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Consolidated Fuel Reprocessing Program

RESULTS OF THE MANIPULATOR TEST TEST STAND STUDY: COMPARISON OF MANIPULATORS AND EVALUATION OF EQUIPMENT ITEMS

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ABSTRACT

This report describes the results of a study jointly conducted by staff members of the Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory (ORNL) in the United States and the Power Reactor and Nuclear Fuel Development Corporation (PNC) in Japan. This study was initiated under the Remote Systems Technology Exchange Program and continued as part of the Joint Collaboration on Reprocessing Technology, each representing agreements between the United States Department of Energy and PNC. The purpose of the study was to evaluate the performance of servomanipulator systems developed by the respective participants as part of their in-cell maintenance systems for use in future nuclear fuel reprocessing facilities. The following servomanipulators were tested: (1) the Central Research Laboratory's model M-2, (2) the advanced servomanipulator (ASM), and (3) the Meidensha Prototype-2 (P-2). A series of experimental tasks and a test platform called the Manipulator Test Test Stand (MTTS) were jointly designed by ORNL and PNC. An evaluation of the servomanipulator system was based on the time required to complete these tasks. A secondary test objective was to obtain information on equipment maintainability for these tasks. PNC and ORNL consider these tasks to be typical of those required for future reprocessing applications.

Because testing was conducted in two countries with different operators, the Manipulator Operator Skill Test (MOST), a supplemental experiment, was designed and conducted prior to the MTTS testing. This experiment evaluated the skill level of the operators and provided a basis for minimizing operator skill differences.

Servomanipulator differences were evaluated through examination of average differences in total task completion time. The M-2 servomanipulator had the lowest task completion times, although not significantly lower than the ASM. Times for both the M-2 and the ASM were significantly lower than for the P-2. Each of the tasks that were completed with the manipulators was evaluated by the operators as to its ease of remote maintainability. This report includes summaries of these evaluations. Overall, all tasks were well designed.

1. INTRODUCTION

The Consolidated Fuel Reprocessing Program at the Oak Ridge National Laboratory (ORNL) in the United States and the Power Reactor and Nuclear Fuel Development Corporation (PNC) in Japan are developing servomanipulator systems for in-cell maintenance systems for use in future nuclear fuel reprocessing facilities. A study was initiated under the Remote Systems Technology Exchange Program and continued as part of the Joint Collaboration on Reprocessing Technology, each representing formal agreements between the United States Department of Energy and PNC, to compare the performance of these servomanipulator systems. ORNL and PNC jointly designed a series of experimental tasks and mounted them on a test platform called the Manipulator Test Test Stand (MTTS). Times to complete these tasks served as the basis for the manipulator comparisons.

Careful experimental design was employed to ensure an accurate comparison. Identical test stands were fabricated in each country and outfitted with duplicate equipment items. Identical hand tools were provided for operators in both countries. A single set of test instructions describing tasks and procedures were used to ensure that the operators performed tasks the same way in both countries. Exchange of videotaped supplements to test instructions and observations of portions of the testing by a single individual in both countries helped to ensure that testing was administered in the same fashion at the two locations.

Even with these precautions, the skill of the operators could have a significant impact on the test results. Differences in operator skiils between ORNL and PNC groups could prevent a valid comparison of manipulator performance. To take into account the effects of differences in operator skill levels, a standard skill test called the Manipulator Operator Skill Test (MOST) was developed. The MOST was designed for the type of tasks performed in this test program. The MOST provided a measure of operator skill which was used to compensate (in part) for differences between the groups. It was administered to all operators participating in this program.

2. PURPOSE

Joint programs comparing manipulator performance provide data for future design decisions. The comparative testing leads to improvements in the next generation of servomanipulators by discovering relative strengths and weaknesses in existing designs. The purpose of this test program was to gather such data. A secondary objective was to obtain information on the maintainability of reprocessing facility equipment items (i.e., tubing jumpers, electrical connectors, flanges, etc.). These may be incorporated into future fuel reprocessing plants typical of those maintained by servomanipulators. This document describes each of the servomanipulator systems, the tasks on the test stand, methods of data analysis, results of operator skill tests, results of data analysis, and an assessment by the operators of the equipment maintainability.

3. TEST STAND DESCRIPTION

The MTTS, including the equipment items available for testing, is shown in Fig. 1. A total of 14 equipment items are available for mounting on the test stand at any one time. Table 1 provides a brief description of each of the test items, as well as the approximate size, the supplier, the drawing number, and other comments where appropriate.

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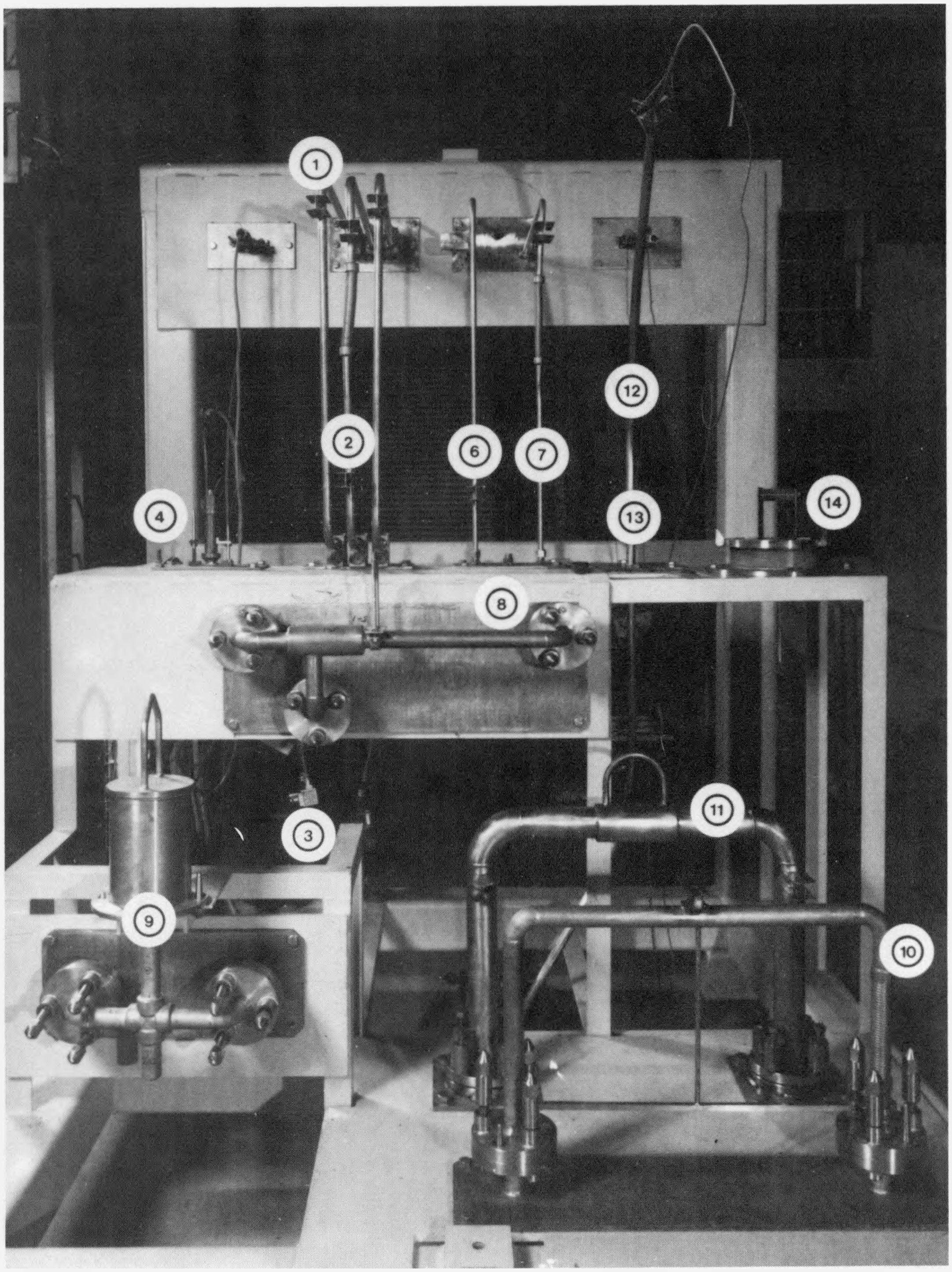

Fig. 1. Manipulator test test stand.

