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TABLE OF CONTENTS

| | Page |
|--|------|
| ABSTRACT | i |
| ACKNOWLEDGEMENTS | iii |
| INTRODUCTION | 1 |
| METHODS | 2 |
| RESULTS | 9 |
| Body Weight and Hydration Status | 10 |
| Heart Rate | 11 |
| Oxygen Consumption Measurements | 12 |
| Mean Skin Temperature | 12 |
| Rectal Temperature | 12 |
| Mean Body Heat Flux | 13 |
| Finger Temperature | 13 |
| Toe Temperature | 14 |
| Net Thermal Temperature | 14 |
| Performance Assessment Battery (PAB) | 15 |
| DISCUSSION | 17 |
| Overall | 17 |
| Hydration Status | 17 |
| Exercise Performance | 18 |
| Thermal Status | 19 |
| Cognitive Performance | 20 |
| REFERENCES | 22 |

APPENDICES

| | |
|---|----|
| Appendix A Lay Language Operational Summary | 24 |
|---|----|

TABLES

| | |
|---|----|
| Table 1 Physical Characteristics of Subjects | 28 |
| Table 2 Exposure times | 29 |
| Table 3 Weight, Body Water, Blood Values | 30 |
| Table 4 Summary of NMRI-PAB Results, Performance Impaired | 31 |
| FIGURE LEGENDS | 32 |

INTRODUCTION

Certain types of diving missions may require a diver to be on land for several hours before returning to the water. During the intervening dry land phase the diver often continues to wear his passive thermal protection while performing various tasks essential to the mission. Little information is available regarding physiological and psychological performance during this type of wet-dry-wet cold exposure.

Vaughan and Andersen (8) conducted a study where U.S. Navy divers were exposed sequentially to 3 h in 6 °C (43 °F) water, 1 h in 10 °C (50 °F) air, and 2 h in 6 °C water. Divers wore wet suits and performed a variety of tasks. Overall, the study showed declines in vigilance, accuracy in solving navigational tasks, and handgrip strength. All of these declines were associated with decreases in skin and core temperature.

In February 1987 a training exercise was conducted that involved a sequential wet-dry-wet exposure where the divers wore a dry suit for passive thermal protection throughout the exercise. The insertion phase was planned to be about a 2-hour transit in 7 °C (44 °F) water. The on-land phase was scheduled to last a maximum of 3 h in 4-9 °C (40-48 °F) air. Two divers waited on shore while two other divers walked about 400 yds (365 m). The extraction phase was planned around a 2-hour transit. The vigilance of the divers appeared to be reduced during the on-land phase and they were shivering noticeably. Procedural errors were noted when the divers prepared to reenter the water. It was uncertain if these observations were due to hypothermia or fatigue.

The present study was designed around the observations of the aforementioned training exercise. The experiments were conducted in an environmental chamber where the air and water temperatures were maintained at

5 °C (41 °F). The initial wet phase was to last 2.5 h, followed by a 2-hour dry phase and another 2.5-hour wet phase. The objectives were to determine 1) if a standard level of passive thermal protection was adequate for both rest and exercise during the cold exposure, 2) if notable changes in physical performance occurred under these conditions, and 3) if significant alterations in cognitive performance could be detected during the dry cold phase.

METHODS

Seven physically fit U.S. Navy First Class Divers participated in the study after giving their informed consent. The physical characteristics of the divers are presented in Table 1.

An immersion tank with an underwater cycle ergometer was located inside an environmental chamber, where both water and air were maintained at 5 °C. Relative humidity in the chamber was $50 \pm 10\%$. A treadmill and a video monitor for psychological testing were also located in the chamber.

Each exposure was divided into 3 phases. Phase I involved a 2.5-hour immersion in 5 °C water, with the subject at rest for the first 2 h. During the last 30 min of Phase I, the subject pedalled the cycle ergometer at 60 rpm and at a workload of 50 watts. This phase simulated an in-water transit where the diver was at rest except for the last 30 min, where exercise would be required to get ashore. Phase II was scheduled to last 2 h in the dry at an air temperature of 5 °C, and was meant to simulate conditions encountered on land. Phase III was another 2.5-hour immersion that simulated extraction, where the subject performed leg exercise for the first 30 min to simulate return to the water followed by 2 h of rest during transit. The time taken for the transition from wet to dry and dry to wet (about 10 min each) was not included in the planned 7-hour exposure.

Each subject performed 2 test exposures (Series A and B). Phases I and III were the same for both series. Phase II of Series A required the diver to walk on the treadmill for 45 min at a speed of 2 mph (3.2 km/h) and 0% grade, followed by a 30-minute cognitive Naval Medical Research Institute - Performance Assessment Battery (NMRI-PAB) test and another 45-minute bout of treadmill walking. Thus, Series A simulated the requirements of a diver who was active on land. The timing of the PAB test coincided with the mid-point of on-land activity. In Series B, the diver remained seated at rest throughout Phase II to simulate the on-land requirements of the inactive diver. The PAB test was given after the first 45 min of rest in Series B to coincide with administration of the test in Series A. The order of test exposures (Series A vs B) was balanced among the subjects, with 4 divers performing Series A first.

Prior to a test day each diver was instructed to follow a planned diet that provided 3400 kcal (52% from carbohydrate). A light breakfast of 580 kcal (76% carbohydrate) was eaten at about 0600 on the test day. No alcohol, caffeine or nicotine were consumed 24 h before the start of a test. Approximately 90 min before the start of each exposure, the subject was weighed and then drank water equal in volume to 0.5% of their body weight (about 400 ml) to insure all divers began the test in a normal hydration status. The divers also drank 250 ml of water at the beginning and end of Phase II.

Venous blood samples were obtained from a forearm vein 80-90 min before each test and approximately 20 min after the end of the exposure in order to measure hemoglobin (Hb) and hematocrit (Hct). Hemoglobin and Hct were also measured at the beginning and end of Phase II using blood obtained from a finger stick. Blood volume and plasma volume changes were estimated from

algorithms using height, weight, Hb, and Hct (1,4). Post-exposure body weight was obtained 10-20 min after leaving the environmental chamber. Total body water was estimated from bioelectric impedance measurements made before and after the exposures.

Prior to donning the diving dress the diver was instrumented with EKG electrodes, heat flux sensors, and a rectal temperature probe. Skin temperatures at 12 sites (2,6) were measured using combination temperature and heat flux sensors (Concept Engineering, Old Saybrook, CT). A three lead ECG was obtained from standard chest electrode placement. All signal wires were attached to a custom molded block assembly and exited the suit through a waterproof penetration. Finger and toe temperatures were measured with YSI 400 series surface temperature sensors. The finger and toe sensor wires exited the suit through a second waterproof penetrator. An exposure was aborted if a finger or toe temperature reached 8 °C for 30 min or 6 °C at any time.

Twelve regional skin temperatures and heat fluxes, plus rectal temperature were recorded every minute by computer. This data was continuously displayed during the experiment and stored for later analysis (11). Environmental chamber air, immersion water bath, finger, and toe temperatures were recorded every 10 min. Mean skin temperatures and heat flows were calculated by body surface area weighting (6).

Rectal temperature was obtained using YSI disposable 400-Series presterilized sensors inserted 15 cm beyond the anal sphincter and was monitored continuously throughout the experiment. Experimental abort criteria for rectal temperature were either a drop of 2 °C below the pre-immersion value or reaching 35 °C at any time.

The divers wore an external urinary catheter (Hollister Inc, Libertyville, IL), which attached to a dry suit penetrator, to obtain measurements of urine volume throughout the exposures. A one-way check valve (Naigene) prevented urine reflux from the collection bag. Polypropylene undergarments were worn beneath a M-400 Thinsulate garment and boots. The outer garment was a tri-laminated dry suit (TIS by Diving Unlimited International) with latex wrist and neck seals. Protection of the hands during immersion consisted of wool gloves worn beneath M-200 Thinsulate gloves. Over the Thinsulate glove was a 5-fingered electrician's rubber glove, which mated to the suit via "O" ring sealed mating rings on both the glove and suit to keep the hands dry. A 6 mm neoprene gauntlet mitt was worn over the entire assembly. During the dry exposure (Phase II) the diver wore only the wool gloves and the Thinsulate gloves to permit administration of the NMRI-PAB. An M-400 Thinsulate cap was worn under a 6 mm neoprene hood throughout all phases of the test.

During immersion the diver wore an AGA full face mask and breathed air at ambient pressure through large diameter respiratory hoses attached to the inlet and outlet blocks on the mask. The diver's position in the water resulted in a negative hydrostatic load of only 6-10 cm, a level of breathing resistance that could be easily tolerated even during the work cycles. During Phase II in the dry, the diver wore a lightweight oronasal mask for measurement of oxygen consumption. Minute ventilation was measured by a turbine flow sensor located on the exhalation side of the breathing masks. Oxygen consumption was calculated by an automated system (Metabolic Measurement Cart 4400, Sensor Medics, Anaheim, CA). Respiratory measurements were made every 5 min during all phases of each exposure.

Cognitive performance was measured at the midpoint of each dry phase by the NMRI-PAB, which is a standardized, microcomputer-driven test for the

measurement of human performance in military environments. The NMRI-PAB is made up of 8 separate performance tests that each measure components of cognitive functioning such as response accuracy, logical reasoning, speed and correctness of response acquisition, short and long term memory, attention, spatial orientation, pattern matching, and color and form discrimination. For the present study, 7 of the 8 available tests were utilized. The 7 component tests of the NMRI-PAB were Matching to Sample, Grammatical Reasoning, Manikin, Numerical Memory, Pattern Comparison, Repeated Acquisition, and Visual Scanning (i.e., Letter Search).

The battery of 7 performance tests took approximately 30 min to administer. Two weeks prior to the initial cold exposure all subjects received individual instruction on how to perform the various tests. Five control baseline trials of the NMRI-PAB (no more than two sessions were run in one day) were completed before the first cold exposure. The first three baseline sessions were performed in an experimental test room under low ambient illumination and at a normal ambient temperature (22-25 °C). The last two baseline sessions were administered under similar darkened conditions in the environmental chamber compartment at the same ambient temperature so that subjects would perform under similar environmental conditions minus the experimental variable of cold. In addition, because subjects during the cold exposure phase would be wearing insulated gloves, all subjects performed the last two baseline sessions wearing these gloves to insure that any performance change would be the result of the cold experimental conditions and not confounded by the protective gloves.

The basic NMRI-PAB test procedure required that subjects be seated in a chair in order to view stimuli on a video monitor. Control of the menu-driven NMRI-PAB test program was accomplished by a technician outside the test

environment. Throughout the experiment the sequence of cognitive tests remained the same. Each test was preceded by a 20-second inter-test interval that consisted of a darkened screen followed by a 6-second "traffic light." During the "traffic light," the screen was red for 2 sec, yellow for 2 sec, and then green for 2 sec. This interval allowed the subject to prepare for the next test. A brief description of each test component in the order in which they occurred is described below:

1) Numerical Memory Test. Measures short-term numerical memory recognition and encoding. The subject was required to remember, and correctly identify with a yes or no response, whether a single digit from 0 to 9 was embedded within an array of 1-4 numbers presented on the screen one second prior to the test stimulus onset. A maximum number of 24 trials could be completed within the 3-minute timeframe of the test.

2) Pattern Comparison Test. Measures visual nonverbal pattern matching and the ability to make pattern similarity judgement. Subjects were presented with two dot patterns that appeared on the right and left hand portion of the screen. The subject's task was to determine, as fast as possible, whether the two dot patterns on the screen were either the same or different by depressing the appropriate button on the response panel. A maximum of 60 trials could be completed within the 3-minute timeframe of the test.

3) Grammatical Reasoning Test. Measures logical, general reasoning abilities, and recognition of relationships. A pair of letters, either "AB" or "BA" appeared on the CRT screen next to a statement that either incorrectly or correctly described the order of the letters of the presented letters (e.g., "A is not followed by B"). The subject had to decide as quickly as possible whether the statement about the letter pair

was true or false and depress the corresponding button on the response panel accordingly. A maximum of 32 different non-repeating permutations could be completed within the 3-minute test.

4) Matching-to-Sample Test. Measures short-term spatial memory and pattern recognition abilities. A single 4x4 square matrix with 16 cells was displayed in either red or green as the unique sample stimulus pattern on each trial. The subject depressed a response button, which removed the stimulus and blanked the screen for 1 sec. Following the 1-second delay, two separate matrices were presented side by side, on the screen. One of the patterns (randomly placed on either the left or right for each trial) was identical to the sample matrix and the other differed from the sample matrix by one cell. The subject was required to press either a left or right response button to indicate which of the two stimuli on the screen matched the sample stimulus matrix seen before. The test consisted of the number of trials accomplished in a 3-minute time period.

5) Letter Search Test. Measures sustained attention, target recognition, and visual pattern discrimination. A single row of 20 letters was presented near the top of the screen. A pair of target letters was presented beneath the row of letters. The subject's task was to determine whether both of the target letters appear in the 20-letter row and respond either true or false on the appropriate response button. A maximum of 24 trials could be completed within a 3-minute period.

