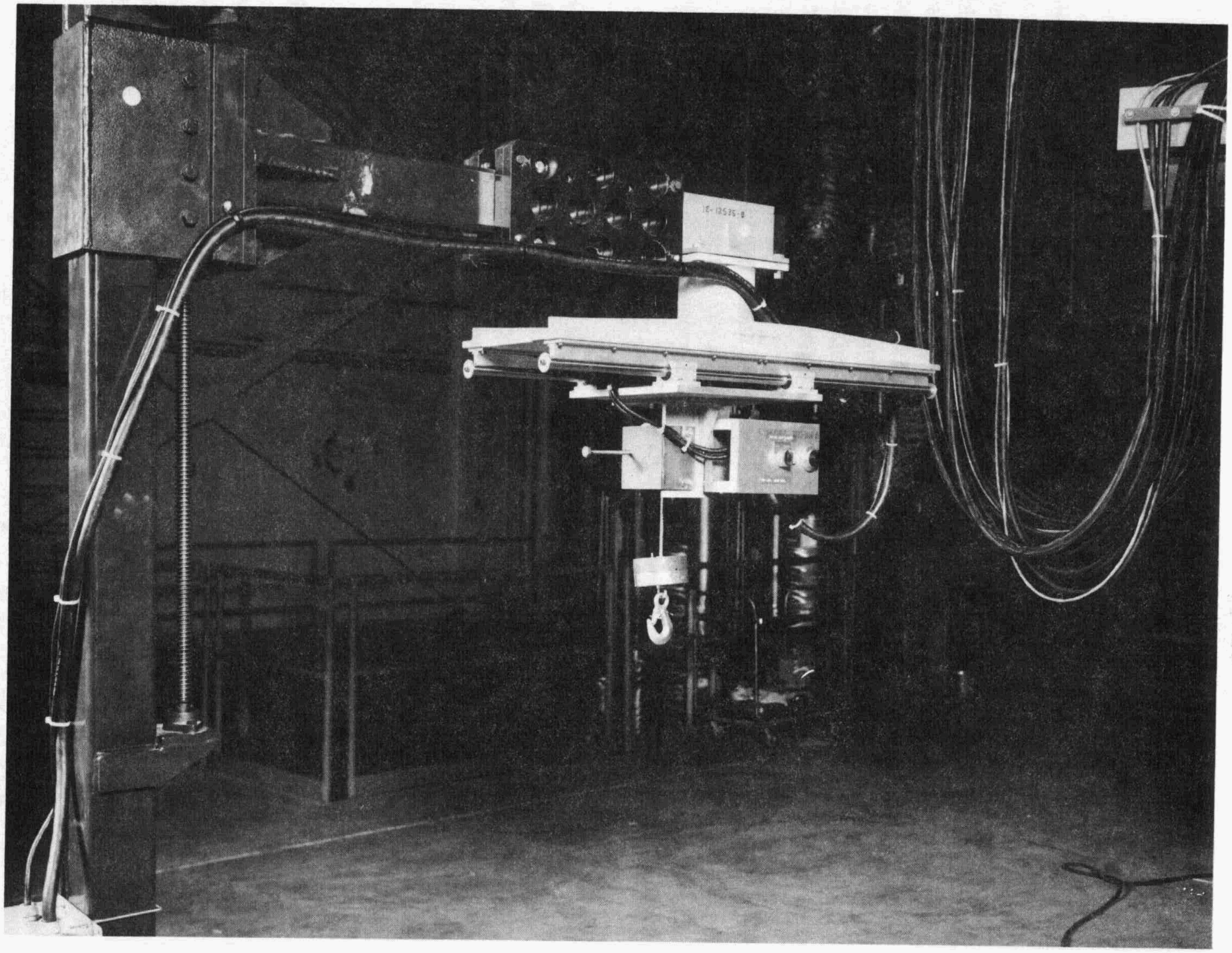

Fig. 6. Positioning hoist fixture.

ORNL-PHOTO 10005-87

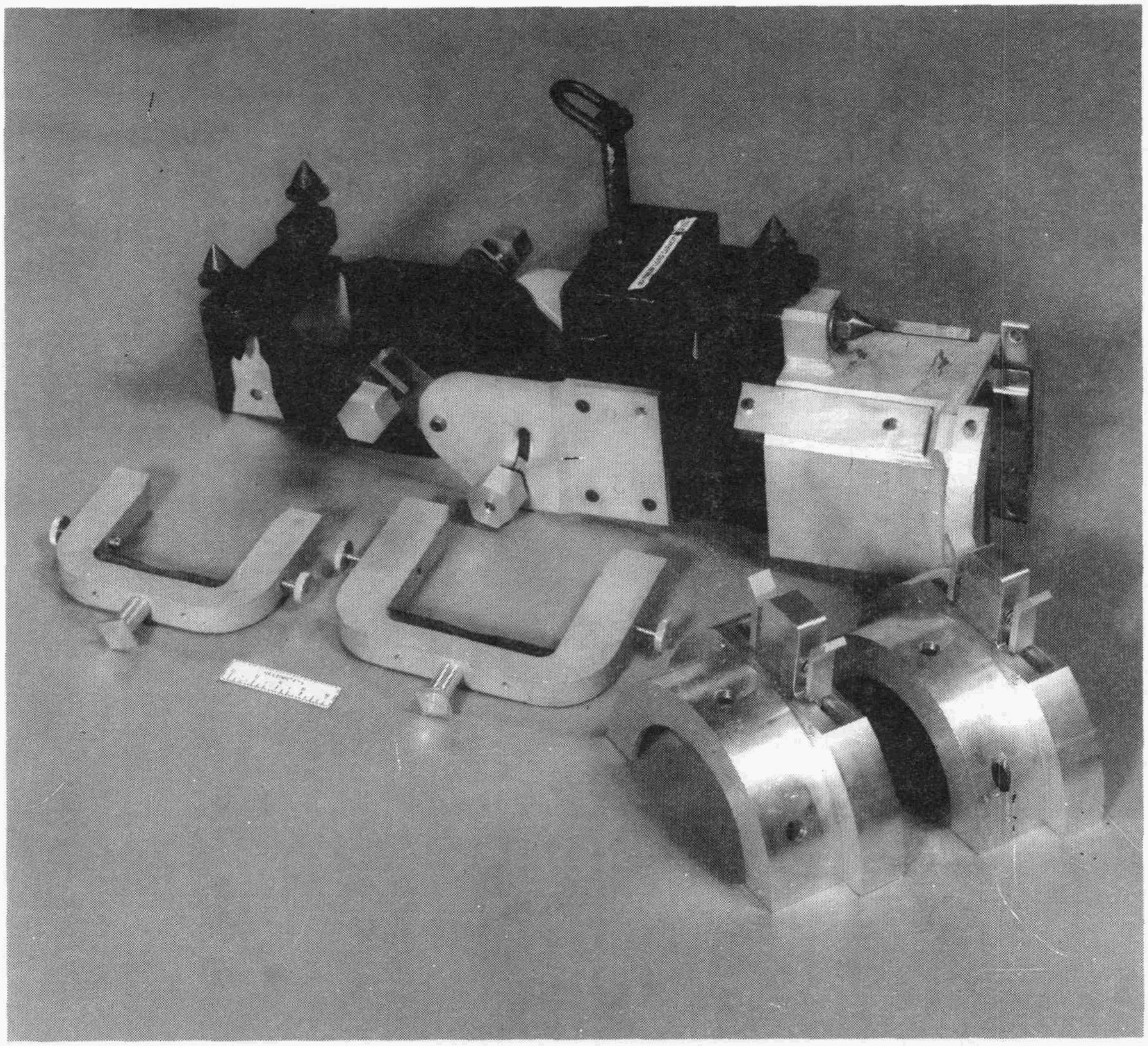

Fig. 7. Arm handling fixture.

4.4 GEAR POD FIXTURE

After the motors are removed, a lift point must be provided for the removal of the gear pod module. Figure 9 shows the gear pod fixture. This fixture attaches to the gear pod module by utilizing three of the six motor mounts on the gear pod. The fixture also provides spindles that engage the couplings on the gear pod and assist in the reassembly of the gear pod module. These spindles can be turned so that the output splines will engage the torque tubes of the arm module.

4.5 ROLL SLEEVE FIXTURE

Figure 10 shows the roll sleeve fixture. This fixture is installed once the gear pod is removed. It also has a spindle, but this spindle is geared so that it can engage the ring gear inside the roll sleeve and retain the shoulder roll position. The fixture attaches to the top of the roll sleeve and is held in place by the three bolts at the top of the roll sleeve module.

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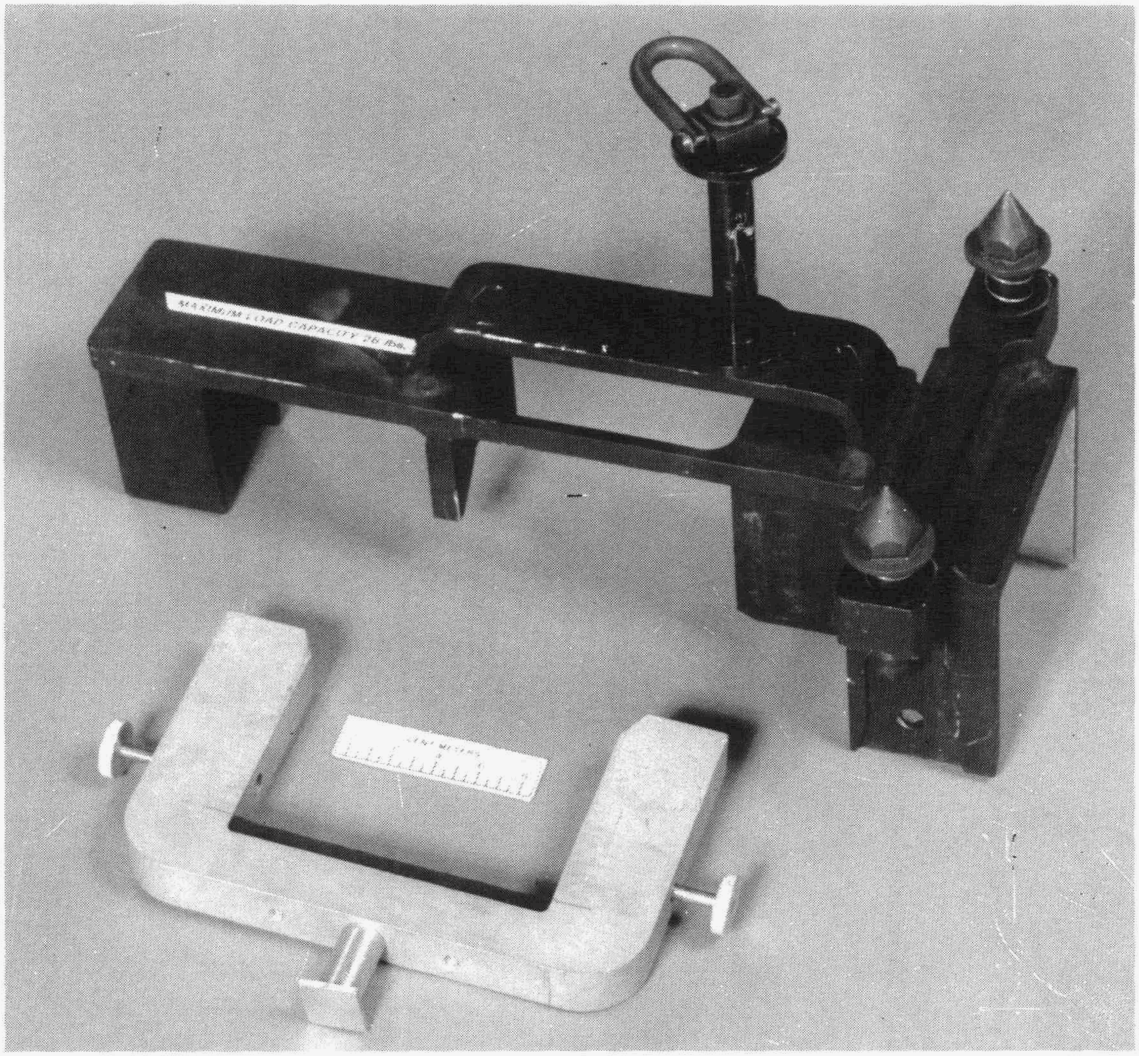

Fig. 8. Wrist/tong fixture.

