

N 70-33907

NASA CR 108508

FINAL REPORT

NASA, MSC Contract No. NAS 9-9418

Title: Development of a Prototype Onboard EEG Analysis System

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Date: April 30, 1970

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I. Summary of Work Completed

A. General

Work carried out as specified in the terms of this contract has resulted in the development of a laboratory prototype system which accomplishes acquisition and automatic analysis of electroencephalographic (EEG) and electro-oculographic (EOG) signals and provides an output display indicative of the subject's level of consciousness (awake or asleep, and stage of sleep). The system has undergone preliminary operational testing, and the results have shown the feasibility of the system for use onboard during manned spaceflight, with on-line telemetry of results to a ground-based monitoring console.

B. Scope of Work (refer to block diagram, Fig. 1)

1. Data-Acquisition Equipment

a. Recording-Electrode Cap (Fig. 1, Assembly 1). A pre-filled, disposable recording cap, utilizing electrolyte-saturated sponge electrodes, has been developed, which minimizes subject participation time prior to recording (approximately 3 minutes of preparation time) and which greatly increases the reliability of the data-acquisition procedure.

b. Preamplification Unit (Fig. 1, Assembly 2). A miniaturized preamplifier assembly has been developed which mounts directly on the subject's recording cap, and which accomplishes initial amplification of the EEG and EOG signals. This unit also contains a small dual accelerometer and associated amplifier which provides head-movement information to the analyzer circuitry. A 3' to 4' flexible multiconductor cable connects the preamplifier to following stages.

c. Control-Panel Assembly (Fig. 1, Assembly 3). This unit is located near the subject's head during sleep periods, and provides final amplification for EEG, EOG, and accelerometer signals received from the pre-amplifiers. The assembly also contains circuitry which accomplishes automatic evaluation of recording-electrode condition and provides a status display visible to the subject. The output signals from this unit enter the automatic-analysis equipment and the analog tape-recording unit.

d. Analog Magnetic-Tape Recorder (Fig. 1, Assembly 4). This unit permits the unprocessed EEG, EOG, and accelerometer data to be preserved for later analysis. Although not essential for the primary goal of on-line sleep analysis, this equipment serves as a back-up system in the event of difficulty with telemetry, and permits more extensive off-line analysis. Existing flight hardware has been utilized in the prototype system (Cook Electric Co. recorder #MSC-REC-SYS-GF-C1, as used in the Gemini program).

2. Automatic-Analysis Equipment (Fig. 1, Assembly 5)

The basic sleep analyzer developed under NASA Grant No. NGR-44-003-025 has been modified and expanded. Seven states or levels of consciousness are automatically recognized and indicated by the device (awake, stages 1-4 of sleep, stage REM sleep, and an abnormal category),

which utilizes one channel of EEG, one channel of EOG, and subject-movement information (accelerometer signal).

3. Telemetry Links

a. Onboard Telemetry-Interface Unit (Fig. 1, Assembly 6).

This unit converts the sleep-stage information provided by the automatic-analysis equipment into a 3-bit binary code which is suitable for telemetry at a rate of one code per 10-second time epoch.

b. Ground-Based Telemetry-Interface Unit (Fig. 1, Assembly 7). This unit accepts the telemetered 3-bit binary code and provides an output voltage indicative of the current sleep stage.

4. Display Console (Fig. 1, Assemblies 8 and 9)

On-line display of the subject's sleep status is provided by this unit. The current sleep state of the subject is signified by illumination of an indicator lamp, and the cumulative time spent in each stage is recorded by elapsed-time indicators. A stepwise analog output voltage proportional to the sleep stage is also provided, and is utilized to actuate the vertical axis of a graphic recorder to provide a continuous display, or profile, of the subject's sleep.

II. Recording-Cap Assembly (Assembly 1)

A. Background

Acquisition of EEG and EOG activity under operational conditions poses a number of problems which are not present in the usual clinical laboratory situation: 1) It is necessary for the subject himself to accurately position and apply the sensors (electrodes). 2) Damage or irritation of the skin cannot be tolerated. 3) Electrodes must be durable and not readily dislodged. 4) Moderate bodily movements of the subject must not seriously degrade the signal-acquisition system. 5) The recording array must be easily and rapidly applied by the subject with minimal effort. 6) The sensors must be lightweight and comfortable, and cannot interfere with normal sleep.

The problems noted above were initially considered by the UCLA group (NASA contract NAS 9-7282), and various proposed solutions were evaluated at Baylor (NASA contract NAS 9-7237). A recording cap was evolved which utilized an integral set of sponge electrodes to maintain proper scalp contact, and which was easily donned by the subject. Operational testing of the electrode-cap assembly during the Tektite Oceanographic Project (1969) proved that items 1 through 4, above, had been adequately solved, but that certain aspects related to problems 5 and 6 were still unsatisfactory.

A considerably modified, miniaturized version of the original cap was developed in the initial phases of the current contract period, and was operationally tested on a crew member during the Grumman/Piccard Gulf Stream Drift Mission (Ben Franklin). The reduction in electrode mass essentially solved the comfort problem, and no interference with sleep was noted. Subsequently, the cap was modified further to its current configuration, which

includes a newly designed, prefilled electrode. The entire cap-electrode array is intended to be used only once (i. e., disposable), and preparation time prior to the sleep period has been reduced to less than 3 minutes.

B. Description

1. General

As illustrated in Fig. 2, the cap is designed to fit snugly over the skull areas which are utilized routinely in clinical electroencephalograph and in addition it extends low enough across the forehead to provide suitable attachment sites for electro-oculographic electrodes. (The current cap contains four EEG electrodes to provide two channels - C_3O_1 and C_4O_2 [International System], two EOG electrodes to provide one channel [left outer canthus to center forehead], and one ground electrode located in the frontal area.) The cap is constructed from an elastic fabric (e. g., Lycra®) which provides the necessary tension to maintain scalp-to-electrode contact.

Accurate positioning of electrodes is ensured by proper location of the ear openings, which prevent the subject's donning the cap in a skewed fashion, and by proper fit in the frontal and nuchal areas. A padded chin strap which is easily connected and disconnected with Velcro® fasteners secures the assembly on the head.

Prefilled electrodes (see description below) are cemented to the fabric on the interior of the cap in the selected locations, and all electrode wires lead to a single miniature electrical connector located near the vertex of the head, which permits rapid connection and disconnection of the preamplifier assembly. The entire cap-electrode array is stored in a sealed polyethylene bag while awaiting use.

2. Electrode Construction

a. Introduction. A major disadvantage of the early sponge-electrode configurations was the time required to prepare the assembly for use and the necessity for special precautions to prevent drying of the sponge between periods of use. Before each period of use, a new supply of electrolyte solution had to be injected or impressed into the sponge contact of each electrode, a procedure which could require up to 15 minutes or more of the subject's time when multiple electrode arrays were used. Between uses, it was necessary to store the electrodes in a closed container to prevent complete drying of the contacts, which would cause hardening and permanent damage to the sponge structure; however, closed storage leads to problems associated with high-humidity environments (corrosion, mold, etc.) which could result in severe damage to associated components (connectors, wires, cloth, etc.).

A new approach to the problems noted above was undertaken, and the resulting prefilled, disposable, electrolyte-saturated sponge electrode may be stored, in unused condition, for long periods of time without deterioration or drying, and is readied for use in a matter of seconds. An electrically conductive solution or paste is incorporated into the electrode assembly during manufacture, and none needs to be added at the time of use in order to obtain

proper operation of the electrode. Each electrode array is used only once, thereby eliminating the problems associated with refilling and post-use care.

b. Configuration. The shape of a completed electrode is indicated by the geometrical view in Fig. 3, and the dimensions are indicated in the three perspective views (A, B, and C) of Fig. 3. As indicated in the construction view (Fig. 4), the electrode assembly is composed of three principal parts: 1) a conical, molded, silicone-rubber sponge whose apex is terminated in a small, cylindrical filling-and-sealing tab; 2) a chlorided silver disc and attached insulated wire; and 3) a flat, flexible, wafer-like silicone-rubber base which incorporates all but one surface of the silver disc, and upon which the molded sponge part is affixed. The relationships of the various components in the completed electrode are indicated in Fig. 5, a cross-section view of the electrode.

c. Construction Details

(1) Silver-Disc Assembly

(a) A 6.37 mm disc is cut¹ from pure silver sheet stock (thickness = 0.3-0.5 mm).

(b) A 3-inch length of silicone-rubber-insulated, stranded copper wire² is bared for 1/8" at one end and attached to the center of one surface of the silver disc, using silver-bearing solder.³

(c) The solder joint between wire and silver disc is insulated with a vinyl preparation. (Surfaces are initially primed with a precoat,⁴ then coated with an air-drying liquid vinyl.⁵)

(d) The uninsulated surface of the silver disc is chlorided by passing an anodizing current (disc positive, 1.5 V) through the assembly for 15-30 minutes while it is immersed in a 0.9% NaCl solution.

(2) Silicone-Rubber Base

(a) The chlorided silver-disc assembly is positioned in the lower portion of a two-part plexiglass mold, and held in place with a small piece of double-sided adhesive tape (see Fig. 6).

(b) 5 cc of liquid silicone rubber⁶ are thoroughly mixed with 2 drops of catalyzing agent⁷ in a 30 cc disposable, graduated container.

(c) The catalyzed liquid silicone rubber is poured into the lower cavity of the two-part plexiglass mold, taking care that no air bubbles are trapped around the silver-disc assembly.

(d) The upper half of the plexiglass mold is positioned, and the two halves of the mold are clamped together during the required curing time (approximately 20 minutes).

(e) The cured part is removed from the mold, and any excess rubber is carefully trimmed off. The exposed, chlorided surface of the silver disc is cleaned with a xylene solution to remove all traces of silicone rubber and other contaminants.

(3) Silicone-Rubber Sponge

(a) 5 cc of liquid silicone-rubber foam base⁸ are mixed for 30 seconds in a 30 cc disposable, graduated container with 6 drops of catalyzing agent.⁹

(b) The foaming mixture is poured into the lower half of a two-part plexiglass mold (pointed object used to force mixture well into tip of mold), and the upper half is then clamped into place (see Fig. 7).

(c) The mold escape port is closed (by sealing the opening with a finger) during the first 60 seconds to achieve slight compression of the sponge structure, then opened during the final 10-minute curing cycle.

(d) The part is carefully removed from the lower half of the mold, and the conical base is cut away from the portion extending into the escape vent of the upper half, using a thin scalpel blade.

(4) Final Assembly

(a) The sponge unit is attached to the base assembly using a silicone-rubber adhesive.¹⁰ (Note: Care must be taken not to allow the adhesive to cover the chlorided silver disc, which must directly contact the sponge material.)

(b) When fully cured (at least 2 hours after application of adhesive), the entire assembly is dipped into a red liquid vinyl material¹¹ which quickly air dries (approximately 5 minutes) to form a thin (0.002"-0.003"), flexible, insulating and moisture-retaining film over the entire electrode.

(c) A final coat is applied by dipping the electrode into a clear liquid vinyl¹² and air drying as in (b). This final coat improves the pliability of the completed assembly.

(5) Prefilling Procedure (refer to Fig. 8)

(a) The vinyl material covering the tip of the filling-and-sealing tab is removed, exposing a small area of the silicone-rubber sponge (Fig. 8, A).

(b) A hollow injection needle which is connected to a pressurized supply of electrolyte solution¹³ is inserted through the exposed tip into the interior of the electrode (Fig. 8, B). Enough electrolyte solution is injected to ensure complete saturation of the entire sponge, and the needle is withdrawn (Fig. 8, C).

(c) The exposed sponge tip is resealed with liquid vinyl (Fig. 8, D), thus preventing further loss of electrolyte and allowing the electrode to be stored indefinitely.¹⁴

3. Cap Construction

a. General. The recording cap is assembled from several panels of an elastic, Lycra-type, nylon-spandex fabric¹⁵ which are cut as indicated in Fig. 9. The dimensions indicated on this illustration are for a medium-sized cap, and for best results the cap is individually tailored to fit a particular subject.

b. Construction Details. The individual pieces (Fig. 9) are sewn together as indicated in Fig. 10, using an elastic thread to preserve the elasticity of the completed unit. Seams are maintained at approximately 1/4", and the free edges of fabric are hemmed (allowing approximately 1/4" for hem). Velcro® patches are sewn into place (Fig. 10) to provide attachment points for the preamplifier assembly at the vertex, and the chin strap below and anterior to the ears. A gripper-type snap fastener is affixed to the cap 1" behind the vertex Velcro® to hold the preamplifier-cable assembly (described below). The chin strap is constructed as a hollow, flattened tube, and contains a strip of foam rubber throughout its length for added comfort.

c. Electrode Placements (see Fig. 10). Electrode positions are marked while the assembled cap is properly positioned on a subject's head. Occipital and central electrode (O_1 , O_2 , C_3 , C_4) positions are measured according to the Ten Twenty Electrode System of the International Federation (Electroenceph. Clin. Neurophysiol., 1958, 10: 371-375; report submitted by H. H. Jasper), one EOG position is marked near the outer canthus of the left eye, and the other EOG site is located in the center of the cap, as low as possible on the forehead.

The cap is then removed from the head, and a prefilled sponge-electrode assembly (see section 2, above) is cemented to each site, using a vinyl adhesive.¹² All electrode wires are brought together in the single miniature electrical connector¹⁶ (Fig. 2) located at the vertex, which allows rapid connection and disconnection of the preamplifier assembly.

4. Principle of Operation

a. General. The purpose of a biomedical electrode array is to provide a pathway for flow of electrical current between the biological system and some external system. The electrode described here accomplishes this by providing an indirect ohmic contact between the skin and the electrode wire.

b. Preparation of Electrode for Use (Fig. 11). As illustrated in Fig. 11, the prefilled, sealed electrode is quickly prepared for use by cutting off the sealing-and-filling tab at the apex of the conical structure. This step exposes the sponge material which was previously saturated with electrolyte solution.

c. Use. During use, the exposed tip of the electrode is placed against the skin and held in contact by the light pressure of the elastic recording cap. The sponge is thereby slightly compressed, resulting in ejection of a small amount of electrolyte solution onto the area of skin contact. The conductive properties of the electrolyte solution thus provide initial ohmic contact between skin and electrode. The interior of the electrolyte-saturated sponge provides an electrically conductive pathway from the skin to the chlorided-silver disc in the base assembly, which in turn electrically couples the electrolyte solution and the electrode wire. The development of unstable contact potentials and electrode-polarization problems at the electrolyte-metal junction is minimized by using the silver-silver chloride interface.

C. Preparation of Cap for Use

1. Use of the recording cap permits EEG and EOG recording to be accomplished with a preparation time of only (approximately) 3 minutes, by the subject himself.

a. The cap is removed from its plastic bag (time $\cong$ 30 seconds).

b. The sealing tab is removed from each electrode, and the preamplifier cable is attached (time $\cong$ 60 seconds for a 7-electrode cap).

c. The subject dons the cap, attaches the chin strap, and rocks each electrode back and forth to position the exposed tip through the hair against the scalp (time $\cong$ 60 seconds).

d. Recording begins.

2. Post-Recording Procedures

At the end of the recording period, the subject may disconnect himself from the apparatus within 60 seconds.

a. Chin strap disconnected and cap removed (time $\cong$ 30 seconds).

b. Cable disconnected and cap discarded (time $\cong$ 30 seconds).

III. Preamplification Unit (Assembly 2) and Control-Panel Assembly (Assembly

A. General Description

As indicated in the system block diagram (Fig. 1), these two assemblies provide the necessary interface between the subject and the analysis and recording equipment, both in terms of data acquisition (from the recording cap) and in terms of subjective control (mode-selection switch, electrode-status-checking circuit and display). These functions are outlined more completely in Fig. 12, which is a detailed block diagram of the proposed onboard configuration. The physical configurations of the existing prototypes are indicated in Fig. 13, which also illustrates the relationships between the recording cap (Assembly 1) and the cap preamplifier (Assembly 2). These assemblies are powered by batteries during operation, and the batteries are automatically recharged when the unit is not in use (see power-system diagram, Fig. 15).

B. Construction Details

1. Amplification Circuitry

a. Initial amplification of EOG and EEG signals from the cap (Assembly 1) is accomplished in the cap preamplification unit (Assembly 2) which provides a gain of 10 at low-output impedance ($\sim$ 1500 ohms). The unit also contains an accelerometer package and associated preamplifier which is capable of detecting changes of acceleration along two axes. Signals from this assembly enter the control panel (Assembly 3) through a multiconductor shielded 4' cable with a quick-release electrical connector.

Each EEG and the EOG channel are provided with a differential input configuration, and the use of selected field-effect transistors results in an input impedance in excess of 1000×10^6 ohms, thus minimizing the effects of

changed electrode impedance. Inherent noise levels can be maintained at less than $3 \mu\text{V}$ peak-to-peak referred to the input.

Final amplification of the EEG and EOG signals (gain = 100) is carried out within the control-panel assembly (Assembly 3) to provide a total gain of 1000 for the complete circuit. The final amplification circuitry also accomplishes preliminary analog filtering of the EEG and EOG signals (bandpass 0.1 to 40 cps [-6 dB points]) and of the accelerometer output (bandpass 0.3 to 30 cps).

b. The amplification circuitry for EEG and EOG is illustrated in Fig. 14, and the components remotely located in the preamplifier assembly (Assembly 2) are enclosed by the dashed line.

Q_2 and Q_3 , a matched pair of N-channel field-effect transistors (Texas Instrument Co., TIS69), are arranged in a standard differential input configuration, and receive the unamplified signal from the electrodes. Q_1 supplies a constant current to the common-source junction of Q_2 and Q_3 to provide improved rejection of common-mode signals applied to the input. R_1 , in the base circuit of Q_1 , is adjusted so that the drain voltage of Q_2 and Q_3 is approximately +5 V when both inputs are shorted to ground. The two diodes in the common-drain circuit of Q_2 and Q_3 prevent flow of current between Q_2 and Q_3 when the electrode-checking circuitry is activated (see description below).

Signals from the preamplifier (Assembly 2) are led to the final amplification circuitry located in the control-panel assembly (Assembly 3) through individually shielded, flexible cables.¹⁷ Final amplification is accomplished in the operational amplifier (Fairchild, type 709), and associated filter circuits limit the bandwidth to the specified values.

c. Specifications

Input impedance	$\sim 1000 \times 10^6 \text{ ohm}$
Output impedance	$\sim 200 \text{ ohms}$
Common-mode signal rejection	$\sim 60 \text{ dB}$
Gain	$\times 1000$
Frequency response	0.11 cps-40 cps (-6dB)
Noise level (referred to input)	$\sim 3 \mu\text{V}$ peak-to-peak

2. Accelerometer Circuitry

a. A dual accelerometer is contained in the preamplifier unit (Assembly 2) and is utilized to provide information concerning movement of the subject's head.

b. The accelerometer circuitry is illustrated in isolated form in Fig. 16, A, and the configuration of the remotely located components is indicated in Fig. 16, B. The accelerometer itself is an Astatic #11T7B stereo crystal cartridge which is modified by the addition of a 0.08 gm mass at the tip of the recording stylus. Signals from the accelerometer are amplified by the field-effect transistor (TIS68) and led to the control-panel assembly through flexible, shielded cable.¹⁷ Both the accelerometer and the transistor

are located within a small aluminum cylinder which serves as an electrical shield to reduce the unit's susceptibility to extrinsic inductive and capacitive influences.

3. Electrode-Testing Circuitry

a. General. This section of the control-panel assembly is designed to assist the subject during application of the recording cap, and to assure proper functioning of the apparatus before the sleep period begins. The control panel, easily visible to the subject during application of the cap (Fig. 13) contains a series of indicator lamps, each representing one of the sponge-electrode sensors on the cap. When the cap is donned by the subject, he moves the panel-selector switch from the "off" position to the "test" position, thereby activating the automatic test circuitry. A small test current ($0-10 \mu\text{A}$) is passed through the ground electrode to each of the 6 recording electrodes, and this current is sensed to provide an indication of interelectrode resistance. If a given electrode is in proper contact with the scalp, the resistance will be 100,000 ohms or less, and this condition is indicated by illumination of the corresponding lamp in the simulated control-panel display. Improper contact can usually be resolved by slight repositioning and rocking of the sensor to firmly seat the sponge against the scalp.

b. Circuit Details. Operation of the electrode-test circuitry is illustrated in isolated form in Fig. 17. In this mode of operation, the input N-channel field-effect transistors (FETs) are disconnected from the remainder of the amplification circuitry and connected to the test circuitry by the mode switch, as shown. All FET drains connect to point A (see Fig. 17) through 1-megohm potentiometers. Each FET gate connects, as usual, to an individual electrode on the recording cap, and the electrodes in turn make contact with the subject's scalp (see discussion of electrodes, section II, B, above). A single cap electrode serves to ground the subject to the system common ground.

In the normal recording mode, the FETs are used as amplifiers and the drain and source points are always biased positive with respect to ground, thus keeping the gate-source/drain junction reverse-biased, resulting in no significant flow of current (high input impedance). In the electrode-testing mode, as indicated in Fig. 17, the drains are periodically driven negative with respect to ground by the 1 cps oscillator circuit, composed of Q_1 and Q_2 and associated components, which is connected to point A. When point A goes negative, the FET gate-drain junction is biased in a forward direction, permitting current flow from gate to drain. The current pathway is illustrated in detail for one electrode of channel 1 in Fig. 17. If the cap ground electrode and the EOG electrode are both in contact with the subject's scalp, when point A goes negative, current will flow from the circuit ground, through the two involved electrodes (R_e = electrode-to-scalp impedance), across the forward-biased gate-drain junction, and through the 1-megohm potentiometer in the sensing circuit to point A. The amount of current passing through the 1-megohm resistor, and thus the voltage developed across it, will depend upon the interelectrode impedance (R_e)

at the scalp. As R_e becomes lower (i.e., the better the electrode contact), the voltage developed across the sensing resistor increases.

The FET in the sensing circuit, Q_3 , detects and amplifies the voltage developed across the 1-megohm resistance. The amplified voltage serves to turn the following stage, Q_4 , fully on when R_e drops below 100,000 ohms (indicating adequate scalp-electrode contact). Q_4 , in turn, drives the final stage, Q_5 , which, in turn, operates the panel-indicator lamp for the appropriate recording electrode. A separate sensing circuit exists for each of the 6 recording electrodes, and the indicator lamps are arranged in a display simulating the cap-electrode configuration, permitting the subject to rapidly identify the faulty electrode. If the common-ground electrode on the cap is at fault, no sensing circuit will operate, and all indicator lamps will be extinguished.

IV. Analog Magnetic-Tape Recorder (Assembly 4)

A. General Description

1. As indicated in Figs. 1 and 12, the EEG, EOG, and accelerometer data are recorded in unprocessed form within the prototype onboard system. Although this assembly is not essential for the operation of the system as an on-line monitor of sleep status, it does ensure that data are not permanently lost in the event of telemetry failure, and also permits a more extensive data analysis to be made later.

2. Specifications

The recorder currently being used in the prototype system is the NASA Biomedical Recording System (MSC-REC-SYS-GF-C1) unit which was developed by the Cook Electric Co. for the Gemini program and which is described in detail in the manual supplied with NASA Contract NAS 9-5199.

The recorder is capable of recording 7 channels of data on 1/2" magnetic tape with a frequency response of 0.1 to 100 cps, and will operate continuously for up to 100 hours.

3. Interconnections (see Fig. 14)

a. EEG, EOG. The amplified EEG and EOG signals from Assembly 3 are attenuated by potentiometers to provide the necessary input level (± 10 mV) for the recorder.

b. Accelerometer. The output signal from the accelerometer preamplifier (Assembly 2) is of adequate magnitude to be recorded directly, and it enters channel 4 of the recorder through a 25 μ f capacitor, which eliminates the DC bias level.

V. Automatic Sleep Analyzer (Assembly 5)

A. Background

In the past, a number of investigators have proposed methods for processing EEG sleep records automatically because of the time factor involved in human visual analysis; even under controlled laboratory conditions. These

may be divided into several categories, based upon the specific features which are derived from the original voltage-time EEG tracing, as indicated in the following selective review.

Spectral Analysis

- Knott, J. R. et al., J. Exp. Psychol. 31: 465-477, 1942
Kaiser, E. et al., Electroenceph. Clin. Neurophysiol. 17: 76-80, 1964
Hord, D. J. et al., Electroenceph. Clin. Neurophysiol. 19: 305-308, 1965
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Walter, D. O. et al., Aerospace Med. 38: 371-379, 1967
Lubin, A. et al., Psychophysiology 6: 122-132, 1969

Period Analysis

- Burch, N. R., Electroenceph. Clin. Neurophysiol. 11: 827-834, 1959
Burch, N. R. et al., Ann. N.Y. Acad. Sci. 115: 827-843, 1964
Fink, M. et al., Comprehens. Psychiat. 8: 521-538, 1967
Itil, T. M. et al., Electroenceph. Clin. Neurophysiol. 27: 76-83, 1969
Roessler, R. et al., Electroenceph. Clin. Neurophysiol. (in press)

Average Amplitude

- Maulsby, R. L. et al., Electroenceph. Clin. Neurophysiol. 21: 501-503, 1966
Agnew Jr., H. W. et al., Electroenceph. Clin. Neurophysiol. 22: 84-86, 1967
Fink, M. et al., Comprehens. Psychiat. 8: 521-538, 1967
Itil, T. M. et al., Electroenceph. Clin. Neurophysiol. 27: 76-83, 1969

Frequency/Voltage Ratio

- Riehl, J. L., Aerospace Med. 32: 1101-1108, 1961

Pattern Recognition

- Smith, J. R. et al., Engineer. Progr. at Univ. of Florida 22 (Tech. Paper No. 421): 12 pp., 1968
Viglione, S. S. et al., Personal communication

Although some of the above techniques have yielded results very close to those of visual scoring, the hardware required in these cases has been too extensive to consider for onboard analysis (large digital or special-purpose computers). A method of EEG analysis was evolved in this laboratory (NASA Grant No. NGR-44-003-025) which was designed specifically to meet the expected size and weight limitations imposed by spaceflight. The general approach was to determine the minimum amount of EEG information actually needed to make a proper decision, and to determine the most direct way in which this information could be automatically extracted. This resulting method has been incorporated

into the current prototype system, and a number of features have been added which greatly increase the reliability and improve the ability to reject extrinsic or artifactual signals.

B. Theory of Operation and Prototype Construction

1. General

The automatic-analysis scheme is indicated in highly simplified fashion in Fig. 12 (Assembly 5), which illustrates the general interaction of the EEG, EOG, and head-movement signals. A detailed block diagram of the signal-conditioning and logic circuitry is provided in Fig. 18, and a schematic diagram of the current prototype analyzer is shown in Fig. 19.

2. EEG Analysis (refer to Figs. 18 and 19)

The EEG-analyzer portion of this system is essentially an amplitude-weighted, dominant-frequency meter for the 0.7 to 13 cps EEG band, with the output restricted to six discrete levels (awake, stage 1, stage 2, stage 3, stage 4, and abnormal).

As indicated in Fig. 18, amplified EEG activity from the final stages of Assembly 3 enters the analyzer circuitry and is first passed through a band-pass filter which limits the response to the 0.7 to 13 cps range. This step greatly attenuates electrode, movement, and muscle artifacts, but retains enough EEG information to allow accurate determination of sleep stages.

The signal next enters three level detectors, each set to indicate a different EEG amplitude (see Fig. 20). Level 3 is greatest, arbitrarily called 100%. Level 2 is at 20% of the distance from the baseline to level 3, and level 1 is at 1%, just above the noise level of the system. The gain of the preamplifier is adjusted for each subject so that only the greatest amplitude, negative-going waves in his eyes-closed waking EEG exceed level 3, with the average peak amplitude falling midway between levels 2 and 3 (i. e., approximately 60%). Thus, the higher voltage activity during sleep will frequently cross the 3rd level, whereas the low voltage activity during stage 1 will exceed only levels 1 and 2.

The logic circuitry (Fig. 18, bistable circuit, logical AND gate) associated with the level 1 and 2 detectors triggers a negative-pulse generator if, and only if, level 1 and level 2 are crossed successively in a negative-going direction (e. g., Fig. 20, A-E, I, J). Fluctuations about either level 1 or 2 alone are ineffective (Fig. 20, E, F). As a result, the number of pulses produced by the negative-pulse generator is proportional to the dominant frequency of the EEG and independent of minor variations or inflections. Each pulse from the negative generator is of a constant amplitude and duration.

The level 3 detector operates in a straightforward fashion, triggering the positive-pulse generator each time it is exceeded (Fig. 20, G, H). The output of the positive-pulse generator is of the same duration as that of the negative generator, but of opposite polarity and one-half the amplitude. The pulses from the two generators enter the mixer amplifier, which supplies a composite pulse train to the integration circuit (see lower tracing, Fig. 20).

The integrator is a buffered RC circuit with a 15-second time constant for both rise and decay. The output is consequently a voltage level that

is dependent upon the number and polarity of pulses received during the preceding approximately 15 seconds.

If only levels 1 and 2 are exceeded by the fluctuating EEG input voltage, then the integrator's output is proportional to the dominant frequency. However, each time level 3 is exceeded (one-half amplitude, positive pulse), the integrator loses one-half the value previously added by a level 1-2 pulse (negative pulse).

In terms of its influence on the output of the integration circuit, an EEG wave of very low voltage, i. e., not exceeding level 2, has zero value, an intermediate amplitude wave has maximum value, and a high amplitude wave (exceeding level 3) has a value of 50%, since it produces both a negative pulse and a positive pulse of one-half the amplitude. When a subject is awake, the EEG voltage is sufficient to cross levels 1 and 2, and is relatively high in frequency. The output of the integration circuit will then be at its highest value. When the EEG pattern changes to stage 1, the amplitude is lower, and the frequency declines, both factors resulting in fewer crossings of levels 1 and 2 and a corresponding decrease in the output voltage level from the integrator. In stage 2, transient EEG forms exceed level 3, and the dominant frequency is still lower, again resulting in further reduction of the integration circuit output level. During stage 3 and into stage 4, progressively more waves of low frequency reach level 3, and the output level declines to its lowest normal value.

Certain abnormal conditions can produce even lower levels, for example the oscillations of deep coma, and if the EEG becomes flat, the lowest possible level (0 V output) is reached, since no pulses will be supplied to the integration circuit.