6) Manikin Test. Measures the ability to perform image rotation and related transformation, as well as recognition of spatial orientation. The subject's task was to respond correctly to a human figure presented in a number of spatial orientations. The manikin is a

human figure placed inside either a green circle or red square outline that appears on the CRT screen. The green circle or the red square is the sample stimulus. The figure holds a green circle in one hand and a red circle in the other hand, which are the comparison stimuli. The task was to determine whether the left or right hand holds the stimulus that matches the sample stimulus surrounding the figure by depressing the correct response button. The figure is presented either upright or upside down and facing either toward or away from the subject. A maximum of 32 trials could be completed in a 3-minute period.

7) Repeated Acquisition Test. The subject was presented with a 4 x 3 matrix, each cell of which would light up when one of three buttons (left, right, and center) was pressed on a response panel. The object was to learn the correct 12-button sequence to light up all 12 squares beginning at the upper left-hand corner, moving left-to-right, and then down. The subject first had to obtain the correct sequence by trial and error. Beginning with the first square, the subject determined which of the three response buttons would light that square. The trial then advanced to the next square. After the correct button to light each square had been determined, a new trial began. Ideally, the subject would have remembered the correct 12-button sequence to light each square in turn without making a mistake. Up to 25 trials were conducted to measure just how rapidly and accurately the 12-button sequence could be learned. At the end of each trial, the screen blunted and a new test with a new 12-button sequence was begun.

RESULTS

Although the exposures were scheduled to last 7 h, 6 of 14 tests were terminated prematurely. Three of the aborts were terminated during Phase III

due to leaks in the dry suit. One run was aborted at 1:00 in Phase II due to low temperature and pain in the fingers. One run was ended early in Phase I because of a flooded suit. This latter run was not included in any subsequent data analysis. Two runs were shortened in Phase I because of suit leaks; but the problems were corrected and the exposures continued. Table 2 presents a summary of the exposure times for each phase.

Body Weight and Hydration Status

Table 3 presents body weight, total body water, and blood values for both series. Body weight was significantly lower after all exposures, with an overall decrease of 2.09 ± 0.43 kg ($p < 0.001$). Similarly, there was a significant reduction in the estimate of total body water of 3.3 ± 0.5 l ($p < 0.001$) for Series A and B. The decrease in total body water correlated with the reduction in body weight ($F = 5.93$, $p < 0.02$). However, the magnitude of the decline in total body water was greater for Series A (4.2 ± 0.5 l) than for Series B (2.38 ± 0.7 l, $t = 5.22$, $p < 0.05$ by paired t-test). The decreases in body water averaged 9% and 6% for Series A and B, respectively.

Pre-exposure Hb values were greater than post-exposure Hb values, but the changes were not significant. Post-exposure Hct was increased in both series by about 13%. Calculations of plasma volume exhibited corresponding decreases of 13 and 12% respectively for Series A and B.

Leaks in the urinary catheter system were encountered in 8 trials. Complete volume collections were obtained in the other 6 trials. In these latter trials the net water intake averaged 927 ± 14 ml, and the urine volume averaged $1,877 \pm 194$ ml (mean \pm SE). Thus, the net fluid loss in these 6 cases (neglecting sweating and respiratory losses) was 950 ± 186 ml.

Heart Rate

Figure 1 presents the mean heart rate (HR) data for the 3 phases of Series A. The resting HR values during Phases I and III averaged 76 ± 3 and 79 ± 1 beats/min respectively, and were not significantly different from one another if one neglects the values for the first 20-min post-exercise in Phase III.

The last 6 data points of Phase I and the first 6 of Phase III reflect the 30 min of in-water leg exercise at 50 W. Analysis of variance revealed that the exercise HR was significantly higher during Phase III than Phase I ($F = 8.03$, $p < 0.02$), with peak values 8 ± 5 beats/min higher than in Phase I.

The middle portion of the Phase II HR graph reflects the decrease in HR when the subjects stopped walking on the treadmill and sat down to take the PAB test. Steady-state HR values while walking on the treadmill did not differ significantly before and after the PAB test, and averaged 97 ± 1 beats/min. Resting HR during the PAB test was 73 ± 2 beats/min.

Figure 2 presents the HR data for the 3 phases of Series B. There were no significant differences in HR for Phases I and II between Series A and B. Likewise there were no significant differences in resting HR between the series during the dry NMRI-PAB test.

In Series B the Phase III exercise HR was higher than in Phase I ($F = 9.13$, $p < 0.01$), with peak values averaging 17 ± 4 beats/min higher in Phase III. There was no statistically significant difference in Phase III exercise HR between Series A and B.

The resting HR values were similar between Phase I (74 ± 1) and Phase III (85 ± 2) for Series B. Overall resting HR during Phase II of Series B was 76 ± 1 beats/min. The HR values during the PAB test averaged 74 ± 2 beats/min.

Oxygen Consumption Measurements

The resting \dot{V}_{O_2} during Phase I increased steadily as a result of the cold exposure. Among all subjects, the slope of the linear increase in resting \dot{V}_{O_2} was 4 ml/min per min of immersion. Technical problems precluded obtaining useful \dot{V}_{O_2} data in most of the subjects during the other phases. However, Figure 3 presents the complete \dot{V}_{O_2} data set on 3 divers for Series A and B. The exercise \dot{V}_{O_2} at the end of Phase I tended to be higher than for the corresponding immersed exercise at the beginning of Phase III. The initial \dot{V}_{O_2} while walking on the treadmill was higher than the final 45 min of treadmill exercise. Resting \dot{V}_{O_2} during the PAB test was the same in both series and was similar to resting \dot{V}_{O_2} data obtained at the start of the exposure.

Mean Skin Temperature

The mean skin temperature of all divers is shown in Figure 4. Mean skin temperatures dropped linearly during the resting portion of Phase I. Initial mean skin temperature upon immersion was 31.1 °C and fell to 27.8 °C during the second hour of immersion. By the end of 30 min of leg exercise in Phase I mean skin temperature was raised to 30.7 °C. Phase II exposure caused skin temperatures to drop significantly to 29.5 °C ($p < 0.05$) in the resting group (Series B). When treadmill exercise was performed (Series A) the mean skin temperature increased slightly to 31.1 °C. This increase was maintained throughout Phase II. During the Phase III underwater cycle exercise the mean skin temperature of both groups approached 31.2 °C. During the subsequent 2-hour immersed rest of Phase III, skin temperature declined linearly in both groups to 27.2 °C at a rate of 1.7 °C/hr.

Rectal Temperature

Rectal temperatures, shown in Figure 5, averaged 37.3 °C upon initial

immersion, and fell linearly at approximately 0.4°C/h to 36.6°C by the end of the second hour. Thirty minutes of leg exercise at 50 W external work elevated rectal temperature to 37°C . During the dry exposure, rectal temperature was maintained during treadmill exercise between 37.1 and 37.2°C , but was significantly lower in the resting condition, falling to 36.6°C . Phase III exercise produced a slow rise in rectal temperature occurring over the first hour during Series b. No further change occurred in the treadmill condition (Series A). Both conditions exhibited a linear decrease in rectal temperature during the last hour of resting immersion, approaching 36.2°C at the end of immersion. Thus, there was a net decrease in rectal temperature of 1.1°C over the 7-hour cold exposure in either condition.

Mean Body Heat Flux

Initial body surface area weighted heat flux was 149 W/m^2 upon immersion, as shown in Figure 6. This value decreased linearly during the first hour of resting immersion to 126 W/m^2 . Thirty minutes of underwater cycle exercise increased heat flux to 133 W/m^2 . Heat flux was significantly elevated during treadmill walking (152 W/m^2) compared to resting condition (96 W/m^2). Heat flux further increased during the 30 min of underwater exercise, elevating the Phase II treadmill group to 174 W/m^2 and the Phase II resting group to 135 W/m^2 . Heat flux decreased substantially during the last hour of resting immersion in Series A. Both conditions resulted in a final net heat flux approaching an average value of 136 W/m^2 .

Finger Temperature

Initial immersion finger temperatures (Figure 7) were 18°C , which decreased linearly during the first hour to 12°C , and approached 11°C by the end of the 2-hour resting immersion. Leg exercise increased finger temperature to 18.6°C in both series. Exposure to the dry cold reduced

finger temperature to 15 °C by the time of the PAB test in the treadmill condition, and to 14 °C by the end of the second hour. Resting (Series B) finger temperatures were 13 °C and 12 °C for the PAB test and end of the dry phase, respectively. Immersed exercise during Phase III elevated finger temperature in both conditions to 18 °C, which then fell linearly during immersed rest to 13.5 °C.

Toe Temperature

Toe temperatures upon immersion averaged 19 °C (Figure 8), and linearly decreased to 13 °C at the end of the 2-hour resting immersion. Immersed exercise significantly increased toe temperatures to 29 °C. Toe temperatures remained elevated during treadmill exercise, averaging 30 °C the first hour and 29 °C during the second hour. Rest in the dry allowed toe temperatures to drop rapidly during the first hour to 13 °C, and slightly increase during the second hour of cold exposure. Immersion exercise during Phase III elicited toe temperatures similar to those exhibited during Phase I in the treadmill exercise series (25 °C), while the Phase II rest group elevated toe temperatures only slightly to 16 °C. Both groups showed linear decreases in toe temperature during the final resting Phase III immersion to final toe temperatures of 16 °C and 10 °C, respectively.

Net Thermal Balance

During the initial resting immersion in the 5 °C water the diver's mean skin temperature declined at a rate of 1.7 °C/h and rectal temperature decreased at a rate of 0.4 °C/h. As skin temperatures fell, the heat flow also decreased (at a rate of 12 W/m² per hour). Divers who had a suit flood-out were not included in this data set, as they showed heat losses of 400-500 W/m² initially upon suit flood-out and rapidly requested termination of the exposure. During the 30 min of bicycle ergometer exercise the whole body heat flux increased by 25 W/m². This is certainly less than the

metabolic cost of this exercise, and the resultant heat storage produced increases in mean skin temperature of 2.9 °C and increases in rectal temperature of 0.4 °C. Finger and toe temperatures (Figures 7 and 8) were also significantly increased by exercise at the end of Phase I.

Treadmill walking (Series A) increased both rectal temperature and mean skin temperatures above Phase I levels, with heat loss remaining at the levels seen at the end of Phase I. These levels were significantly higher ($p < 0.05$ paired t-test) than Phase II series B resting levels for mean skin and rectal temperatures, and heat flux. Heat flux was significantly lower at rest (136 W/m^2) than during treadmill exercise, but was in excess of heat production, producing decreases in skin and core temperatures.

During Phase III exercise the mean skin temperatures of both groups approached a value of 31.2 °C and heat flux increased similarly to 174 W/m^2 . During the final resting portion of Phase III the skin temperature declined approximately 1 °C/h, core temperature decreased 0.25 °C/h, while heat loss remained elevated at 141 W/m^2 .

Performance Assessment Battery (PAB)

Six of the 7 subjects completed the five baseline trials and the two cold condition exposures with the NMRI-PAB. Performance accuracy and response reaction time on the various tasks were stable within the first three trials. Comparison of test performance in the cold environment under Series B (dry REST condition), or on Series A (dry TREADMILL condition), was evaluated relative to the performance on the fifth trial of the baseline series, which typically preceded the first cold exposure by 1-3 days.

NUMERICAL MEMORY TEST: As shown in Figure 9 performance on this test, which measured short-term numerical memory recognition memory and encoding,

indicated no significant changes in reaction time with exposure to the cold for both experimental conditions. A slight, but insignificant ($t = 0.88$, $p > .1$ using a paired t -test), decrease in accuracy was noted in the REST condition.

PATTERN COMPARISON TEST: Figure 10 indicates reaction time to visual nonverbal pattern matching and the ability to make pattern similarity judgments was generally longer than control baseline reaction times for both the REST ($t = 2.05$, $p < .05$) and TREADMILL ($t = -1.77$, $p = .068$) conditions. Accuracy decreased nonsignificantly in the REST condition.

GRAMMATICAL REASONING TEST: Changes in accuracy, shown in Figure 11, were not significant. There was about a 7% decrease in reaction time for the REST condition ($p < 0.05$ from TREADMILL).

MATCHING-TO-SAMPLE TEST: Figure 12 shows matching-to-sample data. No systematic or significant changes in accuracy, reaction time of the sample stimulus, or the response time of the test stimulus occurred during the cold exposures.

LETTER SEARCH TEST: Figure 13 indicates that accuracy was not significantly altered in the TREADMILL condition, but was substantially reduced in the REST condition ($t = 3.01$, $p < .01$). Interestingly, both cold exposures demonstrated increased response times, although only the TREADMILL condition reached statistical significance ($t = 2.87$, $p < .02$). These data show that accuracy and response time did not co-vary with respect to sustained attention, target recognition, and visual pattern discrimination.

MANIKIN TEST: No systematic or significant changes in accuracy or response time was observed in this test, which is graphed in Figure 14.