Table 1. Description of items mounted on the manipulator test test stand

Item No.	Equipment item description	Overall size (approx.)	Supplied by	Drawing No.	Comments
1	Tubing jumpers, rigid with TRU ferrules	3/4-in.-OD tubing 32 in. tall x 32 in. deep	ORNL	12618-001	
2	Tubing jumpers with bellows and TRU ferrules	3/4-in.-OD tubing 32 in. tall x 32 in. deep	ORNL/PNC	12618-001 and 61505	
3	Electrical jumpers with ORNL connectors	10 pin 60 pin	ORNL	12618-003	Both angled and straight connectors are used
4,5	Electrical jumpers with PNC connectors	10 pin 40 pin	PNC	61512 61513	
6	Tubing jumpers, rigid with Swagelok fittings	12-in.-OD tubing 36 in. tall x 25 in. deep	ORNL	12618-002	
7	Tubing jumpers with bellows and Swagelok fittings	1/2-in.-OD tubing 36 in. tall x 25 in. deep	ORNL/PNC	12618-002 and 61505	
8	Three-legged pipe jumper with 3-bolt flanges and dummy ejector	31 in. long x 4 in. deep x 11.4 in. tall 1-11/32-in.-diam pipe	ORNL/PNC	61503 61504-3 61506	Total weight approx. 30 lb
9	Pipe jumper with 3-bolt flanges and simulated valve	24 in. tall x 17 in. wide x 5-1/2 in. deep 1-11/32-in.-diam pipe	PNC	61502	Total weight approx. 38 lb
10	Vertical pipe jumper with 3-bolt flanges and bellows	15 in. tall x 29 in. wide 1-11/32-in.-diam pipe	PNC	61504-1 61504-2 61504-4	Total weight approx. 22 lb
11	Vertical pipe jumper with 4-bolt flanges and lifting bail	24 in. tall x 29-5/8 in. wide 2 in.-diam pipe	ORNL	12618-004	Total weight approx. 25 lb
12,13	Thermocouple with flexible extension wire and end plug	4.5-mm-diam thermocouple sheath 2 thermowells with 16-mm ID	PNC PNC	61501 61501	Length and bend radii of thermo-wells are different
14	Sampling station		PNC	61511	Bottle is the only item removed from sampling station

NOTE: Item number 5 is not shown in figure.

4. MANIPULATOR DESCRIPTION

4.1 CENTRAL RESEARCH LABORATORY'S (CRL) MODEL M-2

The CRL model M-2 manipulator is a bilateral, force-reflecting servomanipulator. The master arms (Fig. 2) are 7 degrees-of-freedom (D.F.) kinematic replica controllers. Each slave arm (Fig. 3) has a continuous handling capacity of 23 kg in any position. The kinematics are in an elbows-up stance. Table 2 lists the range of motion and speed for each joint.

The M-2 slave joints are driven by brushless dc servomotors with integral position and velocity encoding. The outputs of the upper 3 D.F. are gear- and lever-driven. The lower 4 D.F. of the slave are cable-driven. The master controller lower 4 D.F. are tape-driven. A standard position-position technique, implemented in digital control hardware and software, provides force reflection. Force-reflection ratios from 1:1 to 8:1 are available, as well as ∞:1 (no force reflection). The M-2 is equipped with three cameras for operator viewing.

4.2 OAK RIDGE NATIONAL LABORATORY'S ADVANCED SERVOMANIPULATOR (ASM)

The ASM is a bilateral, force-reflecting servomanipulator system. The system was designed and fabricated by ORNL and is the first remotely maintainable servomanipulator. The master arms (Fig. 4) are 7 D.F. kinematic replica controllers. Each slave arm (Fig. 5) has a continuous handling capacity of 16 kg in any position. The kinematics of the master and slave are in an elbows-down stance felt to be more amenable to reaching rack-mounted reprocessing equipment. Table 3 lists the range of motion and speed for each joint.

The ASM slave joints are driven by brush-type dc servomotors with integral position and velocity encoding. All degrees of freedom for the slave are gear and torque-tube drives which accommodate the modularity necessary for remote maintainability. The master controller degrees of freedom are cable-driven. A standard position-position technique, implemented in digital control hardware and software, provides force reflection. Force reflection ratios from 1:1 to 16:1 are available. The ASM is equipped with three cameras for operator viewing.

4.3 MEIDENSHA'S PROTOTYPE-2 (P-2)

The P-2 is a bilateral, force-reflecting servomanipulator system that was designed and fabricated by Meidensha. The 7 D.F. slaves are capable of easily being assembled and disassembled by another manipulator. The master arms (Fig. 6) are 7 D.F. kinematic replica controllers. Each slave arm (Fig. 7) has a continuous handling capacity of 15 kg. The kinematics of the master and slave are in an elbows-down stance felt to be appropriate for operations on rack-mounted hardware. Table 4 lists the range of motion and speed of each joint.

The P-2 has centralized motors and torque-tube drive mechanisms for the three joints of the upper arm and dispersed motors and gear direct drive mechanisms for the four joints of the forearm. The master controller degrees of freedom are cable-driven. A standard position-position