4.6 GEAR BOX FIXTURE

The last module to be removed is the gear box module, which requires a lifting fixture. The gear box lift fixture (shown in Fig. 11) attaches to the gear box motor mounts. Three of the four corners are cut away so that the bolts that retain the gear box can be accessed.

4.7 PITCH LOCK FIXTURE

The pitch lock fixture (shown in Fig. 12) is used to keep the ASM arm in a horizontal position, which enables the wrist and arm modules to be removed horizontally. This fixture is installed on the shoulder after the arm has been raised to a horizontal position and attaches to one post on the gear box module and to one post below the gear box (as shown in Fig. 13).

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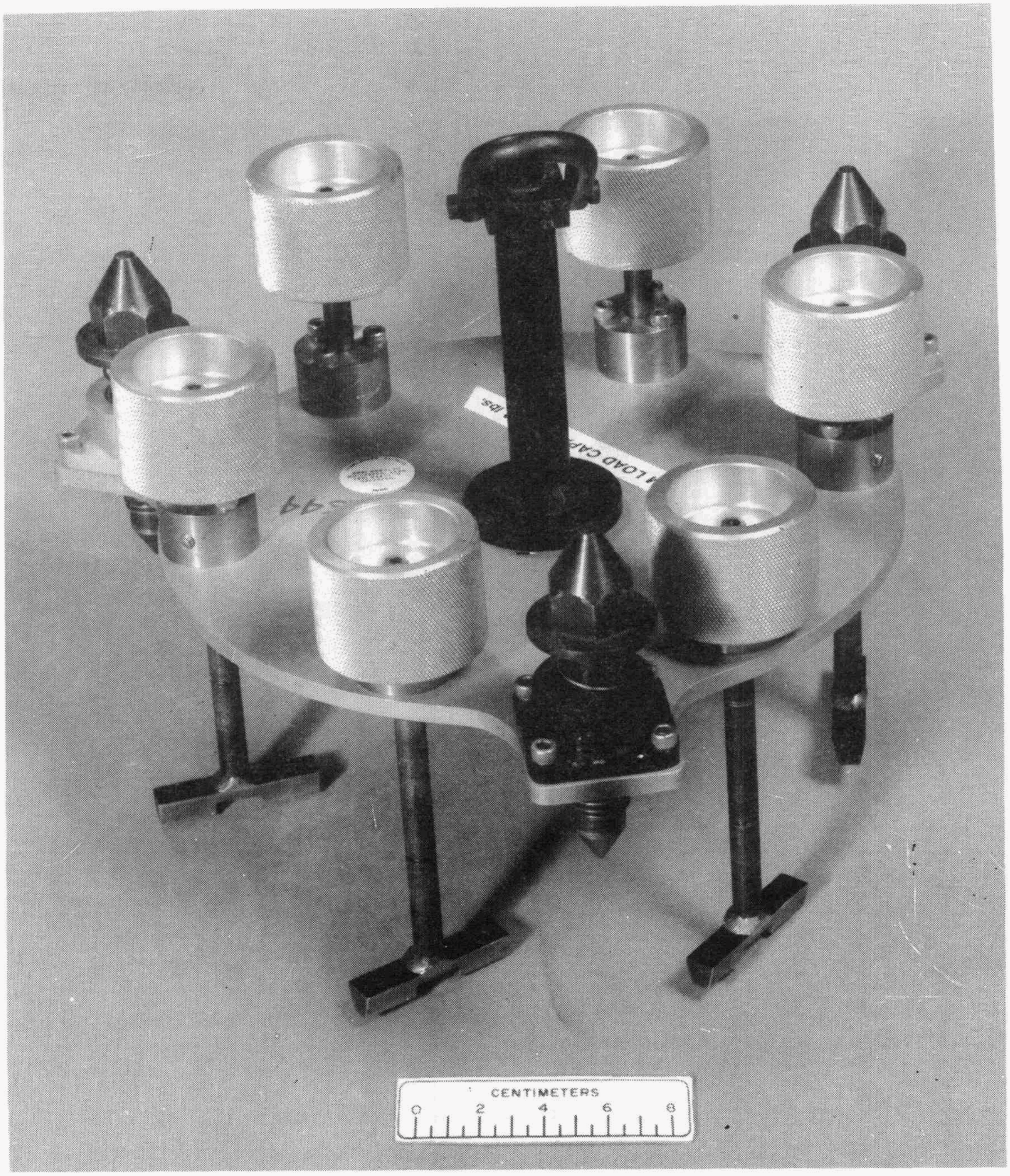

Fig. 9. Gear pod fixture.

ORNL-PHOTO 10008-87

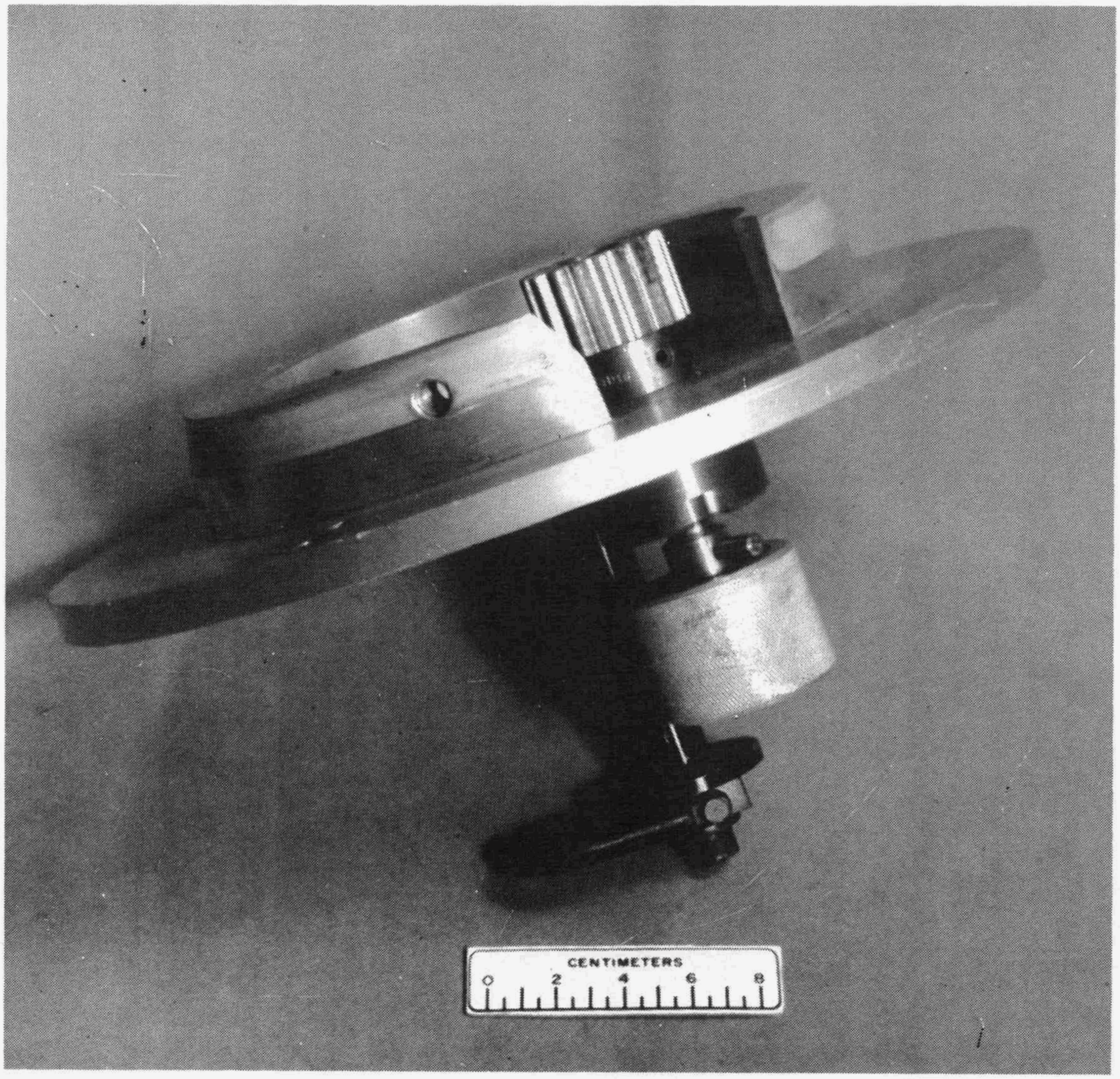

Fig. 10. Roll sleeve fixture.

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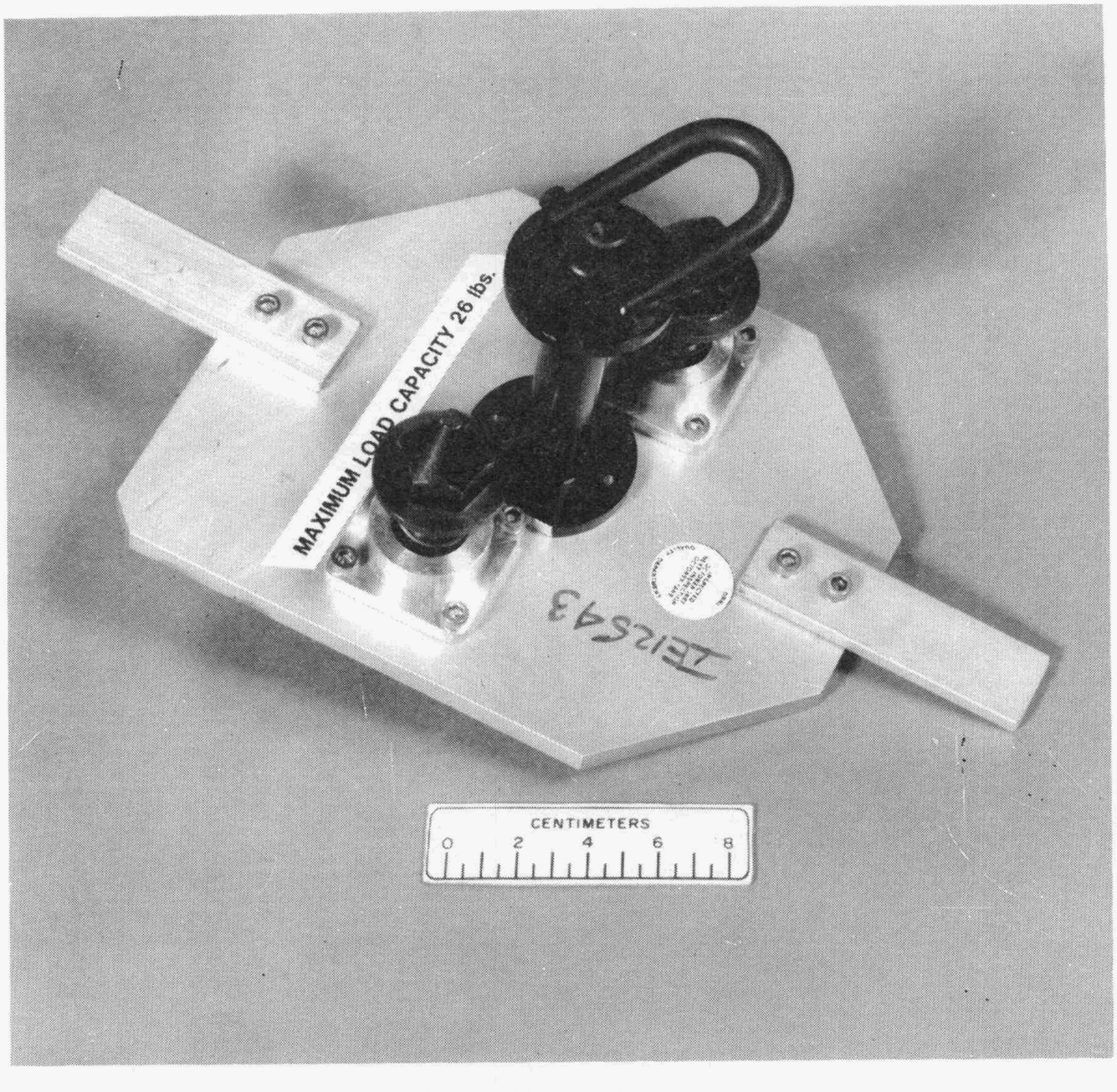

Fig. 11. Gear box fixture.