REPEATED ACQUISITION TEST: The subjects ability to learn a specific sequence of responses was not significantly affected by either exposure to the

cold.' On the other hand, the accuracy of short-term memory for the learned response was significantly impaired ($t = 2.78$, $p < .02$) when subjects were required to exercise on the treadmill prior to performing the NMRI-PAB, (as shown in Figure 15).

DISCUSSION

Overall

The present study simulated a diving mission where the diver would first spend 2.5 h in cold water, followed by 2 h in cold air before reentering the cold water for 30 min. The level of passive thermal protection worn by the divers prevented core temperature from approaching mild hypothermic levels until about the last .5 h of the 7-hour exposure. This level of passive insulation appeared adequate for light exercise on dry land, without resulting in hyperthermia. However, it was inadequate protection when the diver was at rest in the cold air.

Hydration Status

Across the 7-hour cold exposures the divers lost more than 2 kg of body weight that correlated with net loss of body fluid. Although the subjects consumed about 900 ml of water, there were declines in plasma volume of 12-13%, which represent a modest level of dehydration. These declines in plasma volume were somewhat less than the 17% reduction noted in our previous study of 6-hour whole body immersion in 5 °C water where no fluid was ingested (3). Interestingly, the estimated loss of total body water was greater when the subjects walked on the treadmill during the dry cold phase as opposed to sitting quietly at rest. Heat flux was higher when walking on the treadmill, and thus the possibility exists that this level of exercise increased evaporative water loss, especially since urine volumes were equivalent between Series A and B.

Exercise Performance

Exercise HR data indicated that the work effort was greater upon reentering the water (Phase III). Since there was no difference in HR between Series A (treadmill in the dry phase) and Series B (dry rest), it is unlikely that the higher HR in Phase III exercise could be ascribed to fatigue resulting from the treadmill exercise. The higher exercise HR in Phase III most likely resulted from dehydration as measured by decreases in plasma volume, a finding noted in our other cold water dives (3). Declines in plasma volume would reduce circulating blood volume and thereby cause a relative decrease in cardiac stroke volume. Thus, to maintain the required cardiac output during exercise, HR would be higher to compensate for the reduced stroke volume.

Although the \dot{V}_{O_2} data are limited in the present study, they do provide some insight into the aerobic requirements during cold exposure. The rate of rise in resting \dot{V}_{O_2} during Phase I (about 240 ml/h) is much greater than the thermogenic rise noted in our previous 6-hour dives at the same water temperature (about 40 ml/min per hour). However, the present study used M-400 Thinsulate as the thermal protective undergarment, while in our previous study an M-600 garment was used. There is no doubt that the M-600 garment provides more thermal protection while immersed. Additional studies will be required to refine the matching of thermal protection during wet-dry-wet exposures.

During the dry phase it would be expected that the dry suit functioned more efficiently to minimize heat loss, and thus resting \dot{V}_{O_2} in this phase was quite similar to values obtained upon initial cold exposure. Moreover, the preservation or restoration of body heat would lessen the thermogenic drive noted upon reentering the water.

Thermal Status

Cold water immersion while wearing the thermal protective garment produced an initial cooling rate similar to that reported by Thalmann (7). The rate of heat loss exceeded the rate of metabolic heat production; thereby resulting in a negative net thermal balance that subsequently reduced skin temperature, lowered core temperature, and significantly cooled the fingers and toes. Finger and toe temperatures in the range of 10-12 °C can result in pain and numbness (5,9).

A significant thermal benefit was obtained from the additional metabolic heat produced by exercise. Mean skin temperatures are elevated, while body heat loss shows only a slight increase. In addition, rectal, finger and toe temperatures rose concomitantly with exercise.

Changing from the cold-wet to cold-dry environment would be expected to significantly reduce heat loss due to the more insulative thermal properties of air compared to water. This is shown during Phase II, where heat loss dropped nearly 40 W/m^2 in the resting group. Since metabolic heat production was still less than the rate of heat loss, skin and rectal temperatures decreased. The treadmill exercise group showed increased mean skin temperatures and body heat flux. Heat production likely exceeded heat loss, as evidenced by an increase in rectal temperature. A balance between heat production and loss was achieved midway through Phase II exercise, as skin and rectal temperatures remained constant at this higher level.

Phase III exercise maintained the balance between heat loss and production after the dry treadmill exercise. The in-water exercise also raised rectal and mean skin temperatures in the group that rested during the dry cold phase. However, finger and toe temperatures remained significantly

lower in this latter group. Both groups showed a net heat loss during rest in Phase III.

It is apparent that exercise produces increased core and skin temperatures in all subjects. The advantages of increased skin temperatures for long duration missions will depend on the required task to be performed on site. Those mission tasks requiring manual dexterity and tactile sensitivity will be enhanced by warmer finger and hand temperatures. Of particular note is the significant effect of low intensity exercise shown in this study. The elevations in toe temperature with leg exercise, but without similar increases in finger temperature, suggest that arm exercise as a means of supplemental heating may be a productive area for research. It is unlikely that the fingers can remain useful with only passive insulation since the required insulation thickness would encumber manual dexterity.

The relative value of low level physical activity to increase body heat stores was evident even in divers whose extremity temperatures have decreased. Using exercise as an endogenous heat generator has some caveats in terms of endurance versus the intensity needed to maintain heat, the type of exercise (e.g., isometric or isotonic, arm or leg), and whether operational or equipment constraints prevent the exercise from being done.

Cognitive Performance

Table 4 provides a general summary of the cognitive performance. Overall, the data indicated that response accuracy to the visual stimuli for 2 of the 7 cognitive performance tasks was not dramatically affected by either rest or exercise in the cold environment. These tasks involved spatial orientation and short-term memory of spatial relationships. However, data from the other tests indicated that changes in cognitive performance in the cold depended, in part, on diver activity level prior to the test.

For the diver at rest in the dry cold, response times were increased for tests of sustained attention, and for recognizing target patterns and relationships. The resting diver also exhibited decreases in the accuracy of responses to sustained attention, recognizing and matching patterns, and in the short-term recall of numbers.

While the cognitive tests were not task-specific to actual diving tasks, the data do provide important information regarding potential changes in mental performance. It is evident that the cognitive changes in the resting diver were related, in some manner, to the greater loss of body heat. In general, the data suggest that as the resting diver continues to lose heat, he will likely become less vigilant, respond slower to visual stimuli, and possibly make more errors in mental judgement.

Divers who were walking prior to the PAB test also had longer response times to tests for sustained attention and target recognition. In contrast to the resting condition, subjects who walked on the treadmill did not have declines in the accuracy of responses noted above. Since the exercising divers had higher core temperatures, it is unlikely these responses were influenced by a low core temperature.

However, after walking on the treadmill for 45 min there was a significant decrease in the ability to retain newly learned information. Cardiorespiratory measures indicated that this impairment was not due to peripheral muscle fatigue, but it may represent some subtle form of mental fatigue associated with light exercise per se.

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APPENDIX A

LAY LANGUAGE OPERATIONAL SUMMARY

Occasions arise when a diving mission requires a diver to wear a fixed level of passive thermal protection during sequential exposures to wet-dry-wet environments for extended periods. The present study examined thermal balance, physical performance, and cognitive performance during a 7-hour cold exposure. The exposure consisted of 2.5 h immersed in 3 °C (40 °F) water, followed by 2 h in 5 °C air, and then another 2.5 h immersion. The last 30 min of the first wet exposure and the first 30 min of the second wet exposure involved performing light leg exercise that would simulate a work effort required to exit and reenter the water. The 2-hour dry cold exposure involved either walking on a treadmill at a slow pace (to simulate an active diver on land) or sitting quietly at rest (to simulate an inactive diver). A dry suit passive thermal protection garment was worn throughout the 7-hour exposure.

Seven U.S. Navy divers volunteered to participate in the study. Each diver performed two test exposures: one where he walked during the dry cold phase, and one where he remained at rest during the dry phase. A dry suit with M-400 Thinsulate undergarments, dry suit hood, and wool and Thinsulate gloves worn under neoprene mitts was used during the wet phases. The neoprene mitts were removed for the dry phase. Body heat flux and temperatures of the core, fingers, and toes were measured to quantify thermal balance. A cognitive performance test was given at the midpoint of each dry cold phase.

Over the 7-hour exposure period there was a net loss of body weight averaging 2.1 kg (4.4 lbs) that correlated with a significant loss of body fluid. The plasma volume portion of the blood decreased 12-13%, supporting the notion of a moderate level of dehydration even though the divers consumed

about 900 ml of water during the test. Heart rate response to exercise upon reimmersion was significantly higher than the first immersed exercise bout and could be attributed partially to dehydration.

Thermal protection of the hands and feet, using standard issue equipment, was inadequate during periods of rest either in water or in the dry. Core temperature was protected somewhat better since rectal temperature did not approach hypothermic levels (core temperature $<36^{\circ}\text{C}$) until about the last half-hour of the exposures. The periods of light leg exercise, both in water and in air, proved to be quite beneficial in keeping core and extremity temperatures elevated.

When walking during the dry cold phase the core, skin, and toe temperatures remained elevated at normal levels. Finger temperatures were about 18°C during this time, but were significantly higher than when the diver rested throughout the dry phase. Thus, the diver walking at a slow pace would likely arrive in a favorable thermal balance to perform many tasks. The person who remained at rest during the dry cold phase would, on the other hand, continue to lose heat and experience lower finger and toe temperatures.

The amount of passive thermal protection worn in this study would generally be adequate for a diver performing light exercise on land. The risk of hyperthermia (body core temperature $>38^{\circ}\text{C}$) would probably not be encountered if air temperature was approximately 5°C (as it was in this study). However, the same amount of passive thermal protection is inadequate if the diver had to remain largely at rest for the 2-hour dry cold exposure.

The cognitive test was given at the mid-point in the dry cold exposure where the divers might have to be especially vigilant. The results of the test revealed that reaction times were slowed in both groups for tasks that involved sustained attention, pattern recognition, and target recognition.

Divers who were at rest in the dry were also slower to recognize spatial relationships. In addition, they had greater decreases in accuracy of short-term memory of numbers, accuracy of matching visual patterns, and accuracy of recognizing targets. These changes, associated with greater losses of body heat, suggest that the physically inactive diver may be less vigilant and prone to more mental errors.

It is of some practical importance that the ability to learn new information was adversely affected by walking, but not by resting, in the cold environment. This finding is not related to excessive body cooling, since the diver was warmer than if at rest. It may however represent some subtle form of mental fatigue. The importance of this finding suggests that the active diver may have some difficulty acquiring new information relevant to the mission. For example, the diver may count the number of ships in a harbor, but forget the number by the time he returns to base.

In summary, a diver has adequate, but not ideal, passive thermal protection while wearing a dry suit with M-400 Thinsulate insulation for a 7-hour wet-dry-wet exposure in 5 °C water and air if he performs light exercise in the dry. However, this amount of protection is not adequate if the diver had to remain at rest for the 2-hour dry phase. Physical performance is reduced somewhat during the second wet exposure due to the combined effects of dehydration and loss of body heat. For some tasks, cognitive performance was reduced in the cold exposure, in terms of both reaction time and accuracy to processing visual stimuli. The resting diver is more prone to decreases in vigilance and recognition, while the walking diver has a substantial reduction in the ability to learn new information.

The following considerations should be addressed when planning missions around this type of wet-dry-wet cold exposure:

- a. A greater amount of passive thermal protection should be worn by a diver who will be largely at rest during the dry cold phase.
- b. The amount of water consumed during the mission should be increased to more than 1 liter, and consumed during the dry and second wet exposures.
- c. Means of increasing endogenous metabolic heat production should be considered during the wet transit phases, since light exercise is especially beneficial to maintaining a positive thermal balance. Likewise, similar light exercise in the dry is beneficial.
- d. Human factors and mission planning analyses should implement procedures to compensate or lessen the effects of decrements in cognitive performance that might occur during prolonged cold exposure.