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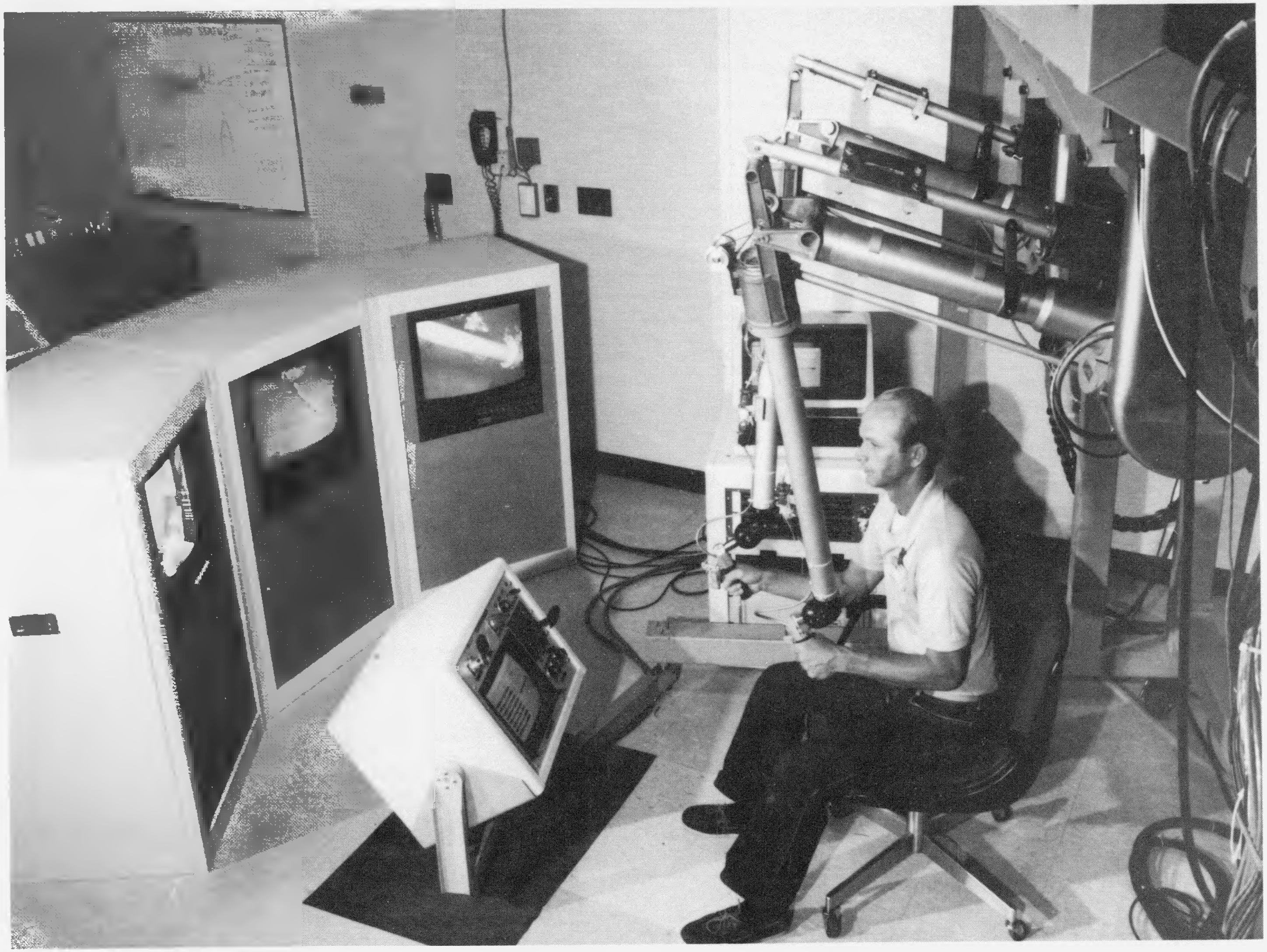

Fig. 2. CRL M-2 master arms.

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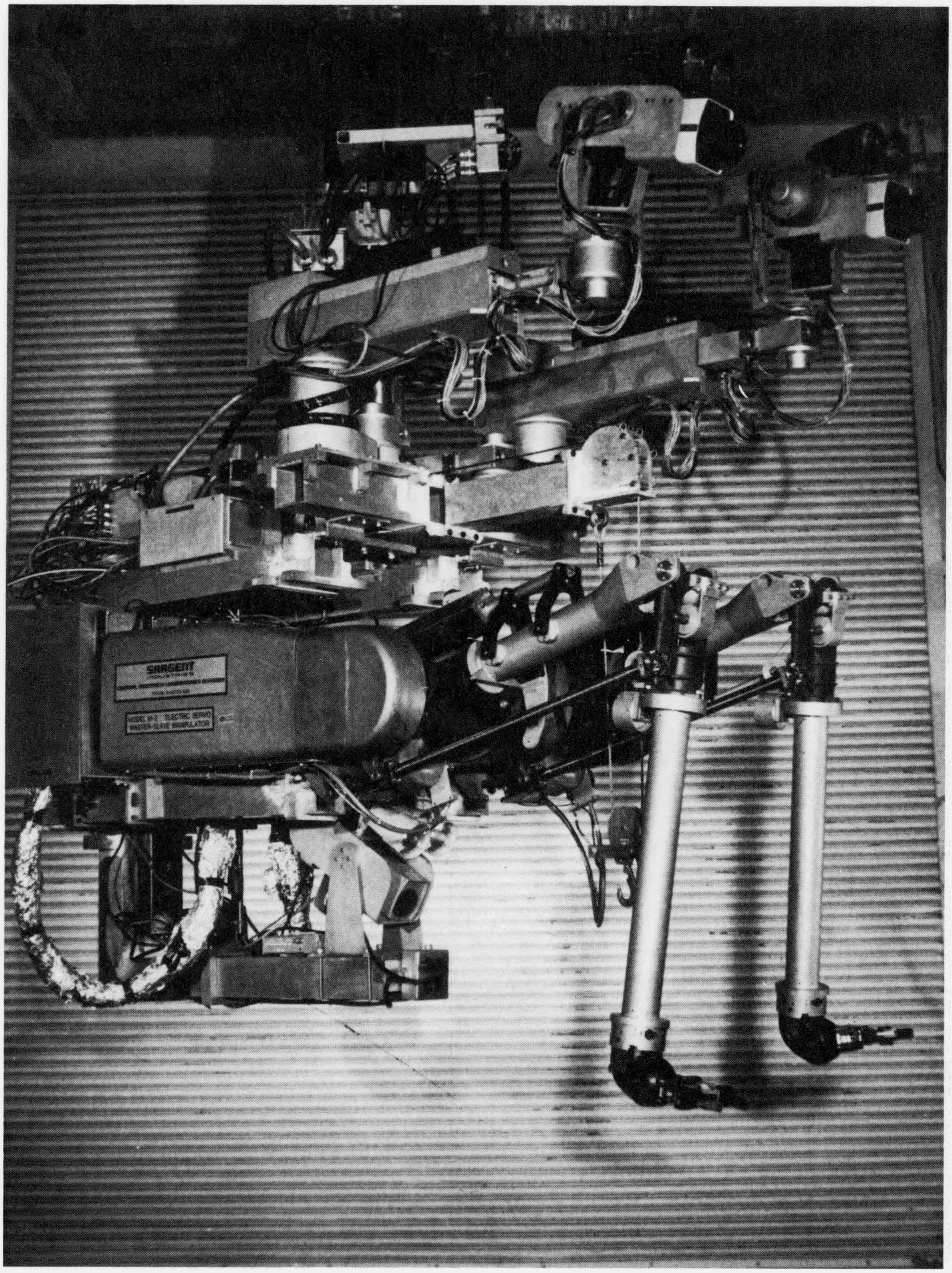

Fig. 3. CRL M-2 slave arms.

Table 2. Ranges of motion and speed of M-2 slave joints

Joint	Range of motion	Maximum no-load speed
Shoulder roll	±45°	>1.5 m/s
Elbow pitch	±45°	>1.5 m/s
Shoulder pitch	±45°	>1.5 m/s
Wrist yaw	±210°	>344°/s
Wrist pitch	+40, -125°	>400°/s
Wrist rotation	±180°	>344°/s
Gripper closure	.08 m	>1 m/s

technique, implemented in digital control hardware and software, provides force reflection. Force reflection ratios from 1:1 to 8:1 are available, as well as ∞:1 (no force reflection). The P-2 is equipped with three cameras for operator viewing.

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Fig. 4. Advanced servomanipulator master arms.