The EEG state of the individual is therefore expressed as a voltage level at the output of the integrator: the awake EEG is associated with the highest output voltage, and progressive stages of sleep are accompanied by correspondingly lower output values.

The analog (or continuous) integrator output enters a series of dual-comparator circuits in the sleep-stage-output section (Fig. 18, section H), where it is compared with previously determined voltage ranges, each corresponding to a discrete clinical stage (awake, stage 1, stage 2, stage 3, stage 4, or abnormal). Initial setting of the range potentiometers is accomplished by determining empirically the output voltages from the integrator that correspond to the transition points between EEG sleep stages. This is most easily accomplished by running a sleep record simultaneously on a conventional EEG machine and on the analyzer. As the subject passes from one stage to another by visual scoring criteria, the appropriate potentiometer is set to the current value of the integrator output voltage. This procedure is necessary only during the initial calibration of the instrument and does not have to be performed for each subject. Thus, while the integrator voltage is within the

range specified for a particular stage of sleep, a voltage is supplied to the corresponding output line of the stage circuit (either awake, stage 1, stage 2, stage 3, stage 4, or abnormal). The sixth output (abnormal) includes all states which do not fall into one of the other categories, e. g., complete loss of signal or an abnormally slow EEG.

3. EOG Analysis (refer to Figs. 18 and 19)

a. Purpose. The basic function of the EOG-analysis circuitry (Fig. 18, section 3) is to recognize the occurrence of rapid eye movements (REMs) which occur during stage 1 or 2 of sleep, as indicated by the EEG-analysis circuitry. If a REM is detected during EEG stage 1 or 2, the analyzer-output circuit indicates the presence of stage REM sleep.

b. Background. It has been determined experimentally that the EEG-analysis circuitry alone, described above (section 2), classifies stage REM sleep as either stage 1 or stage 2 sleep. In most instances, the EEG analyzer indicates a continuous fluctuation between stages 1 and 2 throughout a REM period, reflecting the transient changes in delta-frequency components. During true stage REM sleep, an electro-oculographic recording indicates occasional sharp transient forms reflecting brief bursts of rapid, jerky movements of the subject's eyes. Although these events are sporadic throughout the REM period, they usually occur with a frequency of at least one recognizable event in each 30-second epoch. During true stage 1 or 2 sleep, these events are absent, indicating no rapid movements of the subject's eyes.

The function of the EOG-analysis circuitry described below is to detect EOG events which may be REMs, eliminate certain artifactual signals, and provide a continuous indication of the presence of REM as long as one acceptable event per 30 seconds is detected while the subject's EEG characteristics are those of stage 1 or 2.

c. Theory of Operation and Construction of Prototype. Amplified EOG activity from Assembly 3 enters the analyzer (see Fig. 18, section 3) and is passed through a narrow band-pass analog filter amplifier which limits the response to the 1.0 to 3.0 cps range (-6 dB points). This frequency-response range results in optimal separation of true REM signals from extraneous activity (e. g., EEG activity detected by the EOG electrodes, slow eye movements, movement artifacts).

The output signal from the band-pass filter enters the EOG-transient-detector circuitry formed by the dual comparators (Fairchild 711) and appended components. This circuit detects the occurrence of transient forms which exceed by 50% either the average positive or the average negative peak-voltage value of the filtered EOG signal (averaging occurs continuously over approximately 10 seconds). This transient detection is accomplished by driving the upper and lower voltage reference inputs of the dual comparator with the rectified and filtered positive and negative components, respectively, of the output signal from the band-pass filter. The unrectified EOG signal enters the comparator common input (after attenuation), where it is continuously

compared to the upper and lower reference values. The attenuation factor is adjusted to permit the EOG signal at the comparator to just exceed the upper and lower values when a transient form in the unattenuated EOG output just reaches 50% of the averaged positive or negative peak value. Thus, a trigger pulse is produced by the comparator each time such a transient occurs. Each such trigger pulse resets a 1.5-second timer circuit which in turn supplies a 1.5-second DC pulse to the following circuit (EOG-transient-only comparator). If EOG transients are detected with a frequency of one per 1.5 seconds or greater, a continuous-level output results from the timer circuit for the duration of the train of transients and until 1.5 seconds after the final trigger pulse.

The EOG-transient detector, described above, is quite effective in determining REMs, since these events usually occur sporadically and arise abruptly from the background activity. Since the circuit detects a relative increase in amplitude compared to the average of the preceding 10 seconds (instead of utilizing fixed voltage references), it is not necessary to readjust the circuit for individual differences in EOG amplitude or different electrode placements. Similarly, if a change in background-activity level occurs during the course of the sleep period (e. g., volume conduction of EEG, noisy electrodes, extraneous noise, etc.), the reference levels automatically reset to proper relative values, thereby preventing false triggering of the comparator. Although the EOG-transient detector successfully recognizes most true REMs, it will also be triggered by certain non-REM signals which may be present in the EOG channel. Electrode artifacts are one major source of such signals, and these are considered below in section 4. Certain EEG events (vertex transients, K complexes) which occur frequently during stages 1 and 2 of sleep may also be recorded by the EOG-amplification system and detected as REMs because of their similarity in waveform and frequency components. This difficulty has been resolved by the remaining circuitry of the REM-detector circuit (Fig. 18, section 3), which utilizes the following criteria: 1) High-amplitude EEG-transient events are recorded essentially simultaneously in both the EEG and EOG channels because of their wide spatial distribution over the head. 2) True EOG events are recorded only in the EOG channel (i. e., or are of insignificant amplitude in the central-to-occipital EEG channel) because of their localized (frontal) origin. The final logic scheme permits an indication of the presence of a REM if 1) an EOG event is detected by the EOG-transient detector, and 2) no EEG event is detected by the EEG-transient detector within a time period extending from 1.4 seconds before until 1.4 seconds after the EOG event.

The EEG-transient detector is essentially identical to the EOG-transient detector described above, with the exception that the input signal is obtained from the input amplifier of the EEG analyzer (Fig. 18, section 1). The output of this circuit is, thus, a 1.5-second DC signal following each detected EEG-transient event. Output signals from the

EOG-transient detector and the EEG-transient detector then enter the EOG-transient-only detector, which is composed of a single comparator followed by a 1.4-second RC integration circuit. The comparator produces an output DC level whenever it receives an input signal from the EOG 1.5-second timer alone. No output is possible while an input is received from the EEG timer. As long as the output of the comparator remains at zero, the RC circuit is held in a discharged state. When the comparator switches on, the RC circuit begins to charge with a time constant of 1.4 seconds, and continues to do so until fully charged or until discharged by the comparator's switching off.

The RC integration-circuit output is connected to the input of the following REM-indicator output comparator, and the reference input of this comparator is biased at a voltage equal to the voltage output of the RC integration after charging for 1.4 seconds. Therefore, if an EOG transient alone occurs, the 1.5-second output pulse from the EOG timer results in a 1.5-second output from the EOG-transient-only detector, which in turn is sufficient to charge the RC circuit in excess of the reference voltage on the final comparator, and an output pulse is produced. If an EEG transient occurs within 1.4 seconds of the EOG transient, the pulse-output duration from the EOG-transient-only detector will be shortened (or completely eliminated if EOG and EEG transients occur exactly simultaneously), and the RC circuit will not charge to a voltage level sufficient to trigger the final REM-indicator output comparator. Consequently, there is a pulse produced by the REM-indicator output comparator only when an EOG transient occurs which is not accompanied by a similar EEG event.

If the disable relay (see discussion in section 4, below) is closed (as drawn in Fig. 18, section 3), the output pulse from the REM indicator triggers a 30-second resetting timer, which in turn supplies a DC level to the sleep-stage-output circuitry (Fig. 18, section 4). Since each REM output pulse resets the timer for 30 seconds, a continuous output is produced by the timer if REMs are detected with a frequency exceeding one per 30 seconds.

Within the sleep-stage-output section (Fig. 18, section 4), the REM-timer-output pulse interacts with the outputs of the 6 EEG-analyzer voltage comparators to produce the final 7-stage output of the system. Outputs of the EEG stage 1 and stage 2 comparators enter an OR gate, which produces an output whenever the EEG analyzer is in either stage 1 or 2. This stage 1 or 2 signal enters an AND gate, together with the output of the REM timer, which in turn supplies the final stage REM output signal. Therefore, the analyzer provides a minimum 30-second indication of stage REM sleep if a REM is detected while the EEG-analyzer circuitry indicates either stage 1 or stage 2 sleep. The REM signal is also inverted and used to inhibit all 6 EEG-sleep-stage outputs (6 AND gate circuits, Fig. 18, section 4) while stage REM is present, thus ensuring that only one of the 7 possible output

states can exist at any given time.

4. Artifact-Detection Circuitry

a. General. Although the EEG and EOG acquisition methods outlined in the preceding sections have been designed to minimize the occurrence of artifactual signals, it has not yet been possible to completely eliminate their occurrence. The majority of artifactual signals seen during a number of all-night studies using the electrode-cap and preamplifier assemblies have been directly related to major bodily movements of the subject. While free movement of the head itself causes almost no problems, when the subject is reclining such movements result in changing forces exerted directly on the recording electrodes at the points where contact is made with the bed. Such disturbances of the scalp-electrolyte and electrolyte-electrode interfaces result in changes in the electrode junction potentials and alteration of other characteristics of the electrodes, which are manifested as artifactual signals in the recorded data.

The purpose of the artifact-detection circuitry is to prevent signals with a high probability of artifactual contamination from influencing the sleep-stage-determination systems. This is accomplished by disabling the EEG and EOG analysis sections during and for 4 seconds following any or all of the following three events: 1) excessive EEG amplitude, 2) muscle-potential (EMG) activity in the EEG channel which exceeds acceptable limits, and 3) head movements in excess of tolerable limits (from accelerometer on recording-cap preamplifier).

b. Theory of Operation and Construction of Prototype (refer to Fig. 18, section 2, and Fig. 19, section 2)

(1) Excessive-EEG-Amplitude Detector. Disturbances of the scalp-electrode interface which occur with rapid movement of the head and/or changing forces on the electrodes usually result in low-frequency, irregular, often high-amplitude artifactual signals in the EEG channel. If such events occur when the subject is awake or in stage 1, 2, or REM sleep, the EEG-analysis section, unless disabled, will consider the high-amplitude, low-frequency artifactual signal to be delta activity, and if persistent for several seconds will deliver a false indication of a lower sleep stage (e. g., stage 3 or 4). If not persistent, a transient descent of only one stage may result (e. g., from awake to stage 1 and back), producing a false indication of drowsiness.

Because of the abrupt onset of this type of artifactual signal, when such an event occurs in the EOG channel a transient output is produced by the narrow band-pass filter (1-3 cps) which, if high enough in amplitude, will be detected by the EOG-transient detector. Unless a similar event is detected simultaneously in the EEG channel, a false indication of a REM will then be produced. If the EEG analyzer was indicating stage 1 or 2 at the time, the analyzer final output would switch to stage REM, unless disabled.

The excessive-amplitude detector minimizes the occurrence of such false indications by disabling both the EEG-analyzer section and the REM-indicator-output section during and for a 4-second period following the

occurrence of an excessively high amplitude EEG signal, thus preventing a change in the sleep-stage-output section as a result of this period of artifact.

The EEG signal is obtained after the first stage of amplification within the EEG-analysis section, and enters the artifact-detection circuitry (Figs. 18 and 19, section 3). The signal next enters a dual comparator which produces a trigger pulse if either the positive or negative phase of the EEG-channel voltage exceeds a value of 600% (the same relative amplitude scale used in the EEG-analysis section is used here - see section V, B, 2), which is considered to be in excess of the usual physiological range. The resultant trigger pulse starts the 4-second artifact-detector timer, which in turn operates the disable relay for the 4-second period. If the timer receives trigger pulses at a rate equal to or exceeding one per 4 seconds, the disable relay will remain activated continuously.

When the disable relay is activated, the EEG-analysis section is effectively disabled by disconnection of the pulse-train output of the positive and negative pulse generators from the input to the integration circuit. The discharge pathway for the integration capacitor is also removed during this time, and consequently the output of the integrator remains unchanged for the duration of the disabled period.

Activation of the disable relay also results in disconnection of the REM output indicator from the REM-timer input. Consequently, a REM detected during the 4-second (or longer) period of time has no influence on the final sleep-stage-determination section (Figs. 18 and 19, section 4).

(2) Muscle-Potential Detector. Muscle artifact in the EEG or EOG channel is usually characterized by activity in excess of 18-20 cps, and consequently, unless of extremely high amplitude, has little or no effect on the analysis results. However, the occurrence of muscle artifact is a good indication that the subject is in the process of moving his head, swallowing, chewing, etc.; consequently, during the time muscle artifact is present, there is a high probability of movement artifact occurring as well. Since not all movement artifact is detected by the excessive-amplitude detector discussed above, and cannot be readily distinguished from legitimate EEG activity, the muscle-potential detector is utilized to disable the analysis circuitry during times when movement artifact is likely to be present.

EEG activity from the first stage of the EEG analyzer (Figs. 18 and 19, section 1) is passed through a band-pass filter (20-50 cps range) in the artifact-detector section (Figs. 18 and 19, section 3) to remove most EEG components, then into a rectifier and RC integration circuit. The RC circuit has a time constant (for rise and fall) of approximately 1.5 seconds, and thus produces a DC level proportional to the intensity of activity in the 20-50 cps range (muscle activity), and supplies this level to a voltage-comparator circuit. The voltage-comparator receives a fixed voltage level at its reference input, and thus supplies an output pulse whenever the DC level proportional to muscle activity exceeds this value. Output of the muscle-potential-detector

circuit acts as a trigger to the artifact-elimination 4-second timer in the same manner as the excessive-amplitude circuit described above. Consequently, for the duration of the period of muscle-potential contamination of the EEG signal (and for 4 seconds following its cessation), the disable relay is activated, thereby preventing any change in the EEG and EOG analyzer-output status. The mode of operation of the disable relay is the same as that outlined above for the excessive-amplitude-detection circuit.

(3) Head-Movement Detector. The accelerometer contained in Assembly 2 and attached to the recording cap (Assembly 1) serves as another means for detecting periods of time when artifactual contamination is highly probable. Movement of the head results in the production of an output voltage from the accelerometer which is roughly proportional to the rapidity of the motion; thus, a high-voltage output from this device is more likely to be associated with movement artifact in the EEG and EOG channels.

Output of the dual accelerometer enters the accelerometer amplifier-filter (bandwidth, 0.1-10 cps) in the artifact-detection section of the analyzer (Figs. 18 and 19, section 2), which provides a gain of approximately 500. The amplified and filtered activity enters a dual-comparator circuit which produces a trigger pulse if either the positive or negative phase of the input signal exceeds the fixed reference values. The reference values are set experimentally during preliminary testing so that the output produced by the accelerometer when a subject turns over, while reclining in bed, is sufficient to trigger the comparator. When triggered, the comparator in turn resets the 4-second artifact-detection timer, and the disable relay is consequently activated for the duration of, and for 4 seconds following, the movement. [Principle of operation of the disable relay is outlined in section V, B, 4, b, (1), above.]

VI. Telemetry Link (Assemblies 6 and 7)

A. General

The final output of the sleep-analyzer section, as outlined above, is a series of 7 lines, each one corresponding to one of the defined states of consciousness (awake, stage REM, stage 1, stage 2, stage 3, stage 4, and abnormal). All output lines are normally held at zero potential except for the one corresponding to the current state of the subject, which is switched to +10 V. Although this format is suitable for operation of the various display devices (see VII), a more economical coding scheme is required for telemetry.

The telemetry-coding system described below has been constructed to permit operational testing of the prototype in situations where a conventional telephone or voice radio communication channel serves as the telemetry link. If flight hardware is developed, this telemetry scheme will be modified to suit the particular requirements of the existing spacecraft telemetry system.

B. Coding Scheme

The 7-stage output of the analyzer may be readily coded by 3 binary bits. Since the analyzer output rarely changes more frequently than once per

10 seconds, the required sleep-stage information may be transmitted to a distant display unit by sending one 3-bit binary code each 10 seconds. This has been accomplished in the prototype system by representing each binary bit by a specific audio frequency (tones) and by the addition of one bit (tone) as a reliability check. A 2-second burst of the appropriate tone mixture is transmitted every 10 seconds, and decoded at the receiving terminal, where the original 7-line output of the analyzer is reconstructed.

The coding scheme is arranged as follows:

Sleep Stage	Binary Code	Tone Composition			
		Bit 2 500 cps	Bit 1 1923 cps	Bit 0 1190 cps	Reliability B 741 cps
AWAKE	001	OFF	OFF	ON	ON
STAGE REM	010	OFF	ON	OFF	ON
STAGE 1	011	OFF	ON	ON	ON
STAGE 2	100	ON	OFF	OFF	ON
STAGE 3	101	ON	OFF	ON	ON
STAGE 4	110	ON	ON	OFF	ON
ABNORMAL	111	ON	ON	ON	ON

C. Theory of Operation and Construction of Prototype

1. Telemetry Coder (Assembly 6)

Conversion of the 7-stage analyzer output to the appropriately composed tone burst is accomplished by the circuitry illustrated in Fig. 21, encoder.

The encoder contains 3 gated oscillators, each composed of an operational amplifier (Fairchild 709) with an appropriate feedback network and one free-running oscillator. Each of the 3 gated oscillators supplies one of the 3 tones corresponding to one bit of the 3-bit binary sleep-stage code, while the single free-running oscillator serves as a reliability bit; thus, every stage is coded by at least two simultaneously occurring tones.

Each of the 3 gated oscillators is turned on by a positive (true) output from its associated 4-input OR gate (1N914 diodes). If the OR-gate output is 0 (false), the corresponding oscillator is held in the off state. Each of the 7 input lines (sleep-analyzer outputs) connects to an input of one or more of the 3 OR gates, so that the OR-gate outputs correspond to the specified binary code (see table, section B, above). For example, if the analyzer is indicating "awake," only the OR gate associated with the 1190 cps oscillator (bit 0) is enabled, while if the analyzer is specifying "abnormal," all 3 OR gates are enabled (bits 0, 1, and 2).

The outputs of all oscillators, including the continuously running reliability oscillator (741 cps) are led to the gated mixer amplifier (2N3565 and associated components) which in turn supplies a composite output signal to the data-transmission channel (telephone line or radio transmitter)

when it is enabled by the sample-gate circuit.

The sample gate consists of an asymmetrical, astable, multi-vibrator circuit which supplies a 2-second-duration enable pulse to the gated mixer amplifier with a repetition rate of one pulse per 10 seconds. The final output of the encoder is consequently a 2-second composite-tone burst each 10 seconds.

2. Telemetry Decoder (Assembly 7)

Reconversion of the coded audio-tones signal back to the original 7-state-output format of the sleep analyzer is accomplished in a manner which is essentially the reverse of the encoding procedure (see Fig. 21, decoder). The composite signal received from the telemetry-data channel (telephone line or radio receiver) is led to four narrow band-pass filters, each tuned to one of the specified coding frequencies (i. e., 1190 cps, 1923 cps, 500 cps, and 741 cps). The output of each band-pass filter drives the input of a comparator circuit whose reference input is held at a value which is well above the noise level but below the peak value of the amplifier output at the time it is receiving a tone of the specified frequency. The normally zero-level output of each comparator therefore becomes a train of +3 V pulses when a signal corresponding to the filter's peak frequency is received from the data channel. Each comparator output is therefore equivalent to one bit of the original binary code (see encoder section, above), and the presence of an output-pulse train is equivalent to a binary 1.

The output of each comparator enters an RC integration circuit (time constant = 2 seconds) whose voltage level is in turn sensed and amplified by a field-effect transistor (TIS68). The amplified output thus begins to increase in voltage exponentially with a time constant of 2 seconds when a tone of the proper frequency is received (comparator supplies pulses to integration circuit), and similarly decays to zero after the comparator output returns to zero with the cessation of the tone burst.

The amplified integration output from each of the 4 channels enters a voltage-comparator circuit whose reference level is set to a value equal to the voltage of the integration output at a point in time one second after onset of a received tone whose frequency matches that of the associated analog filter.

The output of the voltage comparator is thus a DC pulse which begins one second after onset of an appropriate tone, and which persists for approximately two seconds. The output of this stage indicates that a tone of the proper frequency has been received for at least one second, thereby eliminating the possibility of false triggering by transients and noise which could be inherent in the telemetry-data channel.

The output signals of the comparators for bits 0, 1, and 2 are also inverted, and the normal and inverted outputs are led to the 6 AND-gate circuits, using the logical scheme illustrated in Fig. 21, along with the output from the reliability-channel comparator. In addition, the normal outputs of bit 0, 1, and 2 comparators are led to a single OR gate, which in turn serves as

one input to AND gates 2, 4, and 6.

The logic circuitry above (6 AND gates, single OR gate) serves to activate the 3 bistable circuits (Fairchild 902) which act to store the binary code representing the current sleep stage between received telemetry signals; i. e., the bistable circuits are properly set during reception of the 2-second tone burst and retain this condition until the next 2-second tone burst, thus supplying a continuous indication of sleep stage to the display circuitry, in spite of intermittent transmission.

All 6 AND gates are disabled in the event the single reliability tone is not received, and, in addition, the OR gate prevents any bistable from being reset unless at least one true output is present from the bit 0, 1, and 2 comparators. As a result, the bistable circuits are changed only if the reliability tone and one or more other tones are simultaneously present, and the received code is different from the one currently held in the 3 bistables.

The 3-bit binary code retained in the 3 bistable circuits is continuously decoded by the final 7 AND gates (Fig. 21) which supply a 7-line output configuration (corresponding to the 7 output lines of the onboard analyzer) in which all lines are at zero potential except the one corresponding to the current sleep stage, which is switched to +10 V.

VII. Display Console (Assemblies 8 and 9)

A. General Description

These assemblies accept the output lines from the telemetry decoder (Assembly 7), and provide a visible display of the current sleep stage (Assembly 8), a cumulative display of the total amount of time spent in each stage (Assembly 8), and a stepwise graphic recording of the subject's sleep stage versus time (Assembly 9).

B. Theory of Operation and Construction of Prototype (see Fig. 22)

1. Sleep-Stage-Indicator Lamps (Assembly 8)

Upon entering the display console, each of the 7 output lines from the telemetry decoder (Assembly 7) is connected to the base of a lamp-driver transistor (2N3565). The transistors are held in the off state by the presence of a zero-level signal in the input line, and are switched on (thereby illuminating the associated panel lamp) when the input line switches positive (+10 V). Since all inputs will normally be at zero, except for the single line which corresponds to the sleep stage, only one lamp will be activated at any time, permitting the observer to readily determine the current sleep status of the subject.

2. Cumulative-Stage-Time Indicators (Assembly 8)

In association with each of the stage-indicating panel lamps is a cumulative-time indicator which runs continuously while the respective lamp is illuminated.

The lamp-driver transistor for each stage also serves to activate the timer-relay circuit. Each of the 7 timer circuits is composed of two transistors (2N3646 and 2N2270) and associated components, and

provides a fixed delay between the onset of a particular sleep stage and the closure of the relay contacts which start the appropriate elapsed-time indicator. This delay time is approximately 0.5 second and is necessary to compensate for the inertial "coasting" effect when the elapsed-time indicator is turned off.

The input line from the lamp-driver transistor collector of the timer-relay circuit is normally at +10 V (lamp off), and this voltage is applied to the basic circuit of each of the two timer-relay transistors which are consequently held in the on state. The on condition of the 2N2270 transistor results in activation of the timer relay, thereby turning the associated elapsed-time indicator off. Since the 2N3646 transistor is also held on, the 200 μ f capacitor between the 2N2270 base and the 2N3646 collector is charged positively on the 2N2270 side.

When the signal representing the appropriate sleep stage occurs, the lamp-driver transistor turns on, driving the voltage at its collector and at the bases of the two timer transistors to zero. Transistor 2N3646 is turned off immediately, but 2N2270 is held on by the charged 200 μ f capacitor connected to its base, and remains on until the capacitor discharges and recharges in the opposite direction (time $\approx$ 0.5 second). When the 2N2270 switches off, the relay switches to the off state, and the resulting contact closure turns the elapsed-time indicator on.

Each elapsed-time indicator thus keeps a cumulative record of the amount of time the corresponding panel-indicator lamp is illuminated, and this value is equivalent to the total amount of time occupied by that particular stage of sleep.

3. Sleep-Profile Display (Assembly 9)

This assembly provides a continuous graphic record of the subject's sleep-stage fluctuations versus time throughout the sleep period. An adder circuit converts the 7-line digital output of the telemetry decoder (Assembly 7) to a stepwise analog output voltage which is proportional to sleep stage (awake = highest output level; abnormal = lowest output level), and this voltage is used to activate the vertical axis of the graphic recorder, which runs at a very slow paper speed (approximately 3 mm/minute).

Each of the 7 input lines from the telemetry decoder activates a transistor switch in a manner similar to that of the lamp-driver transistor circuit. Thus, in the normal or off condition, each collector of the adder-driver transistors is at +10 V, and this condition switches to zero when the appropriate input line is activated (subject is in that stage of sleep). The collectors of all 7 drivers connect to the operational amplifier, which serves as the addition circuit, through potentiometers. The potentiometers are adjusted so that a different output level results from the adder circuit with activation of each of the 7 sleep-stage-input lines. Thus, the awake state produces the highest output voltage, and the abnormal state the lowest, with the other stages occupying intermediate levels. As the subject sleeps, a stepwise progression of voltage changes is thereby produced by the adder, and this

output is further amplified by the power amplifier circuit, which in turn drives the pen motor of the graphic recorder (MFE MDL M-28).

The graphic recorder runs at a constant speed (7"/hour), and thus a graphic plot or profile is formed which illustrates the subject's fluctuation in sleep stage versus time.

VIII. Total-System Performance

A. General Description

The existing complete prototype or "breadboard" system is shown in Fig. 23. The recording cap (Assembly 1) and attached preamplifier unit (Assembly 2) are visible in the foreground, and these components are connected to the control panel assembly (left foreground) by the 4' flexible cable. The control-panel-assembly container also includes the magnetic-tape recorder (Assembly 4). A short cable connects the control-panel assembly to the sleep analyzer itself (Assembly 5, right foreground), which also contains the telemetry coder (Assembly 6).

The ground-based monitoring console is shown in the background, and includes the indicator lamps and elapsed-time meters which are visible on the front panel (Assembly 8); it also contains the telemetry decoder (Assembly 7) and the graphic recorder (Assembly 9).

Fig. 24 is a photograph of the recording cap (Assembly 1) and preamplifier (Assembly 2) in actual use on a test subject.

B. Summary of Operational Testing

1. General

Although the current contract period has seen a continuous evolution of the sleep-analysis system from a relatively limited EEG analyzer to the present complete acquisition-analyzer-display system, a number of operational tests have been carried out which have demonstrated the capability of the various assemblies.

A number of initial tests were carried out in the laboratory to evaluate the reliability of the EEG-analysis portion of the system. Comparisons were made between the analyzer output and the results of expert human interpretation of the same sleep-EEG recordings. An example of such a comparison is illustrated in Fig. 25, where the analyzer analog (integrator) output is shown above, the analyzer sleep-stage output in the center, and the human interpretation below. (Note: This comparison is made with the EEG analyzer only; i. e., the artifact-detection circuitry and the REM-detection circuitry were not operational.) When a point-by-point statistical comparison is made between such plots of analyzer-versus-human interpretations, using a 10-second sampling rate, the agreement ranges between 70% and 85% when each stage is given equal weight. Furthermore, when discrepancies exist, they usually involve a borderline situation; i. e., most errors are within one stage.

Addition of the other component assemblies to the system has improved the reliability and has permitted the addition of stage REM, as illustrated in Fig. 26, which shows the all-night sleep profile of a test subject

2. Tektite I Project

a. Introduction. The Tektite I Oceanographic Project, which was a 60-day study of man's ability to work effectively on the ocean floor, provided an opportunity to test operationally the prototype EEG-analysis system. It was decided to attempt to record, and analyze on-line, the sleep patterns of one member of the Tektite crew during the initial 10 days and again during the final 10 days of the 60-day mission.

b. Equipment Evaluated

(1) Electrode Cap. The electrode cap developed by Dr. W. R. Adey (NASA contract NAS 9-7282) and tested by Dr. P. Kellaway (NASA contract NAS 9-7237) was used with only minor modifications during the initial 10-day recording period. Further changes which became necessary in the electrode system, and which led to early development of the recording cap described in this report, are noted below.

(2) Automatic EEG Analyzer. This system was essentially the same as Assembly 5 (section V, above), but did not include the artifact-detection circuitry or telemetry interfaces. EOG was recorded, and REMs were distinguished by means of a simple analog-filter and amplitude-detection circuit. (The REM-detection circuitry described in this report was not yet operational.)

c. Results

(1) Electrode Cap. Although the quality of EEG and EOG recordings was good, the cap resulted in considerable discomfort after the first night, and was so poorly tolerated by the subject on successive nights that its use was suspended on nights 9 and 10, and conventional EEG electrodes were substituted (applied by other crew members).

Between the first and second 10-day recording periods, an extensive redesign of the electrode-cap assembly was made in an attempt to improve the comfort problem while still maintaining the prime requirements of durability, non-irritability, and satisfactory data acquisition. The major change was made in the electrode itself by reducing its size to 1/3 the original length and removing all rigid plastic components. The sponge was reduced in size and permanently attached to the housing. This electrode thus compromised separation of body fluids and electrode — a feature of the original model — in favor of a flatter, more comfortable shape.

The model 2 cap was worn by the subject during recording nights 50-58. A considerable improvement in comfort was reported by the subject ("80% better"), although he did continue to experience some discomfort in the scalp areas contacted by the electrodes. During the last day he also reported the presence of swellings or "bumps" in the occipital areas, which he felt were related to the electrodes. The quality of the recordings continued to be good, and the increased comfort permitted uninterrupted records during this final period of the project.

After completion of the Tektite project, further modification was made in the cap to increase comfort, and the final design is described in this report.

(2) Performance of Analyzer. In general, this system worked satisfactorily, and no major problems were encountered in the electronic circuitry. Although the significance of alterations in sleep patterns was not the primary goal of our participation in the Tektite project, the data analyzed on-line by the system permitted detection of some points worthy of further consideration.