TABLE 1: PHYSICAL CHARACTERISTICS OF SUBJECTS

| SUBJECT | AGE (yrs) | HEIGHT (cm) | WEIGHT (kg) | % BODY ¹ FAT | VO ₂ max ² (l/min) | HRmax ² (bpm) |
|---------|--------------|----------------|----------------|----------------------------|---|-----------------------------|
| 1 | 29 | 175 | 82.34 | 18.6 | 3.575 | 175 |
| 2 | 27 | 183 | 77.20 | 13.1 | 4.941 | 210 |
| 3 | 33 | 178 | 73.44 | 11.0 | 4.206 | 194 |
| 4 | 25 | 191 | 86.42 | 7.9 | 4.203 | 184 |
| 5 | 29 | 188 | 84.70 | 12.3 | 4.265 | 190 |
| 6 | 26 | 177 | 90.50 | 20.0 | 3.933 | 201 |
| 7 | 32 | 175 | 88.96 | 16.9 | 3.866 | 202 |
| mean | 29 | 181 | 83.37 | 14.3 | 4.141 | 194 |
| S.D. | ± 3 | ± 7 | ± 6.20 | ± 4.4 | ± 0.429 | ± 12 |

¹ estimated from hydrostatic weighing
² obtained from a treadmill protocol

TABLE 2: EXPOSURE TIMES (minutes)

| SUBJECT | PHASE: | SERIES A | | |
|---------|--------|----------|-----|-----|
| | | I | II | III |
| 1 | | 150 | 120 | 70 |
| 2 | | 90 | 120 | 30 |
| 3 | | 150 | 120 | 150 |
| 4 | | 150 | 120 | 150 |
| 5 | | 150 | 120 | 150 |
| 6 | | 150 | 120 | 150 |
| 7 | | 150 | 120 | 150 |
| | | | | |
| SUBJECT | PHASE: | SERIES B | | |
| | | I | II | III |
| 1 | | 150 | 120 | 150 |
| 2 | | 150 | 100 | --- |
| 3 | | 150 | 120 | --- |
| 4 | | 60 | --- | --- |
| 5 | | 150 | 120 | 150 |
| 6 | | 90 | 120 | 65 |
| 7 | | 150 | 120 | 150 |

TABLE 3: WEIGHT, BODY WATER, BLOOD VALUES

SERIES A

| subj | PRE-EXPOSURE | | | | END PHASE I | | END PHASE II | | POST-EXPOSURE | | | |
|------|--------------|------------|------|-----|-------------|-----|--------------|-----|---------------|------------|------|-----|
| | wt | body water | Hb | Hct | Hb | Hct | Hb | Hct | wt | body water | Hb | Hct |
| 1 | 81.9 | 47.7 | 14.9 | 47 | 16.9 | 45 | 15.0 | 46 | 81.2 | 44.0 | 14.8 | 47 |
| 2 | 79.0 | 47.8 | 15.1 | 43 | 17.7 | 47 | 17.5 | 45 | 78.4 | 45.1 | 15.5 | 45 |
| 3 | 73.2 | 46.5 | 13.6 | 45 | 15.4 | 47 | 13.9 | 45 | 72.2 | 42.8 | 15.0 | 47 |
| 4 | 89.1 | 51.7 | 14.8 | 44 | 15.8 | 44 | 15.3 | 44 | 85.8 | --- | 15.5 | 48 |
| 5 | 87.2 | 57.7 | 17.0 | 43 | 16.8 | 48 | 12.7 | 47 | 83.7 | 52.9 | 14.9 | 49 |
| 6 | 91.2 | 49.8 | 13.6 | 44 | 16.5 | 46 | 16.5 | 46 | 88.5 | 45.4 | 16.4 | 59 |
| 7 | 93.6 | 51.3 | 12.8 | 39 | 16.7 | 45 | 14.7 | 46 | 88.3 | 45.3 | 14.7 | 48 |
| mean | 85.0 | 50.4 | 14.5 | 44 | 16.4 | 46 | 15.1 | 46 | 82.7 | 45.9 | 15.3 | 49 |
| S.D. | 7.3 | 3.8 | 1.4 | 2 | 0.8 | 1 | 1.6 | 1 | 6.0 | 3.6 | 0.6 | 5 |
| S.E. | 2.8 | 1.4 | 0.5 | 1 | 0.3 | 1 | 0.6 | 0 | 2.3 | 1.6 | 0.2 | 2 |

SERIES B

| | | | | | | | | | | | | |
|------|------|------|------|----|------|-----|------|-----|------|------|------|-----|
| 1 | 82.2 | 45.8 | 14.5 | 43 | 16.0 | 46 | 15.6 | 47 | 81.0 | 43.9 | 15.3 | 48 |
| 2 | 80.1 | 47.4 | 14.6 | 37 | 16.5 | 45 | --- | --- | 78.9 | 46.1 | 15.5 | 47 |
| 3 | 73.7 | 46.2 | 14.4 | 43 | 16.1 | 46 | 16.6 | 47 | 73.3 | 44.6 | --- | --- |
| 4 | 88.2 | 52.6 | 13.7 | 40 | --- | --- | --- | --- | --- | --- | --- | --- |
| 5 | 86.2 | 54.4 | 17.0 | 48 | 18.0 | 51 | 14.8 | 50 | 82.8 | 52.1 | 17.3 | 48 |
| 6 | 91.0 | 50.0 | 15.7 | 45 | 17.2 | 47 | 17.2 | 47 | 88.5 | 48.4 | 15.0 | 49 |
| 7 | 93.2 | 52.4 | 15.2 | 41 | 15.2 | 47 | 15.1 | 46 | 90.6 | 46.8 | 16.2 | 49 |
| mean | 84.9 | 49.9 | 15.0 | 42 | 16.5 | 47 | 15.9 | 47 | 82.5 | 47.0 | 15.9 | 48 |
| S.D. | 6.3 | 3.4 | 1.1 | 4 | 1.0 | 2 | 1.0 | 2 | 6.3 | 3.0 | 0.9 | 1 |
| S.E. | 2.6 | 1.3 | 0.4 | 1 | 0.4 | 1 | 0.5 | 1 | 2.6 | 1.2 | 0.4 | 0 |

UNITS OF MEASURE: wt = kg, body water = liters, Hb = gm/dl, Hct = %

TABLE 4: SUMMARY OF NMRI-PAB RESULTS, PERFORMANCE IMPAIRED

| <u>TEST</u> | <u>Resp. Speed</u> | <u>Accuracy</u> | <u>Resp. Speed</u> | <u>Accuracy</u> |
|----------------|--------------------|-----------------|--------------------|-----------------|
| Num. Memory | NO | S1+ | NO | NO |
| Pattern Comp. | YES | S1+ | PARITALLY | NO |
| Gramm. Reason. | + | NO | NO | NO |
| Match Sample | NO | NO | NO | NO |
| Letter Search | PARTIALLY | YES | YES | NO |
| Manikin | NO | NO | NO | NO |
| Repeated Acq. | - | NO | - | YES |

FIGURE LEGENDS

- Figure 1: Mean heart rate values of 7 divers during Series A (walking on treadmill in dry phase). Left curve during first immersion at rest (min 0-120) and exercise (min 120-150). Middle curve during dry cold phase, where decrease in rate at midpoint occurring PAB test. Right curve obtained during second immersion at exercise (min 270-300) and rest (min 330-420).
- Figure 2: Mean heart rate during Series B (resting throughout dry phase). See Figure 1 for details.
- Figure 3: Mean oxygen consumption values for 3 divers who completed Series A and B.
- Figure 4: Mean skin temperatures (\pm SD) for Series A and B. See text for details.
- Figure 5: Mean rectal temperature (\pm SD) for Series A and B. See text for details.
- Figure 6: Mean body heat flux (\pm SD) for Series A and B. See text for details.
- Figure 7: Mean finger temperature (\pm SD) for Series A and B. See text for details.
- Figure 8: Mean toe temperature (\pm SD) for Series A and B. See text for details.
- Figure 9: Mean scores for accuracy and response time for PAB test of numerical memory. See text for details.
- Figure 10: Mean scores for accuracy and response time for pattern comparison. See text for details.
- Figure 11: Mean scores for accuracy and response time for grammatical reasoning test. See text for details.
- Figure 12: Mean scores for accuracy and response time for matching-to-sample test. See text for details.
- Figure 13: Mean scores for accuracy and response time for letter search test. See text for details.
- Figure 14: Mean scores for accuracy and response time for manikin test. See text for details.
- Figure 15: Mean scores for accuracy and response time for repeated acquisition test. See text for details.