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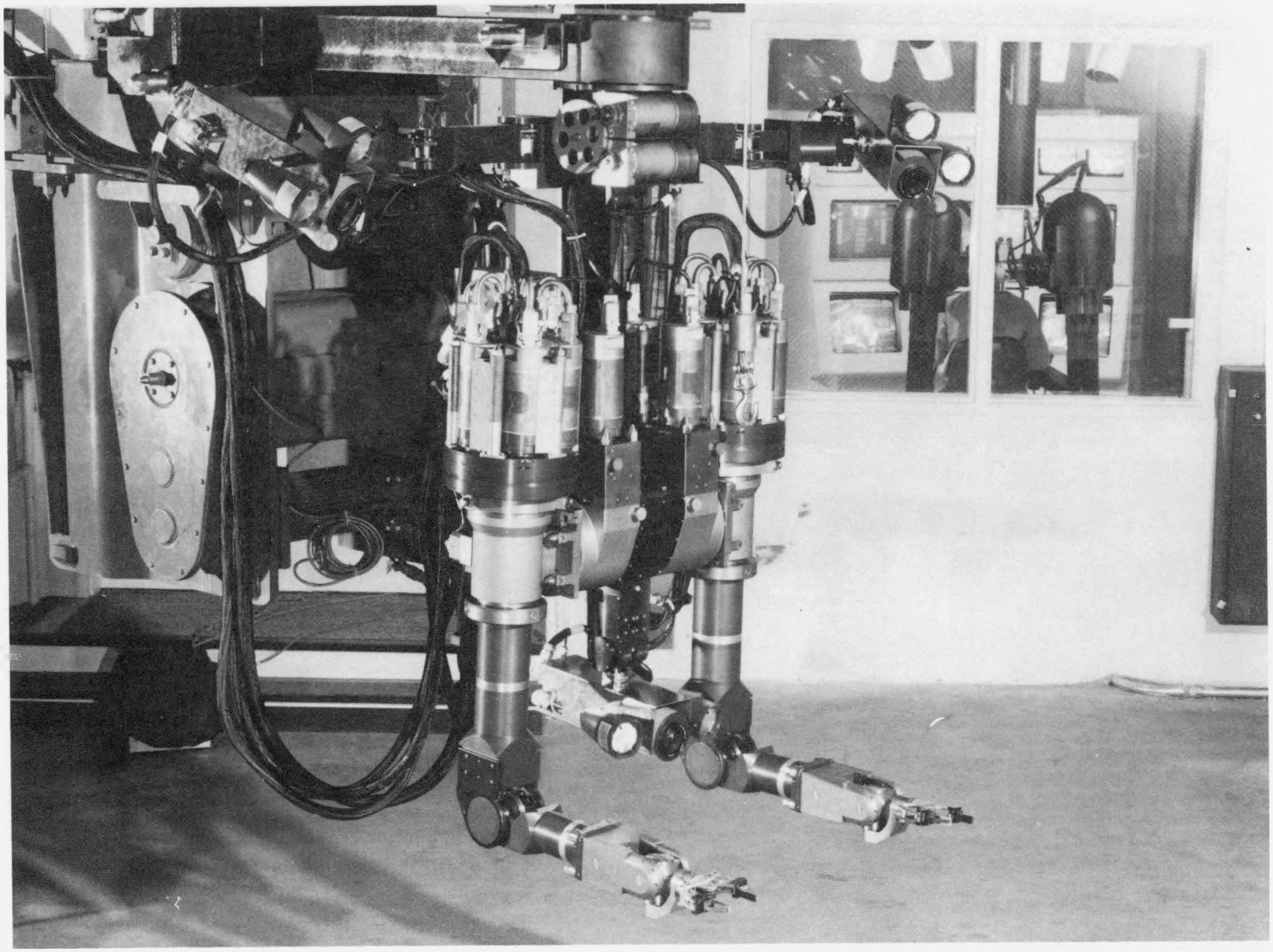

Fig. 5. Advanced servomanipulator slave arms.

Table 3. Ranges of motion and speed of the ASM slave joints

Joint	Range of motion	Maximum no-load speed
Shoulder roll	+80, -60°	>1.5 m/s
Elbow pitch	+45, -50°	>1.5 m/s
Shoulder pitch	±50°	>1.5 m/s
Wrist yaw	±90°	450°/s
Wrist pitch	±135°	450°/s
Wrist rotation	±505° (2.8 rev)	550°/s
Gripper closure	.08 m	.5 m/s

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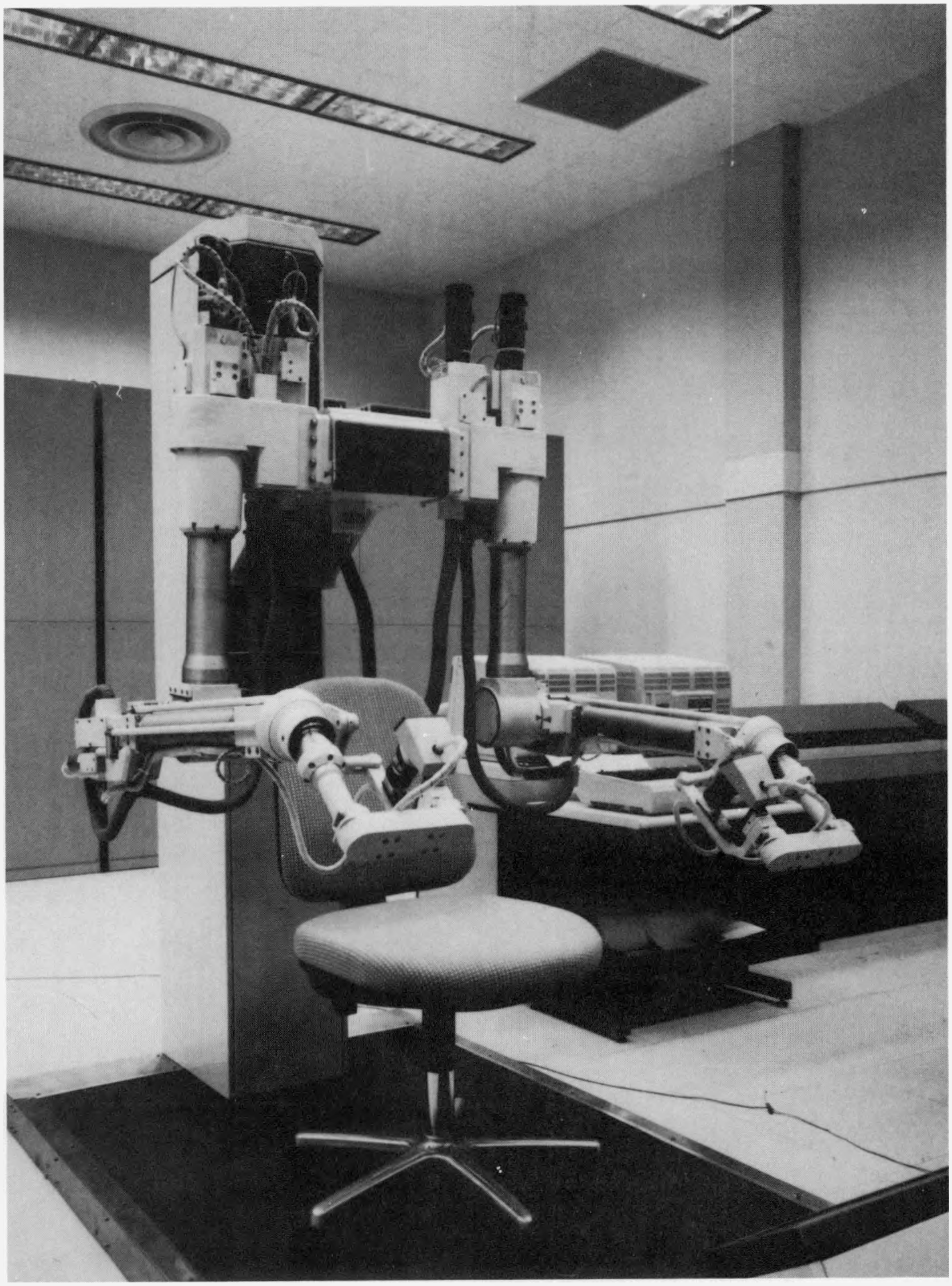

Fig. 6. Prototype-2 master arms.