(a) Time to Fall Asleep (Fig. 27). Fig. 27 shows the amount of time which the subject spent in bed before falling asleep for the first time. This time was measured from the point at which he was observed to get into the bunk until the first EEG signs of stage 2 sleep (vertex transients and spindles). Thus, for this measure, brief periods of drowsiness (stage 1) were included in the cumulative time.

The subject thus experienced no difficulty going to sleep during the first 10-day period, although the time does not appear to be significantly shorter than the baseline times. During the final days of recording, however (nights 56 and 57), there was a marked increase in the time before sleep onset — in both cases, exceeding an hour.

It might be postulated that perhaps this increase in time before sleep onset was related to the anticipation of events associated with the end of the mission.

(b) Total Sleep Time. Although the data are incomplete for the first 10 nights because of the electrode-cap problems, in general the subject's sleep time was considerably reduced below the baseline values during the first 10 nights, while the time during the final 10-day period was generally normal or more than normal (Fig. 28). This situation reflects the workload of the subject, which was heavy during the initial part of the project when a number of minor difficulties were present and night watches were required, and which was relatively light during the final phases when most systems were running smoothly.

(c) REM Time. Although the total sleep time was generally reduced below normal during the first 10 days, as indicated in Fig. 29 there was a definite tendency for the total REM time to approach the baseline values (compare Figs. 28 and 29). This effect is seen more clearly in Fig. 30, which shows the percentage of total sleep time occupied by the REM stage. It is obvious in this figure that there was a marked increase above the baseline values in the percent REM time during many of the nights in the first 10-day session. During the final 10 days, the percent REM time was similar to or slightly below baseline values. The significance of this finding is unknown, but, again, it could be related to the increased workload, and perhaps stress, of the initial portion of the project.

(d) Conclusions. The operational testing situation provided by the Tektite project led to three major conclusions or accomplishments:

(i) The compatibility of all phases of the EEG acquisition and analysis system was assured, and no significant problems were encountered with respect to extraneous electrical interference.

(ii) The problems encountered with the electrode-cap assembly in the early phases of the mission led to extensive redesign and miniaturization of this unit. Further improvement since the end of the Tektite project has resulted in a much more satisfactory recording cap with respect to wearer comfort and ease of application.

(iii) The performance of the automatic-analysis system demonstrated the ability to obtain reliable information concerning the subject's quantity and quality of sleep. Because of the immediate availability of the results, this information could theoretically be utilized to optimally regulate the subject's next work/rest period.

3. Grumman/Piccard Gulf Stream Drift Mission (Ben Franklin Project)

a. General. This project provided an opportunity to test operationally certain components of the total sleep-monitoring system. The Grumman/Piccard PX-15 deep-sea submersible vehicle (the "Ben Franklin") carried out a 5-week, free-drift experiment in the Gulf stream while its 6-man crew carried out a number of oceanographic, geological, and biological research objectives.

b. Equipment Evaluated

(1) Electrode Cap. This assembly was revised following the Tektite project, and the newer model was considered to be more satisfactory in terms of personal comfort.

(2) Electrode-Testing System. An early version of the automatic electrode-testing device described in this report was to be evaluated.

(3) Tape-Recording Assembly. A self-contained (battery powered) amplification and recording unit was constructed which contained the Gemini magnetic-tape recorder (see description in section IV, above).

c. Objectives and Scope. EEG and EOG were recorded from one selected crew member during approximately one-half of the scheduled sleep periods. The data so recorded were analyzed after completion of the voyage by utilizing the automatic sleep-analysis system, and were compared with control records obtained in the laboratory before the mission.

d. Results

(1) General. Recording was attempted during 15 nights of the 31 total scheduled periods. Satisfactory data were obtained on 10 of the nights (mission days 1, 2, 3, 5, 6, 10, 14, 17, 21, and 23). A power failure in the circuit supplying power to the magnetic-tape recorder occurred on day 4, and these data were lost. Although recording was apparently accomplished

satisfactorily on days 25, 27, 29, and 30, no data were recorded in retrievable form on the magnetic tape (possibly due to an error in tape threading).

(2) Total Sleep Time. Analysis of the recorded EEG and EOG activity revealed no disturbance in the total sleep time during the recording nights except for the first day, when the subject slept only (approximately) 5 hours. Fig. 31 illustrates this finding in graphic form, and provides a comparison with the results of three pre-mission baseline recordings obtained approximately one month prior to the voyage.

(3) Time to Fall Asleep (Stage 2). A marked increase in the sleep-onset latency was seen during the last four recording nights (mission days 14, 17, 21, and 23) (see Fig. 32), both in comparison with the three baseline nights and with the initial nights of the mission. This observation is also evident in the measurement of time required to attain stage 4 sleep, as illustrated in Fig. 33.

(4) REM Periods. Both the number of REM periods (Fig. 34) and the number of sleep cycles (Fig. 35) tended to increase progressively during the course of the mission, starting somewhat below the baseline level but eventually reaching values considerably above it.

(5) Recording Cap. The subject experienced no significant discomfort while wearing the cap, and successful recordings were obtained during all periods except those lost through recorder malfunction. Some visible skin irritation was noted by the subject in the areas of the EOG electrodes after several days of cap use, and this resulted in further modification of the shape of the recording electrodes.

e. Conclusions

(1) Problems related to the comfort of the electrode cap were found to be negligible.

(2) The suitability of the magnetic-tape-recording apparatus was proven.

(3) The automatic-analysis system was used successfully in evaluating the subject's sleep status, and permitted rapid detection of long-term alterations in sleep pattern throughout the mission

4. A Study of the Effects of Spacecraft Noise on Sleep

The automatic sleep analysis was utilized to carry out a study of the effects of spacecraft noise on the sleep of crew members. A complete report of the methods and results of this project is included in the Appendix.

Acknowledgments

Work completed during the contract period was made possible by the collaboration of a number of members of the Section of Neurophysiology, Baylor College of Medicine, and the Neurophysiology Department, The Methodist Hospital, Houston, Texas. Mr. Kenneth Nevill and Mr. Carl E. Hillman, Jr., participated extensively in the design and construction of the prototype system, and Mrs. Sandra Strickler was responsible for documentation and illustrations, and assisted during many of the experimental procedures. Dr. Peter Kellaway, Chief, Section of Neurophysiology, Baylor College of Medicine, and Director, Department of Neurophysiology, The Methodist Hospital, provided the necessary clinical evaluation of the results of the automatic analysis.

Notes

1. Gem Manual Hole Punch, McGill M. P. Co., Marengo, Ill.
2. Caltron Industries, 2015 Second St., Berkeley, Calif.; type #3003-028029, 1 cond., 29 AWG, silicone insulated.
3. Ersin multicore five-core silver alloy solder, Multicore Solders Ltd., Hempstead, Hertfordshire, England.
4. Vyna-Kote, Precoat, Spectra-Strip Wire and Cable Corp., P. O. Box 415, Garden Grove, Calif.
5. Vyna-Kote Red Liquid Vinyl, Spectra-Strip Wire and Cable Corp., P. O. Box 415, Garden Grove, Calif.
6. Silastic-A RTV mold-making rubber base, Dow Corning Corp., Midland, Mich.
7. Silastic-A Catalyst #4, Dow Corning Corp., Midland, Mich.
8. Silastic S-5370 RTV silicone-rubber foam base, Dow Corning Corp., Midland, Mich.
9. Silastic S-5370 Catalyst, Dow Corning Corp., Midland, Mich.
10. G. E. RTV 112 White Silicone Rubber Adhesive, General Electric Co., Waterford, N. Y.
11. Vyna-Kote Red Liquid Vinyl, Spectra-Strip Wire and Cable Corp., P. O. Box 415, Garden Grove, Calif.
12. Vyna-Kote Clear Liquid Vinyl, Spectra-Strip Wire and Cable Corp., P. O. Box 415, Garden Grove, Calif.
13. A suitable electrolyte solution contains the following: NaCl, 1.36 g; KCl, 0.08 g; $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, 0.04 g; $\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$, 0.3 g; KH_2PO_4 , 0.002 g; Natrosol-250, 2.5 g; polyvinylpyrrolidone-K90, 2.0 g; Zephiran chloride concentrate, 2 ml; H_2O to make 100 cc total solution volume.
14. Some loss of fluid content can occur with the passage of time because of the slight permeability of the vinyl coat to water vapor, particularly if the completed electrodes are stored in a low-humidity environment. This effect may be eliminated by storing a number of completed electrodes or electrode assemblies in sealed polyethylene bags, or by utilizing a coating material with lower water-vapor permeability.
15. Nylon-Spandex XK-56292 or XK-56295, Ashaway Textile Mills. Office: 90 Park Avenue, New York, N. Y. 10016.
16. MIK6-1-7PH, ITT-Cannon Electric Co., 415 Airways Bldg., Exchange Park, Dallas, Tex. 75235.
17. No. 260-3816, MicroDot Inc 220 Pasadena Avenue. South Pasadena. Calif. 90130.

Figures

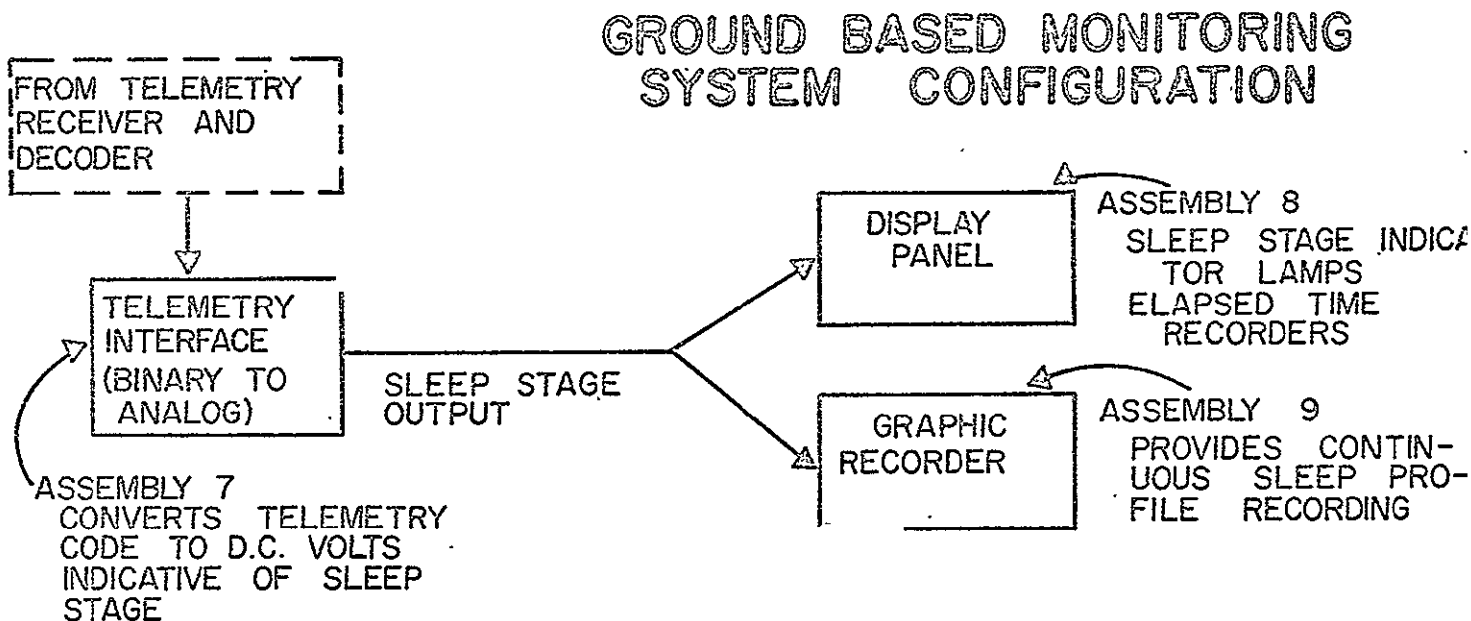
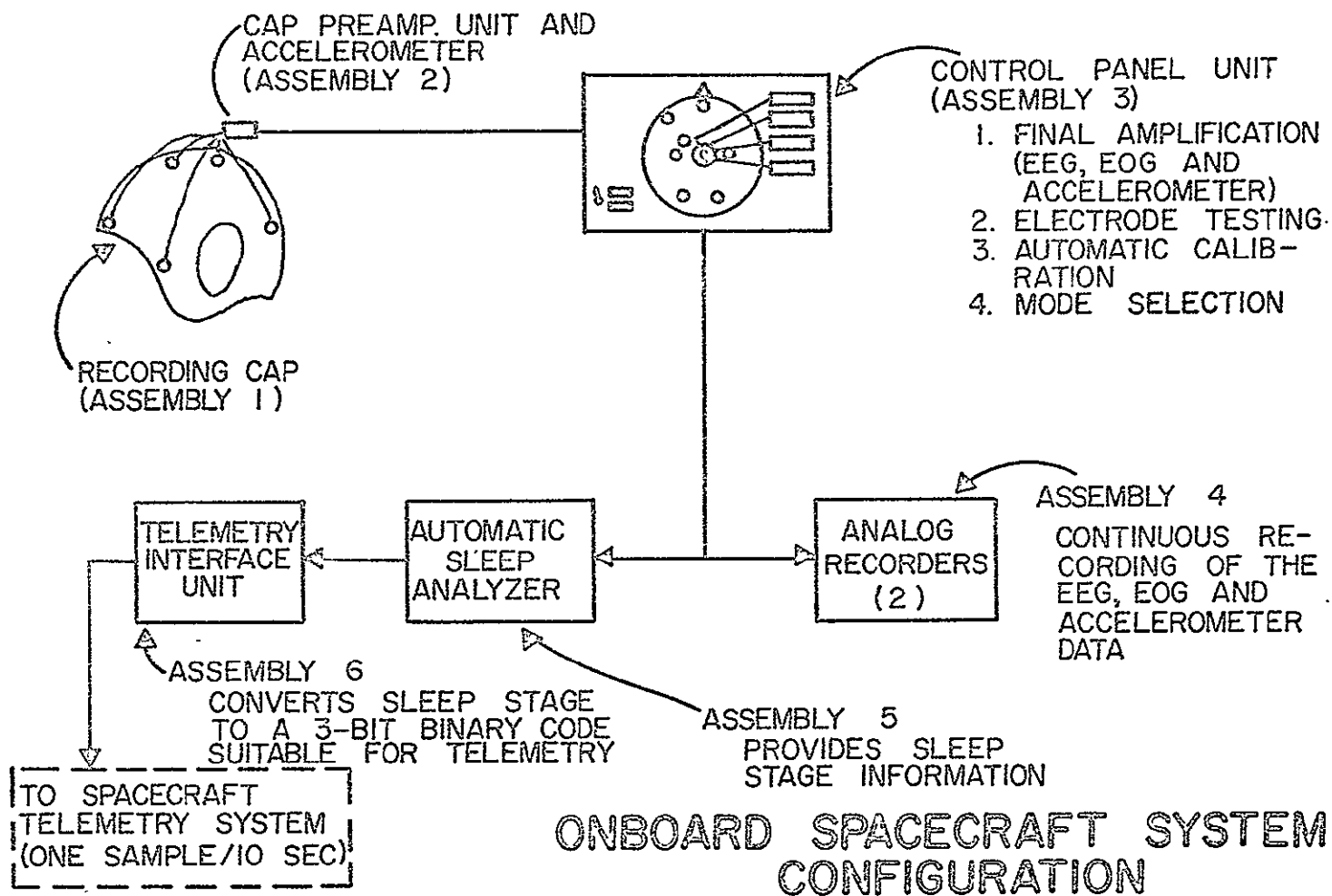


FIG. 1
BLOCK DIAGRAM OF PROTOTYPE SLEEP ANALYSIS SYSTEM

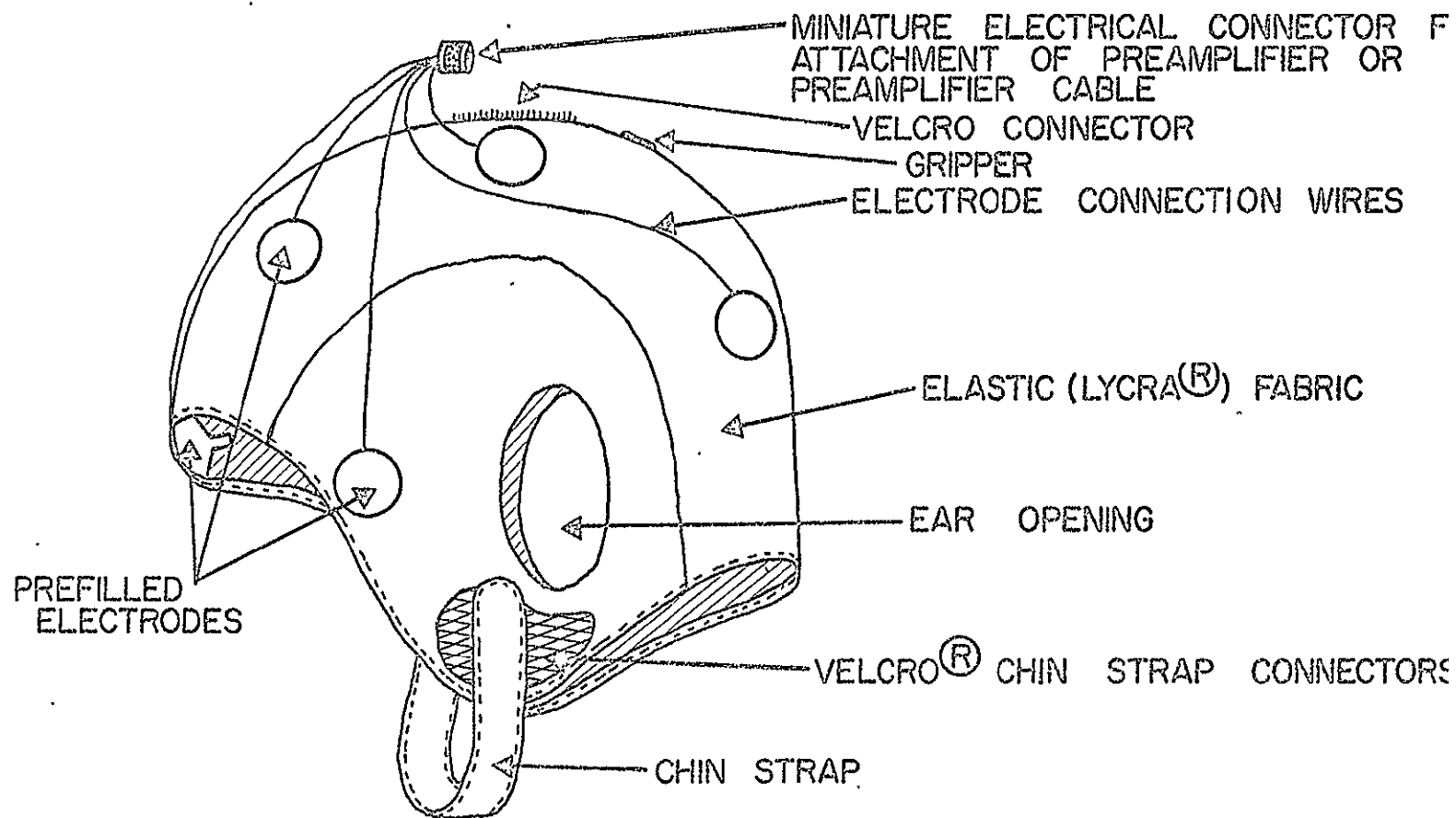
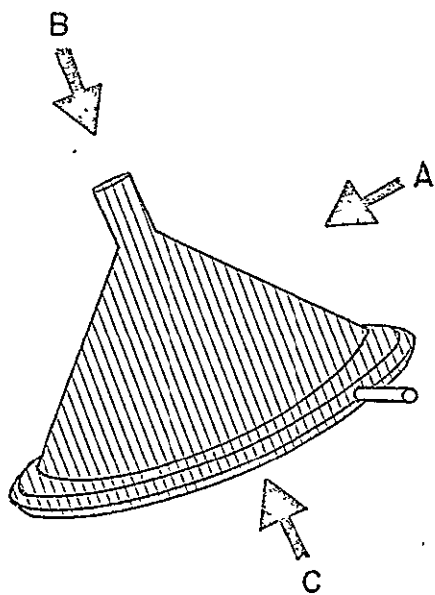
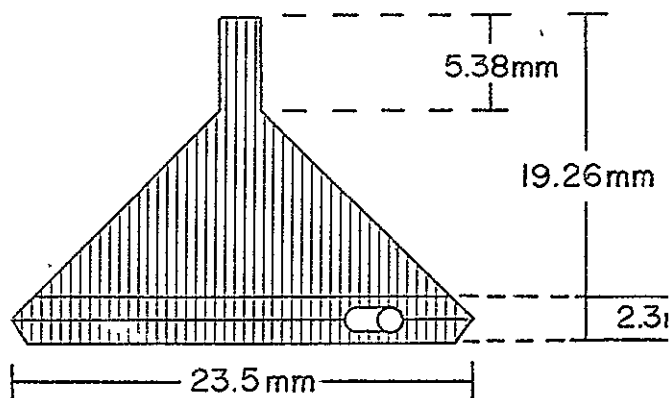


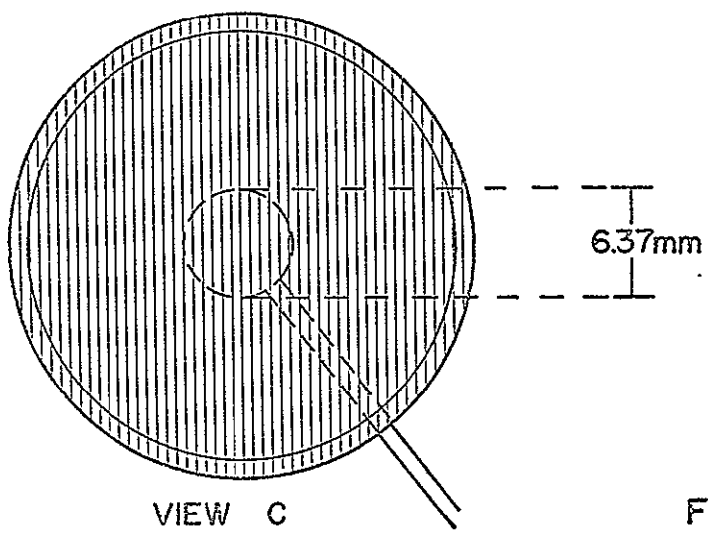
FIG. 2
EEG RECORDING CAP



GEOMETRICAL VIEW

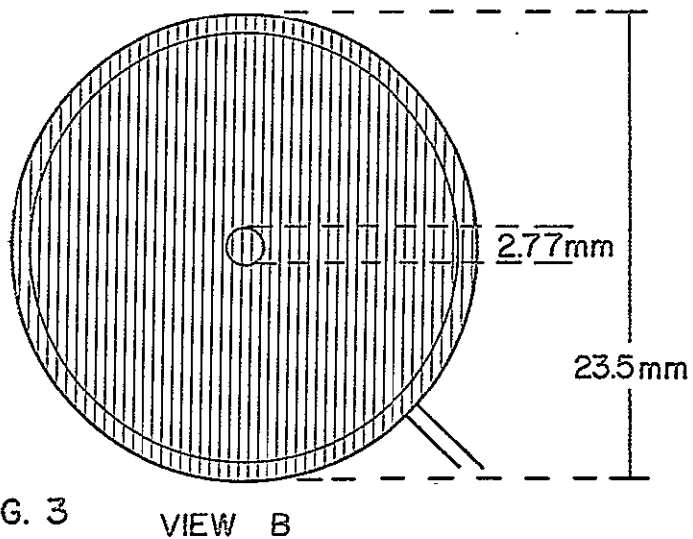


VIEW A



VIEW C

FIG. 3



VIEW B

CONSTRUCTION VIEW (without vinyl coating)

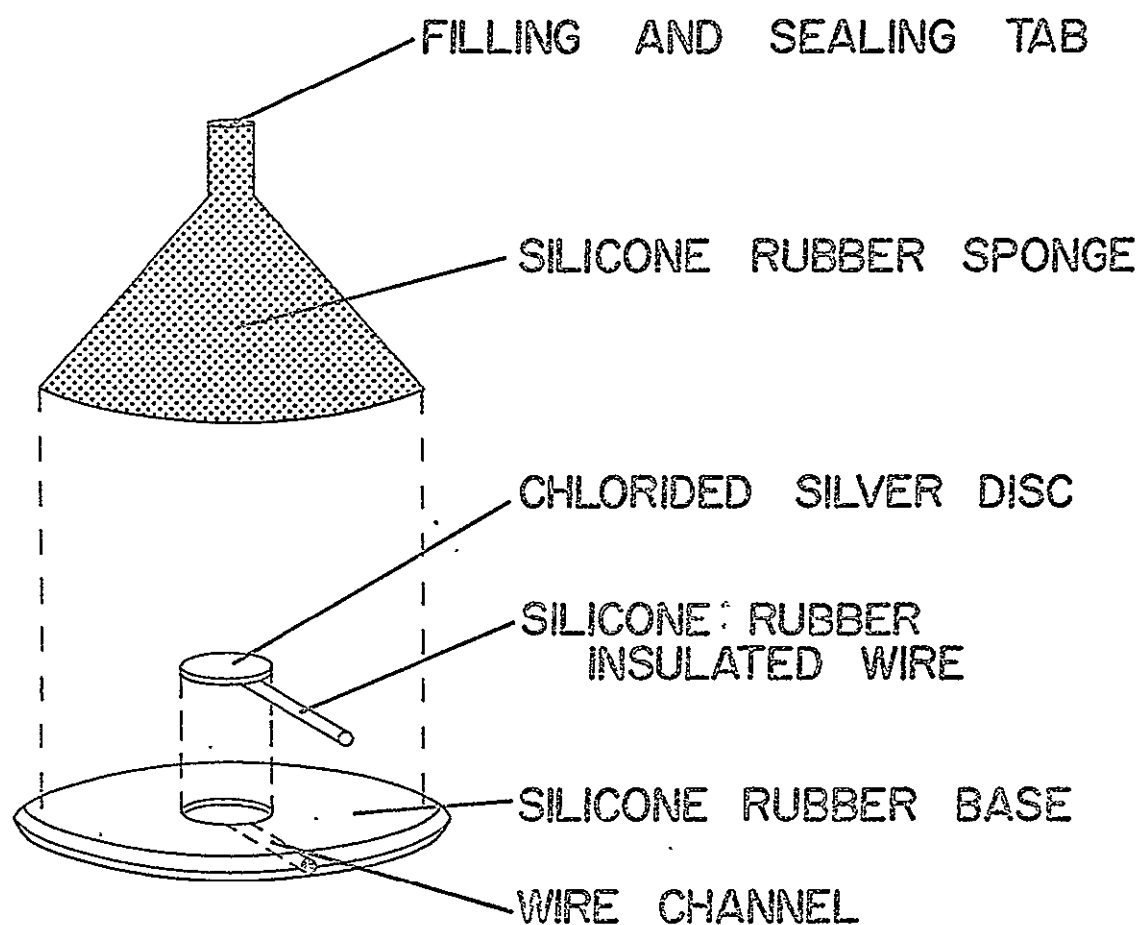
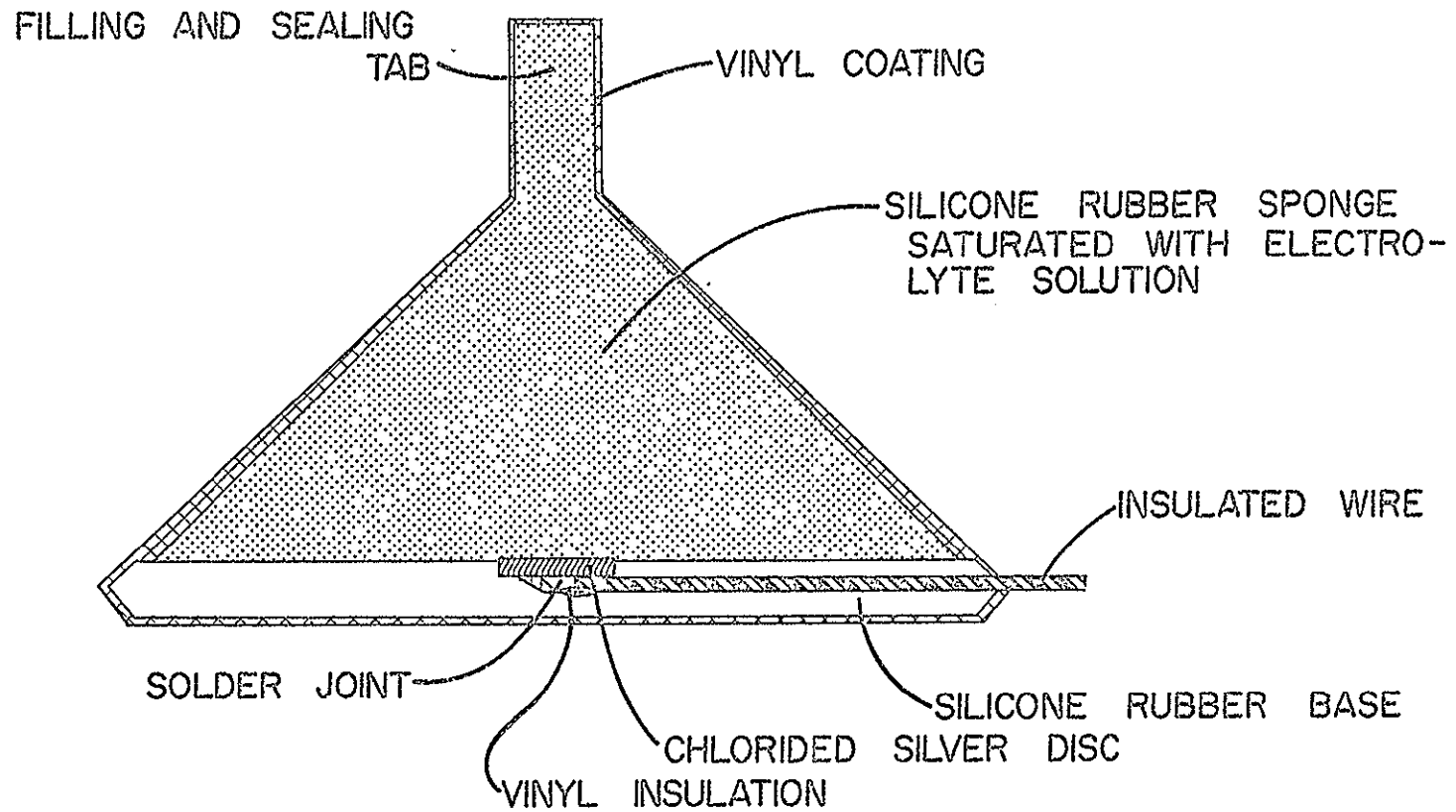