SERIES A

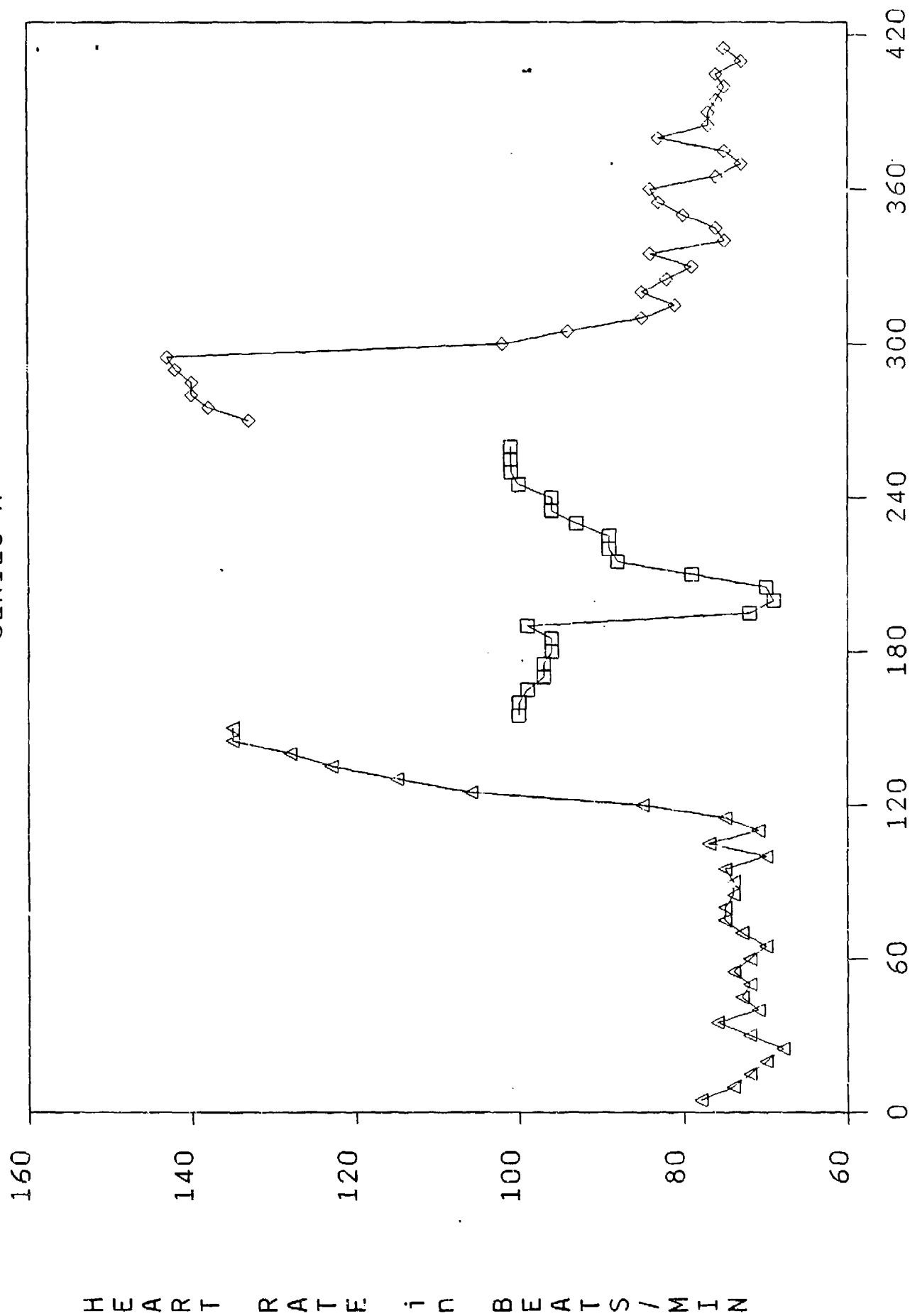


FIGURE 1

SERIES B

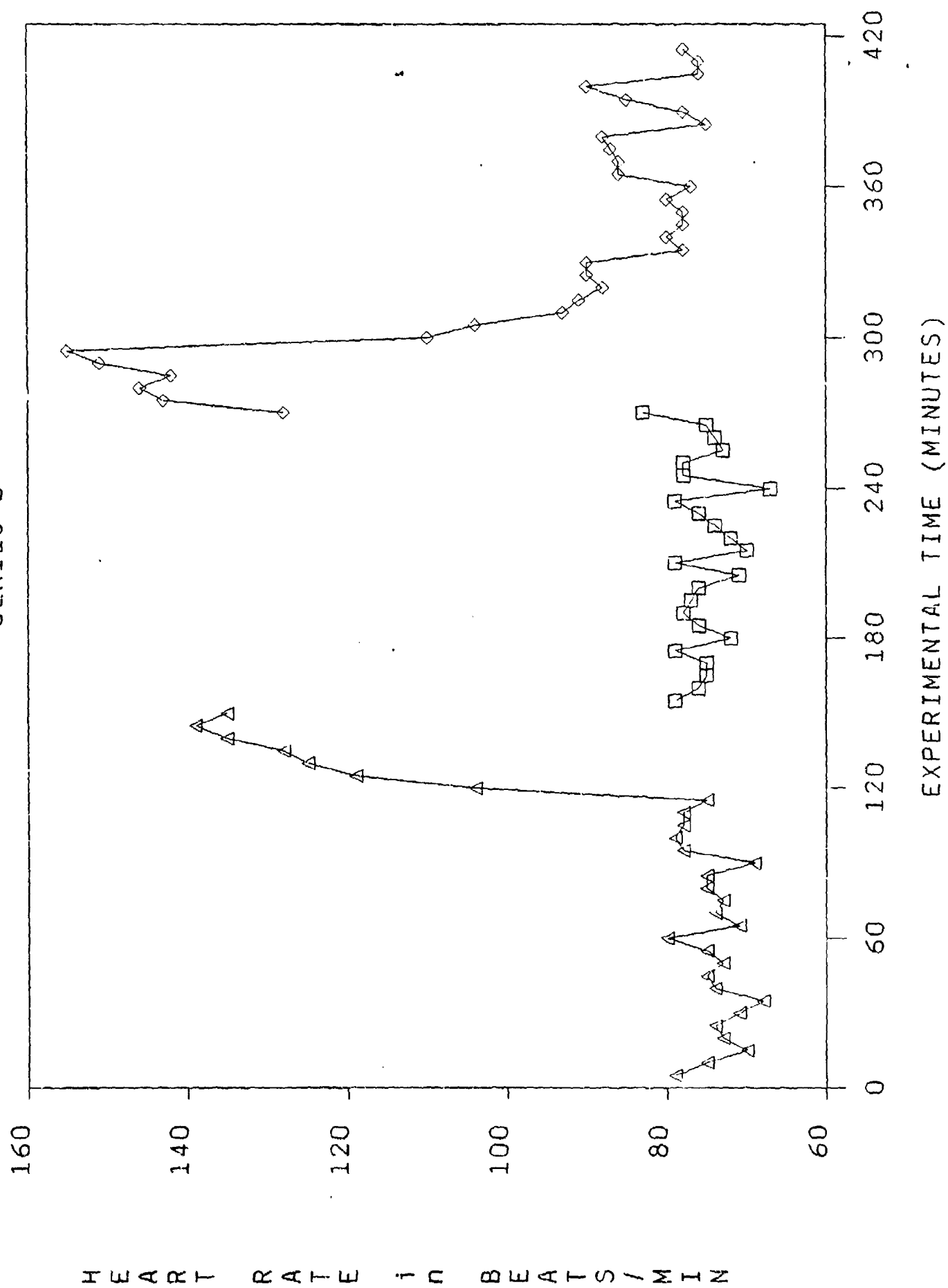
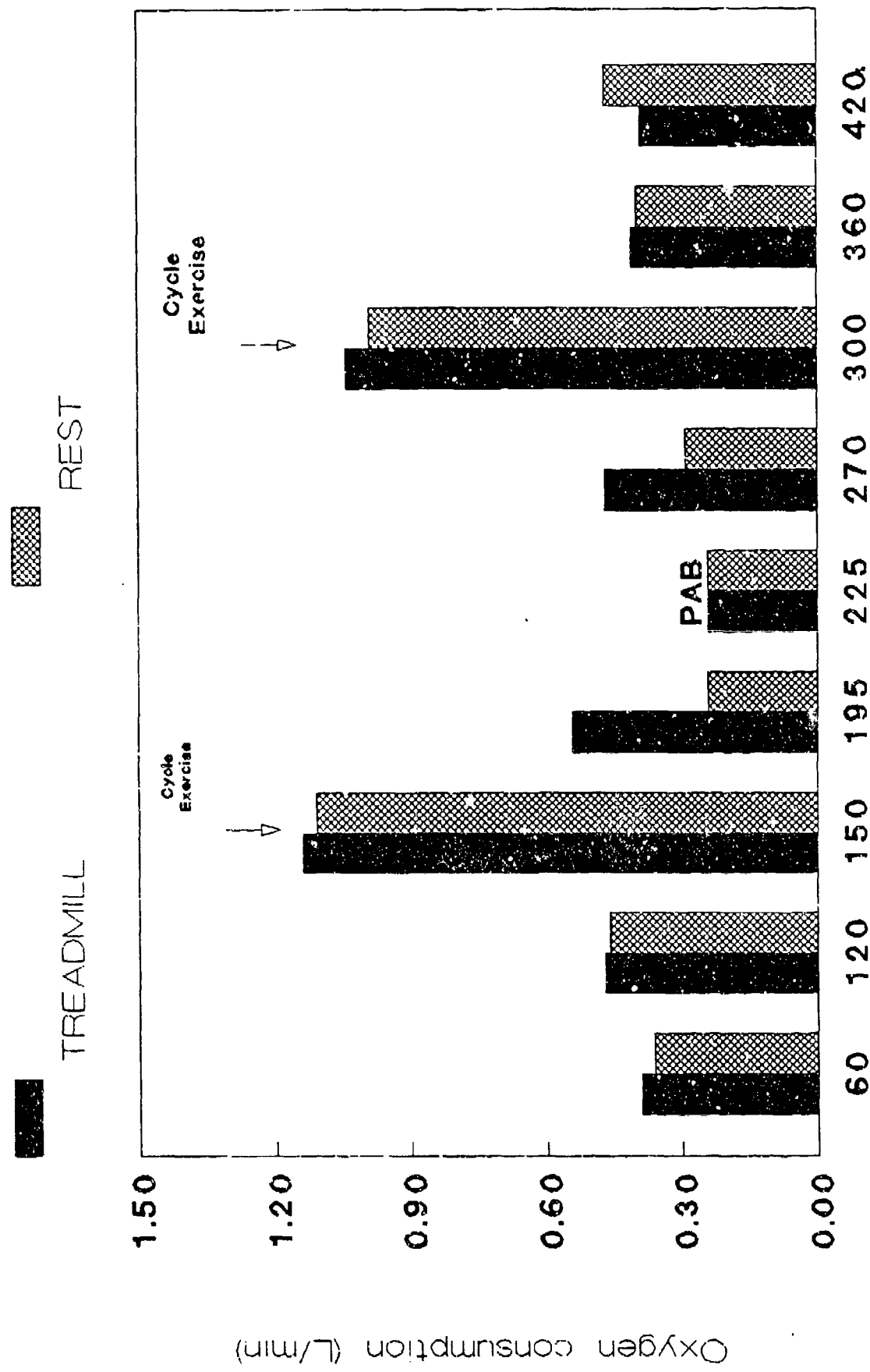


FIGURE 2



Average cumulative time (minutes)