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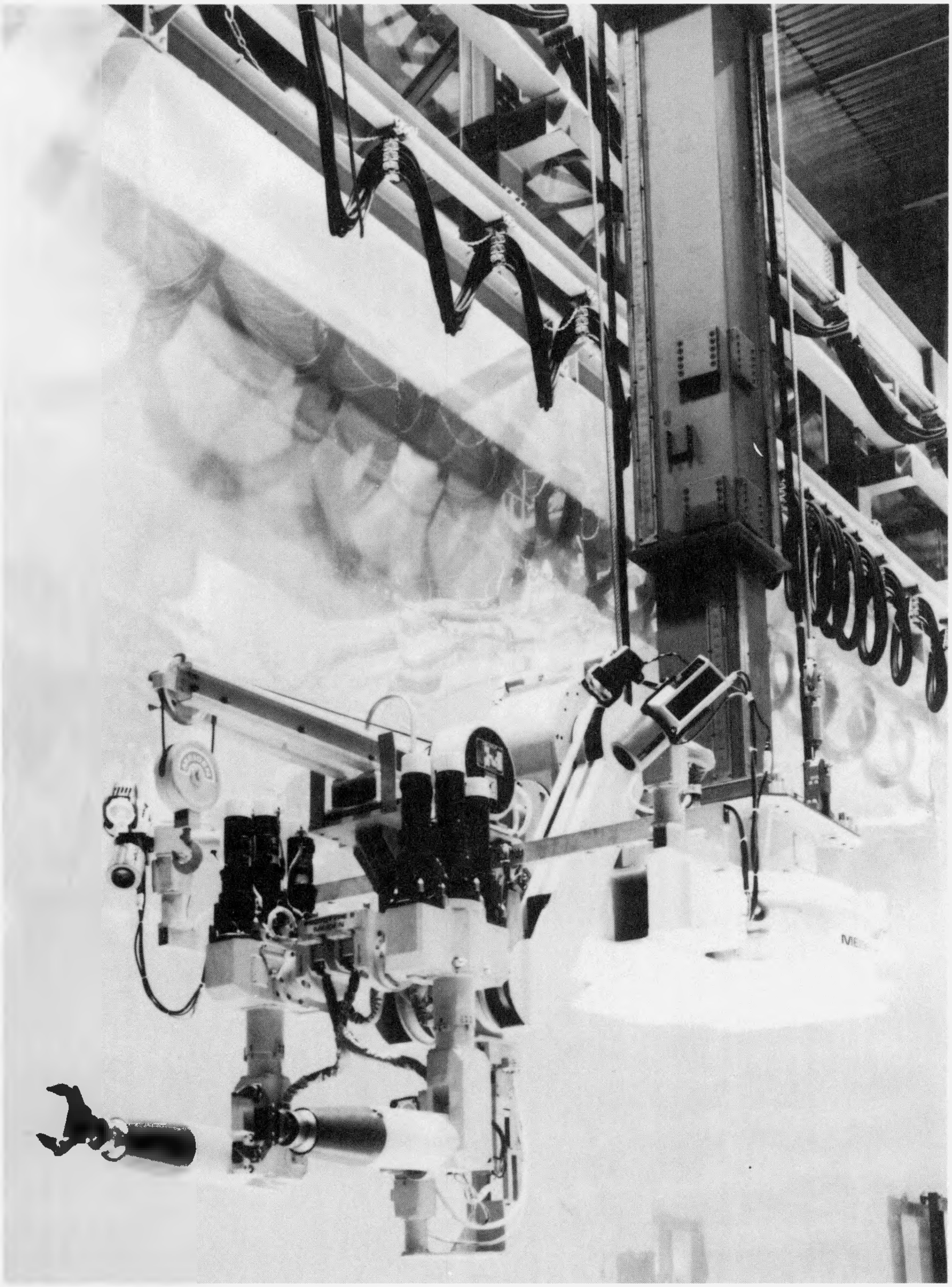

Fig. 7. Prototype-2 slave arms.

Table 4. Ranges of motion and speed of P-2 slave joints

Joint	Range of motion	Maximum no-load speed
Shoulder roll	+45, -60°	60°/s
Shoulder pitch	+135, -45°	40°/s
Elbow pitch	+35, -215°	60°/s
Wrist yaw	±45°	160°/s
Wrist pitch	+45°	160°/s
Wrist rotation	±150°	160°/s
Gripper closure	.08 m	1 m/s

5. GENERAL TEST REQUIREMENTS AND INSTRUCTIONS

All test requirements and instructions, including test sequence, descriptions of specific tasks, and other pertinent details, are discussed in the test plan/test instructions. Four experienced operators in each country participated in the study by performing various sequences of tasks. Sixteen separate tasks involving the 14 equipment items were identified. All four operators completed three sequences of 12 tasks twice. The two most experienced operators completed an additional three sequences of four difficult tasks twice. Generally, each operator performed each task three times with their respective manipulators. The order in which the tasks were completed was designed to prevent practice from giving any task an advantage over other tasks. An observer was present for each test to ensure that it was performed according to test instructions and to record all test data. All tests were videotaped.

6. ANALYSIS METHODS

This section describes analysis of data collected during the course of Manipulator Test Test Stand testing. It is concerned specifically with the rate at which operators completed tasks, expressed as the time in seconds required to complete tasks. The objective of the analysis was documentation of differences among manipulators involved in testing. There were three data analysis phases: (1) comparison of the performance of the M-2 servomanipulator with performance of the ASM; (2) comparison of the P-2 manipulator with the M-2; and (3) comparison of the ASM and the P-2.

There were two important difficulties in the analysis. First, the operators at ORNL completed task repetitions with the M-2 manipulator first and then completed repetitions with the ASM. Therefore, the experiment is vulnerable to bias caused by differences in operator practice levels. Operators using the M-2 completed a short series of repetitions of selected tasks after completion of ASM repetitions to assess the magnitude of this effect. Second, the analysis must treat the ORNL versus PNC manipulator comparisons as a between-subjects model because repeated measurements on the same subjects (between manipulators) were not possible. Unfortunately, it was not possible to assign operators to experimental groups randomly. This makes the experiment vulnerable to group differences. Potential differences in skill levels of the groups are particularly important. Because the experiment employed small sets of operators and random assignment to experimental groups was not possible, it is not reasonable to expect that skill levels will be equivalent in the two groups (in fact, skill tests demonstrate skill level differences between groups). Therefore, the experiment is vulnerable to bias due to group performance differences not related to manipulator quality. The analysis of covariance (ANCOVA), with skill level scores as the covariate, was used to reduce the effect of this bias.

6.1 COMPARISON OF ORNL MANIPULATOR SYSTEMS

Task time totals were submitted to analysis of variance (ANOVA) to identify average differences among tasks and between manipulators for the ORNL manipulators. Analysis of variance is a widely used statistical technique which assesses the probability that two averages could come from the same population of scores. Data collected in a testing program may be considered a subset or sample of data from a larger population of possible performances. An operator may perform differently each time he attempts a task, due to random fluctuations in attention levels, effort, environmental differences, or any of many other factors that affect people and machines. The sum of all possible performances by an operator with a given manipulator on a given task is the population of performances. ANOVA examines the averages and the variability of observed performance to determine whether the averages represent two (or more) samples from the same population of performances or samples from different populations of performances. For example, in this testing program differences between manipulators will be evaluated. If the two ORNL manipulators do not differ in performance, the time required to complete tasks should not be different. In other words, the completion times will be from the same population of possible completion times. However, random fluctuations in operator performance, the effects of practice, etc., will combine to prevent the averages from being the same. ANOVA examines the average differences in light of what may be expected from such random errors and determines whether differences are large enough to be statistically significant. Completion time differences were considered statistically significant if there were less than a 1 in 20 chance of them being observed between times taken from the same population of completion times (alpha $\leq$ 0.05).