FIG. 4



CROSS SECTION OF
PREFILLED SPONGE ELECTRODE

FIG. 5

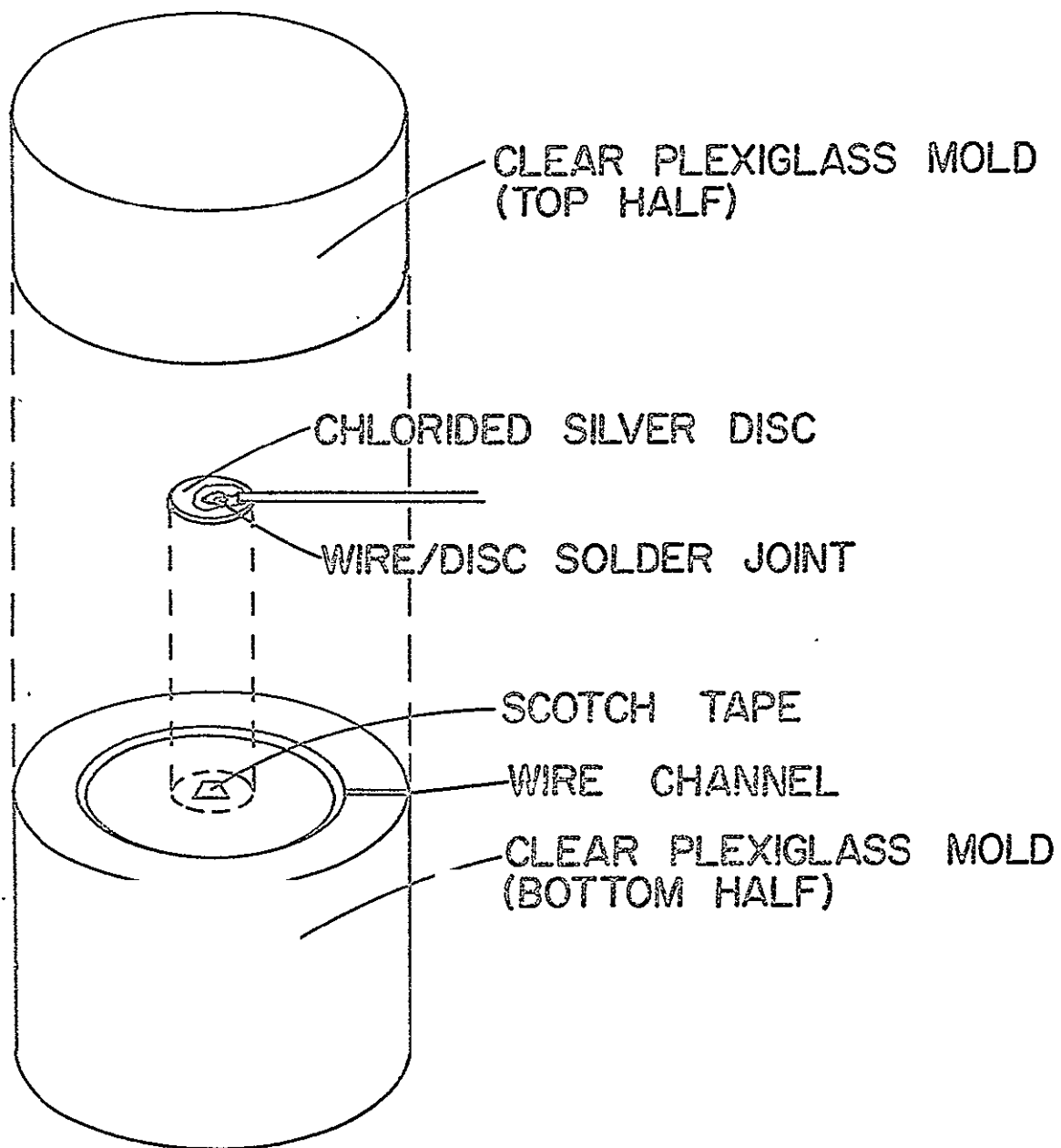


FIG. 6
MOLDING PROCEDURE FOR SILICONE RUBBER BASE

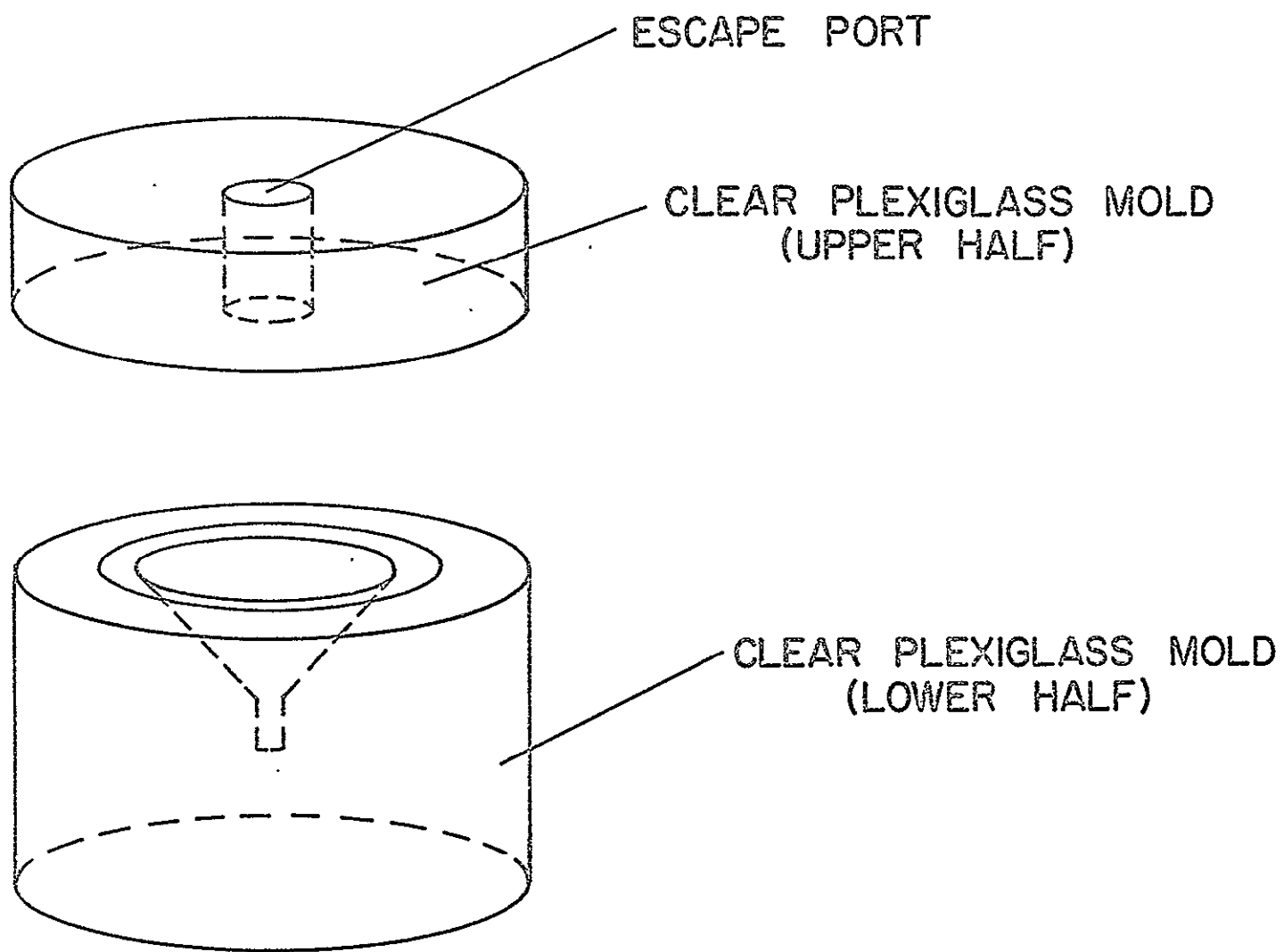
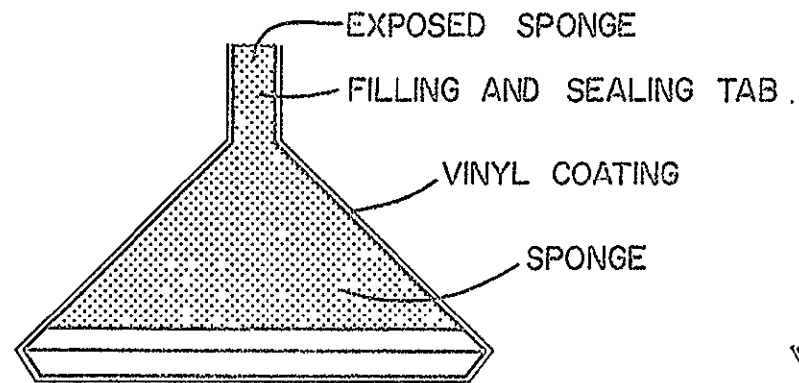


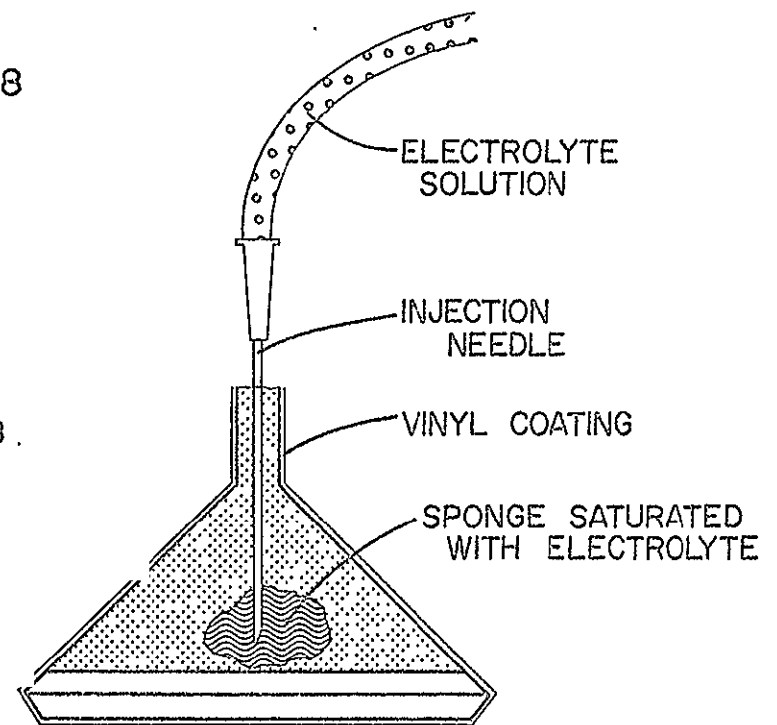
FIG. 7

MOLDING PROCEDURE FOR SILICONE RUBBER SPONGE

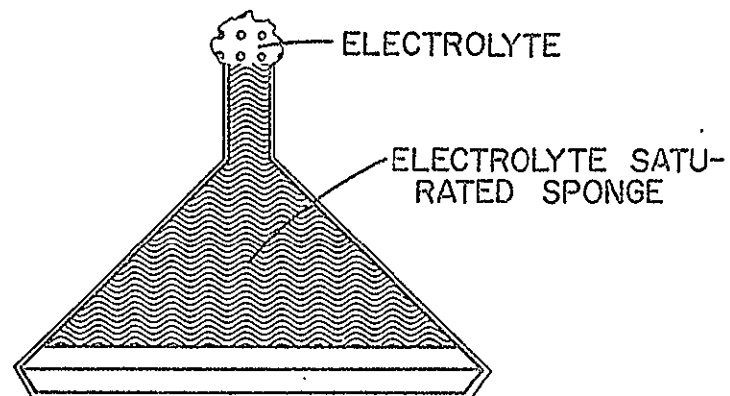
FIG. 8



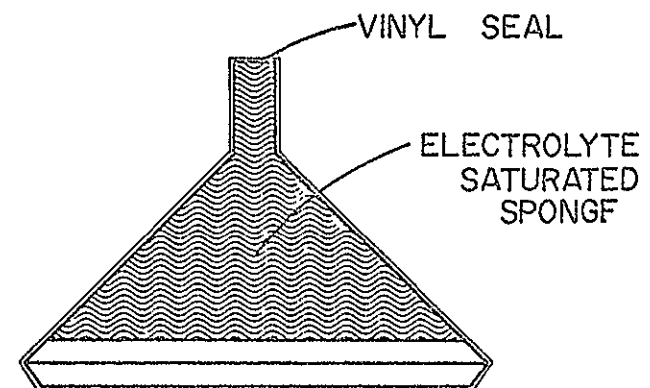
A. UNFILLED ELECTRODE



B. INJECTION OF ELECTROLYTE



C. FILLED ELECTRODE



D. FILLED, SEALED ELECTRODE

RECORDING CAP PATTERN

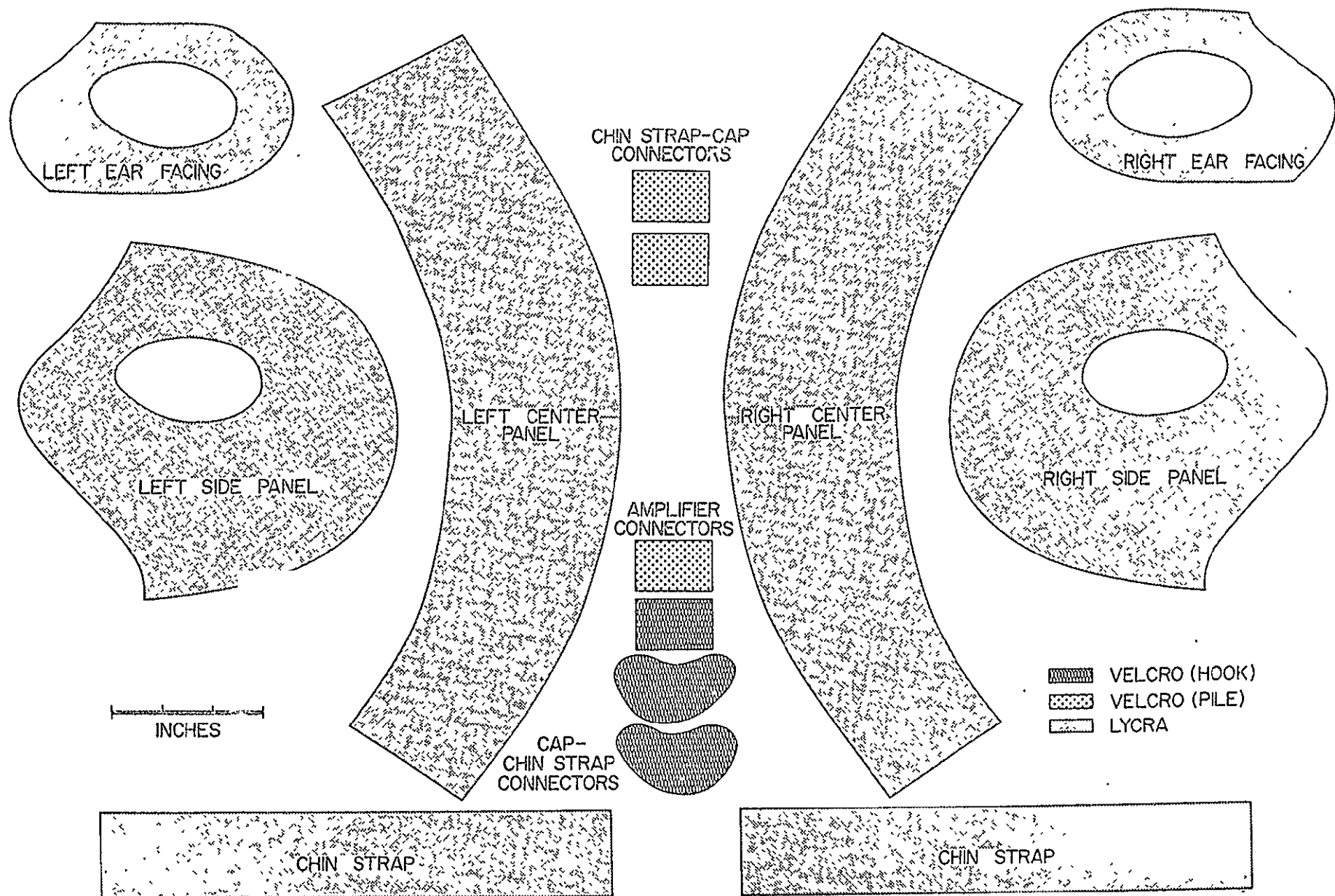


FIG. 9

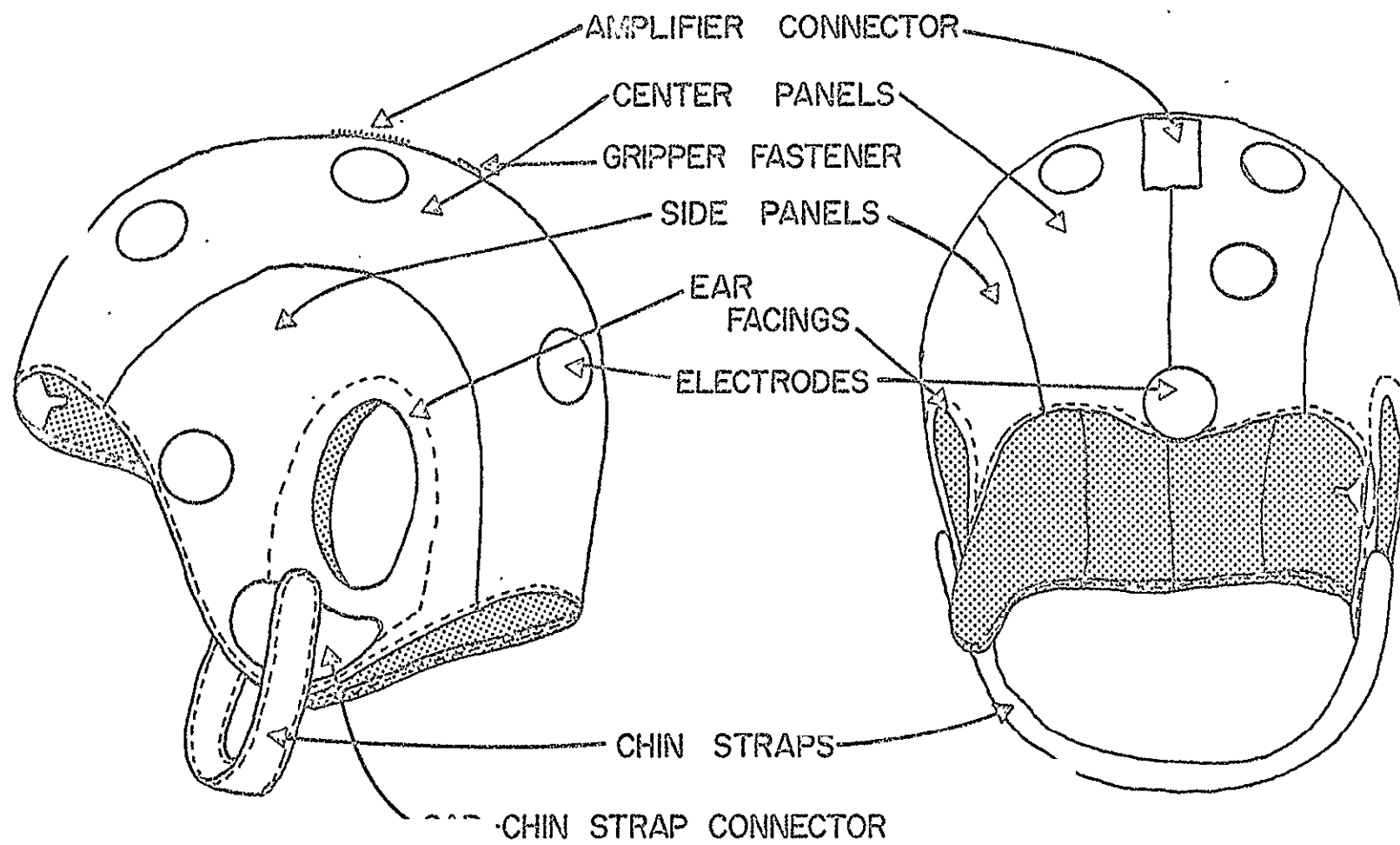
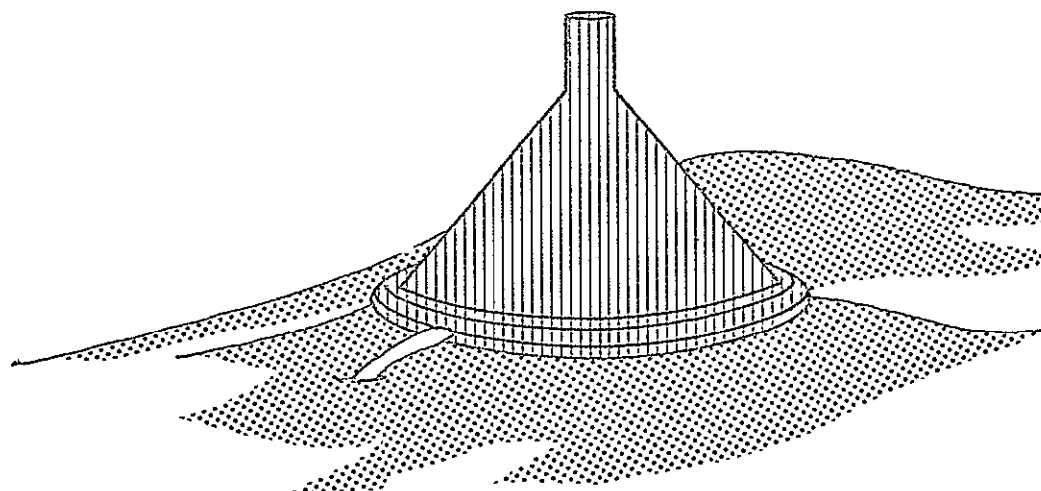
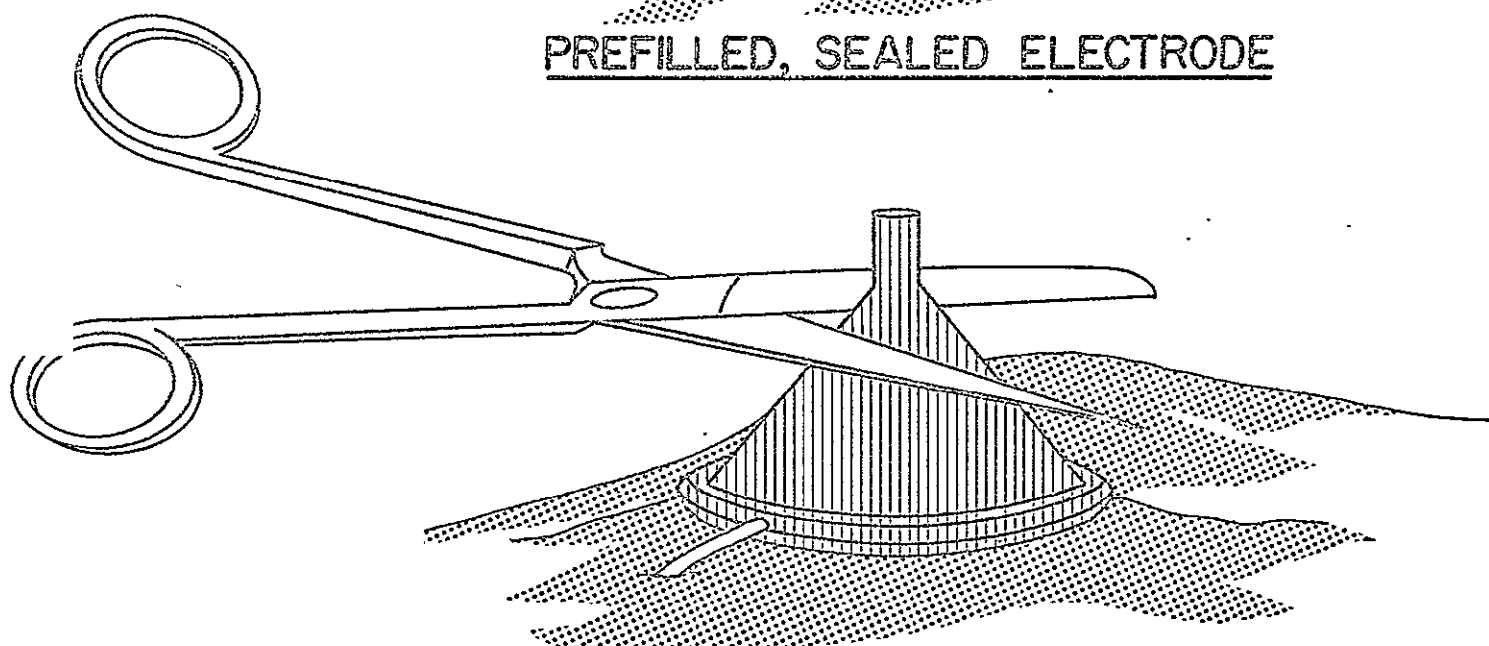