FIGURE 3

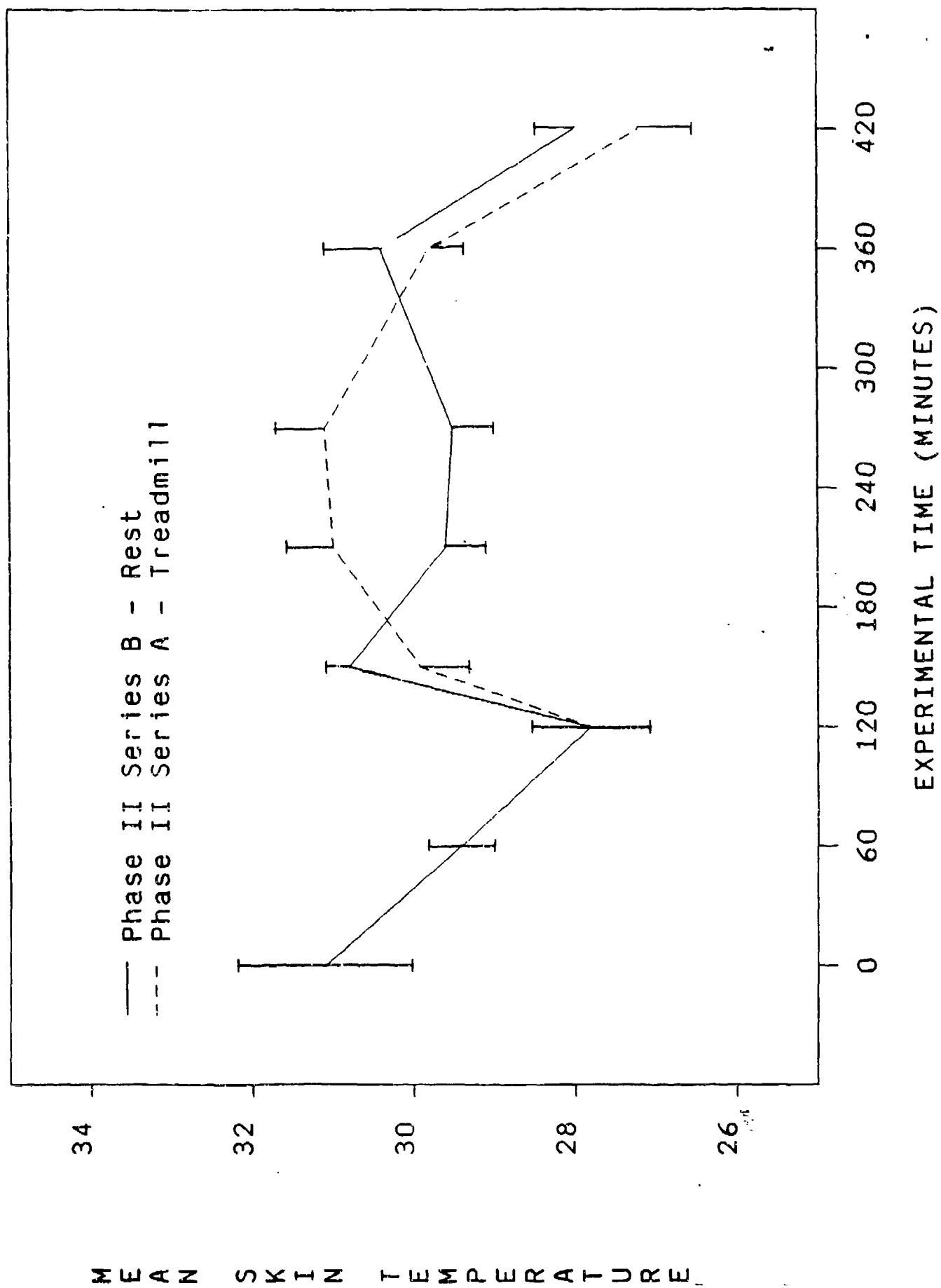


FIGURE 4

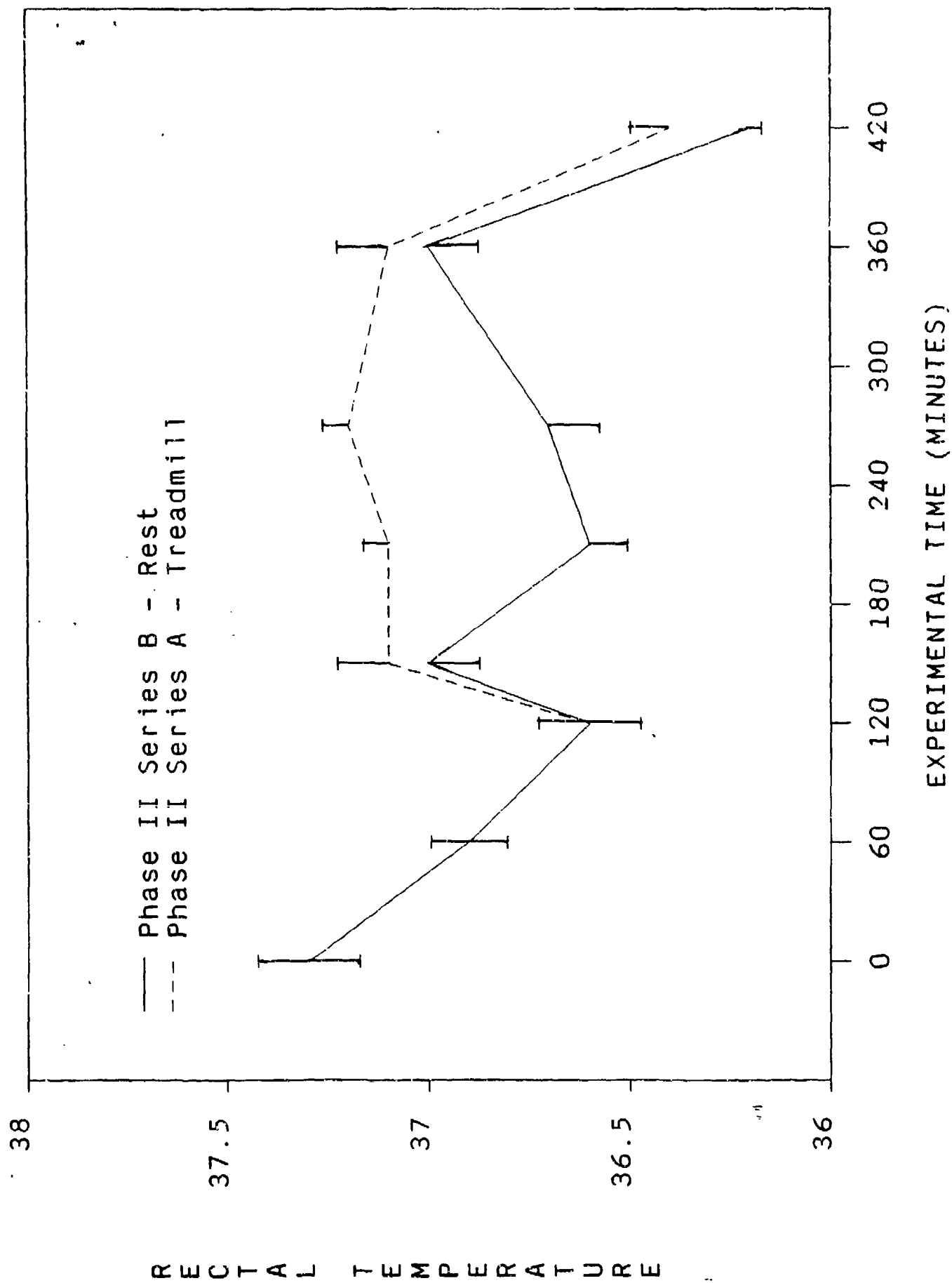


FIGURE 5

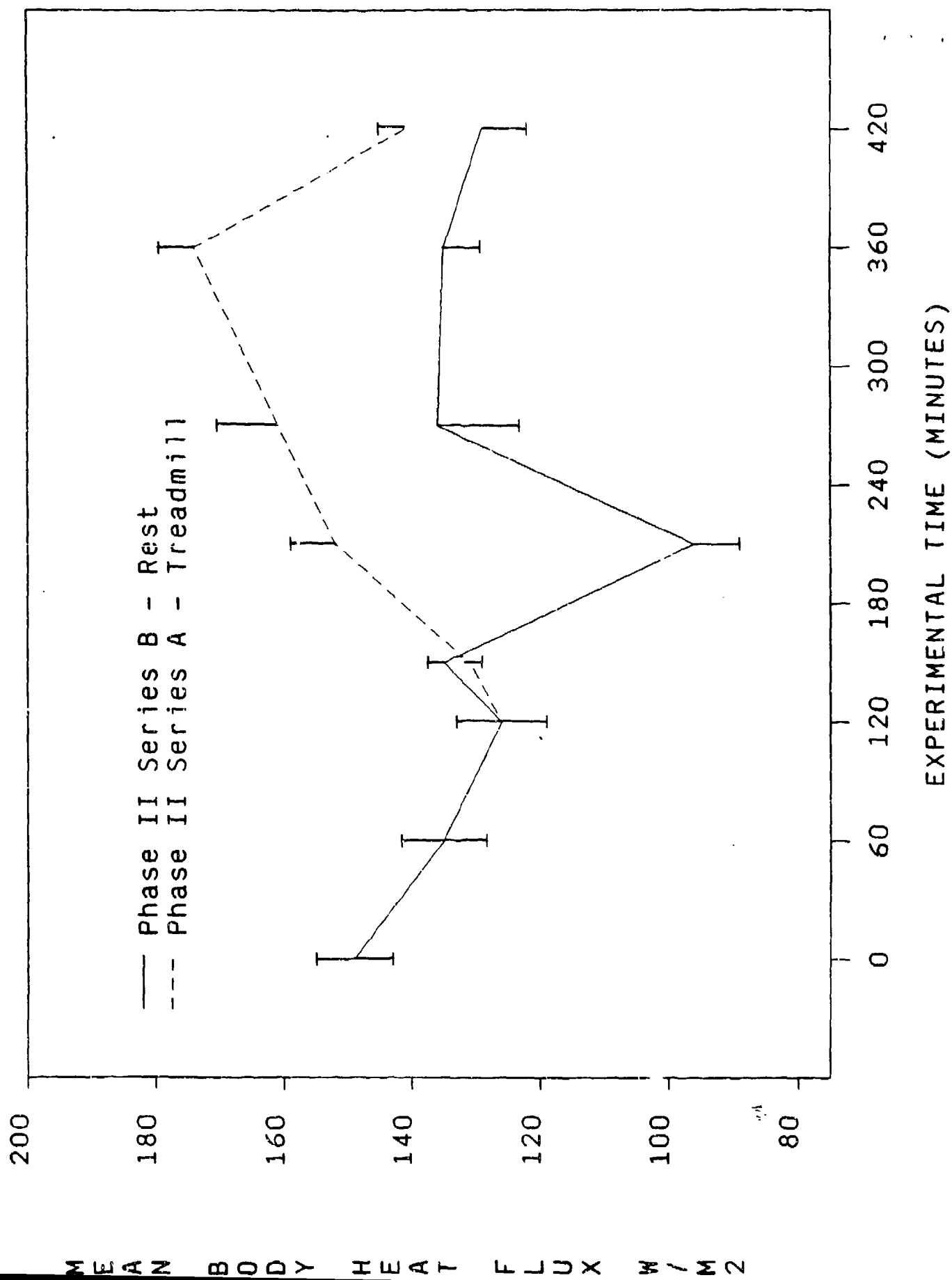


FIGURE 6

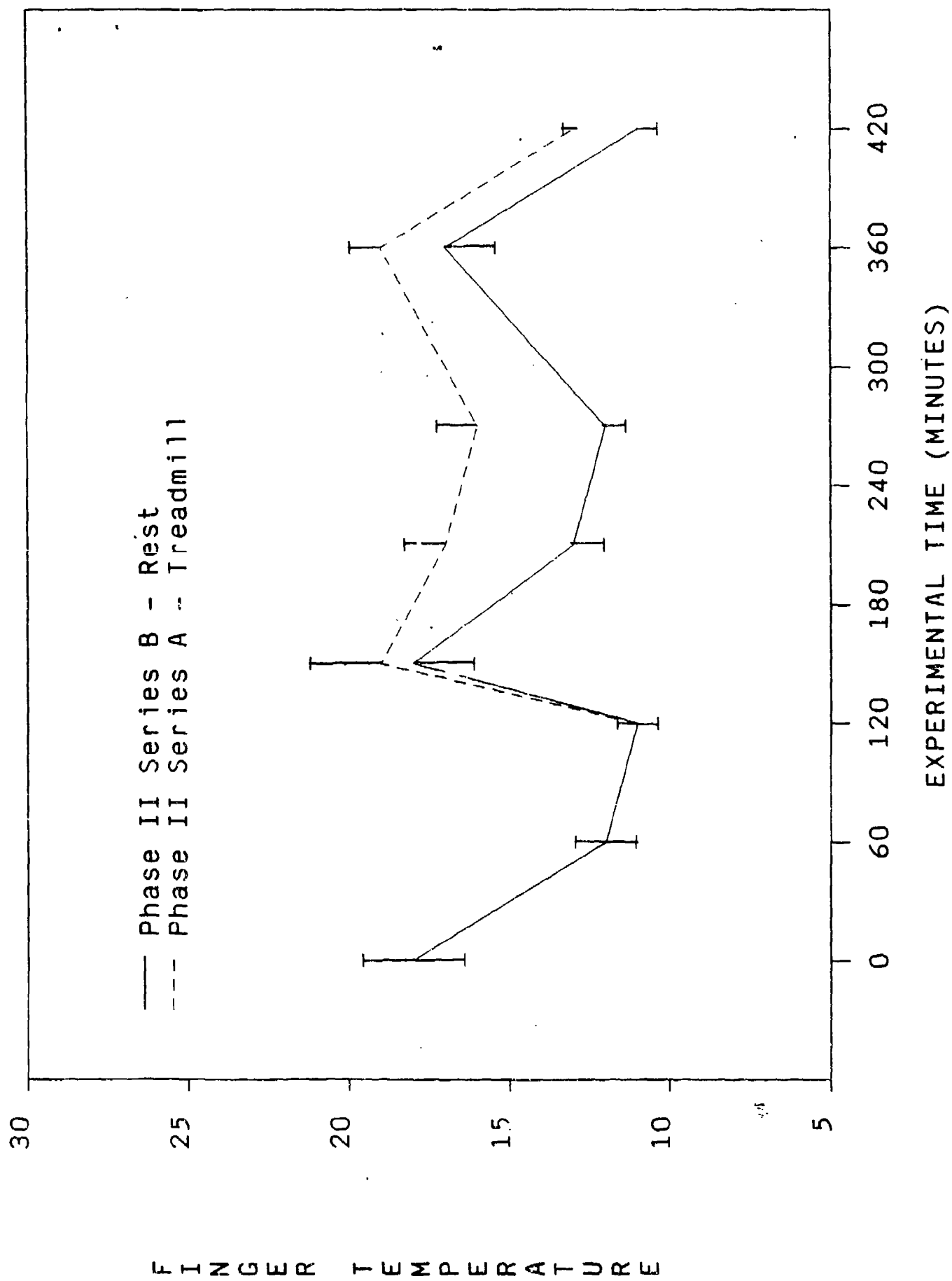


FIGURE 7

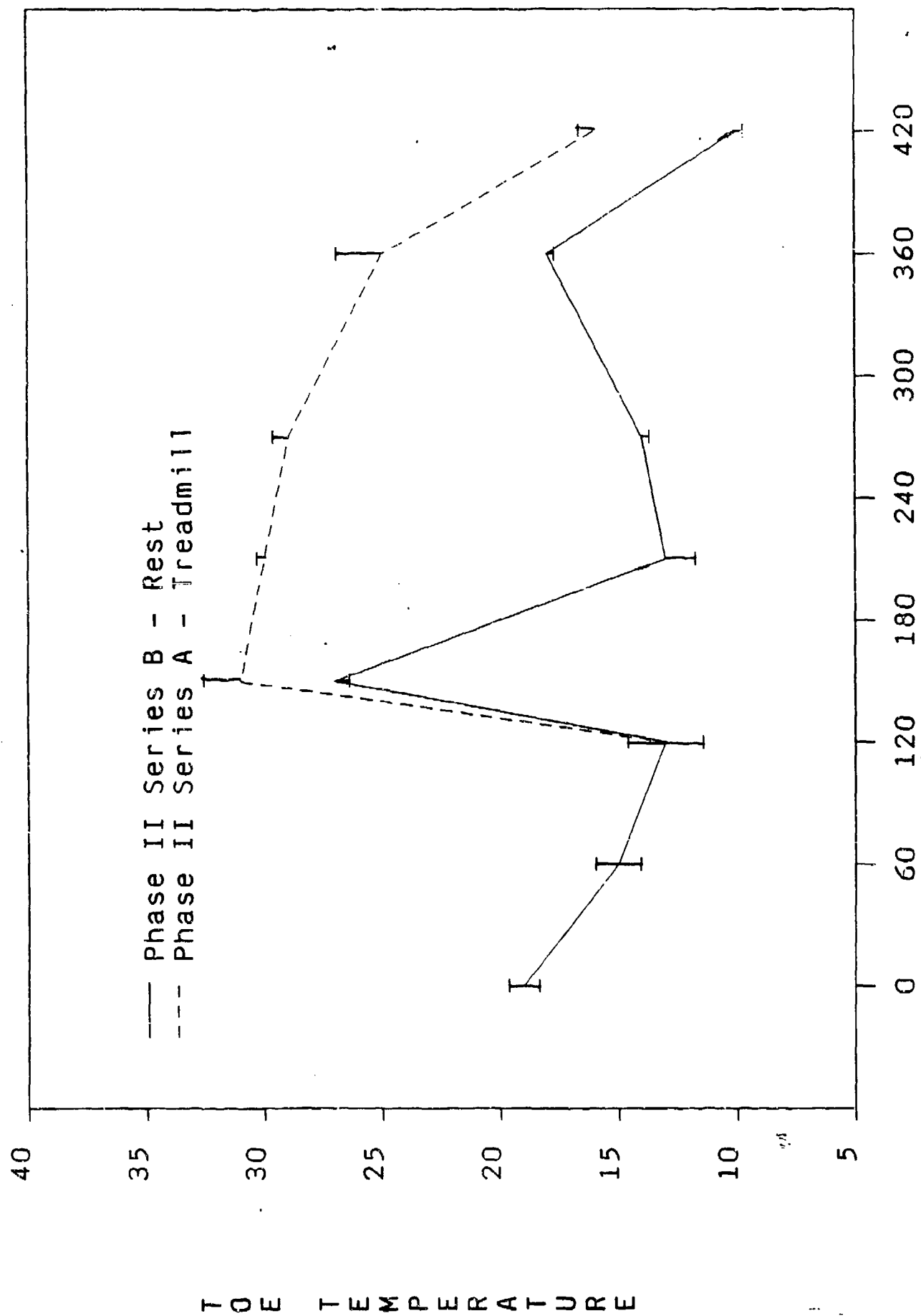


FIGURE 8