6.2 COMPARISON OF ORNL MANIPULATORS WITH THE PROTOTYPE-2 MANIPULATORS

In the comparison of ORNL manipulators with the P-2, data were submitted to ANCOVA, which is very similar to ANOVA, and involves the same sort of tests for statistically significant differences between groups. It differs from ANOVA in that a continuous variable, which related to the criterion variable, may be included in the analysis. This additional variable (called a covariate), if carefully selected, provides greater power to ANCOVA than is possible with ANOVA. For test stand data, the covariate was score on the Manipulator Operator Skill Test.

ANCOVA uses the covariate to predict the score that should be observed by an operator in a particular condition. For example, if operator A has a skill index of 10 and operator B has an index of 5 (with low scores representing greater skill), their performance on test tasks should reflect their skill levels. Operator B should complete tasks more quickly than operator A. If operator A uses a different manipulator than B, and if A completes the tasks at the same rate as B, one may conclude that the manipulator used by A is better than the one used by B. ANOVA only compares the observed averages and would not detect this effect, while ANCOVA, which can use the skill test scores, would detect the effect. In other words, ANCOVA adjusts for differences on the covariate, which in this case is a measure of operator skill. Completion time differences were considered statistically significant if there were less than a 1 in 20 chance of them being observed between times taken from the same population of completion times (alpha $\leq$ 0.05).

6.3 MANIPULATOR OPERATOR SKILL TEST

The ORNL and PNC operators participating in the study completed the MOST before the start of test stand testing. Reference 1 gives details of the MOST. It was developed to measure important servomanipulator operator skills and is based on careful analysis of servomanipulator motions and prototypical remote maintenance tasks. The MOST measures the time operators require to complete a simple (one-armed) task with television cameras in three different positions: directly in front of the task (part 1), offset 45° to the right (part 2), and offset 90° to the right (part 3). The task was also repeated using two-armed manipulator operation with the camera directly in front of the task (part 4). Table 5 lists averages and standard deviations for the two groups of operators.

In Table 5, it appears that the PNC operators are (on average) more skilled than the ORNL operators. They also appear to be a more homogeneous group than the ORNL group: the standard deviation for the PNC operators is consistently lower than the standard deviation for the ORNL operators.

The MOST data were used to identify an index of operator skill. PNC's initial treatment of these data used a ranking approach and searched for the best correlation of available skill test scores and test stand task time rankings. The nonparametric (ranking) approach is not considered entirely appropriate since the data satisfy the requirements for an interval scale; therefore, the analysis in this report will use Pearson product-moment correlations to select a variable for use as a covariate. This report does, however, adopt the PNC method for searching for a covariate, but uses parametric statistics.

Table 5. Averages and standard deviations of ORNL and PNC operators for time (in seconds) to complete the MOST

	MOST Segment			
	Part 1	Part 2	Part 3	Part 4
ORNL average	51.10	102.85	122.60	152.00
Std. dev.	17.13	75.93	65.59	77.18
PNC average	43.74	77.36	93.48	119.60
Std. dev.	4.46	27.90	43.34	14.56
Overall average	47.01	88.69	106.42	134.00
Std. dev.	12.45	56.17	56.26	54.99

The average time operators required to complete each segment of the MOST, differences between average time in the offset conditions and the center-camera condition, and measures of performance variability were correlated with the average time required to complete MTTS tasks. The time required to complete the MOST segment with cameras offset 45° was selected to serve as a skill index because it showed the highest correlation in both groups. The highest correlation in the ORNL group was between center-camera times and MTTS average, and the highest correlation in the PNC group was between the 90° offset condition and the MTTS average. However, the 45° offset showed the strongest correlation in both groups, at 0.71 in the PNC group and 0.85 in the ORNL group (where 1.0 would indicate total correlation and 0.0 indicates no correlation). The 45° offset time for each operator was used as a covariate in the ANCOVA conducted on the combined data sets.

7. RESULTS

7.1 COMPARISONS OF MANIPULATORS

The ANOVA for ORNL manipulators failed to find consistent differences between the M-2 and the ASM*, although the ASM (on average) required longer times to complete tasks. The ANCOVAs (one comparing the P-2 to the ASM and the other comparing the P-2 to the M-2) found significant differences between both ORNL systems and the P-2.†‡ Figure 8 shows the average time to complete tasks for each system, and Fig. 9 shows the time for each manipulator for each task. Figure 10 shows these data in a more revealing format. In Fig. 10, the data are scaled to the performance of the best (on average) manipulator—the M-2. The y-axis on the graph is the ratio of average time for each manipulator (on each task) to the average time on each task for the M-2. The graph shows that the P-2 required between two and four times as long to complete tasks as the M-2. The ASM required only slightly more time than the M-2 on most tasks and was faster than the M-2 on three tasks.

7.2 TASK EVALUATION

A secondary objective of this test program was to obtain information on the maintainability of individual equipment items. The following is a discussion of each of the remote maintenance tasks included on the MTTS from the operator perspective considering remote maintenance characteristics of each. No consideration was given to the operational functionality; only the remote maintainability was considered. These comments represent a consolidation of ORNL operator comments only.

Task No. 1 - Rigid TRU Jumper: This was a fairly simple task. A significant portion of the time this task required a two-armed operation. One arm was required to hold the jumper in place while the other arm tightened the bolt. Cone head bolts would have been better. The rigid TRU jumper was preferred to the flexible TRU jumper.

Task No. 2 - Flexible TRU Jumper: This was a two-armed operation 100% of the time. The flexible bellows allowed the jumper to bend, and it was necessary to hold it in place with the second arm. The rigid jumper was preferred.

Task No. 3 - Electrical Connector (ORNL 10- & 60-pin): These connectors were fairly easy to operate. Turning of the connector inserts makes the alignment marks useless. The inserts should be pinned to prevent turning. The connectors are easily damaged when misaligned.

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*The ANOVA for the ASM versus M-2 difference found that $F[1,3] = 0.80$, alpha ≤ 0.44.

†The ANCOVA for the P-2 versus M-2 difference found that $F[1,5] = 85.66$, alpha ≤ 0.01.

‡The ANCOVA for the P-2 versus ASM difference found that $F[1,5] = 57.47$, alpha ≤ 0.01.