FIG. 10
CAP CONSTRUCTION

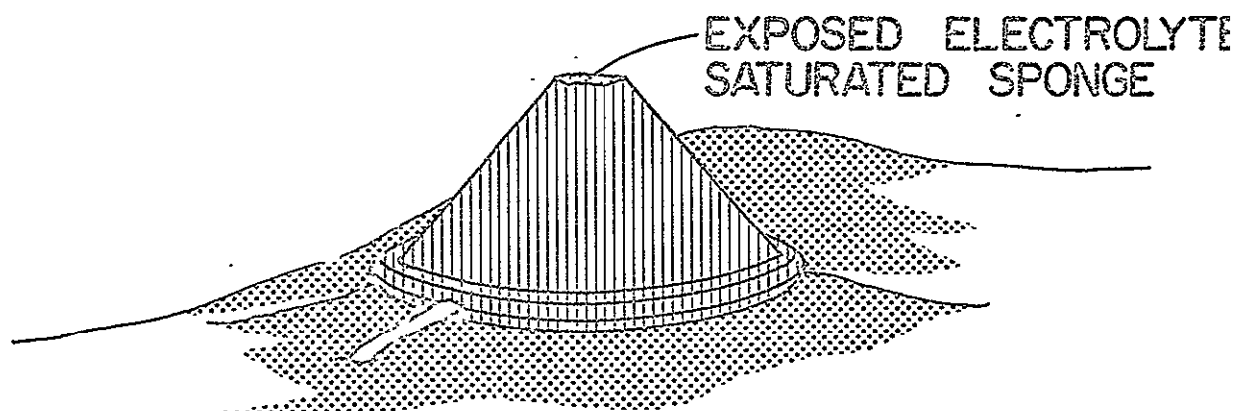
PREPARATION OF ELECTRODE FOR USE



PREFILLED, SEALED ELECTRODE



REMOVAL OF SEALING TAB



PREPARED ELECTRODE

ONBOARD FLIGHT SYSTEM

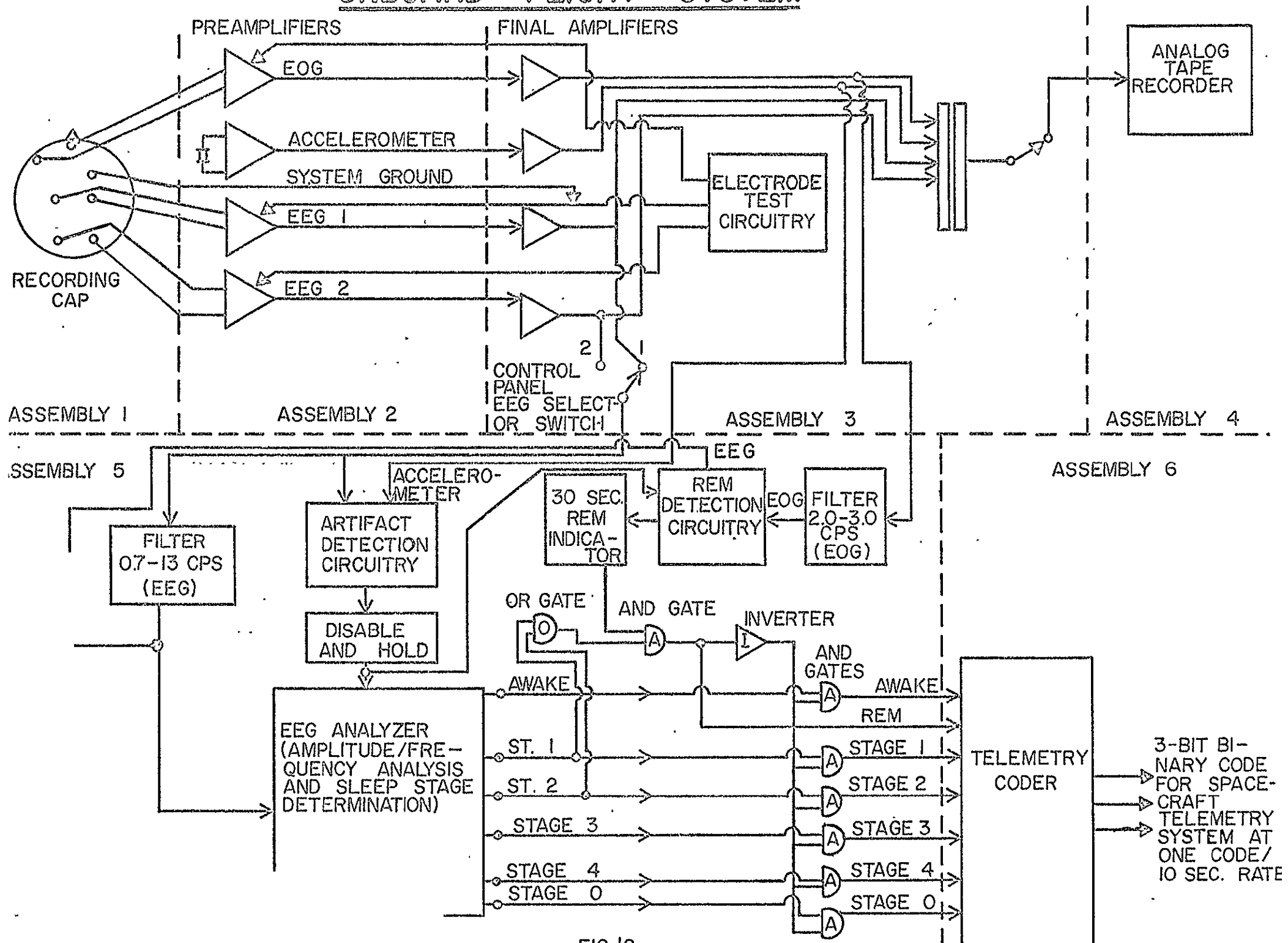


FIG 12

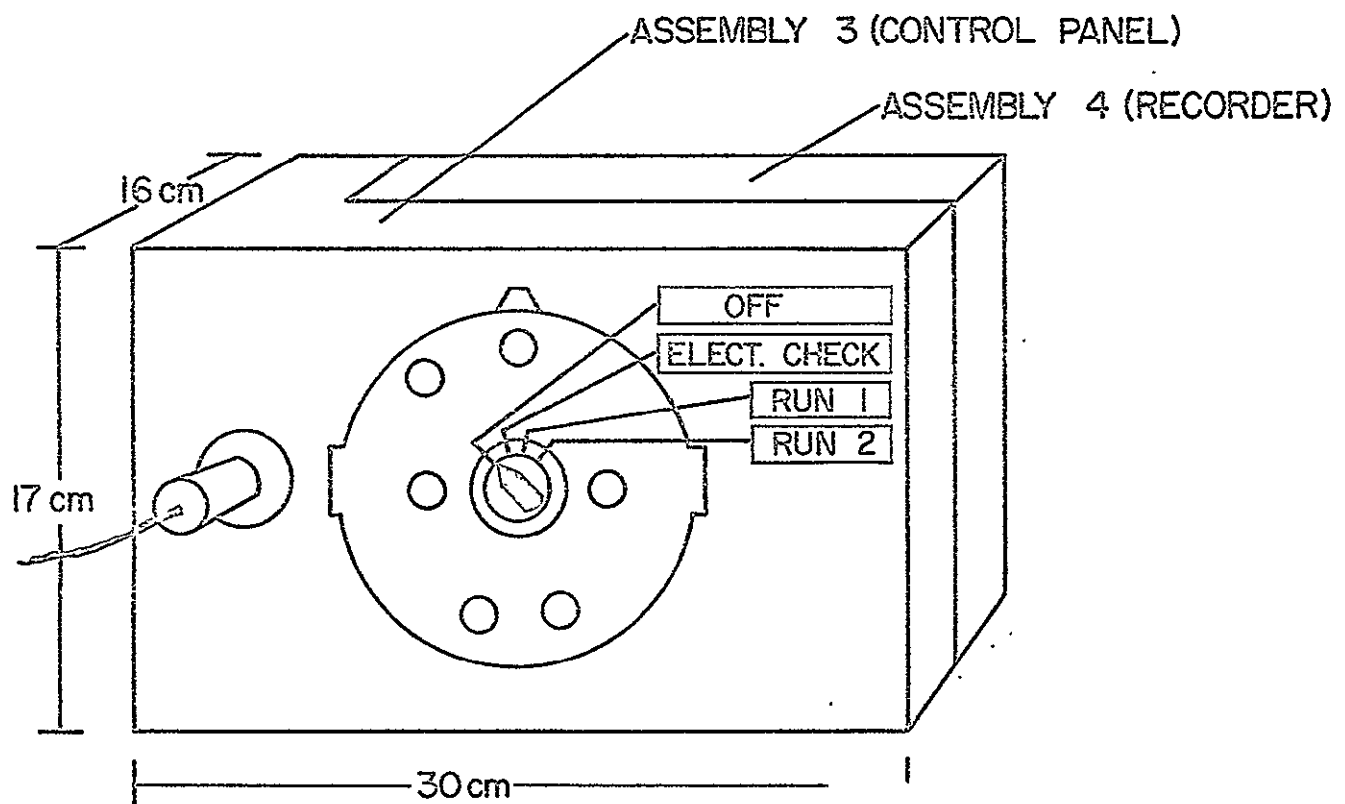
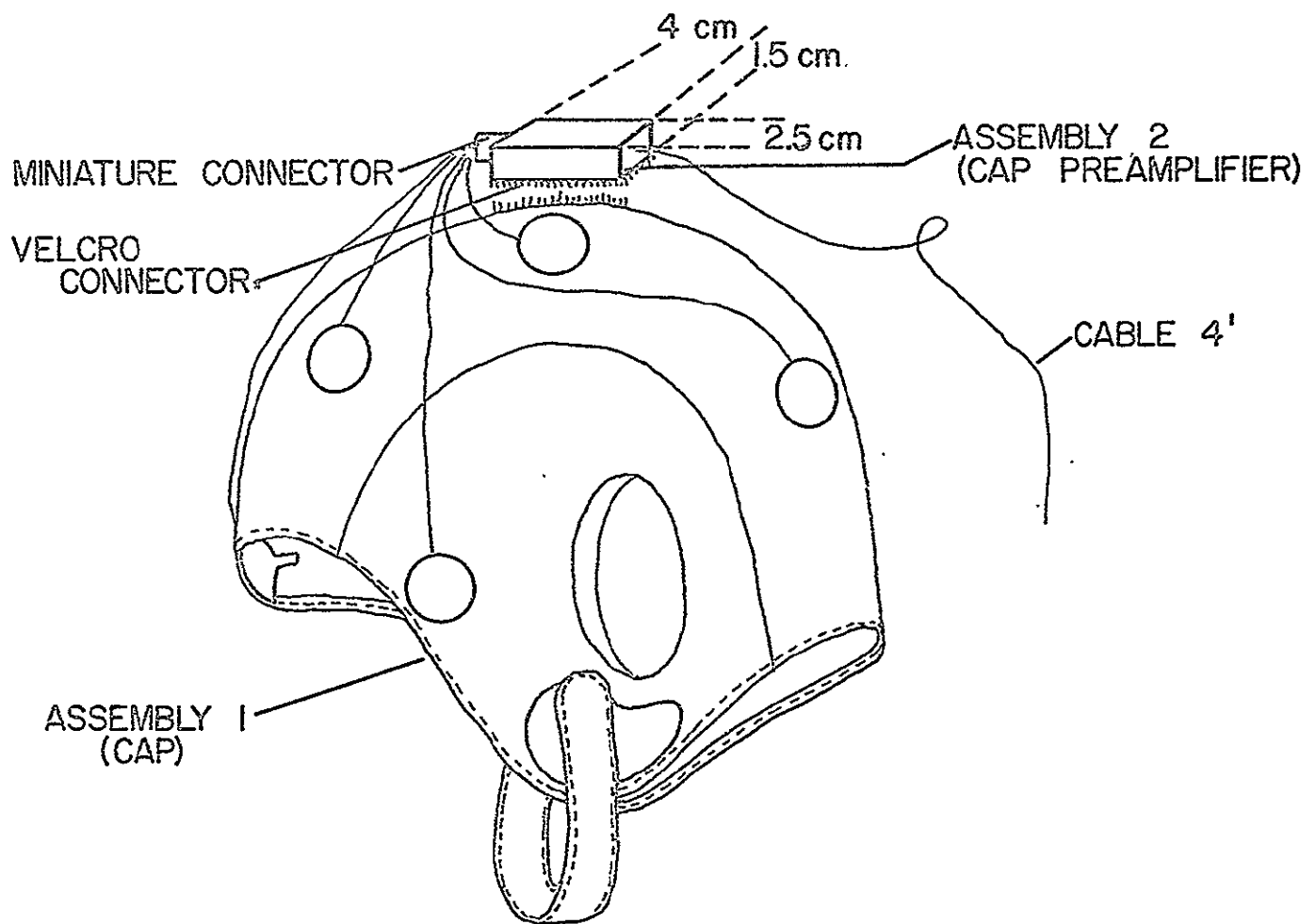
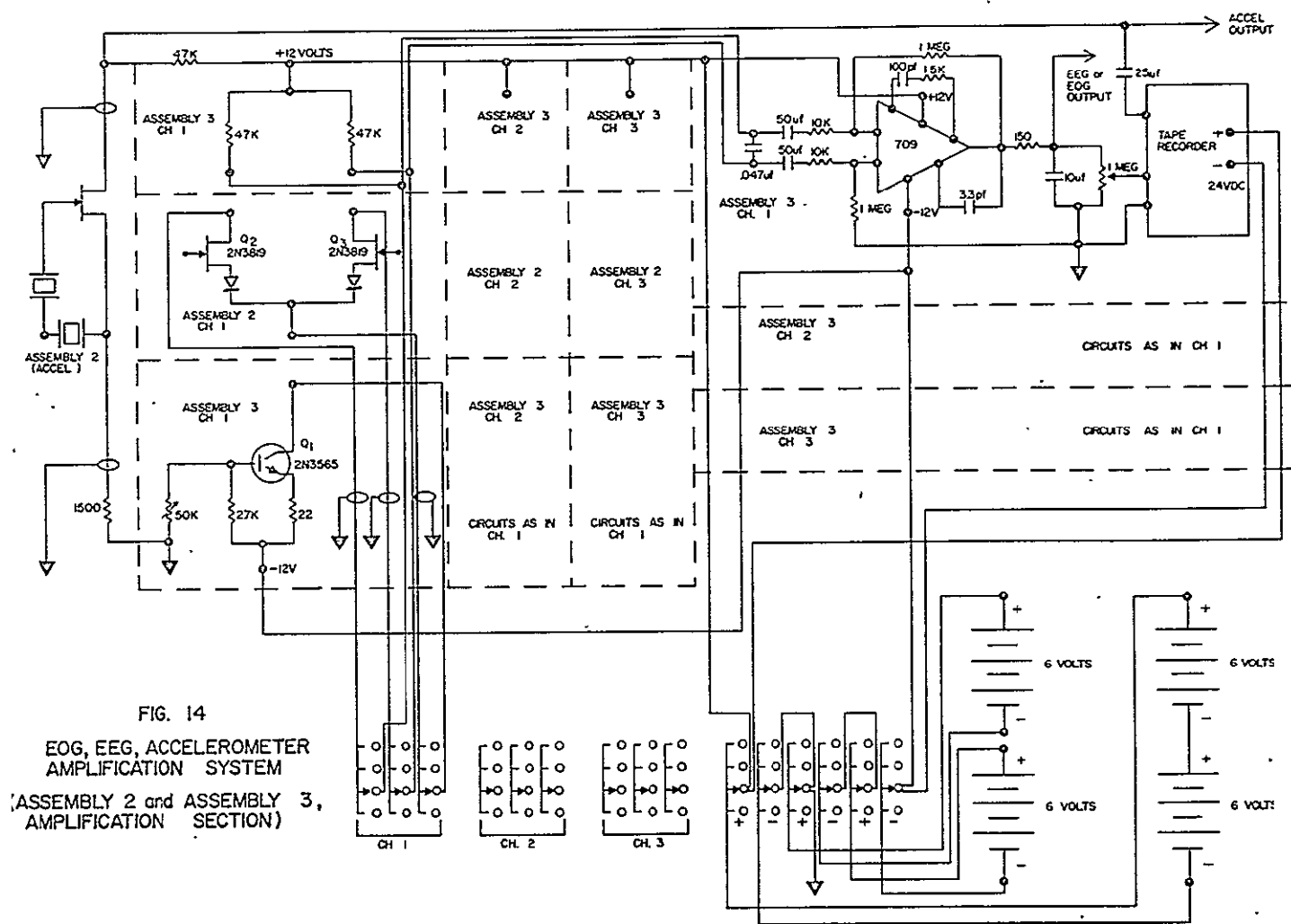


FIG. 13



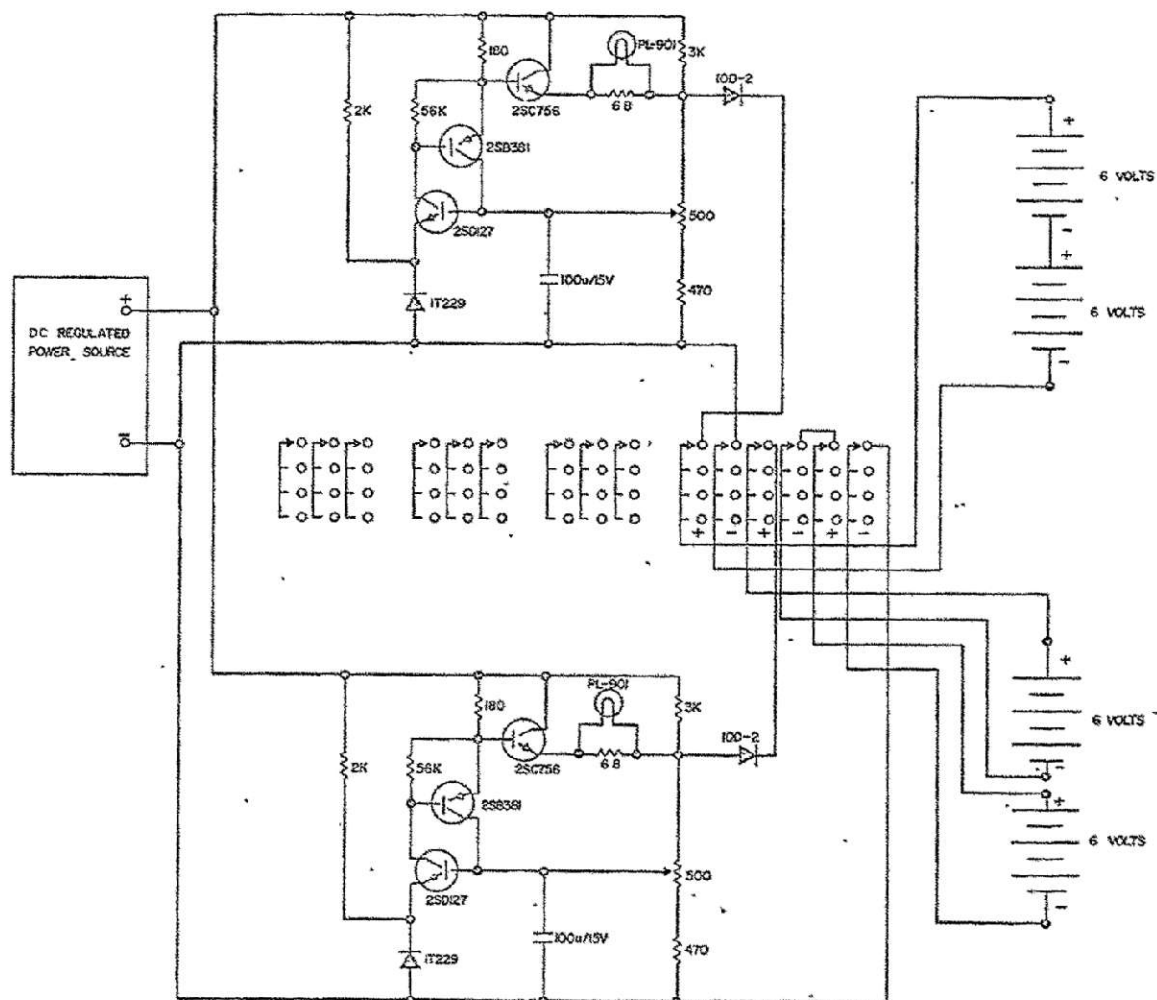
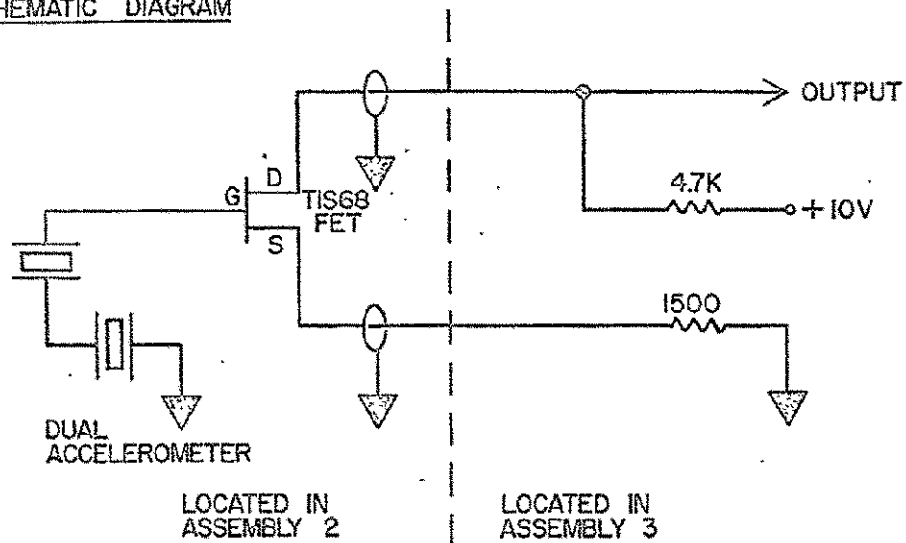


FIG. 15
POWER SYSTEM (ASSEMBLY 3)

A. SCHEMATIC DIAGRAM



B. CONSTRUCTION DETAILS

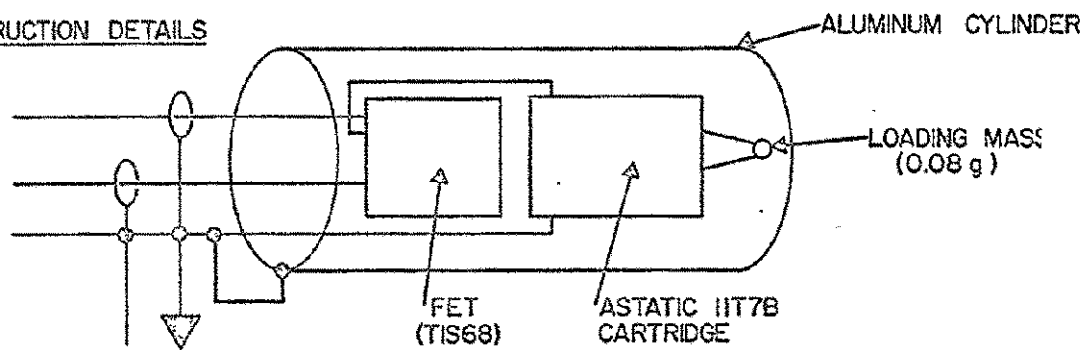
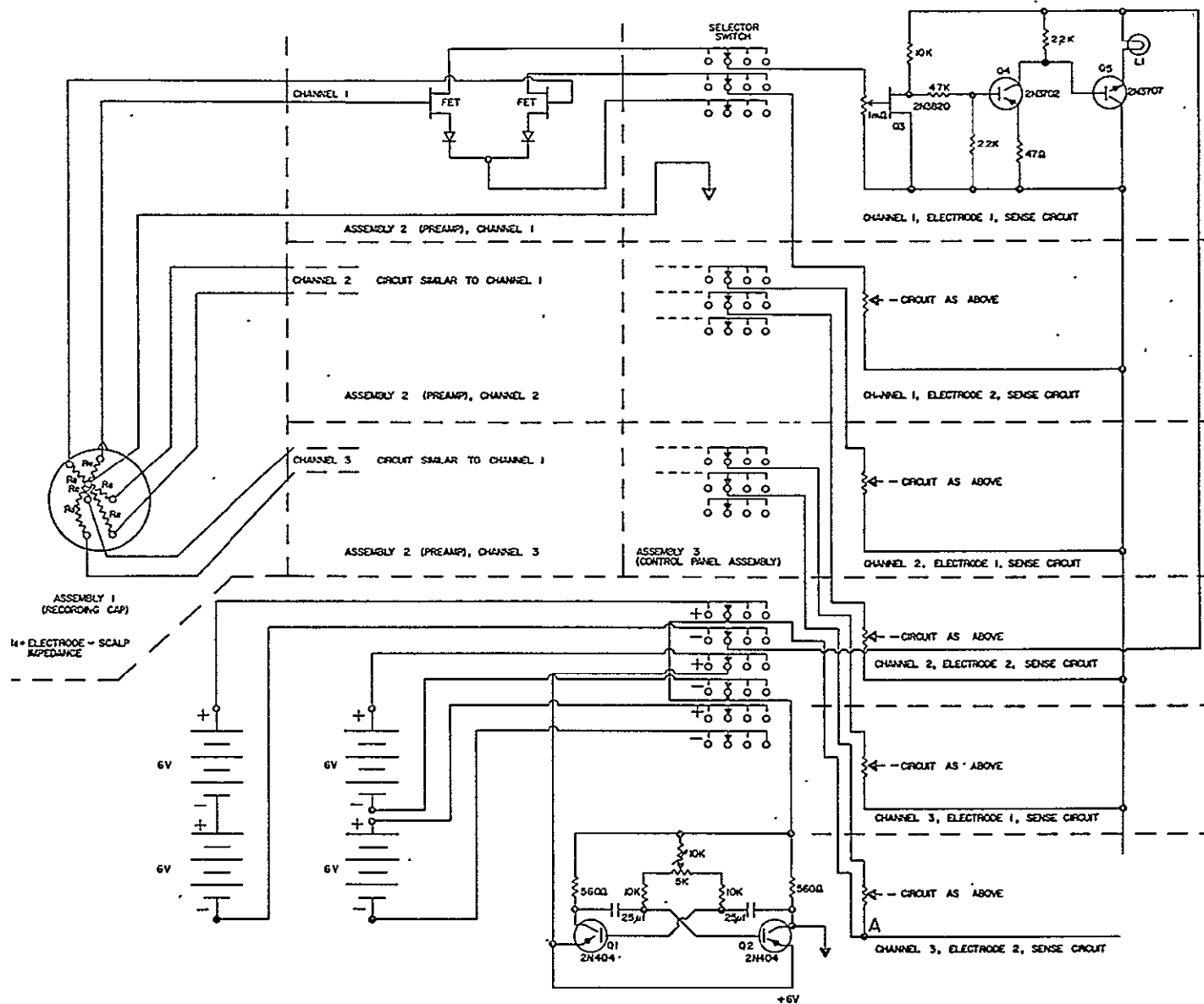


FIG. 16
DUAL ACCELEROMETER



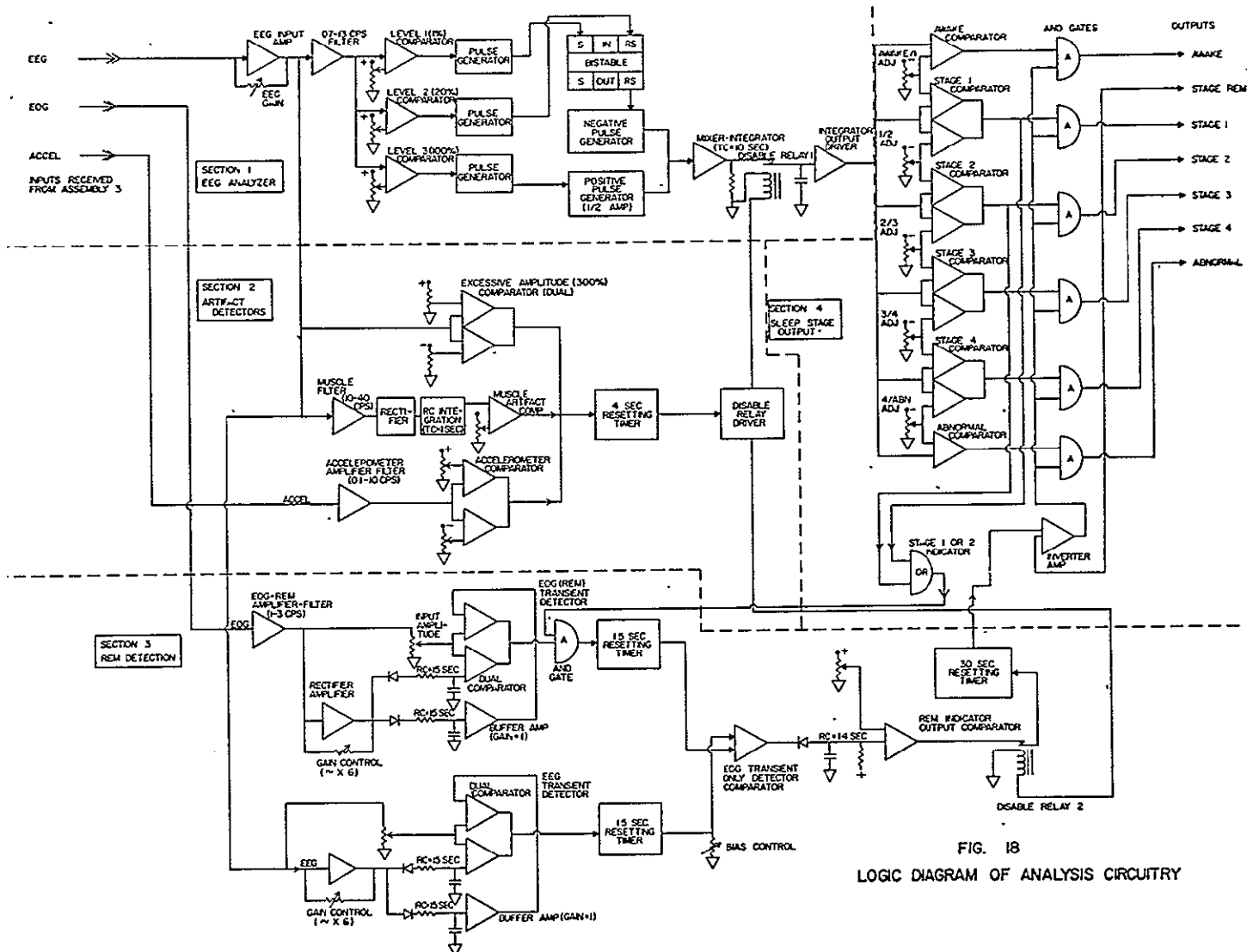


FIG. 18
LOGIC DIAGRAM OF ANALYSIS CIRCUITRY

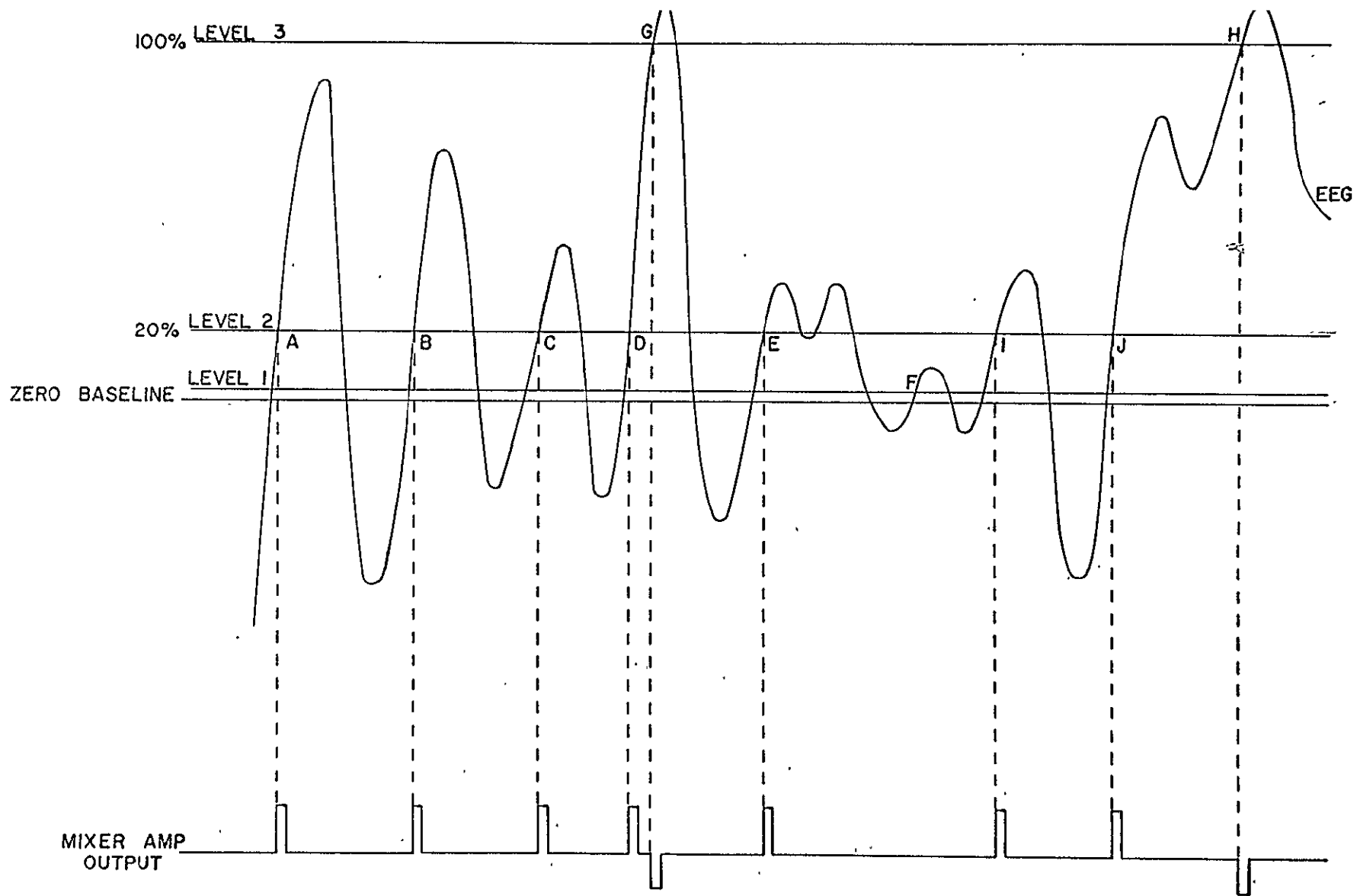


FIG. 20

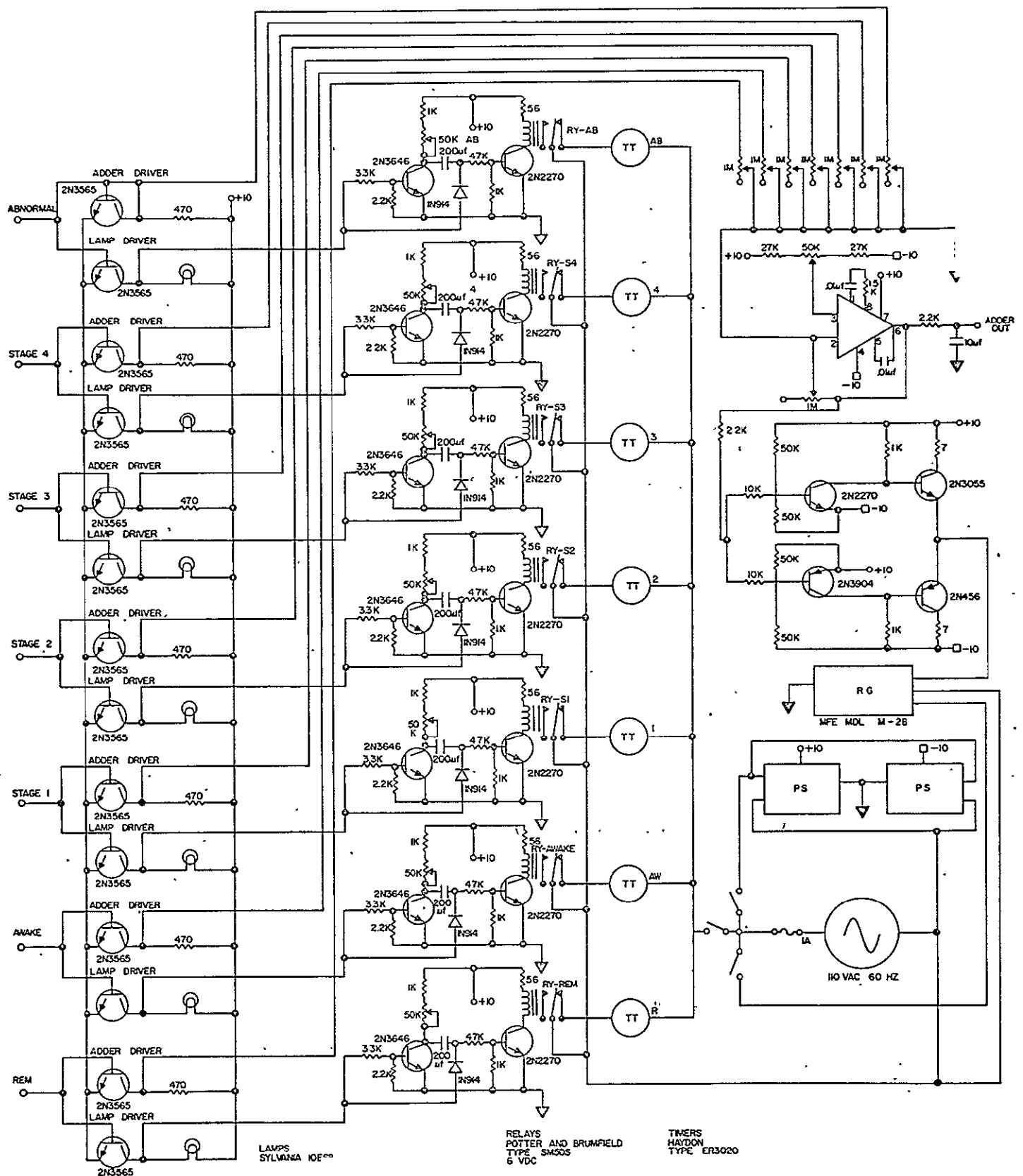


FIG. 22
SPLAY CONSOLE (ASSEMBLIES 8 & 9)