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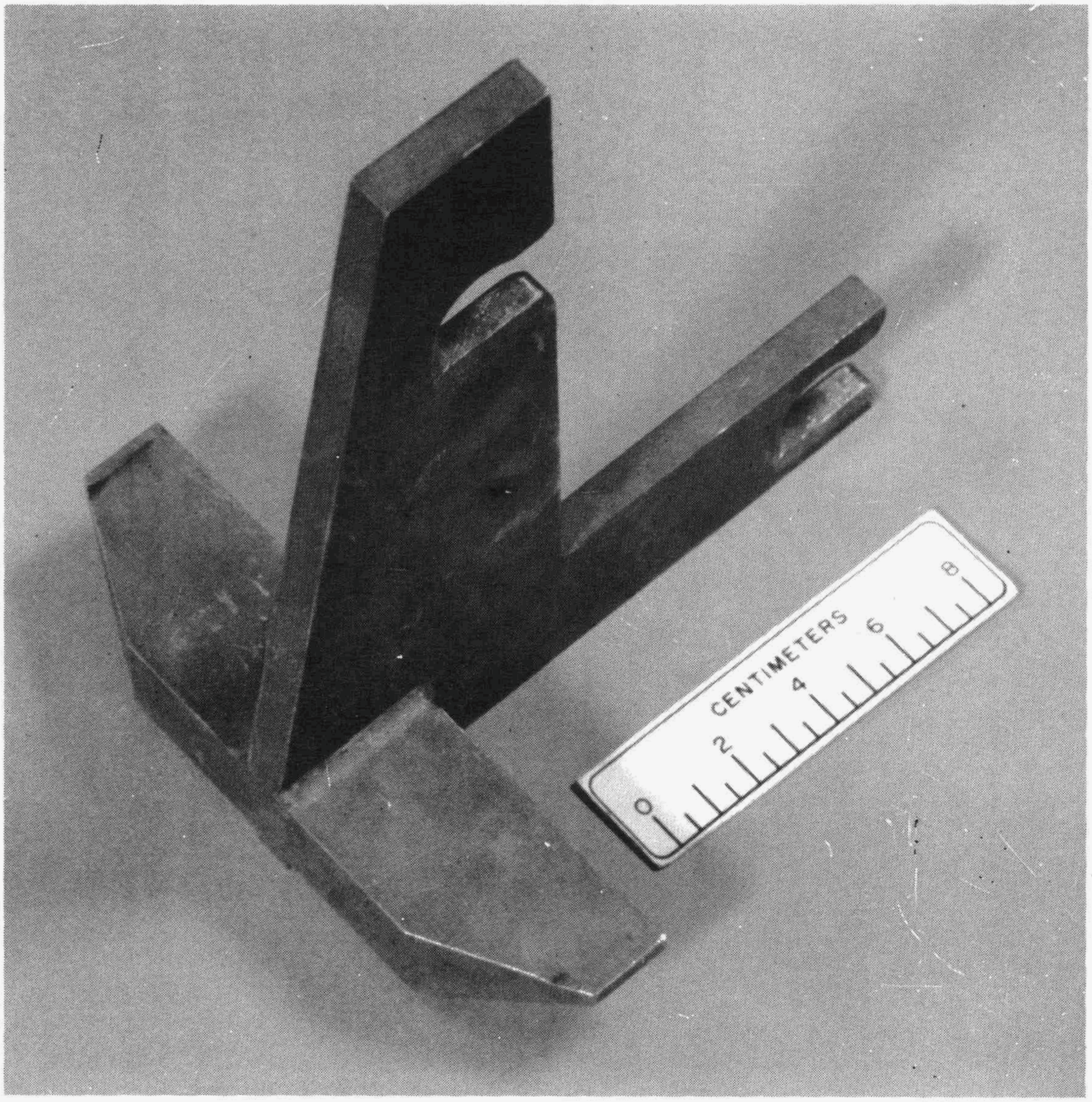

Fig. 12. Pitch lock fixture.

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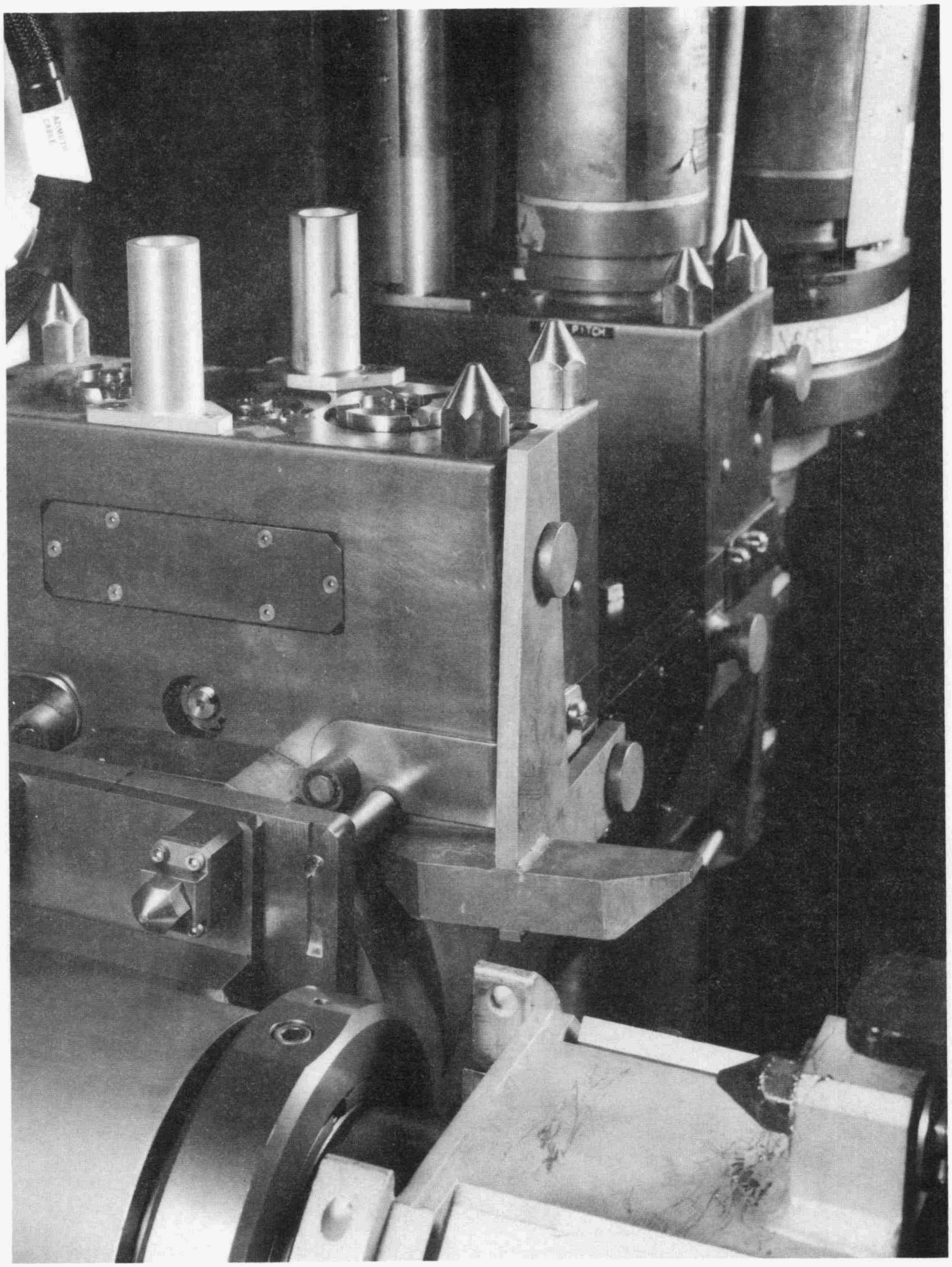

Fig. 13. Pitch lock fixture installed.

5. TEST CONDITIONS AND PROCEDURE

This entire test was conducted under simulated remote conditions. An observer was stationed at the work site during remote operations with an open channel of communication to the control room for safety purposes only and was not allowed to "coach" operations. Test data and video recordings were collected by control room operators and also by the observer stationed at the work site. Since the M-2 transporter and ASM transporter bridge cranes run on the same rails, some preparations were needed to allow the two manipulators to come close enough together to perform this demonstration. Travel stops for both cranes were removed from the rails. Also, the bumper posts on the ASM transporter were removed so that the bridges could come closer together. Even with these accommodations, the two systems could not get as close as would be optimal for this demonstration.

The maintenance demonstration was performed according to conditions and procedures specified in approved test instructions. These procedures are summarized in this section. Before the remote demonstration was conducted, a manual disassembly was performed using the procedure. After this disassembly and reassembly was completed, several revisions were made to the procedure prior to the remote demonstration. These revisions are discussed in Sect. 6.

5.1 ASM DISASSEMBLY

5.1.1 Arm Fixture Installation (Item 1, Dwg. 3000)

Before installing the fixture, the upper arm should be in a vertical position and the lower arm positioned at a 45° angle below horizontal. Place the arm handling fixture on the arm. Connect the two U-shaped frames to the fixture and insert detent pins. Install two captive bolts on each U-shaped frame. Tighten the elbow lock screws on the fixture.

5.1.2 Wrist Fixture Installation (Item 1, Dwg. 4000)

The wrist should be positioned as straight as possible, with the tongs open and in a horizontal position. Place the wrist fixture weldment on top of the wrist. Connect the U-shaped frame to the wrist fixture weldment from beneath the wrist. Secure together by snapping the two locking pins in place and installing two captive bolts on the U-shaped frame.

5.1.3 Removal of the Arm Drive Motors [weight 8.3 kg (18.25 lb) each]

The six arm drive motors should be removed in the following sequence.

- wrist left motor
- wrist right motor
- wrist roll motor
- tongs grasp motor
- shoulder roll motor
- elbow pitch motor

To remove a motor, first disconnect the electrical cable by spreading the retainer latches and lifting the connector head. Retract the captive bolt holding the motor. Lift the motor and remove it. Repeat these three steps for each motor of the six motors. Release the elbow lock pins on the arm fixture. Move the lower arm to the vertical position.