NMRI PAB - NUMERICAL MEMORY

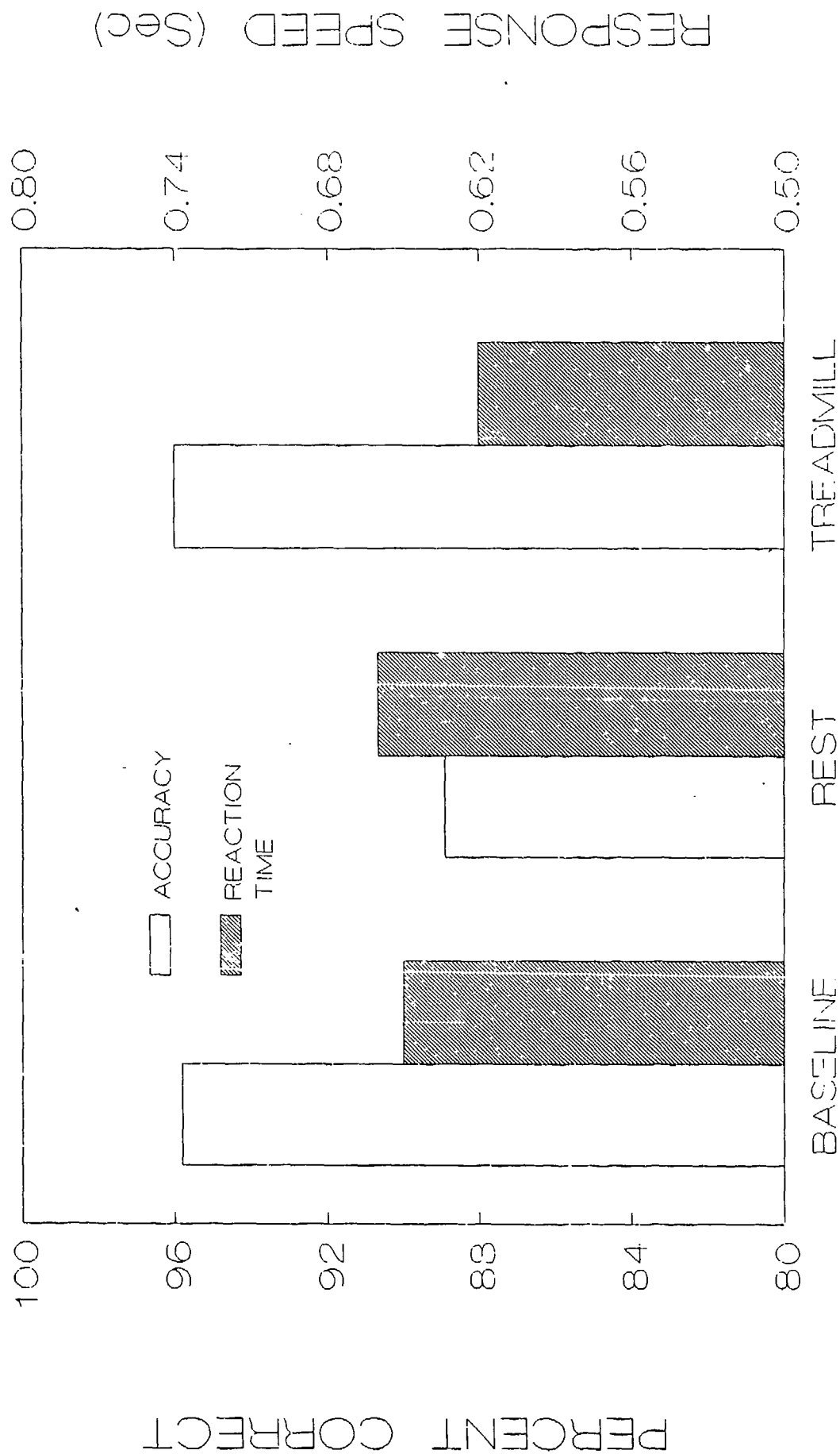


FIGURE 9

NMRI PAB - PATTERN COMPARISON

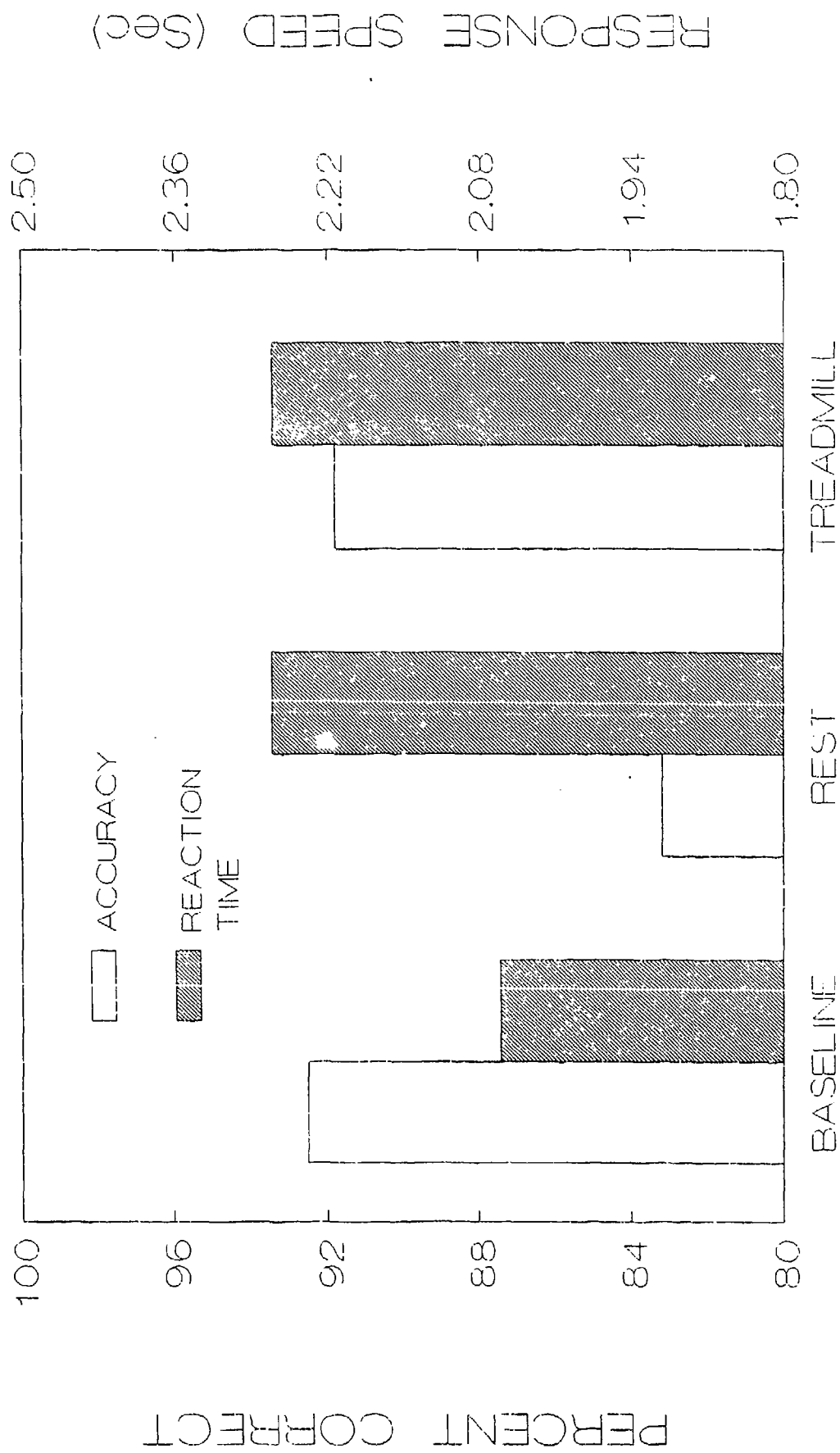


FIGURE 10

NMRI PAB - GRAMMATICAL REASONING

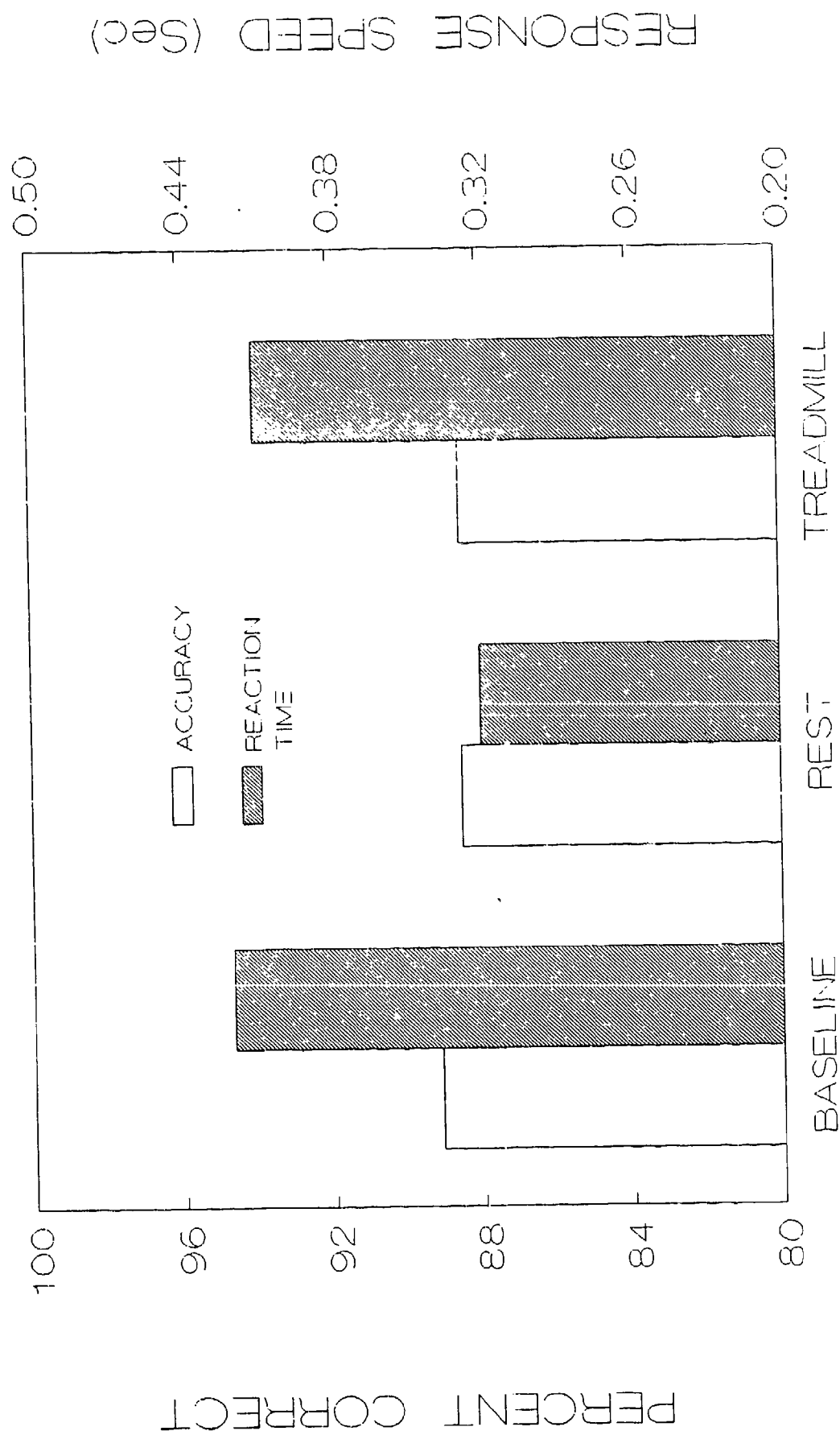


FIGURE 11

NMRI PAB - MATCHING-TO-SAMPLE