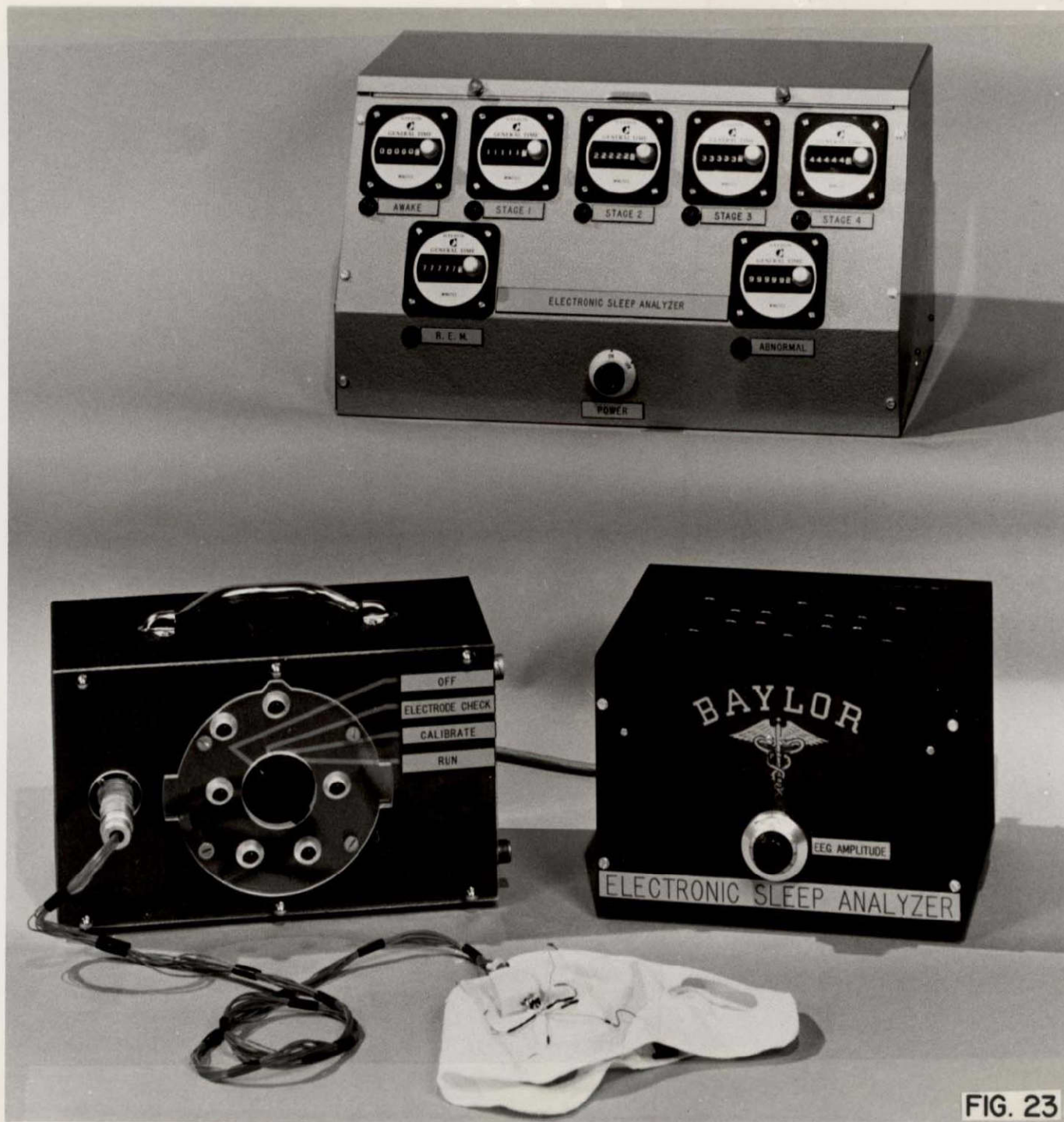
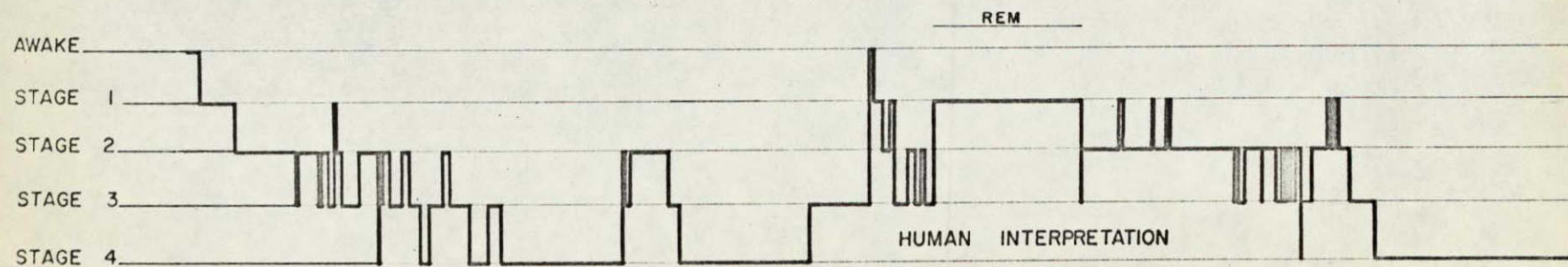
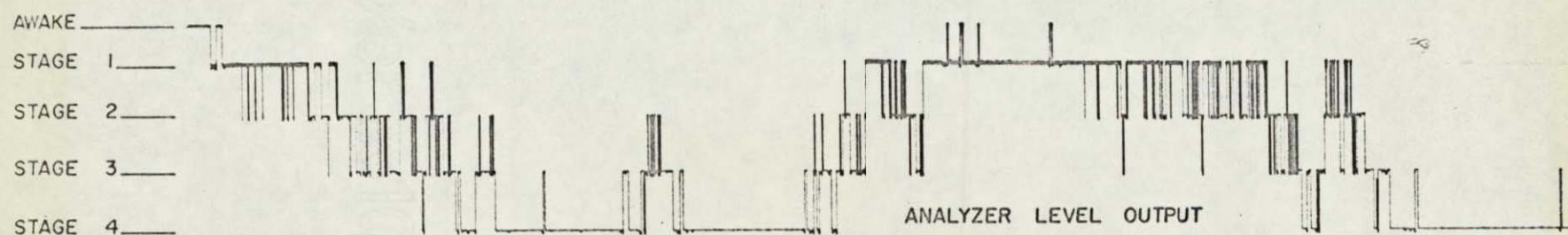
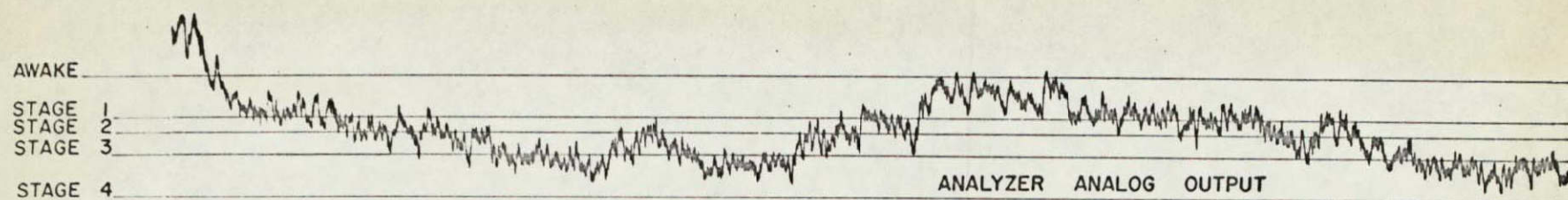


FIG. 23



FIG. 24



0

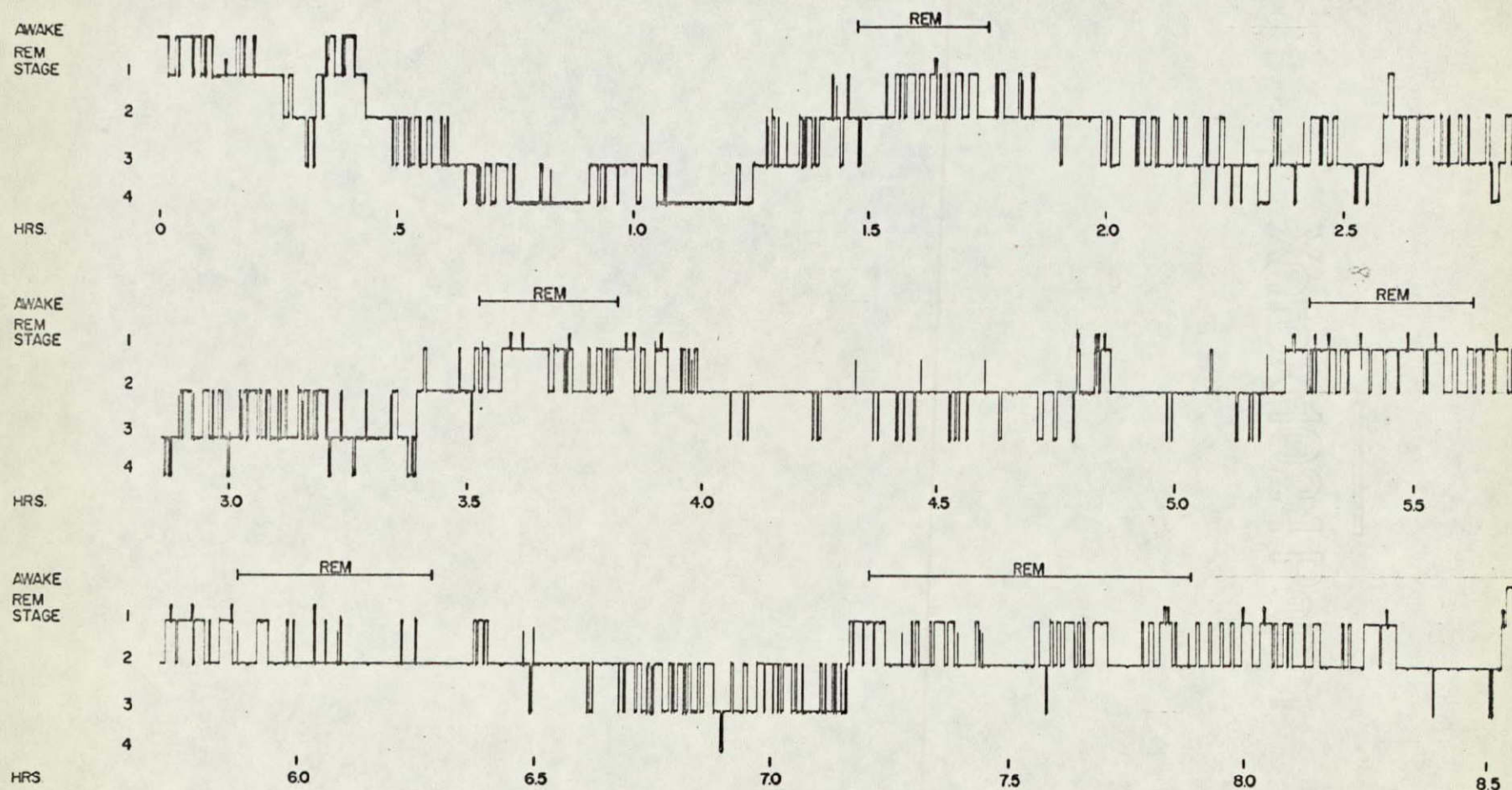
30min.

60min.

90min.

120min.

FIG. 25



SUBJECT NO. 1, NIGHT NO. 9

FIG. 26

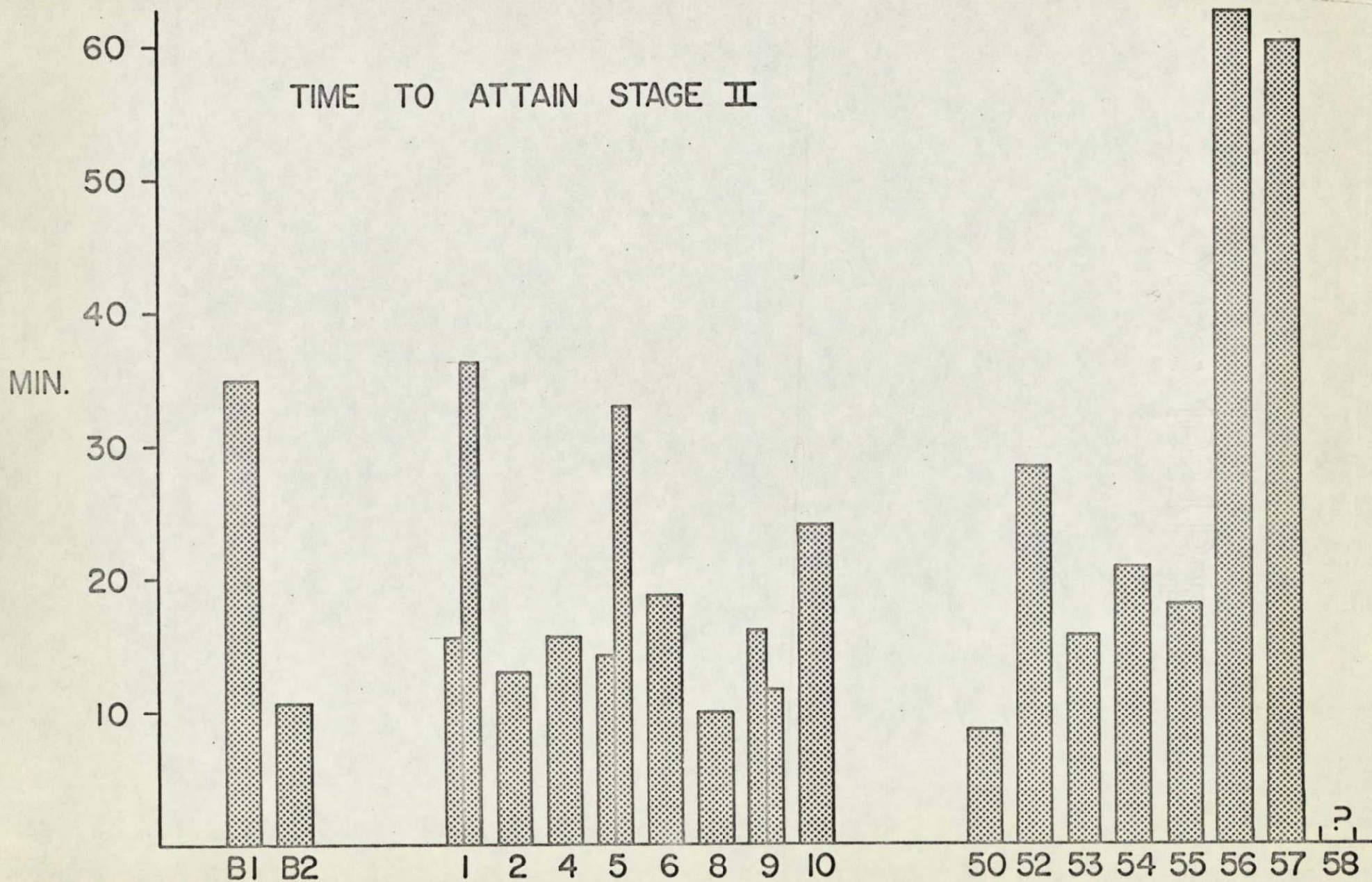
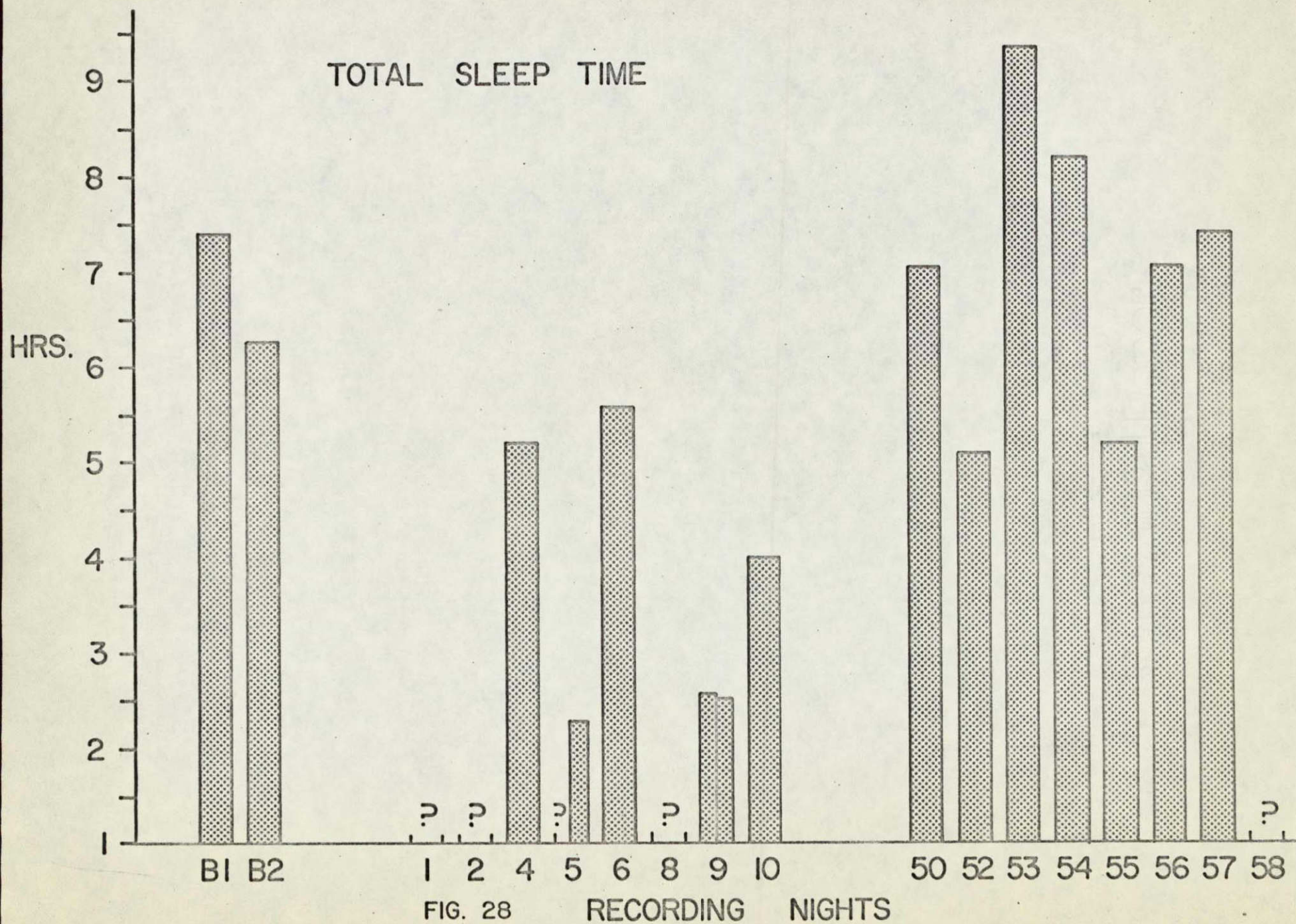


FIG. 27

RECORDING NIGHTS



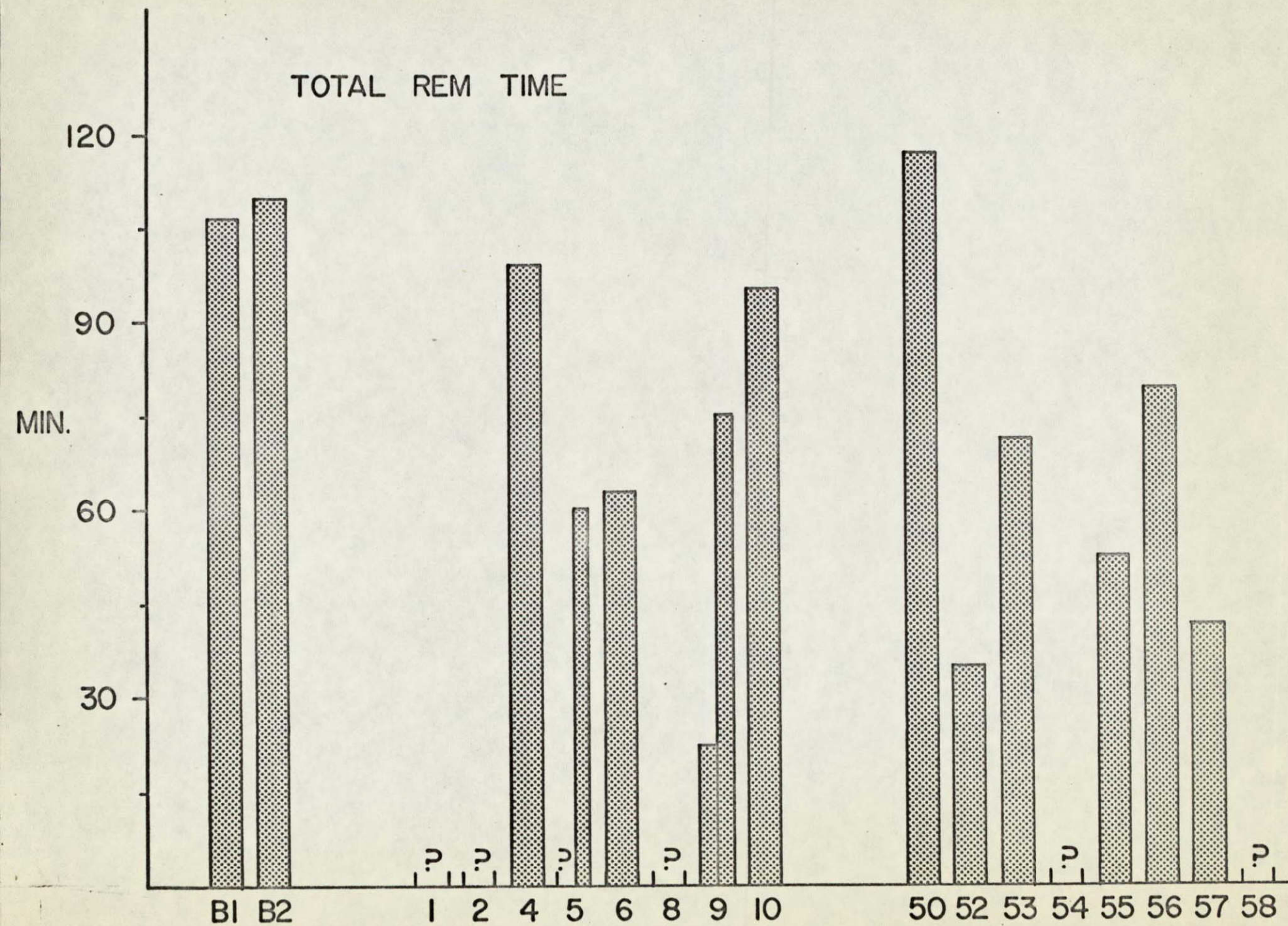


FIG. 29

RECORDING NIGHTS

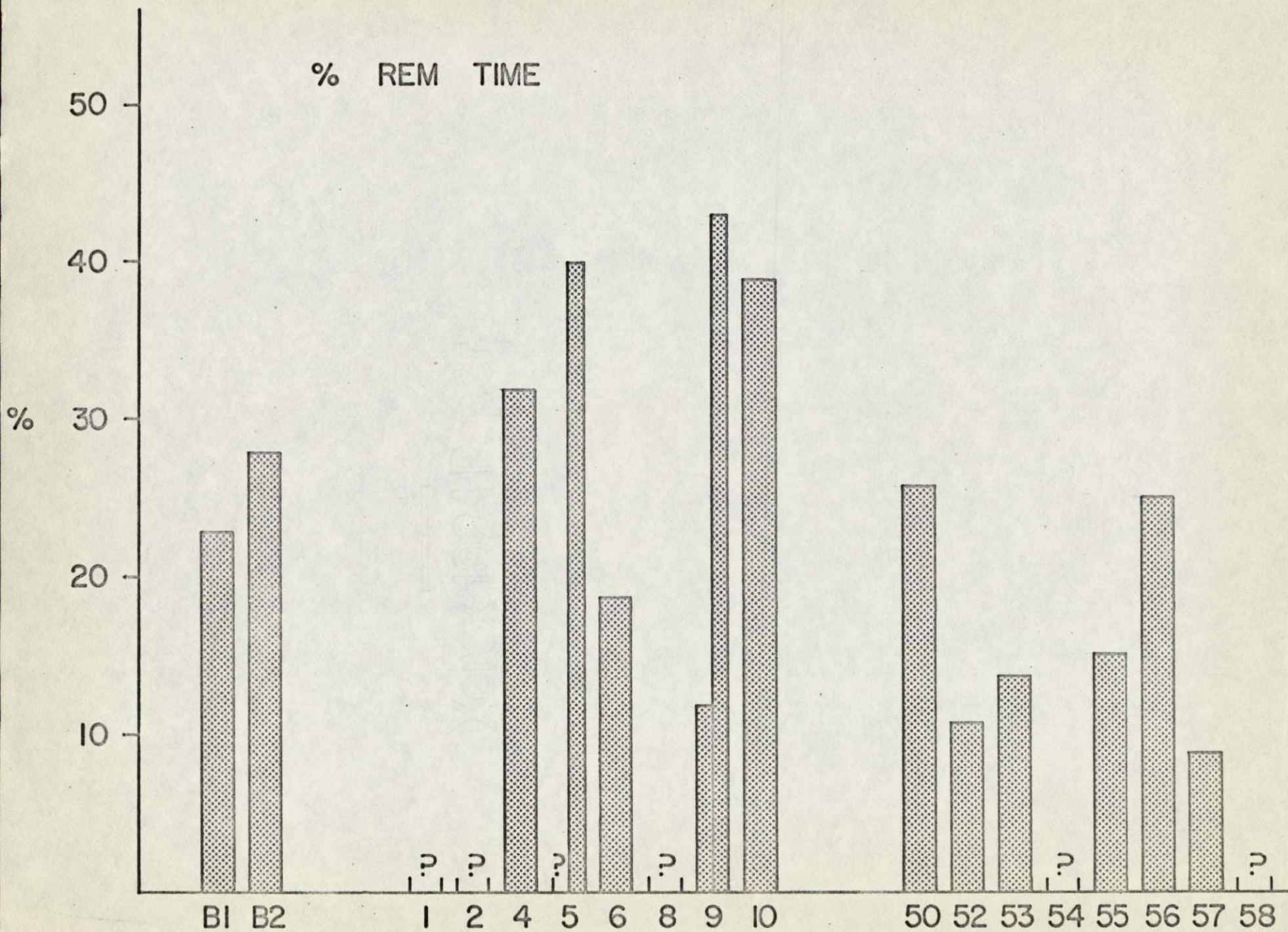


FIG. 30

RECORDING NIGHTS

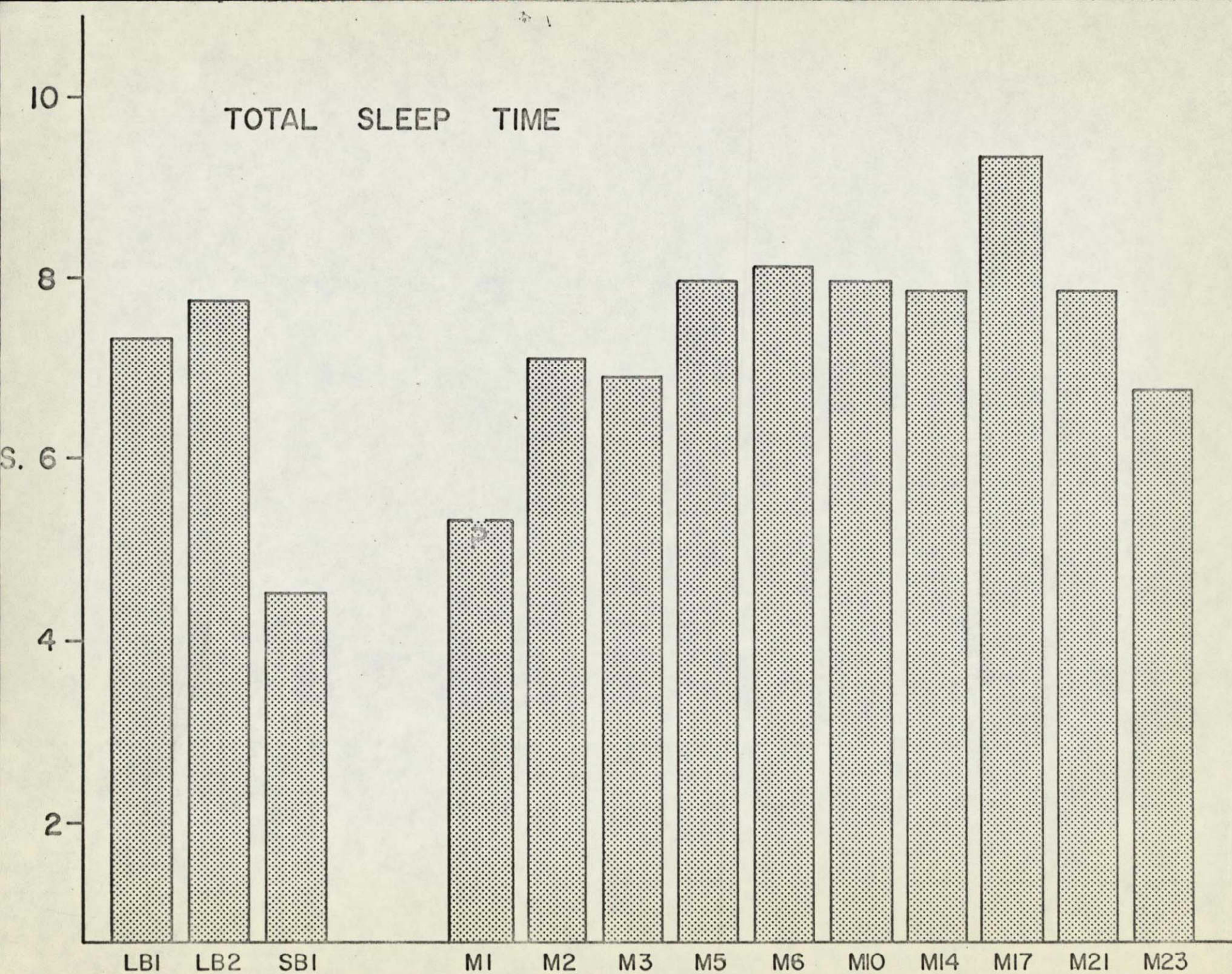


FIG. 31

MIN.