5.1.4 Removal of the Cable Harness [weight 3.6 kg (8 lb)]

Disconnect the electrical connectors for all the arm cables at the interface package. Retract the two captive bolts on the cable retainer block on the roll sleeve module. Retract two captive bolts on the cable retainer block on the shoulder pitch drive housing. Remove the harness.

5.1.5 Installation of the Gear Pod Fixture (Item 1, Dwg. 2000)

To install this fixture, the upper arm should be in a vertical position. Place the fixture on the gear pod module. Match the black fixture bolt retainer to the black motor bolt stand. Engage the six alignment rods of the gear pod fixture with the six motor couplings. Tighten the three captive bolts on the fixture into the motor stand holes.

5.1.6 Removal of the Gear Pod Module [weight 22.2 kg (49 lb)]

Retract the three captive bolts around the top outside of the roll sleeve which hold the gear pod in place. Lift and remove the gear pod module.

5.1.7 Installation of the Roll Sleeve Fixture (Item 1, Dwg. 8000)

Place the roll sleeve fixture on the roll sleeve module with the three holes aligned. Engage the spur gear on the fixture with the internal gear in the roll sleeve. Tighten the three captive bolts at the top of the roll sleeve.

5.1.8 Removal of the Two Shoulder Pitch Drive Motors [weight 8.3 kg (18.25 lb) each]

Disconnect the electrical cable for each motor by spreading the retainer latches and lifting the connector head. Retract the captive bolt holding each motor. Lift the motor and remove it.

5.1.9 Installation of the Pitch Lock Fixture

This fixture is installed on the shoulder to lock the shoulder pitch in a horizontal position. Using the positioning hoist, raise the arm to the horizontal position determined by the stop-motion pin. Install the pitch lock fixture on the two posts and engage it under the stop-motion pin.

5.1.10 Removal of the Tong and Wrist Assembly [weight 9.44 kg (20.8 lb)]

Attach the positioning hoist hook to the wrist fixture. Retract the four captive bolts holding the wrist module to the arm. Remove the wrist module by pulling horizontally off the arm.

5.1.11 Removal of the Arm/Elbow Module [weight 23.0 kg (50.75 lb)]

Attach the positioning hoist hook to the arm fixture and raise the hoist to support the arm. Retract three captive socket head bolts and one set screw on the lower collar of the roll sleeve. Slide the arm/elbow module out of the roll sleeve horizontally to remove.

5.1.12 Removal of the Pitch Lock Fixture

Support the roll sleeve module in the horizontal position and remove the pitch lock fixture from the stop-motion pin. Move the roll sleeve module to the vertical position.

5.1.13 Removal of the Roll Sleeve Module [weight 12.3 kg (27 lb)]

Attach the positioning hoist hook onto the roll sleeve fixture. Retract four captive bolts holding the roll sleeve module. Lift the roll sleeve module off the mounting tabs and remove.

5.1.14 Installation of the Gear Box Fixture (Item 1, Dwg. 7000)

Install the gear box fixture on the shoulder gear box. Tighten the two captive bolts on the gear box fixture into the holes located in motor stands.

5.1.15 Removal of the Shoulder Gear Box [weight 16.8 kg (37 lb)]

Retract four captive bolts on the shoulder gear box. Lift and remove the gear box module.

5.2 ASM ASSEMBLY

5.2.1 Installation of the Shoulder Gear Box [weight 16.8 kg (37 lb)]

Place the shoulder gear box module on the shoulder pivot guide pins. Tighten four captive bolts on the gear box module.

5.2.2 Removal of the Gear Box Fixture (Item 1, Dwg. 7000)

Retract two captive bolts on the gear box fixture. Lift and remove the gear box fixture.

5.2.3 Installation of the Roll Sleeve Module [weight 12.3 kg (27 lb)]

Replace the roll sleeve module onto the mounting tabs on the shoulder pivot. Tighten four captive bolts on the roll sleeve module.

5.2.4 Installation of the Pitch Lock Fixture

Move the roll sleeve to horizontal position. Install the pitch lock fixture on the two posts and engage it with the stop-motion pin.

5.2.5 Installation of the Arm/Elbow Module [weight 23.0 kg (50.75 lb)]

Using the positioning hoist, locate the arm on the centerline of the roll sleeve module and insert as far as possible. Use the jacking screw to lengthen the fixture, and then install the two clamshell covers. Tighten the jacking fixture (see Items 2, 3, and 4; Dwg. 3000) and complete the insertion of the arm into the roll sleeve. Remove the two clamshell covers. Tighten three captive socket head bolts and the set screw on the lower collar of the roll sleeve module while supporting the arm.

5.2.6 Installation of the Tong and Wrist Module [weight 9.44 kg (20.8 lb)]

Replace the wrist module by sliding it over the guide pins on the lower arm until it contacts the mounting surface. Tighten four captive bolts that hold the wrist module on the arm.

5.2.7 Removal of the Pitch Lock Fixture

Attach the positioning hoist onto the arm fixture to support the arm. Remove the pitch lock fixture to disengage the arm. Move the arm into a vertical position.

5.2.8 Installation of the Two Shoulder Pitch Drive Motors [weight 8.3 kg (18.25 lb)]

Place the motor on the mount bracket on the shoulder gear box. Engage the bolt into the guide of the motor mount bracket. Position the motor over the drive coupling and engage the coupling by slightly moving the drive components until the motor can be lowered onto the mount surface. Tighten the captive bolt holding the motor. Repeat the above steps for the second motor.

5.2.9 Removal of the Roll Sleeve Fixture (Item 1, Dwg. 8000)

Retract three captive bolts on the top retainer of the roll sleeve module. Remove the roll sleeve fixture.

5.2.10 Installation of the Gear Pod Module [weight 22.2 kg (49 lb)]

Align the gear pod module with the roll sleeve using the alignment pin. Lower the gear pod module while turning the six drives on top of the gear pod fixture to align the splined shaft couplings in the arm drives. NOTE: The shafts are properly aligned when the gear pod drops fully into the top of the roll sleeve module. Tighten the three captive bolts around the top outside of the roll sleeve which hold the gear pod in place.

5.2.11 Removal of the Gear Pod Fixture (Item 1, Dwg. 2000)

Retract the three captive bolts on the gear pod fixture. Remove the fixture.

5.2.12 Raising the Lower Arm

Raise the lower arm to a position 45° below horizontal. Insert the elbow lock pins when the arm reaches the position of the matching holes. This returns the arm to the same position that it was when the motors were removed. Now the motors can be replaced.

5.2.13 Installation of the Arm Drive Motors [weight 8.3 kg (18.25 lb)]

Ensuring that the proper motor is used, place the motor on the mount bracket on the gear pod for the appropriate drive. Engage the bolt into the guide of the motor mount bracket. Position the motor over the drive coupling and engage the coupling by slightly moving the arm components until the motor can be lowered onto the mount surface. Tighten the captive bolt holding the motor. Repeat for each motor.

5.2.14 Removal of the Arm Fixture (Item 1, Dwg. 3000)

Retract the four captive bolts on the U-shaped frames. Withdraw the detent pins and remove the U-shaped frames from the fixture. Lift and remove the arm fixture.

5.2.15 Removal of the Wrist Fixture (Item 1, Dwg. 4000)

Retract the two captive bolts on the U-shaped frames. Withdraw the detent pins and remove the U-shaped frame. Lift and remove the wrist fixture.

5.2.16 Replacement of the Cable Harness [weight. 3.6 kg (8 lb)]

Install the cable harness into the cable retainer block on the shoulder drive module and tighten the two captive bolts on the cable retainer block. Install the cable harness into the cable retainer block on the roll sleeve module and tighten the two captive bolts on the cable retainer block. Replace the electrical connectors to all the motors. Replace the electrical connectors to the interface package.

5.3 SYSTEM CHECKOUT

If the ASM slave arms have been reassembled correctly, the system sould be operational at this point. For the final step of the maintenance demonstration, the ASM control system will be started to verify proper operation of the ASM as assembled.

6. RESULTS

Remote maintenance of the ASM slave arms was successfully demonstrated using the model M-2 servomanipulator and special fixtures. The entire disassembly process took about 4 h and the assembly took about 3 1/2 h. The ASM was operational when reassembled.

Each of the maintenance operations demonstrated is discussed in the following sections. Problems that were encountered are identified, and modifications that might improve the remote maintainability of the modules are addressed. Table 1 shows task completion times for each operation.

6.1 REMOTE DISASSEMBLY

6.1.1 Arm Fixtures

Figure 14 shows the ASM's right arm with the arm and wrist fixtures installed. Vertical installation of the arm fixture was somewhat awkward. Also, proper positioning of the arm was found to be an important prerequisite. Unless the arm was positioned properly before starting, the fixture could not be installed. The only other difficulty encountered was that each U-shaped frame had two detent pins that were to be engaged before bolting them onto the fixture. Due to the positioning of the arm and the location of these pins, the detent pin on the side opposite the M-2 could not be engaged. However, having one detent pin engaged was sufficient to enable the U-shaped frame to be bolted on.

6.1.2 Arm Drive Motors

For the six-arm drive motors, the markings that were already on ASM were found to be too small for remote viewing; so, before the motors were removed, each electrical connector, motor, and their locations on the gear pod were labeled with large letters visible with the M-2 cameras.

The electrical connectors on the motors were the AMP type with external spring latches to hold the connector body. When the electrical connectors were removed from each motor, difficulties were encountered due to the retaining latches. The M-2 tongs had to spread the latch and at the same time pull the connector out. This was more of a problem on the connectors farthest from the reach of the M-2 than it was for the connectors up front. One retaining latch was broken due to the difficulty in removing the connector; however, the connector itself was not damaged.

The motors were taken off, and the order of removal was as follows:

- wrist left motor
- shoulder roll motor
- tongs grasp motor
- wrist roll motor
- wrist right motor
- elbow pitch motor

Table 1. Task completion times for remote maintenance steps

Step	Disassembly times (h:min:s)
Arm fixture installation	19:27
Wrist/tong fixture installation	4:04
Motor removal	26:55
Cable harness removal	24:05
Gear pod fixture installation	5:05
Gear pod removal	13:26
Roll sleeve fixture installation	5:07
Shoulder pitch motor removal	7:17
Shoulder pitch fixture installation	7:39
Wrist/tong removal	43:23
Arm removal	46:05
Shoulder pitch fixture removal	1:41
Roll sleeve removal	15:31
Gear box fixture installation	4:54
Gear box removal	3:04
Total disassembly time	3:47:43

Step	Assembly times
Gear box installation	5:10
Gear box fixture removal	1:51
Roll sleeve installation	8:54
Shoulder pitch fixture installation	1:41
Arm installation	31:00
Wrist/tong installation	26:56
Shoulder pitch fixture removal	2:37
Shoulder pitch motor installation	6:01
Roll sleeve fixture removal	1:44
Gear pod installation	18:09
Gear pod fixture removal	2:20
Raise arm to 45°	3:29
Motor installation	20:09
Arm fixture removal	4:16
Wrist/tong fixture removal	1:59
Cable harness installation	1:07:02
Total assembly time	3:23:18