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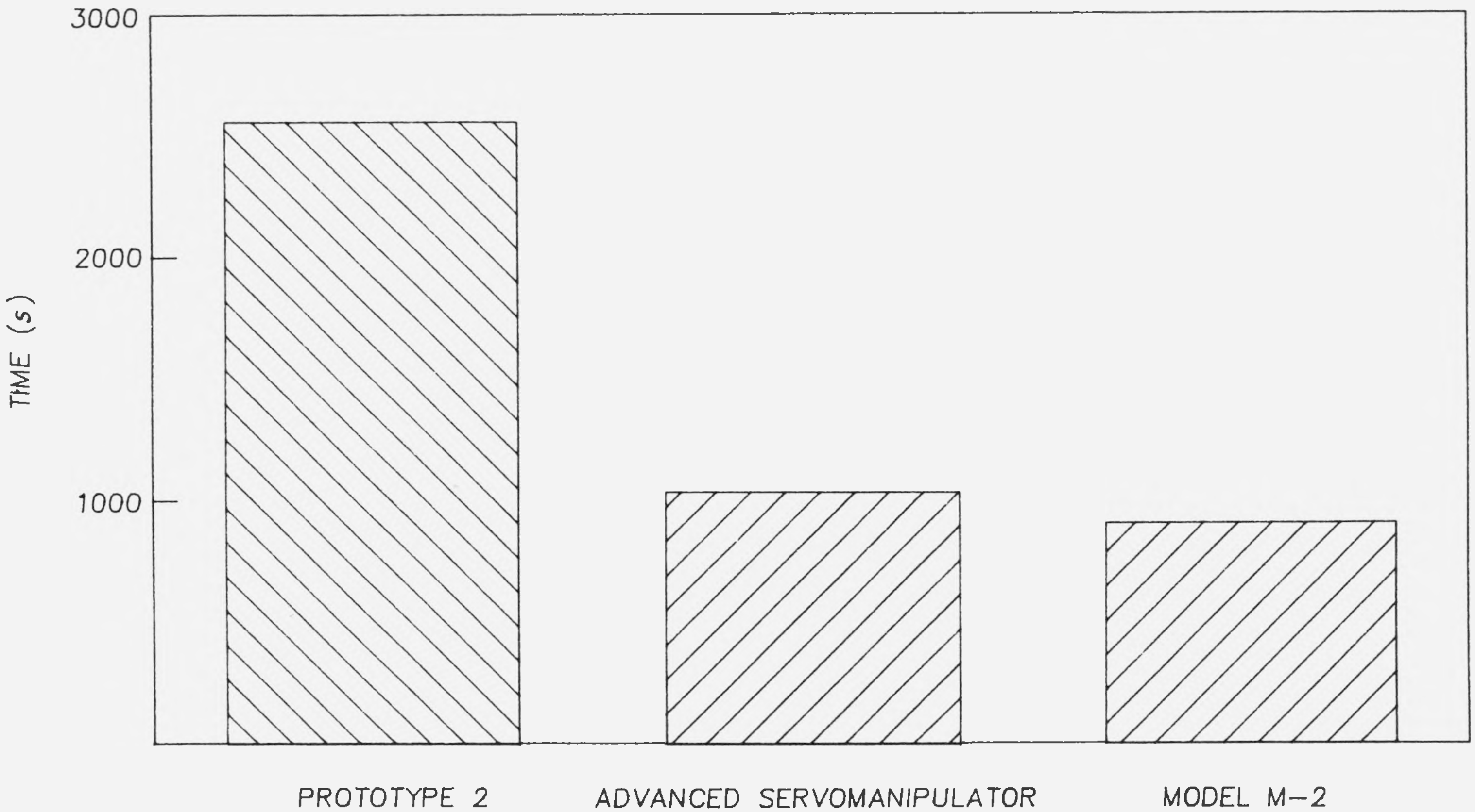

Fig. 8. Average time to complete tasks.

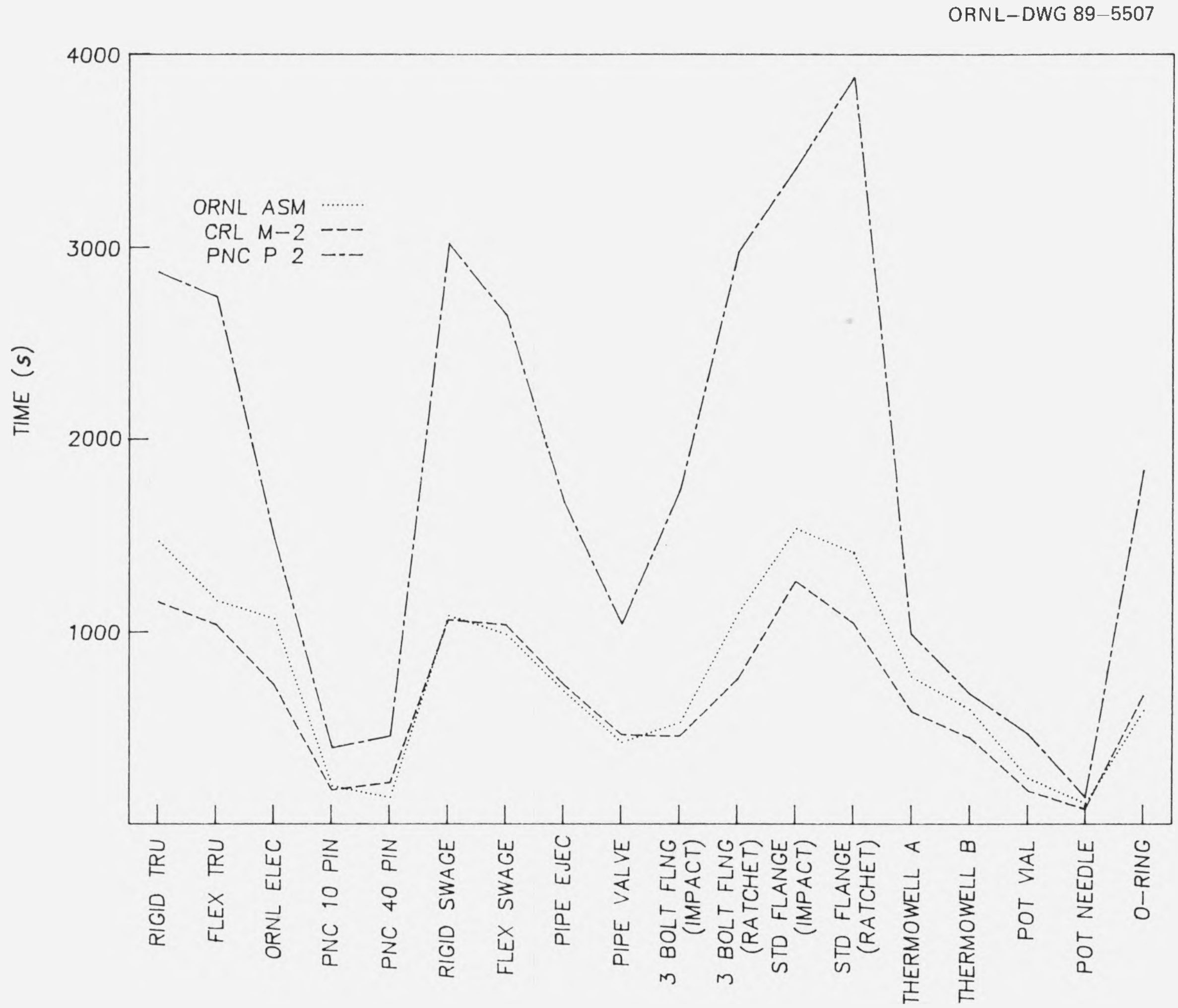

Fig. 9. Time for each manipulator to complete each task.

Task No. 4 - Electrical Connector (PNC 10-Pin): These connectors were also easy to operate. The guide pins incorporated into the connector design are easily bent and also work loose. Set screws to prevent rotation of the connector body work loose, easily allowing the guide pins to engage but having the connector misaligned. The wire bail kinks easily and was too weak. This connector is preferred to the ORNL-supplied (Lemo) 10-pin connector.

Task No. 5 - Electrical Connector (PNC 40-Pin): This was the easiest of all the electrical connectors to operate remotely. Snap rings holding the component together should be stronger. The connector is somewhat bulky but is still preferred to the ORNL-supplied (Lemo) 60-pin connector.