TIME TO ATTAIN STAGE II

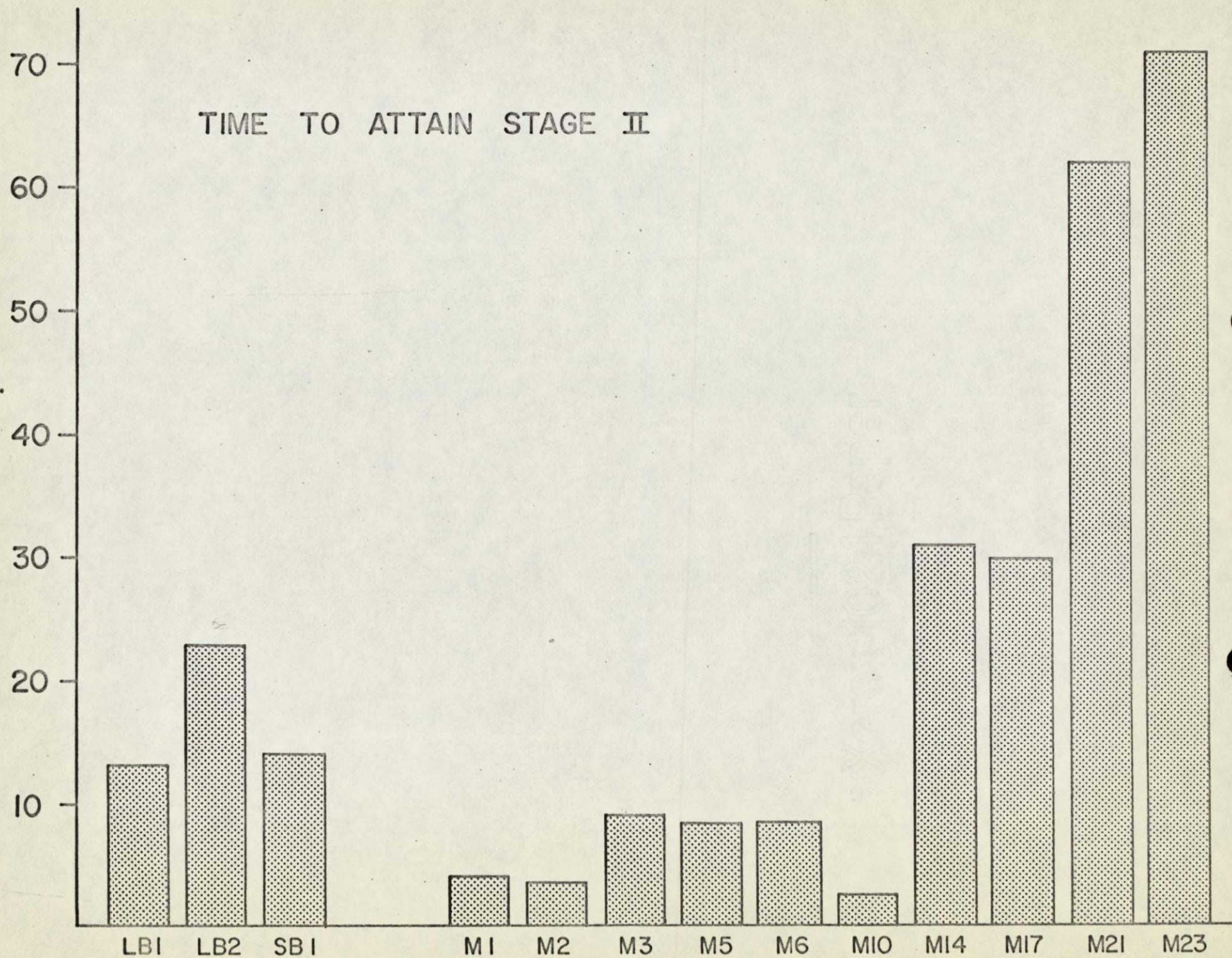


FIG. 32

HRS.

TIME TO ATTAIN STAGE IV

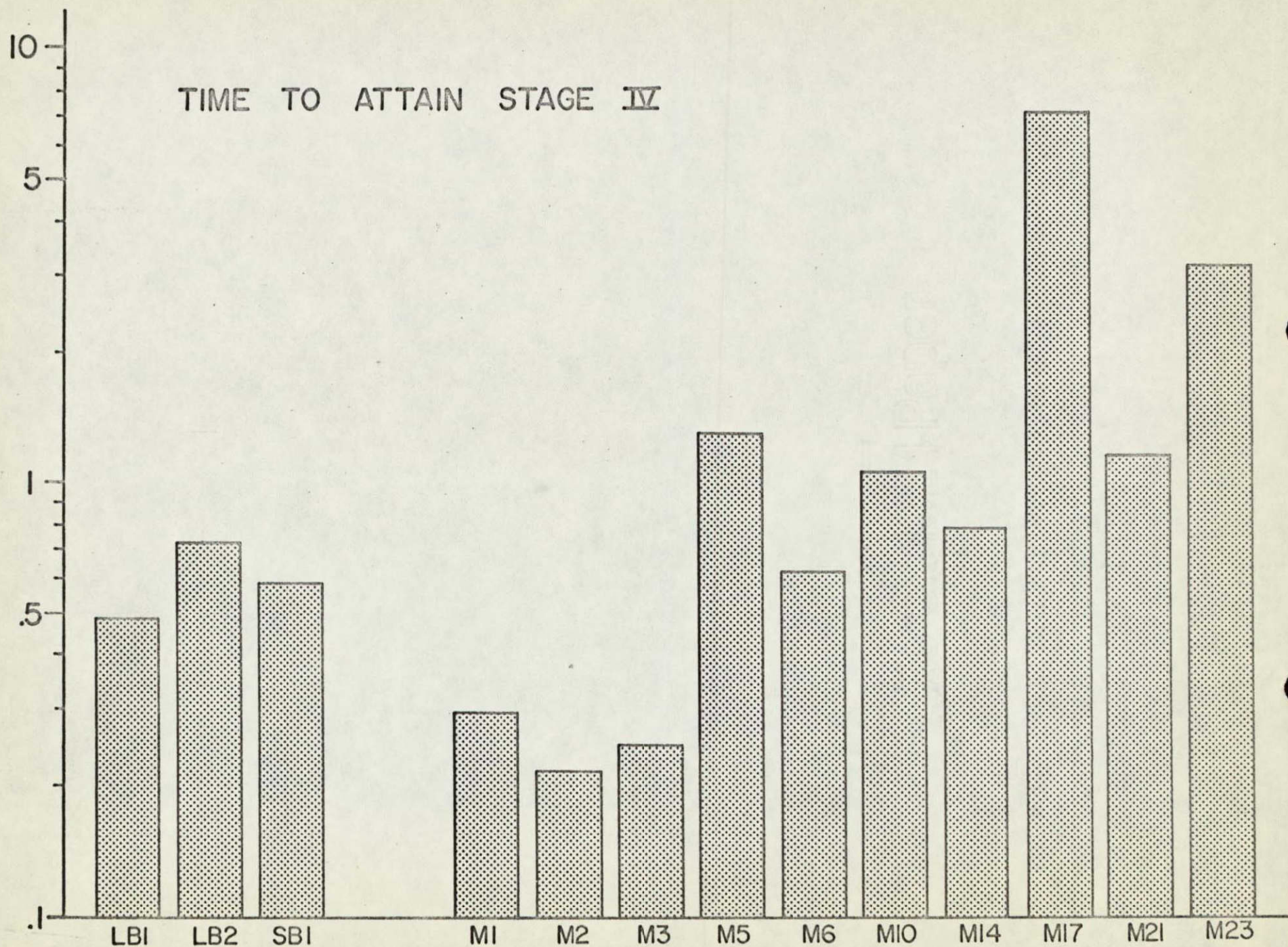


FIG. 33

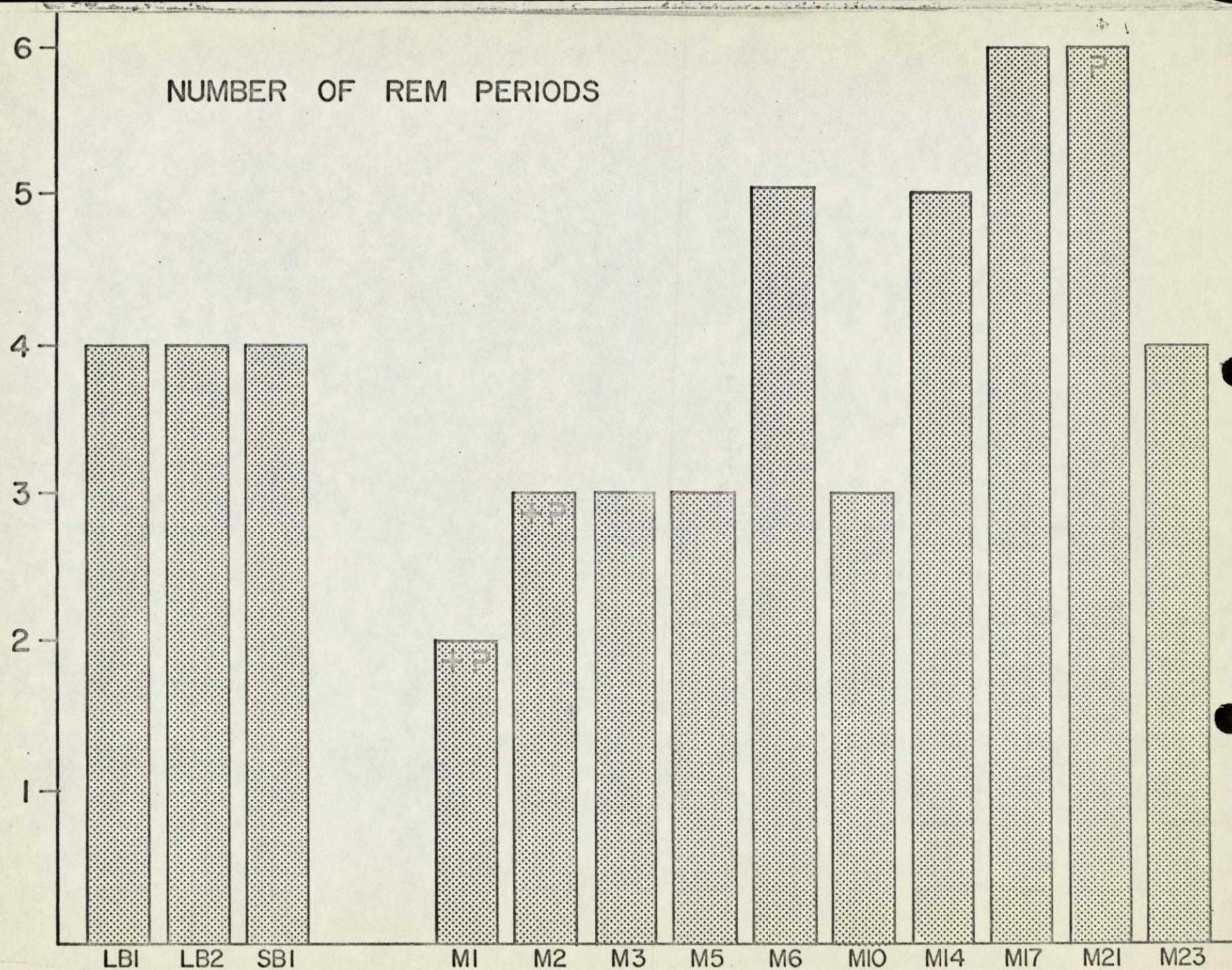


FIG. 34

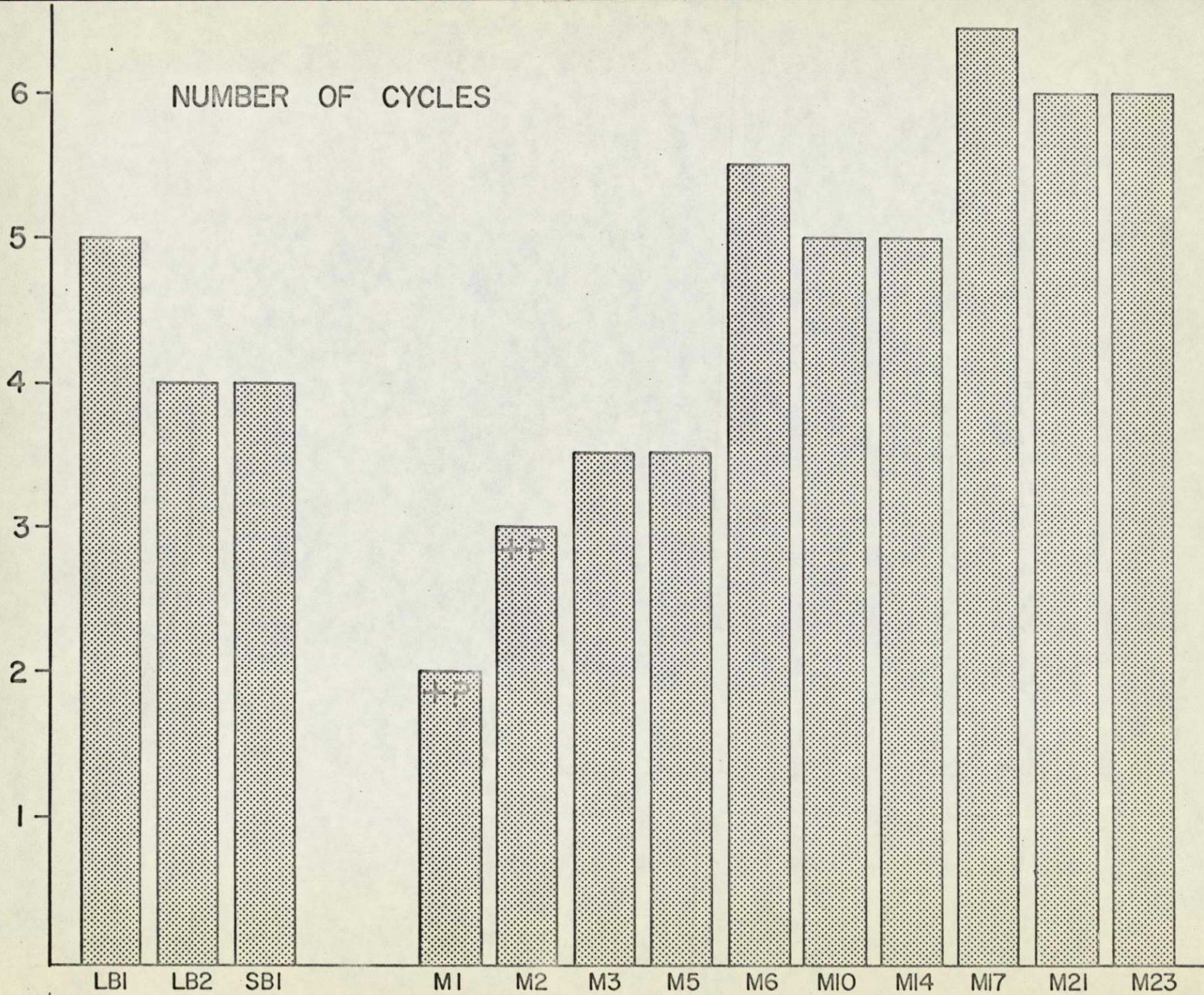


FIG. 35

PRECEDING PAGE BLANK NOT FILMED.

Appendix

Final Report - The Effects of Spacecraft Noise on Sleep

(Amendment 2 S to Contract NAS 9-9418)

THE EFFECTS OF SPACECRAFT NOISE ON SLEEP

Contract NAS 9-9418

Submitted by:

James D. Frost, Jr., M.D.
Associate Professor of Physiology
Baylor College of Medicine
1200 Moursund Avenue
Houston, Texas 77025

Date:

February, 1970

As Required by Amendment No. 2-S to Contract NAS 9-9418

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Introduction

This laboratory was requested by the Manned Spacecraft Center to carry out a study concerning the effects of spacecraft noise on the sleep of crew members. The proposed study was required by NASA in order to evaluate two specific noise-reduction devices which had been proposed for use in the Lunar Excursion Module.

Methods

A. General

Electroencephalograms (EEGs) and electro-oculograms (EOGs) of two test subjects were monitored continuously and simultaneously during 15 consecutive nights of sleep. Testing procedures were carried out in the Neurophysiology Laboratories at The Methodist Hospital, Houston, Texas, between January 8 and January 23, 1970. The two subjects slept in a small (approximately 8' x 8'), electrically-shielded chamber which was located within a conventional laboratory room. The testing chamber could be provided with a simulated (recorded) spacecraft-noise environment when required.

B. Test Subjects

The subjects were experienced test pilots employed by the Grumman Aircraft Corporation. Subject #1, J. E., was a 25-year-old male, and subject #2, G. K., was a 35-year-old male. Both were apparently in good health. The auditory status of each subject is presented below (Results section).

The goals of the project were explained to the subjects in general terms beforehand, but the details of noise scheduling were not revealed.

C. Recording Techniques

A block diagram of the recording and monitoring apparatus is shown in Fig. 1.

EEG and EOG activity was detected from the scalp using conventional chlorided silver-disc electrodes (Grass Instrument Co.) attached with an electrolyte paste (Grass Instrument Co.). Two EOG channels were provided by recording between electrodes near the outer canthus of each eye and electrodes positioned on the forehead directly above each eye (L_f and R_f). Each channel was thus capable of detecting eye movements in either up-down or right-left directions. Additional

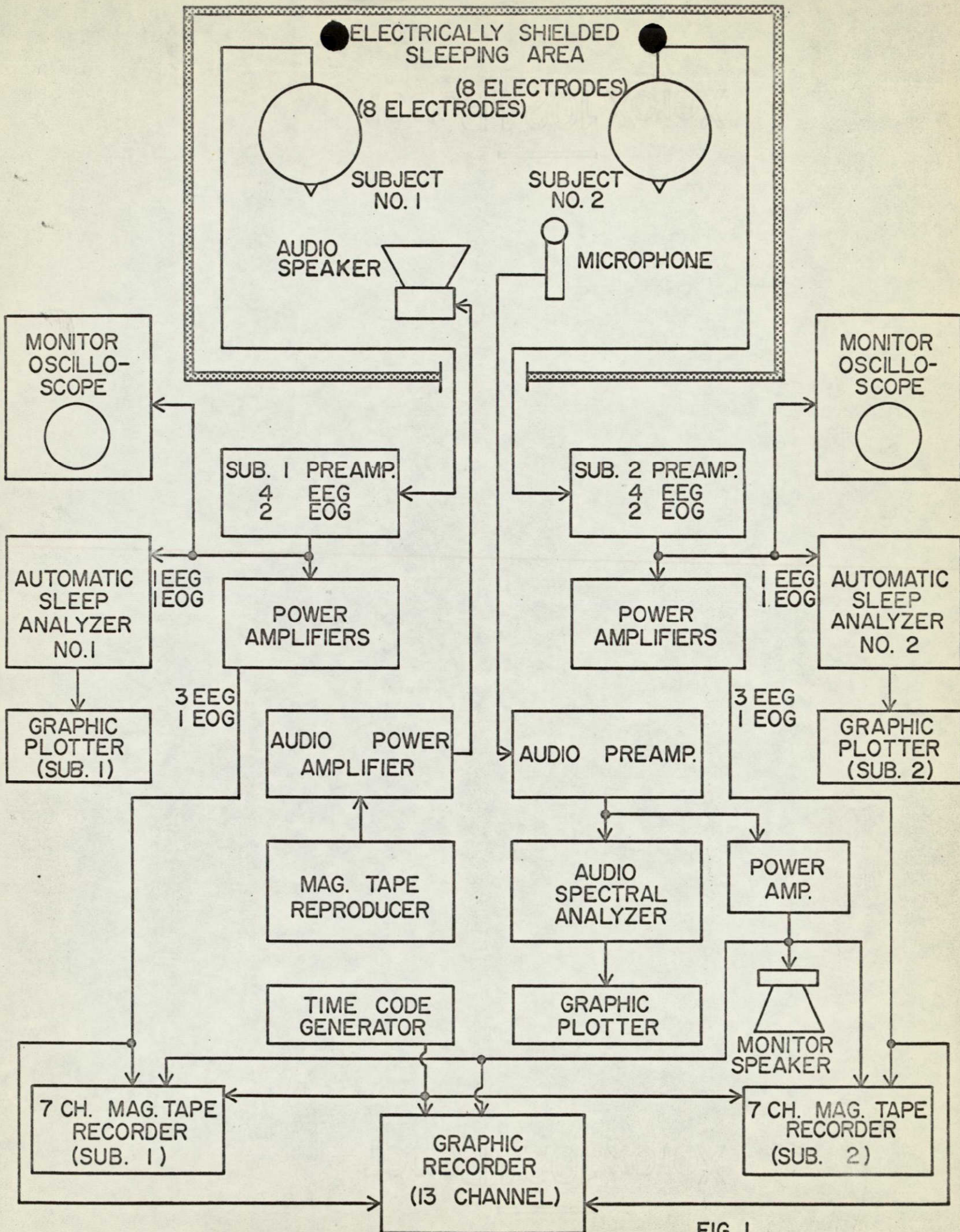


FIG. 1

electrodes were placed in the left and right central and left and right occipital regions (C_3 , C_4 , O_1 , and O_2 , respectively). EEG activity was recorded from two frontal-to-central derivations (L_f-C_3 and R_f-C_4) and two central-to-occipital derivations (C_3-O_1 and C_4-O_2).

One channel of EOG (L eye- L_f) and three channels of EEG (L_f-C_3 , C_3-O_1 , and C_4-O_2) from each subject were continuously displayed on a conventional EEG graphic recorder (Grass Instrument Co.) at a paper speed of 3 cm/sec and a recording bandpass of 0.3 to 60 cps (6 dB points), and the same information was continuously recorded on magnetic tape (two Ampex 7-channel FM recorders at 1 7/8"/sec). A 24-hour time code was simultaneously recorded on all three devices. The right EOG channel (R eye- R_f) and the additional EEG channel (R_f-C_4) served as spares and could be switched into the recorders in place of the corresponding left channels if necessary.

D. Spacecraft-Noise Simulation¹

As indicated in Fig. 1, the sleeping area could be provided with a controlled noise environment. A recording of actual spacecraft noise (from the LTA-8) was contained in loop form on the magnetic-tape reproduction unit (Sangamo), which in turn drove a power-amplification unit (McIntosh) and, finally, a speaker located in the sleep area. Output of the audio system was monitored by means of a microphone located in the subject room whose output fed an audio spectral analyzer. Sound intensity and spectral composition were determined at hourly intervals throughout the study, and minor corrections in the system output were made, as needed, to ensure that the simulated-sound environment matched actual spacecraft conditions.

An indication of total sound-intensity variation was provided on one channel of the EEG recorder to permit correlation of changes in sleep status with alterations in the sound environment. The output of the sound-monitoring system was also recorded on one channel of each magnetic-tape recorder simultaneously with the EEG, EOG, and time-code information.

Three specific noise conditions were tested during the 15-day study as indicated in the schedule below (section E).

E. Experimental Schedule

The 15 recording nights of the study were divided as indicated below.

Date	Night	Waking Noise Exposure	Sleep Period	Audiometric
1/p. m. - a. m. /70	No.	8:15 a. m. - 10:15 p. m.	10:30 p. m. - 7:15 a. m.	Tests
1/8-9/70	1		Baseline (ambient noise)	
1/9-10/70	2		Baseline (ambient noise)	3-4 p. m.
1/10-11/70	3		Baseline (ambient noise)	
1/11-12/70	4	Unmodified LEM noise	Unmodified LEM noise	
1/12-13/70	5	Unmodified LEM noise	Unmodified LEM noise	7-8 a. m.
1/13-14/70	6	Noise modification #1	Noise modification #1	
1/14-15/70	7	Noise modification #1	Noise modification #1	
1/15-16/70	8	Noise modification #1	Noise modification #1	
1/16-17/70	9	Noise modification #2	Noise modification #2	
1/17-18/70	10	Noise modification #2	Noise modification #2	
1/18-19/70	11	Noise modification #2	Noise modification #2	
1/19-20/70	12	Unmodified LEM noise	Unmodified LEM noise	
1/20-21/70	13	Unmodified LEM noise	Unmodified LEM noise	
1/21-22/70	14		Baseline (ambient noise)	3-4 p. m.
1/22-23/70	15		Baseline (ambient noise)	

On the baseline nights, electrodes were applied between 9:30 p. m. and 10:15 p. m. On noise-exposure nights (4-13), electrodes were applied between 7:30 p. m. and 8:15 p. m. The subjects then entered the sleep area and were exposed to the spacecraft noise for a two-hour period. During this time they were permitted to read, relax, work on projects, talk, and move about the room. Recording was not carried out during this time.

On the baseline nights (1-3, 14, 15), a 5-minute period of relaxed waking activity was recorded immediately before and immediately after the scheduled sleep period. On the nights with simulated spacecraft noise, an additional 5-minute awake period was recorded before the start of the two-hour waking noise-exposure period. These periods of waking activity were later subjected to computer analysis to determine certain features of the subjects' alpha activity (see Results section).

Audiometric tests were performed on each subject three times during the study, as indicated on the schedule above.

F. Data Analysis

Preliminary data analysis was accomplished on-line (Fig. 1) by automatic sleep analyzers^{2, 3} which continuously processed one channel of EEG (C₃-O₁ or C₄-O₂) and one channel of EOG for each subject. The stage of sleep, as determined by the electronic analyzer, was plotted on a graphic recorder moving at a

very slow paper speed, thus permitting a compact display of each subject's sleep profile throughout the night (Figs. 2 and 3).

The output of each sleep analyzer was also recorded in a coded form on the EEG graphic recorder, thus permitting later correlation and comparison of human and machine scoring.

Final analysis was accomplished by scoring each 10-second epoch in the entire all-night record using a combination of human and automatic interpretation. The criteria for scoring sleep stages were based upon both EEG and EOG characteristics as specified in the APSS manual.⁴ All graphic records were scanned at least twice by the visual method, and discrepancies between human and automatic analysis were resolved. All stage REM periods (the dreaming phase of sleep) were precisely determined by visual criteria. The tabulated data obtained from this analysis were utilized to determine, for each subject, each night, the total sleep time, the time to fall asleep, the number of awakenings, the absolute and percent time spent in each of the stages of sleep (stages 1, 2, 3, 4, and REM), and the number of discrete REM periods.