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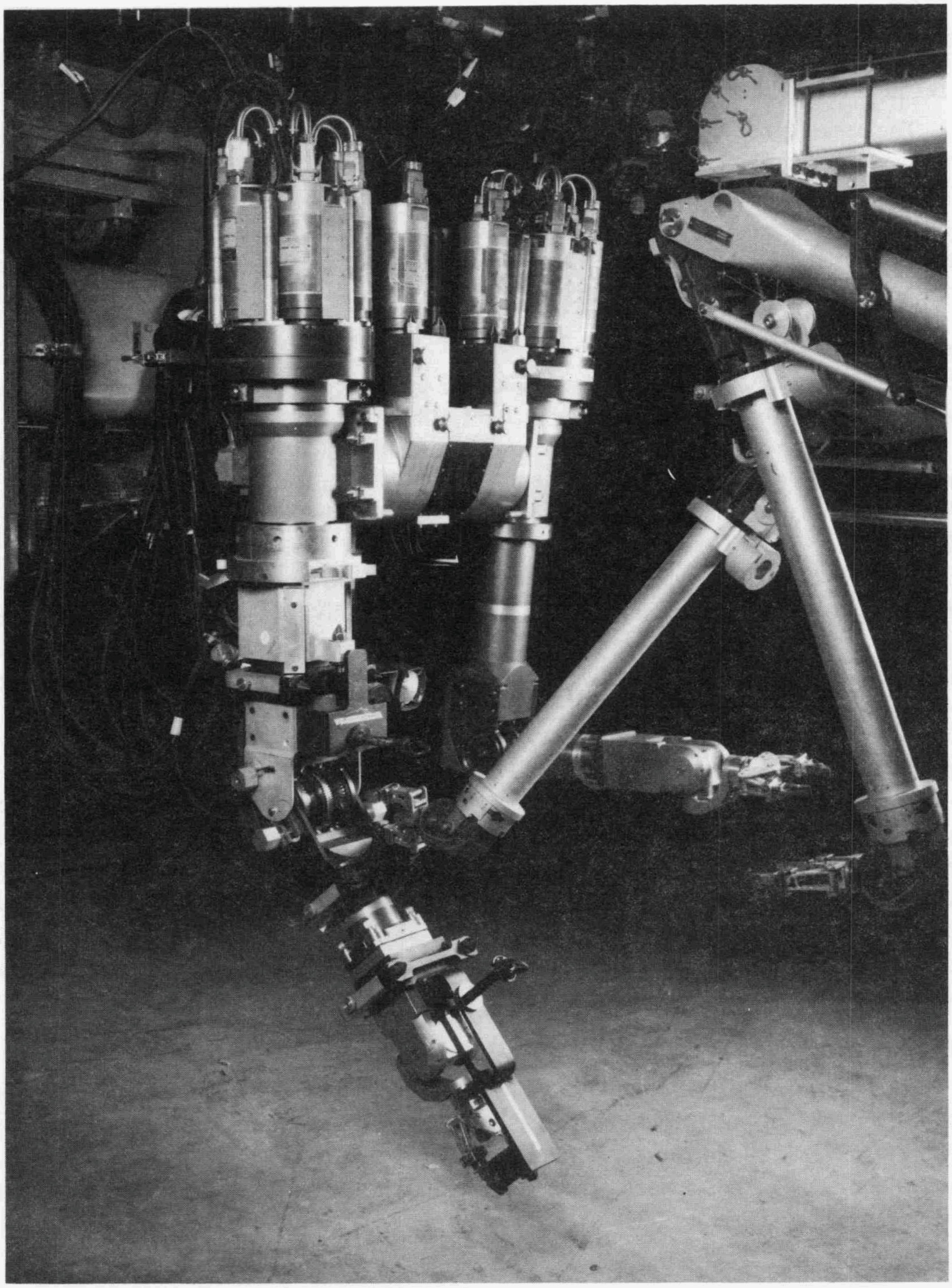

Fig. 14. ASM slave with arm and wrist fixtures.

A problem that had not been anticipated was that when the shoulder roll motor was removed, the arm began turning inward. This was caused by the weight of the fixture being above the shoulder roll axis, causing an instability. This turning would not have occurred if the shoulder pitch had been in a true vertical position. Inspection of video tapes after the demonstration was over showed that the arm was forward from true vertical by about 5° to 10°.

6.1.3 Cable Harness

The cable harness task was difficult due to the M-2 not being able to easily access the bolts of the cable retainer blocks on the shoulder pitch housing. Also, the M-2 was too far away from ASM to easily access and disconnect the LEMO electrical connectors from the interface package. After the LEMOs were disconnected, another cable retainer block on the roll sleeve was removed. The bolts were easily retracted, but the block was very difficult to remove, probably because of minimum clearance on the alignment pins.

6.1.4 Gear Pod and Fixture

For the gear pod fixture, the three bolts had to be sequenced down alternately to prevent binding. Figure 15 shows this fixture installed on ASM.

The gear pod removal steps were completed without difficulty. After the gear pod fixture was installed, the gear pod module was removed. The arm had to be turned to retract the three bolts around the top of the roll sleeve. It would have aided the operation if these bolts had been spring loaded.

Figure 16 shows the gear pod module being lowered to the floor. As can be seen, the gear pod module does not have a stable base for set down. The only contact points for this module are the splines at the bottom, and these are not ideal to be used to set the module on. This was less of a problem for this demonstration than it would be in an actual facility because padding was provided for all components to rest on.

6.1.5 Roll Sleeve Fixture

The roll sleeve lift fixture is shown in Fig. 17. This fixture was modified after fabrication due to a design error. Instead of using three bolts to hold it on, only two could be used. It also had two lifting tabs that were removed because they prevented the arm from being rotated. Rotation of the module is required in order to install the fixture. The knurled knob with the spur gear was also awkward to use. The purpose of this gear was to retain the correct roll position of the roll sleeve; however, since all the bolts could not be accessed from one side, the gear could not be used as planned.

6.1.6 Shoulder Drive Motors

The two shoulder pitch drive motors were removed with some difficulty. The front motor was easily removed, but because the back motor has the lifting slot in the rear, it was more difficult to access and remove. These motors also have the same AMP type electrical connector with retainer latches. The connector latch on the rear motor was broken because the M-2 was not able to get as close as desired to remove the connector.

6.1.7 Raise Arm

The arm was raised to a horizontal position, and the pitch lock fixture was installed. This fixture worked well, although a larger grip area on the fixture would have made it easier to install. Figure 13 shows the pitch lock fixture installed.

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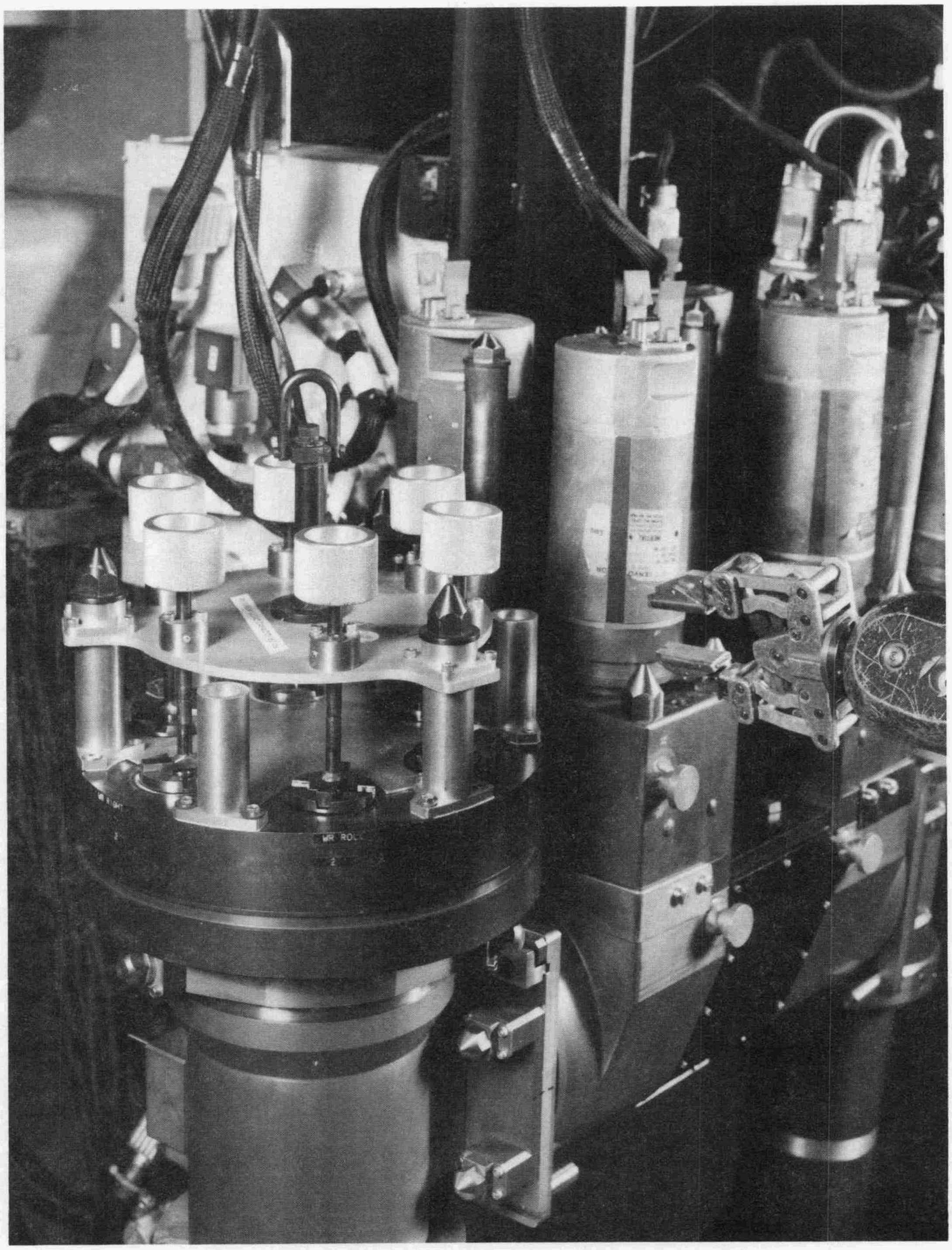

Fig. 15. Gear pod fixture installed.