Task No. 6 - Rigid Swagelok Jumper: This was the easiest of the tubing jumpers to install, primarily because it was self-supporting and could be accomplished with only one arm. If the jumper becomes bent, it is difficult to start and spin the nuts finger tight. It is preferred to the rigid TRU connector, provided proper alignment exists.

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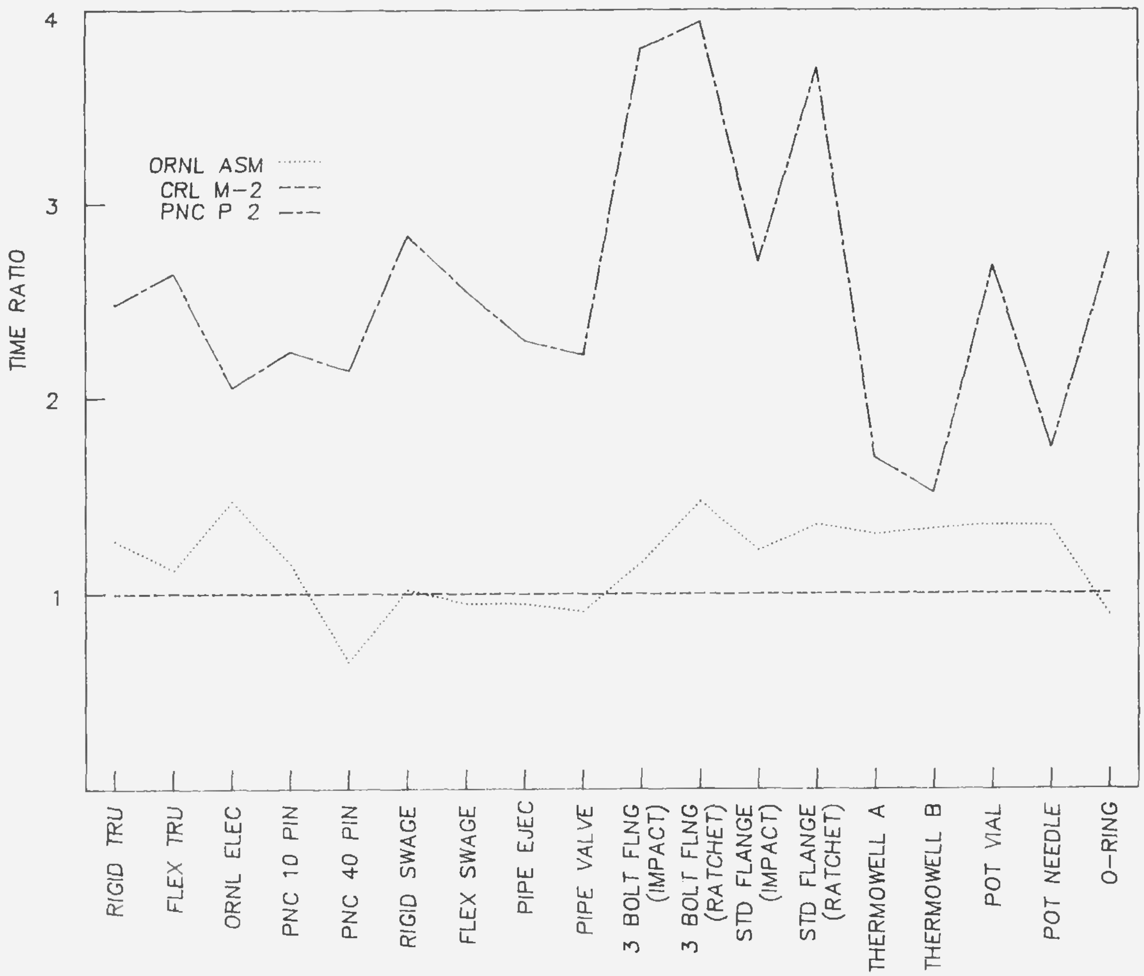

Fig. 10. Time ratio for each manipulator for each task scaled to the M-2.

Task No. 7 - Flexible Swagelok Jumper: From the perspective of the operator, bellows caus more problems than they help. Again, two arms are necessary to accomplish this operation. Sinc alignment is very important for the swagelok jumper, the rigid jumper is preferred.

Task No. 8 - Dummy Ejector Jumper: The hangers are excellent for keeping the bolts and hole aligned during installation. Cone head bolts are also good. Spring loading the bolts would be eve better. The hanger nuts occasionally back off, allowing the clamps to turn and bind in the "V slot. Jumpers with the flange face in the vertical position are preferred by operators because o easier access and because the bolts do not have as much tendency to re-thread themselves.

Task No. 9 - Dummy Valve Jumper: This is a good design. The only improvement needed i spring-loaded bolts. This task and the dummy ejector jumper were judged best of the pip jumpers.

Task No. 10 - Three Bolt Jumper: Alignment guides and hangers work well. With the bolts i the vertical position, they tend to re-thread themselves after loosening. Spring loading woul correct this problem. The bellows kink easily as well. This jumper was preferred to the standar flange jumper.

Task No. 11 - Standard Flange Jumper: Bolts should be cone head and spring loaded. The rear inside bolts are difficult to access

Task No. 12 and 13 - Thermocouple: Thermowells "A" and "B" are almost identical and comments apply to both. The length of the thermocouple is the characteristic that makes the operation difficult. The test required that the thermocouple be handled from the connector end. Installation would have been much easier had the testing allowed handling of the thermocouple at other locations.

Task No. 14 - Samplepot/Vial: The vial is easily squeezed, which deforms it to the point that removal is almost impossible. The center position of the lever is difficult to determine. Bolts holding the handle on had to be tightened several times. The handle should be redesigned for greater strength.

Task No. 15 - Samplepot/Needle: The needle is easily bent during operation. The latch lever is easily misaligned during installation.

Task No. 16 - O-Ring: Installation tools worked well; however, the removal tool bent during the first use and was modified and made stronger.

8. CONCLUSIONS

While it is not possible to separate the effects of potential differences in skill in the two operator groups from manipulator performance, it seems that the M-2 and the ASM are more dexterous than the P-2. The differences in performance observed between the ORNL manipulators and the P-2 are very large (between 200 and 450%). It would require larger differences in operator skill than those observed on the MOST to account for such a large difference in task performance. The M-2 and the ASM performed the tasks at equivalent task completion times; the P-2 required significantly longer.

Each task was evaluated by the operators as to its ease of remote maintainability. Overall, all tasks were well designed; however, operators did express a preference to some designs over others. The PNC-supplied electrical connectors were preferred to the ORNL-supplied connectors. For the 3/4- and 1/2-in. tubing, the rigid swagelok jumpers were favored to both the rigid and flexible TRU connector jumpers and the flexible swagelok jumpers. For the larger 1 11/32- and 2-in. jumpers, the dummy ejector jumper and the dummy valve jumper were preferred to the others.

The defects (which were recognized and addressed by the experimental design as much as possible, given international participation in the testing) in this study include (1) inability to randomly assign subjects to groups; (2) inability to balance the order of manipulator use at ORNL, so practice levels were different on the systems (giving the ASM an advantage); (3) data collection by two different groups of experimenters, at widely separated facilities, preventing rigorous control of data collection methods (although a spirited and creative attempt was made to ensure uniform methods); and (4) failure to fully measure performance (only rate of performance was measured, with performance quality, impact on the remote area, and impact on the operator ignored). However, the differences observed between the two ORNL manipulators and the P-2 are large enough to be conclusive in spite of these problems.

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