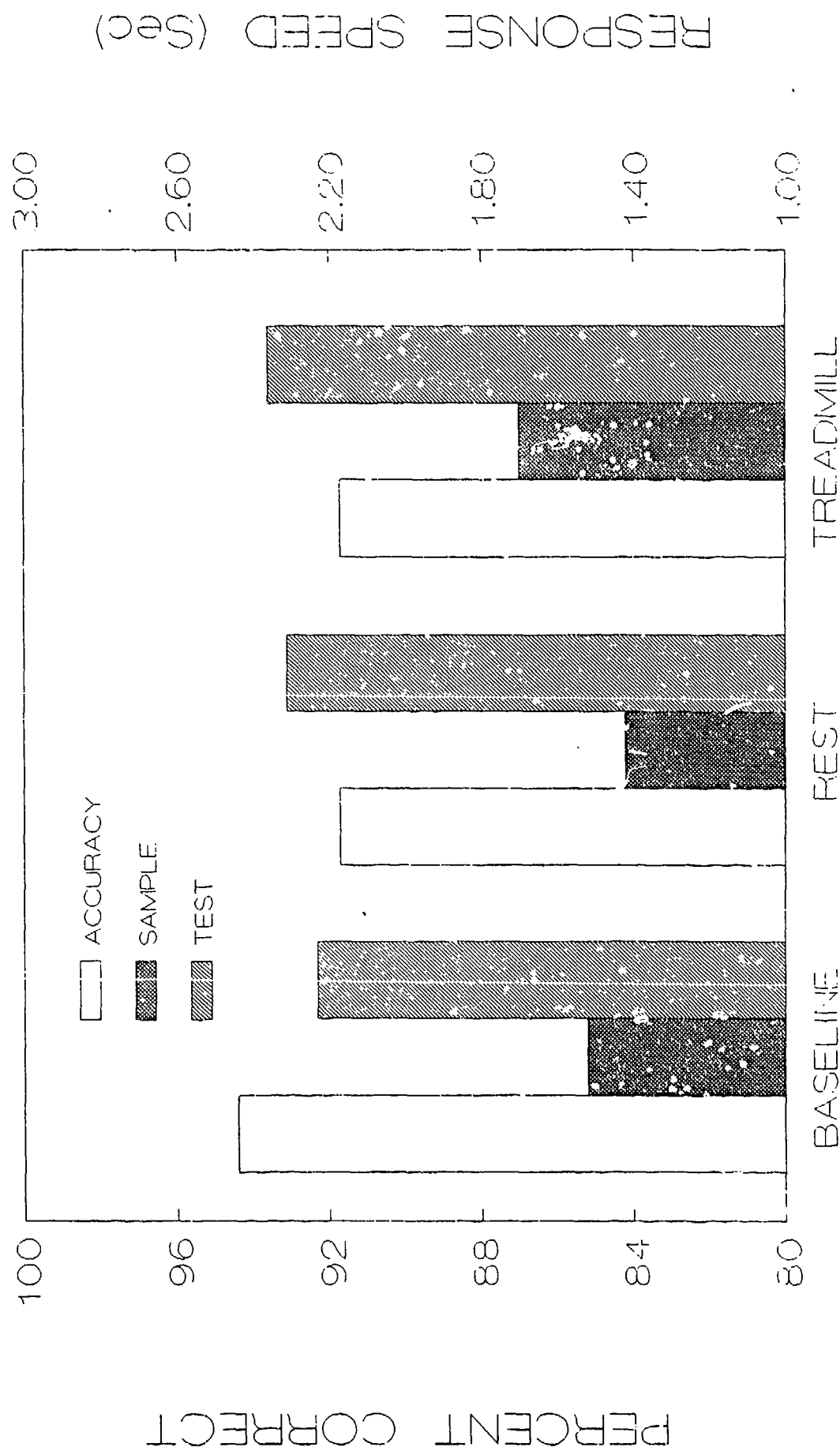


FIGURE 12

NMRI PAB - LETTER SEARCH

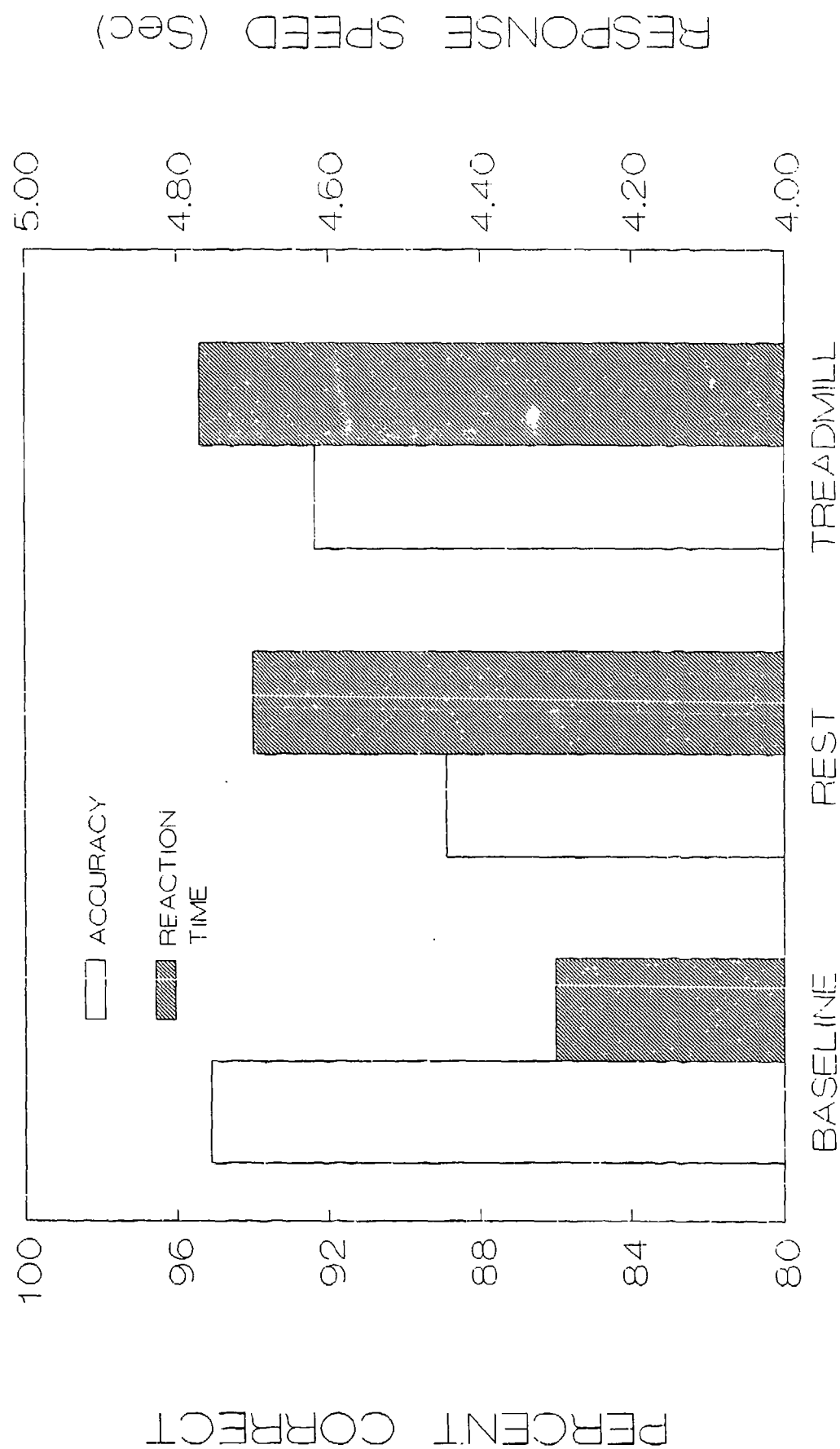


FIGURE 13

NIMRI PAB -- MANIKIN

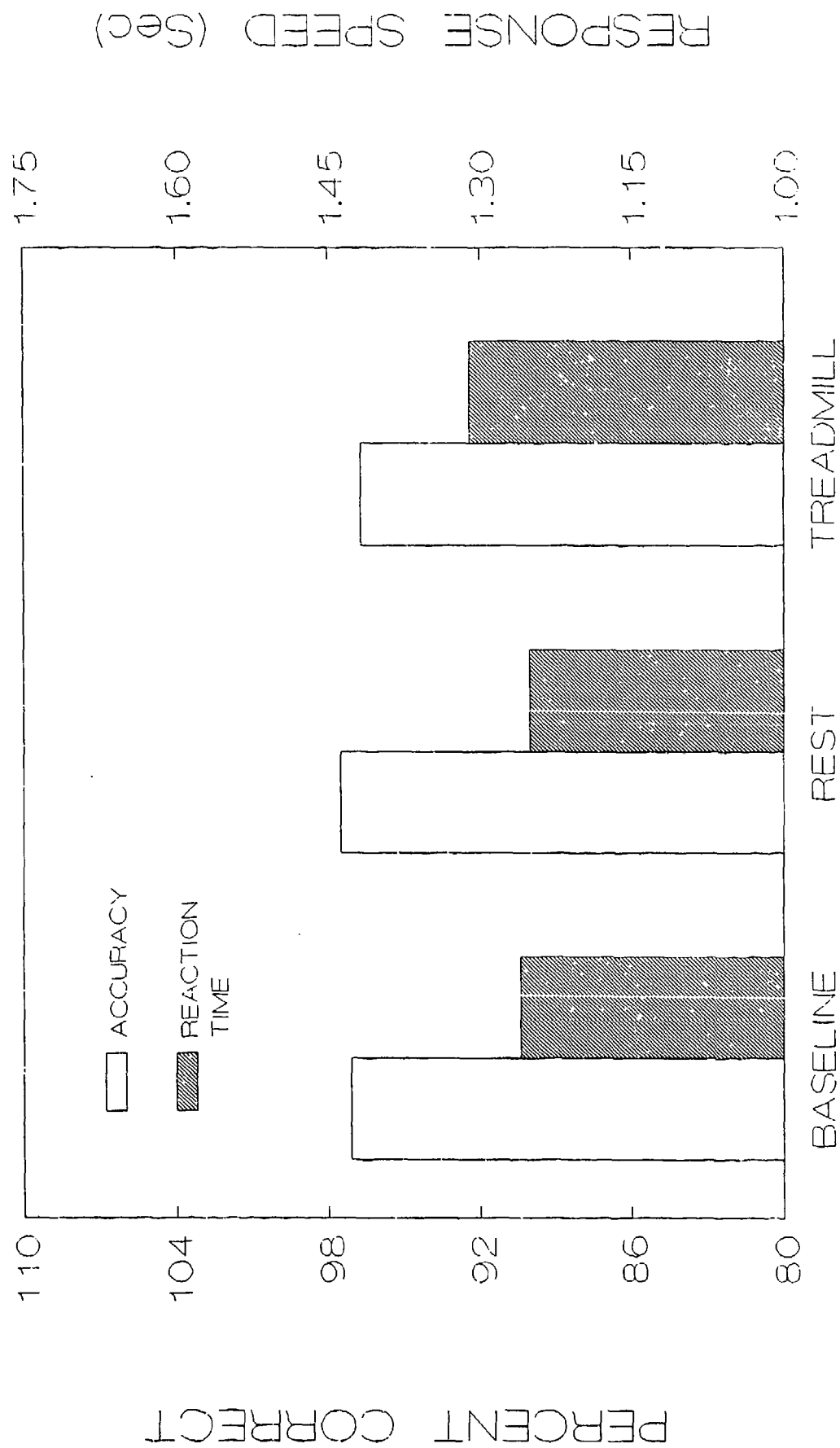


FIGURE 14

NMRI PAB - REPEATED ACQUISITION
ACCURACY

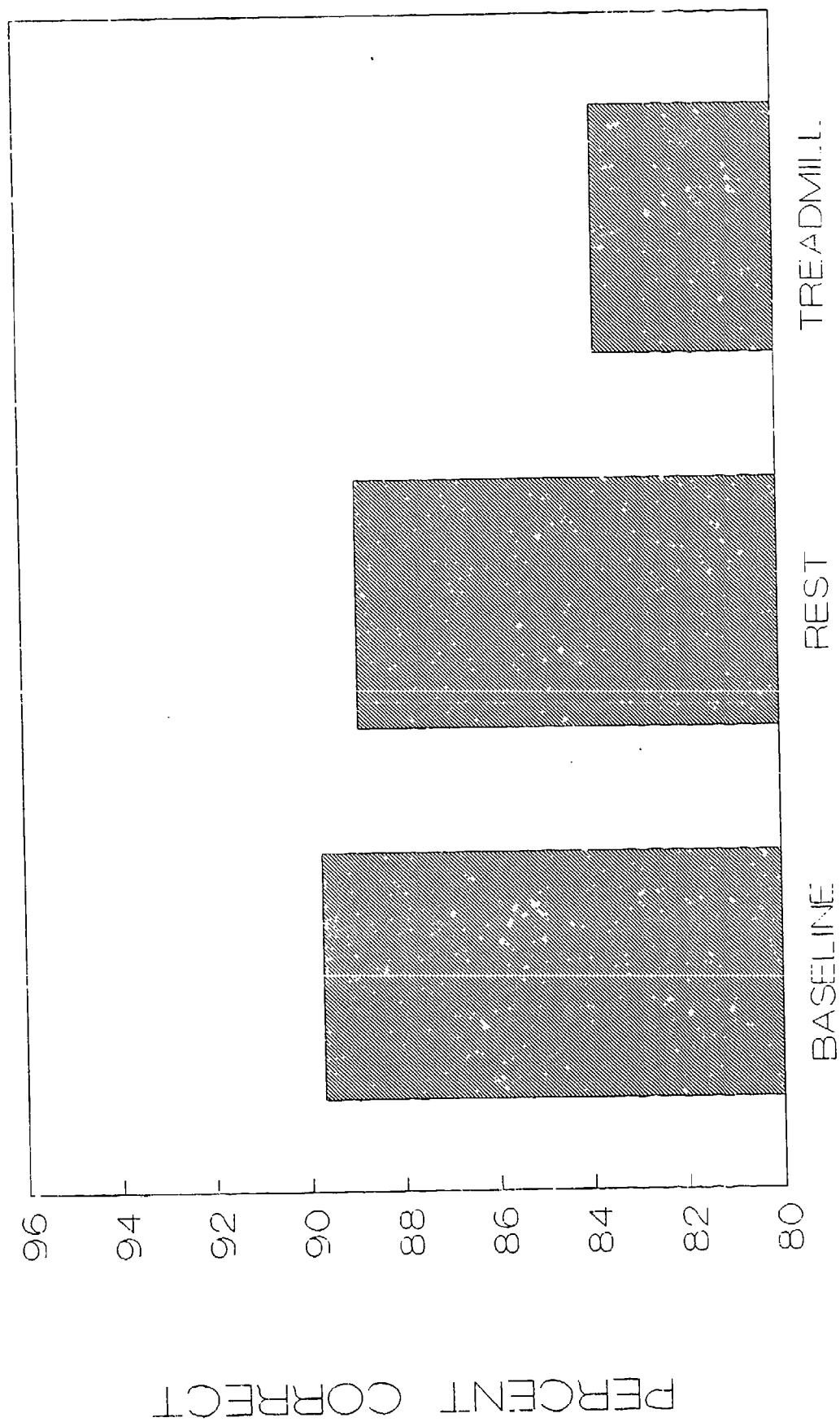


FIGURE 15