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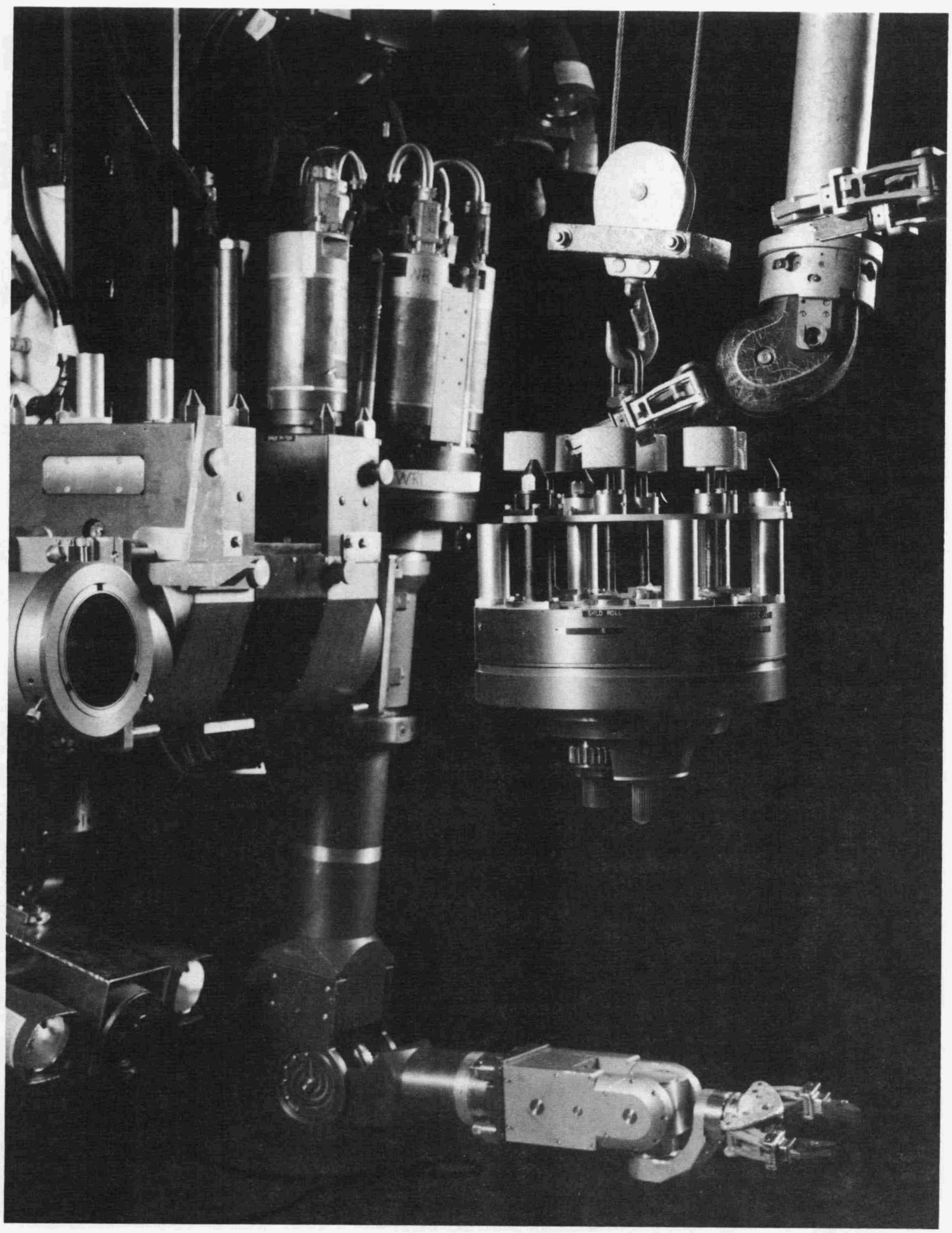

Fig. 16. Gear pod module removed.

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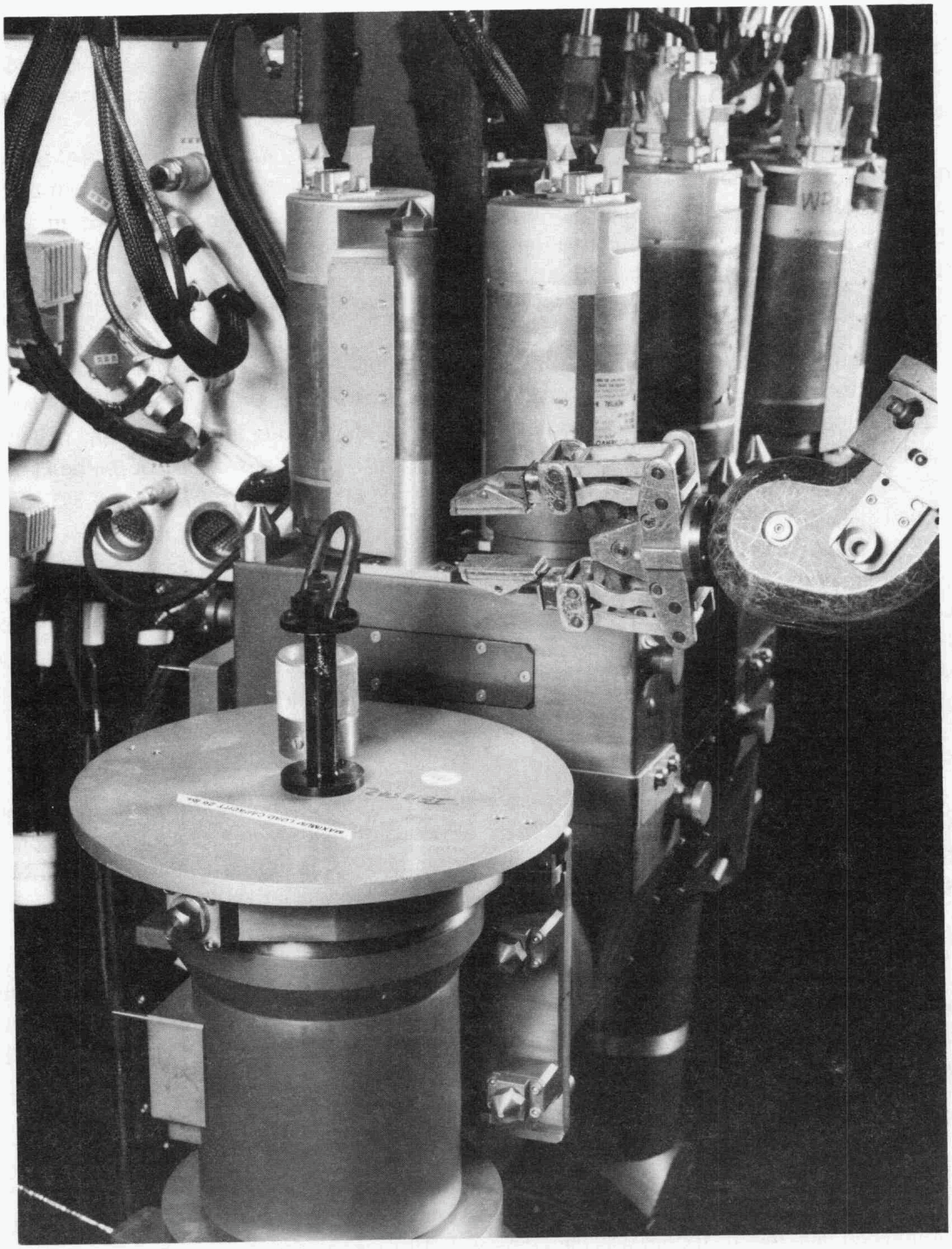

Fig. 17. Roll sleeve fixture installed.

6.1.8 Tong/Wrist Module

In order to remove the tong/wrist module, the arm was rolled over to permit access to all the bolts. To do this, the spur gear on the roll sleeve fixture was disengaged, which was difficult because the M-2 was positioned to work on the wrist and had to reach to the back of the arm to release the spur gear. When the arm rolled over, the lower arm bent at the elbow and ended up 90° below the horizontal position because the arm fixture was not equipped with provisions to maintain the arm horizontally in this position.

The removal of this module was difficult due to the inability to access the bolts of the wrist module with the pneumatic air wrench. This was caused by insufficient room between the bolt heads of the wrist module and the edge of the arm fixture and by minimal clearance around the bolt heads. Therefore, a 3/4-in. combination wrench was used to loosen the bolts, which was time consuming. Figure 18 shows the wrist/tong module removed.

6.1.9 Arm Module

The arm module was removed utilizing the positioning hoist. The removal of the arm module required that four bolts be loosened on the roll sleeve. Three of these bolts were captive, socket head bolts and the other one was a set screw. As with the other modules, all the bolts were not accessible from one side, and the arm had to be rolled over to retract one of the bolts. Also, the set screw was not captured, so it was difficult to determine when it had been sufficiently loosened.

The positioning hoist was used to slide the arm out of the roll sleeve. However, the arm could not be removed because one of the socket head bolts had fallen back into its hole. This bolt was backed out locally because it was not spring loaded, and the wrench could not get it backed out into the second set of threads. After this had been done, the arm came out easily. The arm was then lowered to the floor using the positioning hoist as shown in Fig. 19. The controls of the hoist were also somewhat difficult to operate.

6.1.10 Roll Sleeve

The roll sleeve was brought back to a vertical position for removal. The M-2 hoist was attached to the fixture, and the four bolts were loosened. This job would have been easier and faster had the 5-in. extension been used on the air wrench instead of no extension at all. Reach was about the only problem encountered here. Figure 20 shows the removed roll sleeve module.

6.1.11 Gear Box Fixture

The gear box lift fixture was installed with no problems (see Fig. 21 for the installed fixture). Removal of the gear box module required loosening four captive bolts. These bolts were retracted, and the module was removed. Like the gear pod module, the gear box has a protruding gear (as seen in Fig. 22). This gear prevents the module from having a stable base for set down.

6.2 REMOTE REASSEMBLY

6.2.1 Gear Box Fixture

The gear box module was replaced with ease and presented no problems. The four bolts were tightened, and the lift fixture was then removed. This was also an easy operation.

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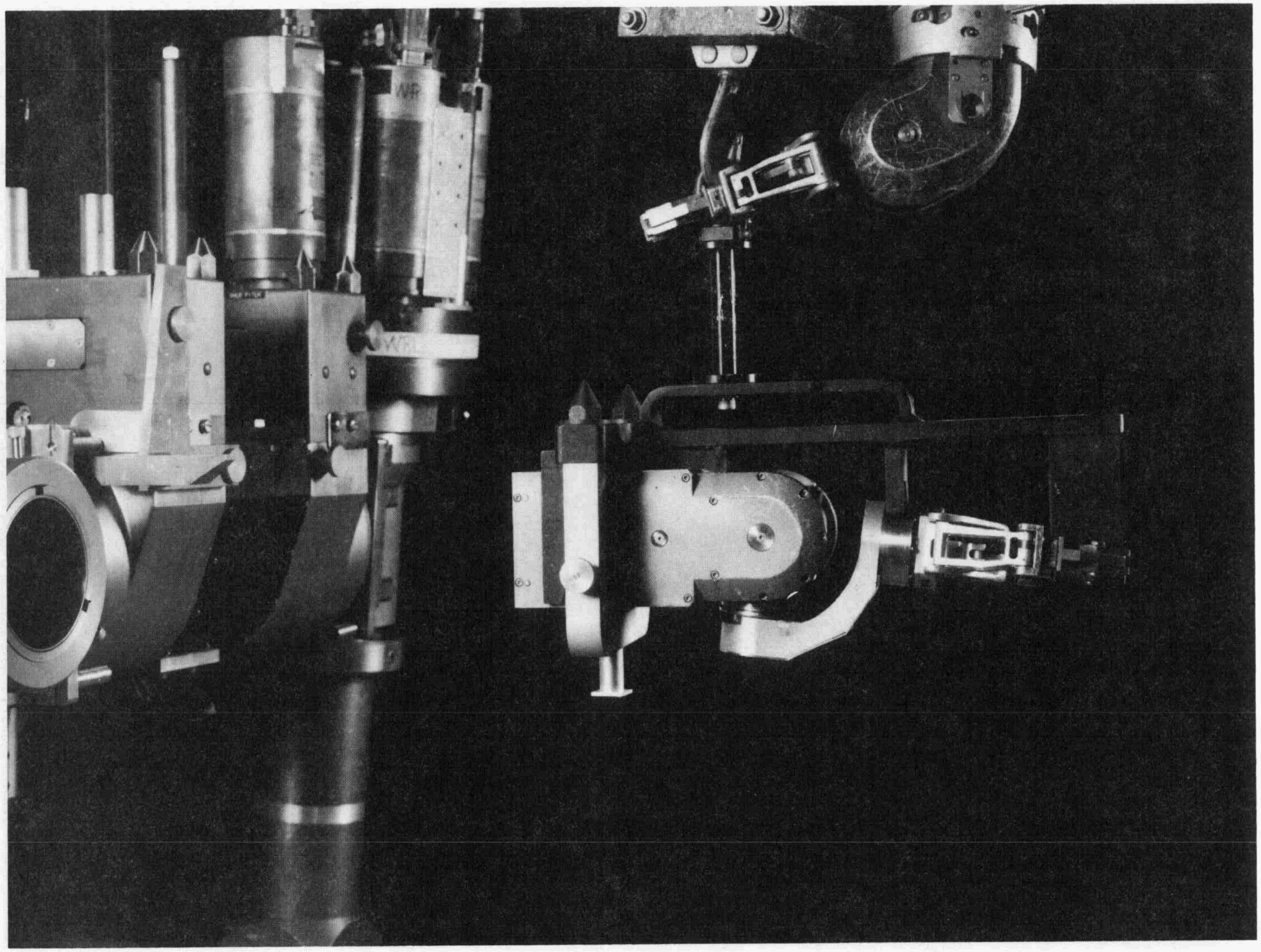

Fig. 18. Wrist module removed.

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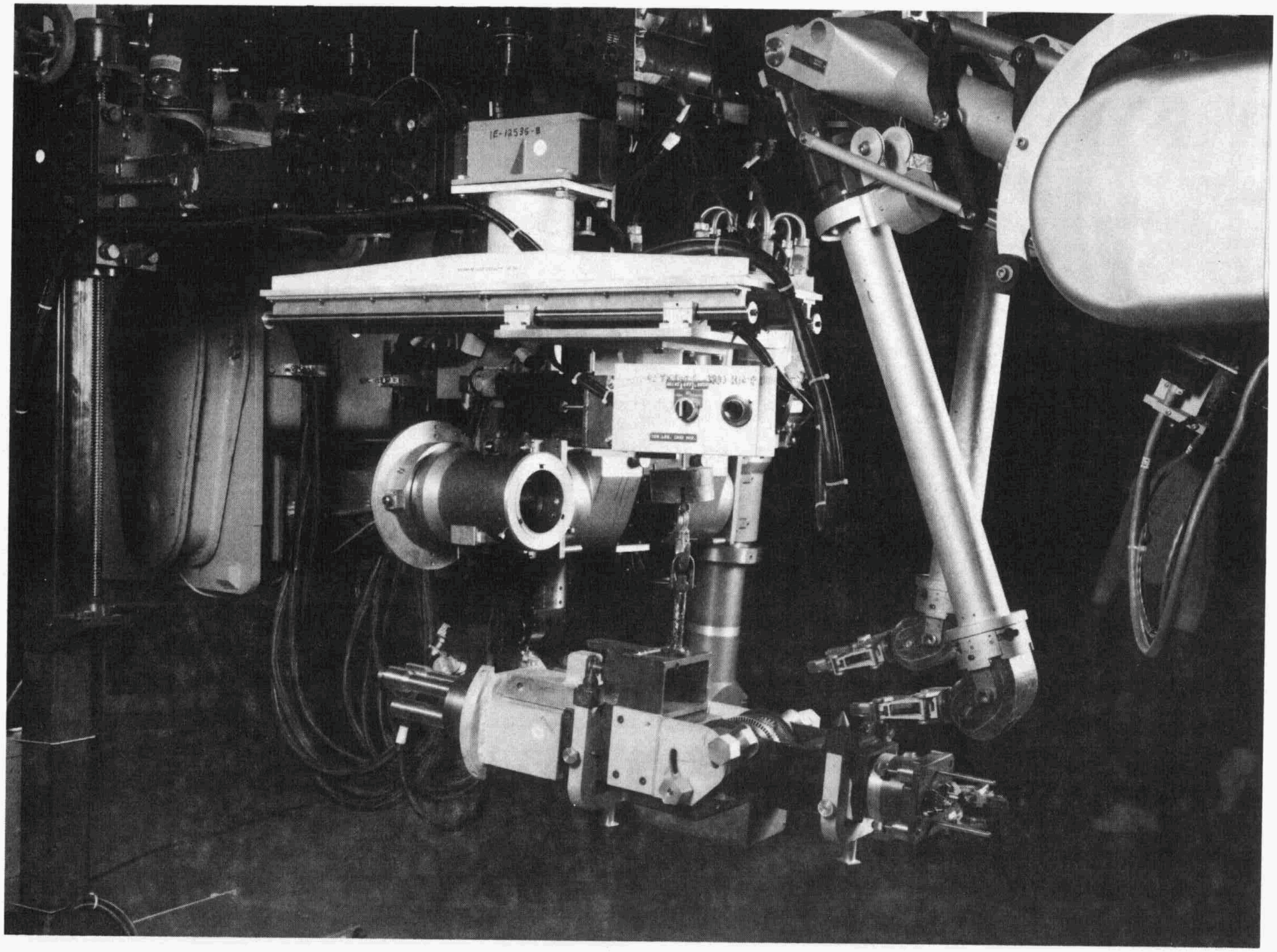

Fig. 19. Arm module removed.

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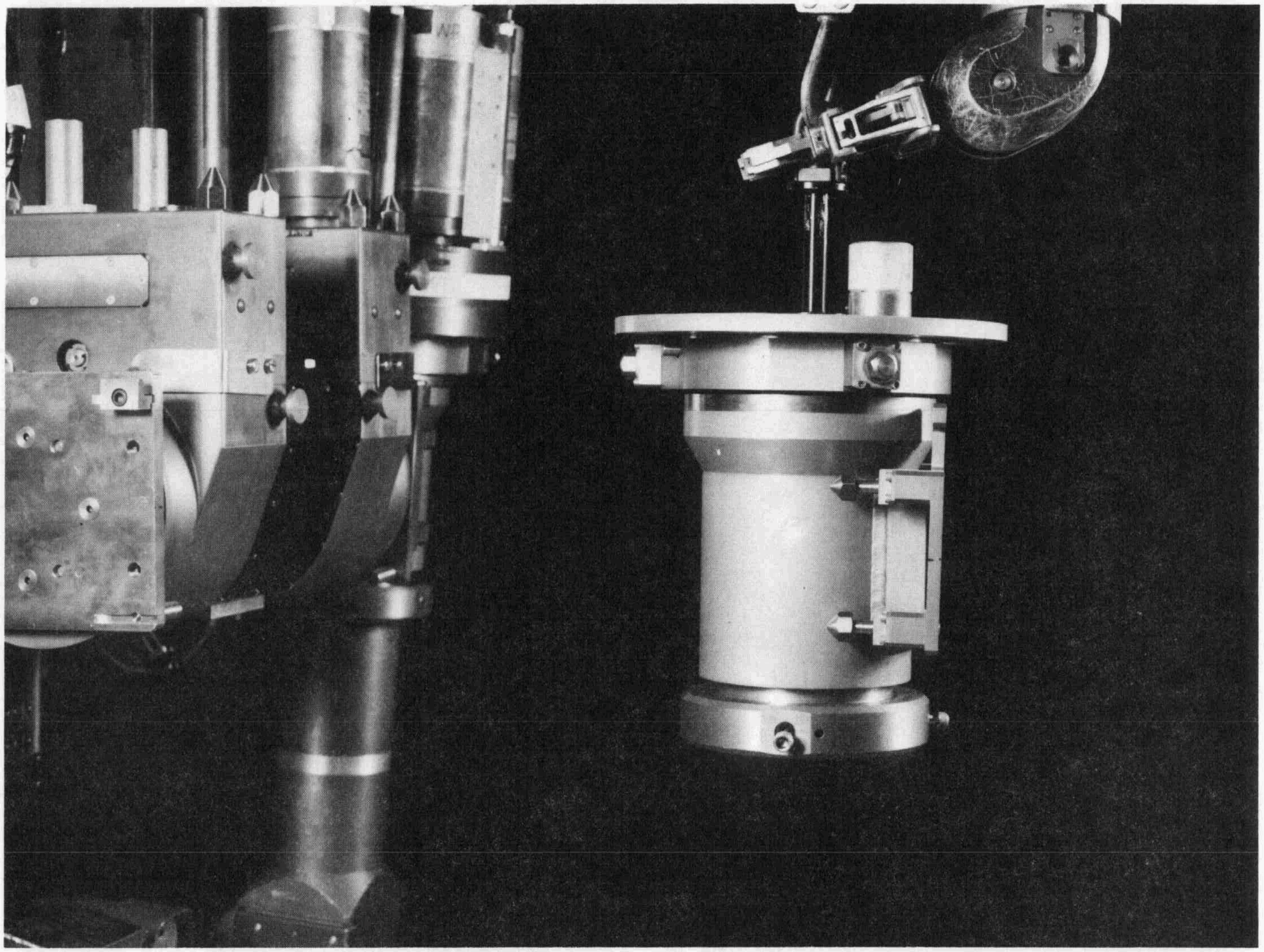

Fig. 20. Roll sleeve module removed.

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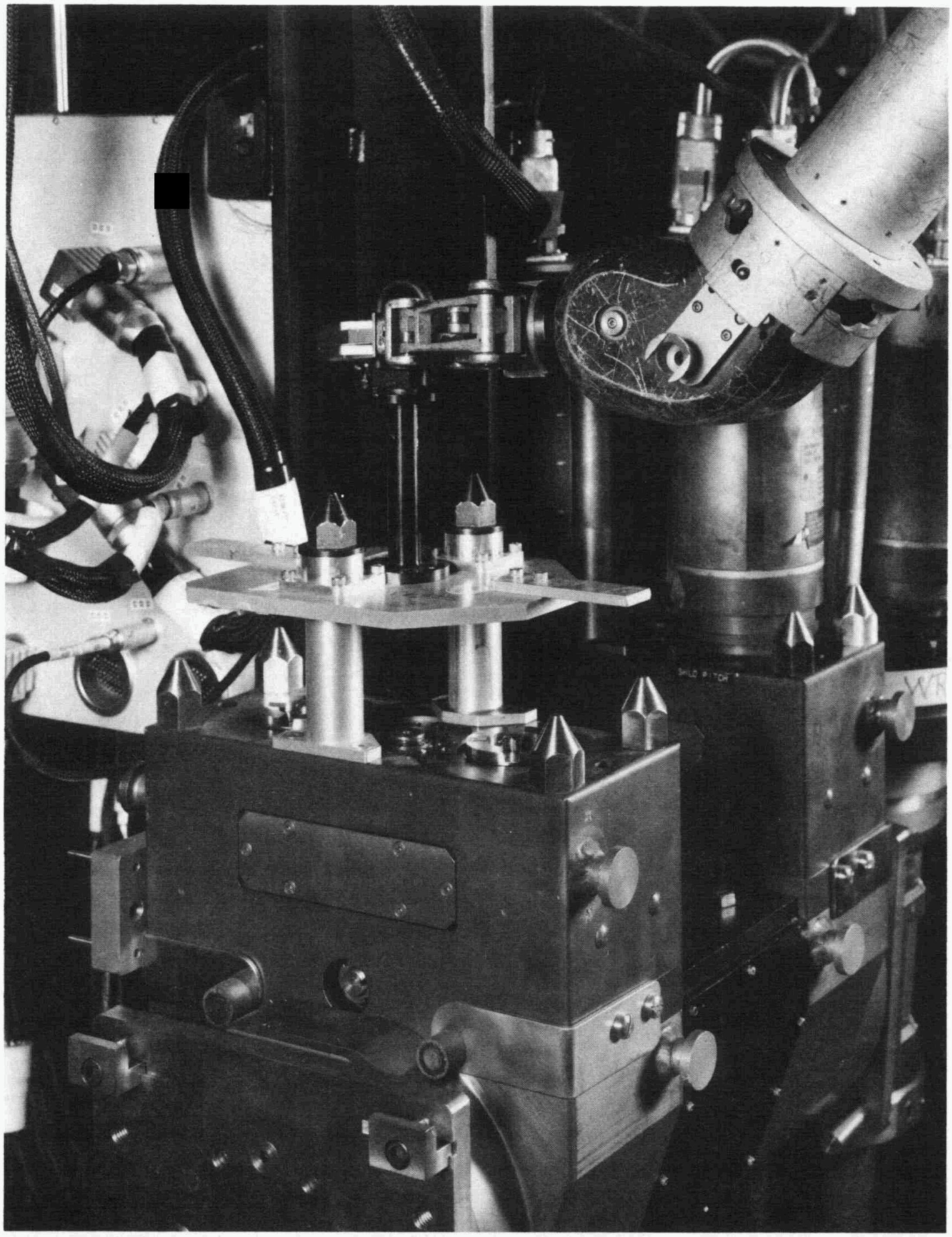

Fig. 21. Gear box fixture installed.

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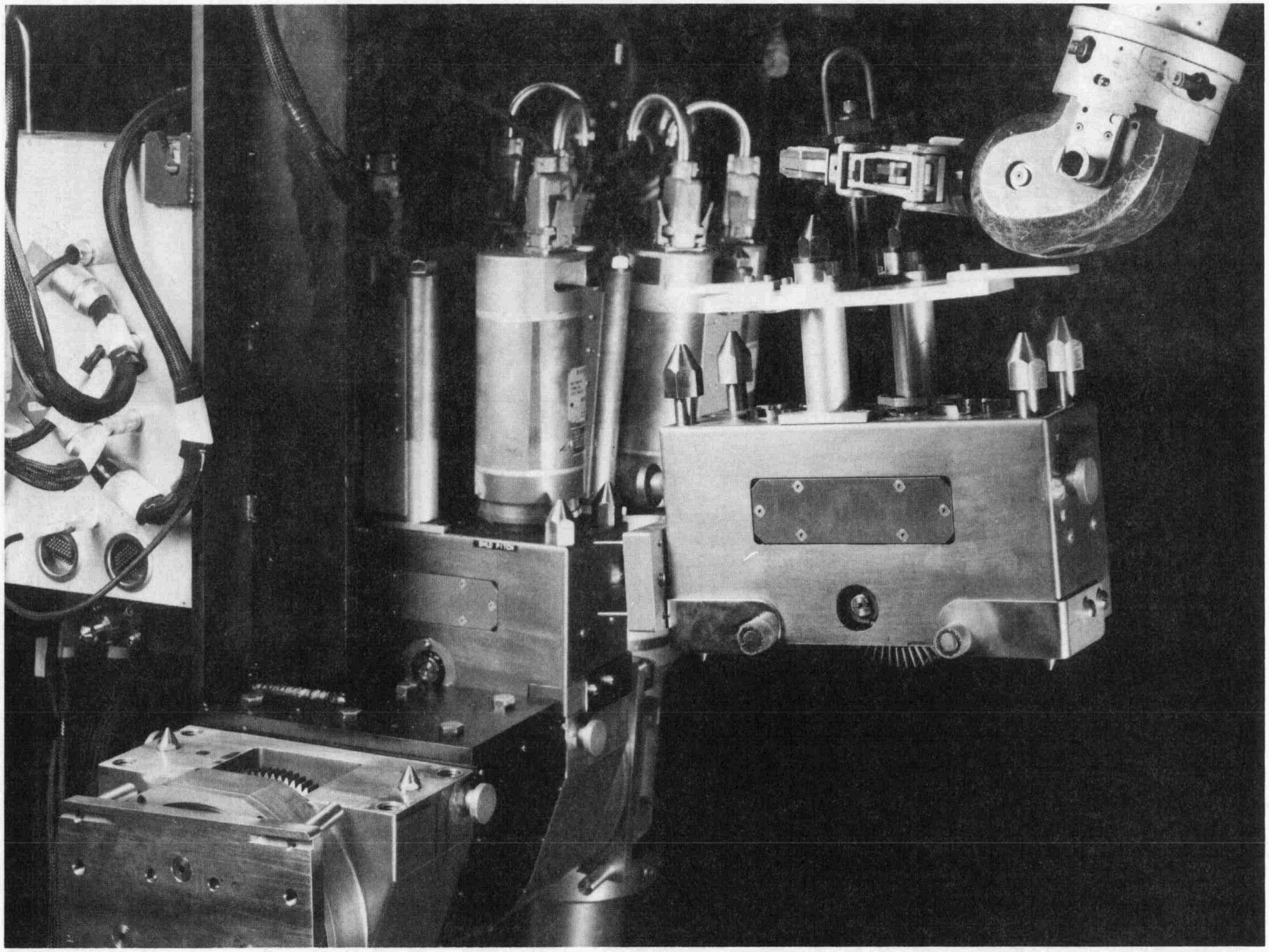

Fig. 22. Gear box module removed.

6.2.2 Roll Sleeve

When the roll sleeve module was put onto the mounting tabs, it would not remain in an upright position. There was no provision for keeping this part in a vertical position, so one of the shoulder drive motors was installed after the mounting plate was positioned vertically. This enabled the roll sleeve module to be put on and secured in place. Once the roll sleeve module had been tightened, the motor was removed.

6.2.3 Arm Module

Since the arm module was to be installed horizontally, the pitch lock fixture was reinstalled. As noted before, this fixture needed a larger grip area, but it presented no other problem to install. The positioning hoist was utilized to install the arm module. The controls of the hoist were once again difficult to operate remotely, but once the arm was positioned to be inserted into the roll sleeve, the installation went smoothly.

During insertion of the arm module, it was evident that the arm fixture had been lengthened during the removal procedure, which prevented full insertion into the roll sleeve. The fixture was taken back to its normal size by tightening the jack screw. Once this was done, the arm went all the way into the roll sleeve, and the bolts on the roll sleeve were tightened. As with the disassembly, the arm had to be rolled over in order to access one of the bolts.

6.2.4 Tong/Wrist Module

For assembling the tong/wrist module, the M-2 was positioned so that it could reach the bolts without having to roll the arm over. A 3/4-in. ratchet wrench was used instead of the combination wrench used in the disassembly. This helped speed up the reassembly. The module was easily aligned with the alignment guides provided on the arm module. The assembly would have been easier if the M-2 had been able to use the air wrench on the bolts of the wrist module, but as noted before, the arm fixture interfered, and there was insufficient clearance around the bolt heads to permit the usage of the air wrench.

6.2.5 Shoulder Drive Motors

There were no alignment marks for the shoulder pitch position, so the vertical position was determined by letting the arm hang. The back motor was to be installed first. Mounting this motor required that the lifting slot face away from the M-2 tongs. Trying to seat the motor in this manner turned out to be very difficult and required a local assist. The front motor was installed next, which was much easier because the tongs were able to utilize the lifting slot.

6.2.6 Roll Sleeve Fixture

Removing the roll sleeve fixture required removing the two bolts that held the fixture onto the roll sleeve and disengaging the gear on top. This procedure was done quickly and easily.

6.2.7 Gear Pod Fixture

The gear pod fixture had been equipped with spindles that were to be turned in order to engage the gear pod splines with those of the arm module. The fixture worked well, except the knobs that were on the spindle shafts were difficult for the tongs to grip. Another problem encountered in the reinstallation of the gear pod was that one of the captured bolts on the roll sleeve module was protruding and prevented the gear pod from seating. This problem was alleviated locally, and the gear pod was bolted into place. Removal of the gear pod lift fixture presented no problems and was accomplished quickly.

6.2.8 Arm Drive Motors

Since the drive motors have integral brakes, this procedure called for each motor to be engaged with its gear pod coupling by moving the respective joint. However, this was difficult, particularly for the arm and wrist modules because of the fixtures that held them. The motors had also been designed with spring-loaded couplings so that they would engage automatically when powered up. This provision did not seem to work for two motors because motors could not be bolted down securely before being powered up. During the reassembly, the two motors were bolted down as far as they would go, and yet this was not enough to securely seat the motor. These two motors were then reseated locally since damage might occur if they were powered up without being properly seated. The other motors were seated properly when installed. The last problem encountered in this step was that the M-2 operator could not determine the correct shoulder roll position of the ASM arm from his camera views, so the arm was positioned according to his perspective. This positioning turned out to be between 25° and 30° off from the correct position. This problem could be corrected with alignment marks on the shoulder roll sleeve module.

6.2.9 Arm Fixtures Removal

Removal of the arm and wrist fixtures posed no problem, and they were removed quickly, according to the procedure described previously.

6.2.10 Cable Harness

The installation of the cable harness was difficult. Part of the problem involved the fact that the retainer blocks that held the cables were too small to be easily handled by the M-2 tongs. The cable weight also hampered the ability of the M-2 to guide the retainer blocks onto their alignment pins. After the cable retainer blocks were installed, the LEMO connectors were connected, although it was necessary to apply alignment marks to the connectors before attempting this remotely.

6.2.11 Operation Checkout

Operation checkout was the final step in the remote maintenance demonstration. The ASM was powered up after the connectors were attached, and it was found that all components were operational and functioning as required.

7. CONCLUSIONS AND RECOMMENDATIONS

The remote maintenance testing described in this report successfully demonstrated that ASM can be remotely maintained with minimal fixtures. The problems that were identified are not major problems that defeat the design objectives for remote maintenance. In most cases the problems were such that they cause delay and difficulty doing remote maintenance.

In general, the ASM modules have been adequately designed for remote removal and replacement.[5] The ASM possesses many good features for remote maintainability; however, the test indicated several areas where recommendations can be made for maintainability improvements. Remotely maintained equipment should be designed in compliance with the guidelines presented in ORNL's Remote Maintenance Design Guide[5] where applicable. Some additional recommendations have been listed below for improvements in the design of ASM and equipment to be remotely maintained in general.

7.1 FASTENERS

The most significant problem with the current design of ASM from the remote maintenance standpoint is that all the bolts cannot be accessed from one side. This requires that the arm be turned during the disassembly, which causes loss of positioning when this occurs. If the arm can be redesigned so that all the bolts are accessible from one side, then this loss of positioning would be much less of a problem.

Ample clearance should be provided for all bolt heads so that a power wrench can be used on them. Clearance should also be provided for bolts next to any fixture; for example, clearance for the air wrench between the wrist module bolts and the arm fixture.

All bolts should be captured and spring loaded. Bolt heads should be of uniform design and size to minimize tool changes.

7.2 ALIGNMENT MARKS

These marks are needed for the rotating portions of the arm, such as the roll sleeve, shoulder pitch, and for the electrical connectors on the interface package. These joints need to rotate during the maintenance steps, and alignment marks would allow this while also maintaining the ability to return to original positions. Alignment marks should also be provided for installing the arm module into the roll sleeve so that the bolt holes are properly aligned.

7.3 HANDLING

Stable bases should be provided for the gear box and gear pod modules, if possible, in order to prevent damage to the gears. At present, these gears and splines protrude from the bottoms of the modules and are susceptible to damage from handling; they also make the module unstable for set down.

Modules with built-in lifting points should be accessible from more than one direction. As an example, the ASM modular motor has a lifting slot for manipulator tongs, which is only accessible from one side. This significantly restricts motor accessibility for remote handling.

7.4 MOTOR COUPLINGS

Motor couplings should be designed so that they can engage before the motor fasteners engage. Alternatively, they should automatically engage for any angular position of the coupling parts.

7.5 ELECTRICAL CONNECTORS

The ASM employs two different types of electrical connectors on either end of its cables. This demonstration indicated that the LEMO connectors are preferred over the AMP connector, due to simplified operation for both connecting and disconnecting.

7.6 LETTERING

All visual markings and lettering need to be large enough to be easily read with remote viewing equipment. Labels on the ASM electrical connectors, receptacles, and positions for the motors should be larger.

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