In addition to the sleep analysis, the 5-minute waking periods preceding each night's sleep were subjected to computer analysis in order to detect variations in the subjects' alpha rhythms during the course of the study. The details of this analytic method are presented in the attached abstracts.^{5, 6}

G. Subjective Evaluation

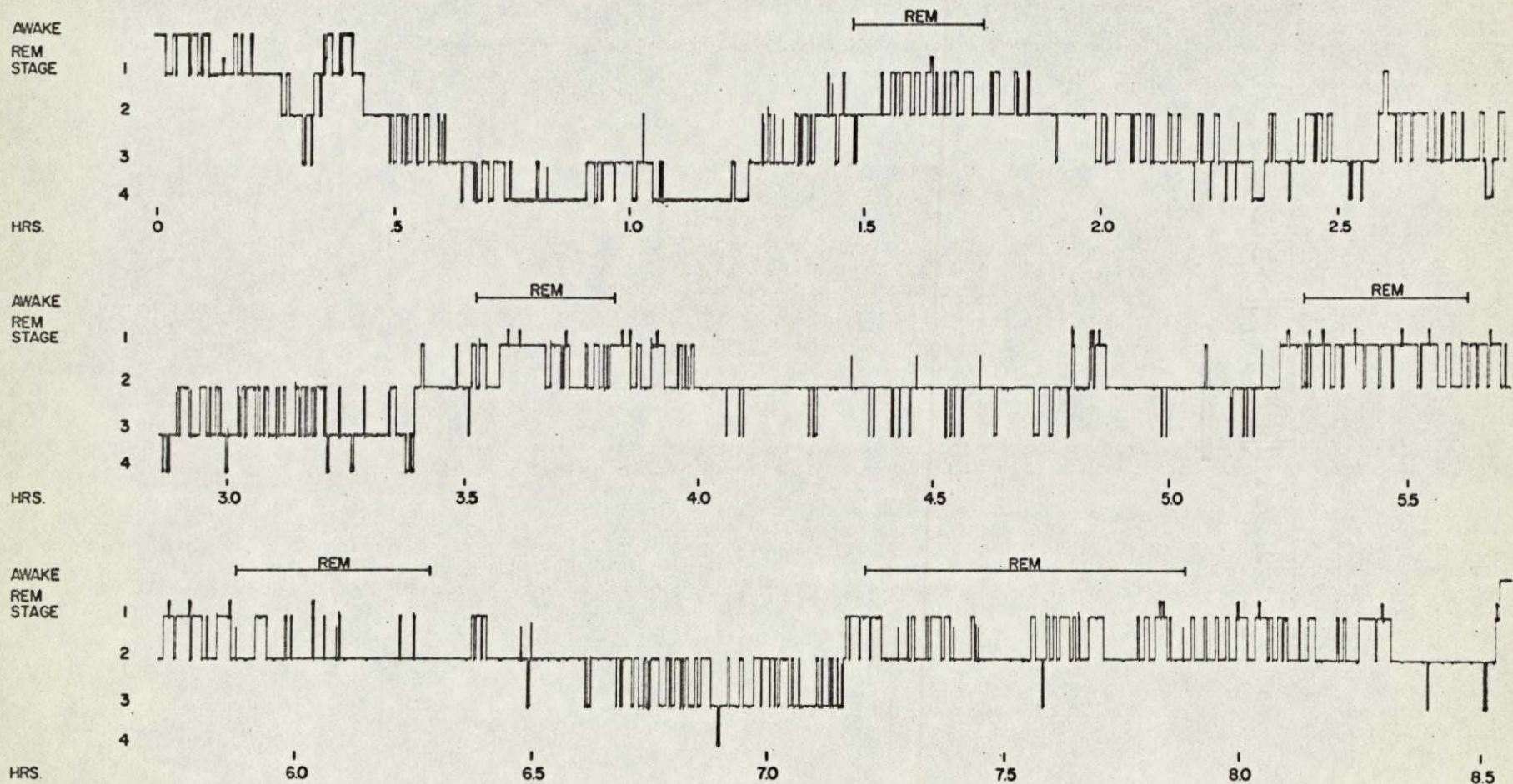
Each subject was requested to fill out a simple log immediately after awakening each morning (Fig. 4). Comparisons were later made between the subjects' estimation of selected sleep characteristics and the actual values as determined by the data-analysis procedures.

Results

A. Quality of Data

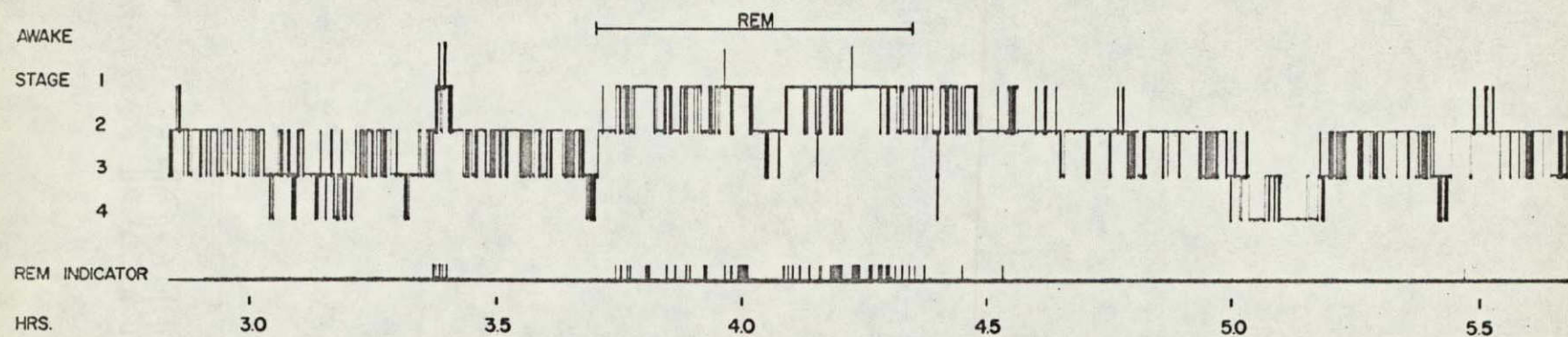
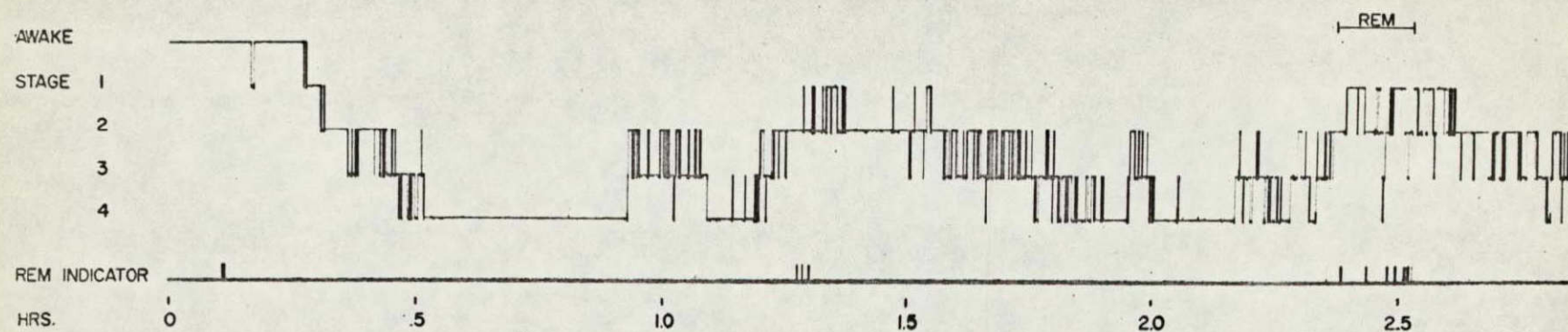
1. EEG and EOG

The technical quality of the recorded activity remained satisfactory throughout the 15 nights of the study. No problems were encountered with the recording electrodes with respect to comfort or skin irritation. On two occasions one EOG electrode was dislodged (subject #1), but the analysis was continued essentially without interruption by switching to the second EOG channel. On two



SUBJECT NO. 1, NIGHT NO. 9

FIG. 2



SUBJECT NO. 2, NIGHT NO. 9

FIG. 3

Name: _____

FIG. 4

occasions subject #1 inadvertently pulled the electrode plugs out of the terminal box near his bed. It was necessary for a technician to briefly enter the room in both instances to reconnect the electrodes (night #12, approximately 6:00 a. m. ; night #14, approximately 5:00 a. m.). Recording from subject #2 was interrupted on two occasions (nights #6 and #14) for 10-minute periods (approximately) when he made trips to the bathroom. The first time (night #6) he complained of nausea and "indigestion" and was given Tigan[®], 250 mg (trimethobenzamide hydrochloride).

2. Simulated Spacecraft-Noise Environment¹

Frequent analyses made throughout the study confirmed that the simulated-noise environment within the sleeping area matched very closely the actual environment as recorded within the spacecraft. Representative samples of the spectral plots for each noise condition are presented in Figs. 5 through 7.

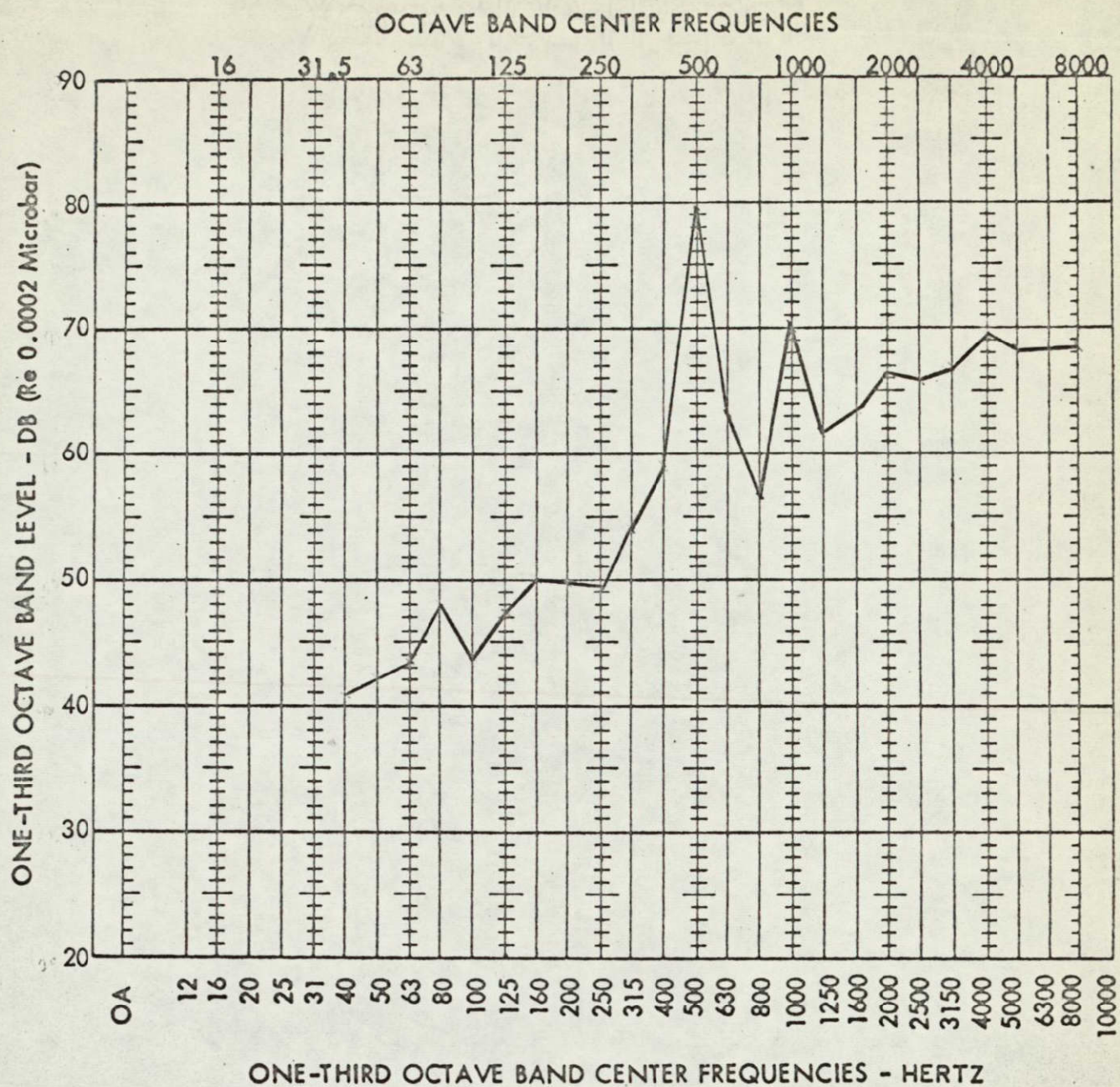
However, although the overall quality of the reproduced noise was excellent, its effectiveness was degraded by frequent transient alterations in the magnetic-tape reproduction system's drive speed, which resulted in transient, audible, frequency shifts. These frequency shifts varied in degree and sometimes produced a "warbling" effect on the sound and at other times sounded like a "pop" or a "squeak."

The problem first occurred on night #5 and necessitated switching to the backup sound-reproduction system, which, however, soon proved to have a similar problem. This problem continued for the duration of the noise study (through night #13) and required frequent shifts between the primary and backup systems. Occasionally the transients resulted in awakening both subjects (e. g. , nights #5, #9, #12, and #13), but usually they either produced no noticeable change in sleep status or resulted only in a partial arousal (e. g. , temporary shift from stage 4 to stage 2, or stage 3 to stage 1, etc.).

B. Data Analysis

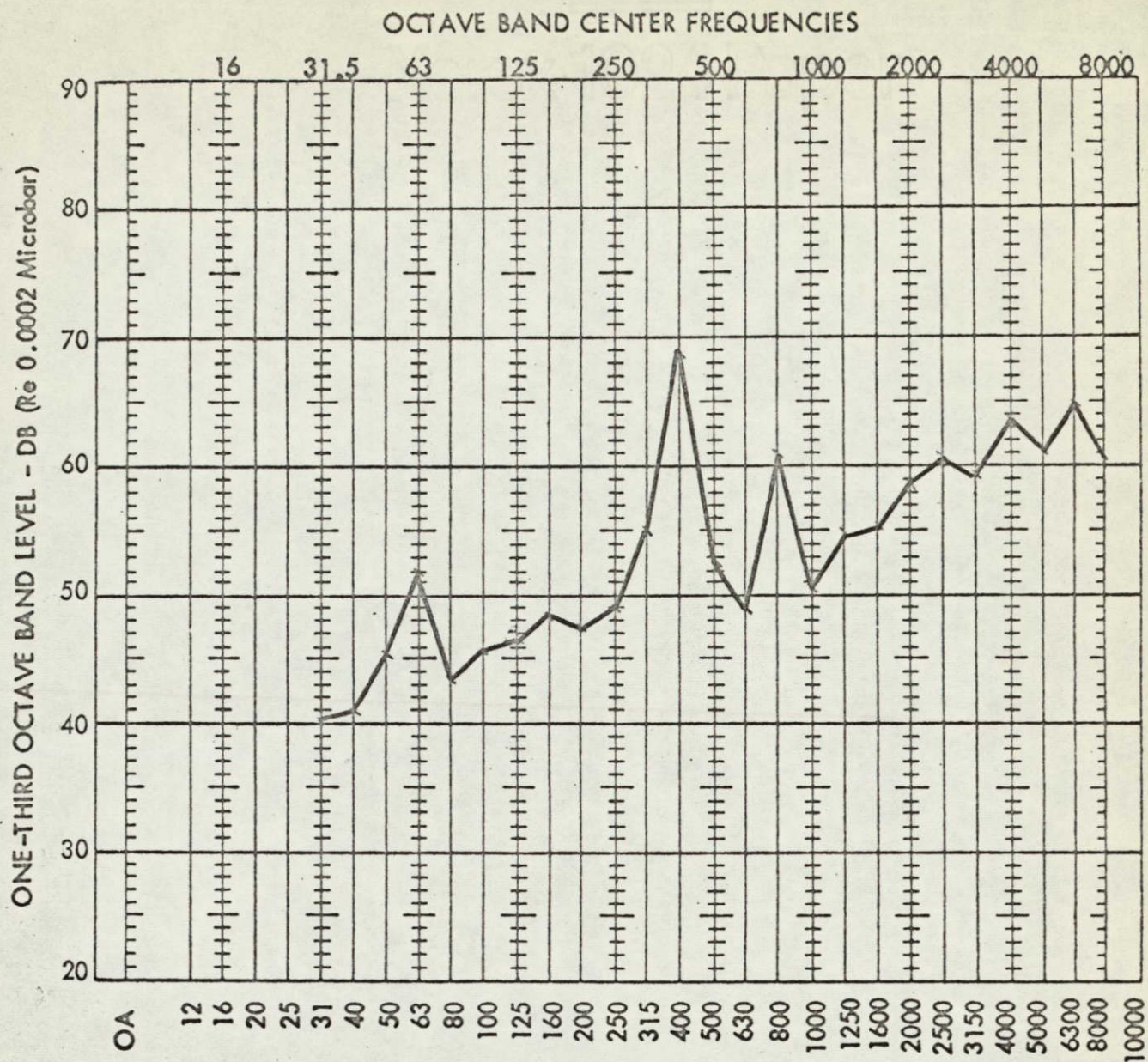
1. General

The results of data analysis for each subject for each night of the study are summarized in Table 1. The sleep-stage information is also presented in graphic form in Fig. 8 for subject #1 and in Fig. 9 for subject #2. The data are presented in an averaged form in Table 2 to facilitate comparison of the different test situations (i. e. , each column of Table 2 is the arithmetic mean of the corresponding two or three values for the specific condition as shown in Table 1). The sleep-stage information of Table 2 is also presented in graphic form in Figs. 10 and 11 for subjects #1 and #2, respectively.



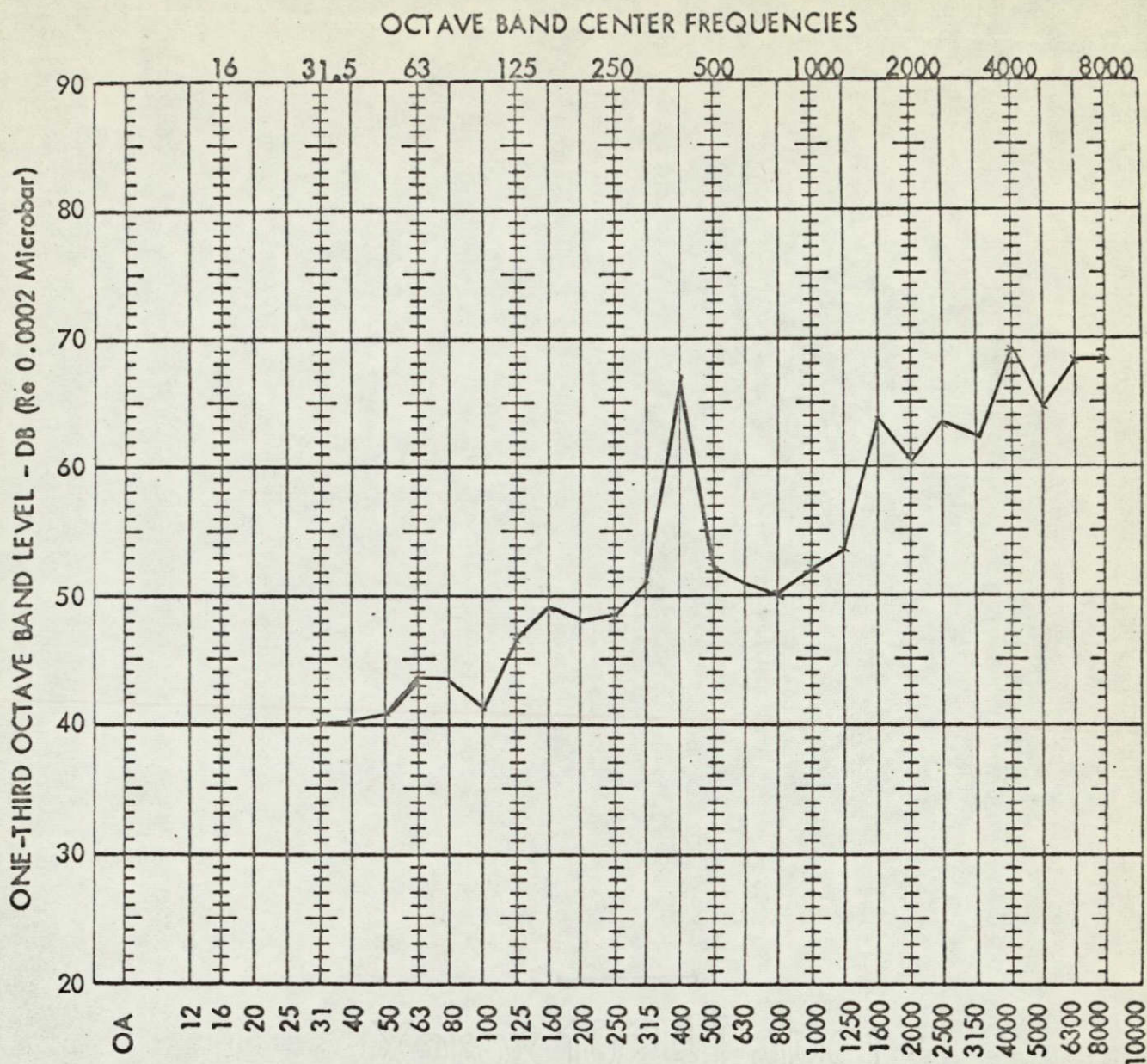
LTA-8 NOISE
PUMP #1 UNTREATED

FIG. 5
UNMOD. NOISE



LTA-8 NOISE
PUMP #1 AND MUFFLER #1

FIG. 6
NOISE MOD. I



LTA-8 NOISE
PUMP #1 AND MUFFLER #2

FIG. 7
NOISE MOD. 2

TABLE 1. TABULATED DATA

		Baseline Nights			Unmodi- fied Noise		Noise Mod. #1			Noise Mod. #2			Unmodi- fied Noise		Baseline Nights	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Total sleep time (hours)	Sub. 1	7.8	8.5	8.6	8.6	8.2	8.2	8.4	8.2	8.3	8.4	8.4	8.0	8.2	8.5	7.4
	Sub. 2	7.9	8.2	8.4	7.7	7.7	6.7	8.2	7.0	7.4	6.0	6.6	6.7	7.7	6.0	7.5
% REM time	Sub. 1	24.4	24.5	32.4	21.7	17.2	20.2	29.2	18.4	26.2	22.7	27.8	20.5	19.0	30.4	24.9
	Sub. 2	17.2	15.8	26.2	20.3	18.6	22.1	20.0	19.7	19.9	23.5	18.2	14.1	27.1	23.6	21.8
% stage 3-4 time	Sub. 1	28.8	38.8	4.9	17.8	20.2	27.1	34.4	25.5	25.9	41.2	28.8	31.5	45.9	17.9	24.7
	Sub. 2	20.5	22.7	19.1	10.7	21.7	18.9	27.5	22.5	31.5	20.7	32.5	25.9	26.6	22.1	27.5
% stage 1 time	Sub. 1	7.3	9.9	44.0	6.3	6.4	3.2	1.6	6.4	9.4	2.6	7.6	6.4	3.7	6.1	9.4
	Sub. 2	14.9	13.7	10.8	17.1	14.4	13.9	11.0	15.6	9.7	21.6	12.5	10.4	8.1	17.3	12.4
% stage 2 time	Sub. 1	39.5	26.9	18.7	54.3	56.3	49.6	34.9	49.7	38.4	33.4	35.8	41.7	31.5	45.7	41.1
	Sub. 2	47.3	47.7	43.9	52.0	45.3	45.1	41.0	42.1	38.9	34.2	36.7	49.6	38.2	37.3	38.4
% stage 3 time	Sub. 1	20.3	31.1	4.8	15.5	17.1	22.8	24.0	19.9	19.9	29.5	18.6	22.9	30.6	12.7	15.4
	Sub. 2	16.8	16.8	10.0	8.2	13.5	11.5	14.5	14.4	17.6	13.1	17.0	20.1	17.2	9.3	12.1
% stage 4 time	Sub. 1	8.5	7.7	0.1	2.3	3.1	4.3	10.4	5.6	6.0	11.7	10.2	8.6	15.3	5.2	9.3
	Sub. 2	3.7	5.9	9.1	2.5	8.2	7.4	13.0	8.1	13.9	7.6	15.5	5.8	9.4	12.8	15.4
Time to fall asleep (stage 2) (min.)	Sub. 1	14.3	12.3	17.0	7.6	8.3	10.7	5.0	7.0	21.6	6.0	8.6	21.0	6.3	7.6	13.0
	Sub. 2	19.3	21.3	21.3	32.6	17.3	45.0	16.0	46.0	24.0	37.0	16.0	56.3	27.3	68.6	24.3
No. of arousals (> 10 sec.)	Sub. 1	7	1	7	0	4	4	0	2	1	1	4	3	2	4	9
	Sub. 2	17	15	19	18	13	13	14	20	12	18	13	17	13	19	14
No. of REM periods	Sub. 1	4	4	4	5	4	5	5	5	5	5	6	3	3	6	3
	Sub. 2	5	8	6	6	7	7	8	5	5	3	4	4	7	7	6
Total REM time (hours)	Sub. 1	1.9	2.1	2.8	1.9	1.4	1.7	2.5	1.5	2.2	1.9	2.4	1.6	1.6	2.6	1.8
	Sub. 2	1.4	1.3	2.2	1.6	1.4	1.5	1.6	1.4	1.5	1.4	1.2	1.0	2.0	1.4	1.6
Total stage 1 time (hours)	Sub. 1	0.6	0.8	3.8	0.5	0.5	0.3	0.1	0.5	0.8	0.2	0.6	0.5	0.3	0.5	0.7
	Sub. 2	1.2	1.1	0.9	1.3	1.1	0.9	0.9	1.1	0.7	1.3	0.8	0.7	0.6	1.0	0.9
Total stage 2 time (hours)	Sub. 1	3.1	2.3	1.6	4.7	4.6	4.1	2.9	4.1	3.2	2.8	3.0	3.3	2.6	3.9	3.0
	Sub. 2	3.7	3.9	3.7	4.0	3.5	3.0	3.4	3.0	2.9	2.1	2.4	3.3	2.8	2.2	2.9
Total stage 3 time (hours)	Sub. 1	1.6	2.6	0.4	1.3	1.4	1.9	2.0	1.6	1.6	2.5	1.6	1.8	2.5	1.1	1.1
	Sub. 2	1.3	1.4	0.8	0.6	1.0	0.8	1.2	1.0	1.3	0.8	1.1	1.4	1.3	0.6	0.9
Total stage 4 time (hours)	Sub. 1	0.7	0.7	0.0	0.2	0.3	0.4	0.9	0.5	0.5	1.0	0.9	0.7	1.3	0.4	0.7
	Sub. 2	0.3	0.5	0.8	0.2	0.6	0.5	1.1	0.6	1.0	0.5	1.0	0.4	0.7	0.8	1.2

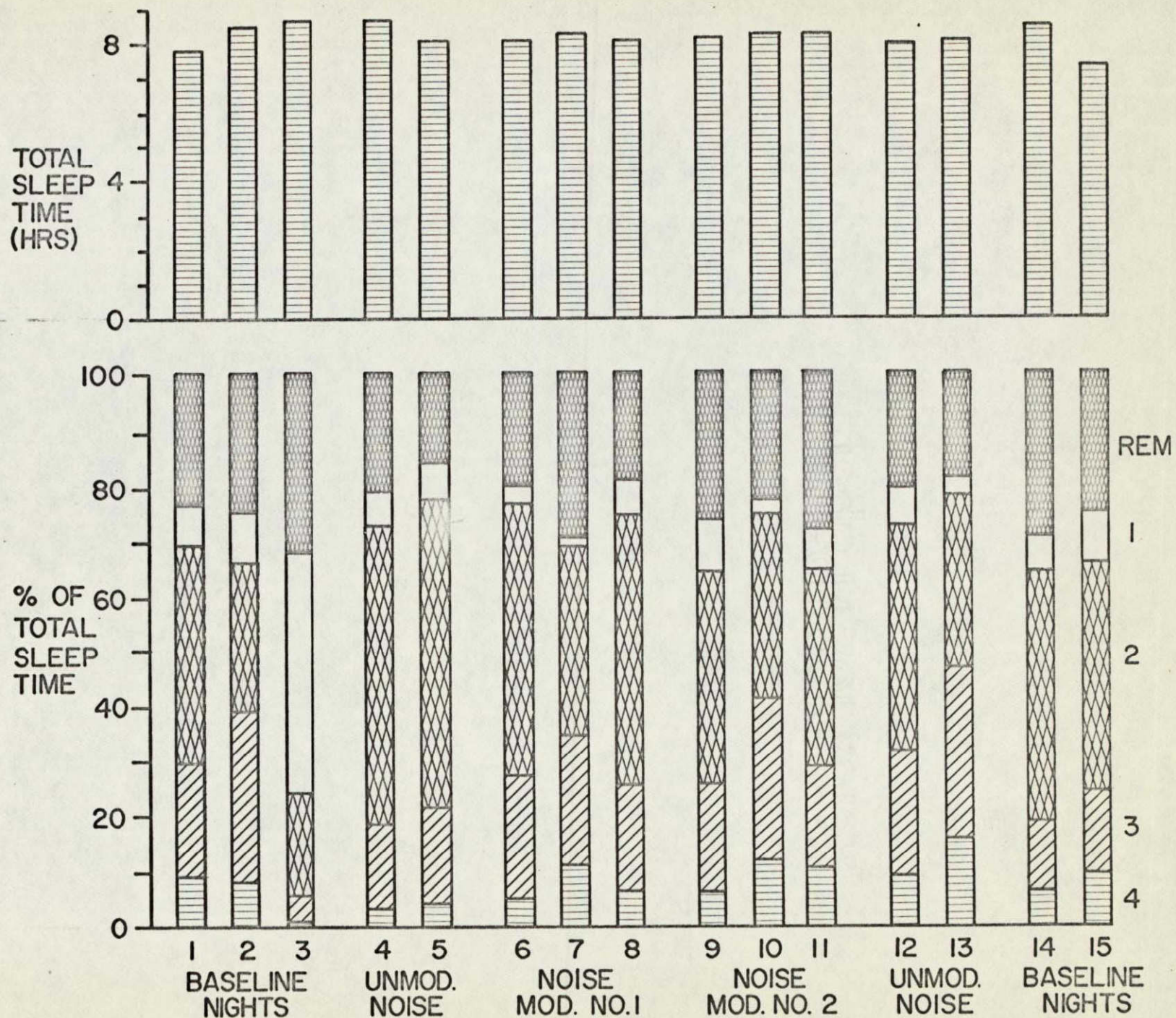


FIG. 8 - SUBJECT NO. 1 - TOTAL SLEEP TIME AND % VALUES FOR EACH STAGE

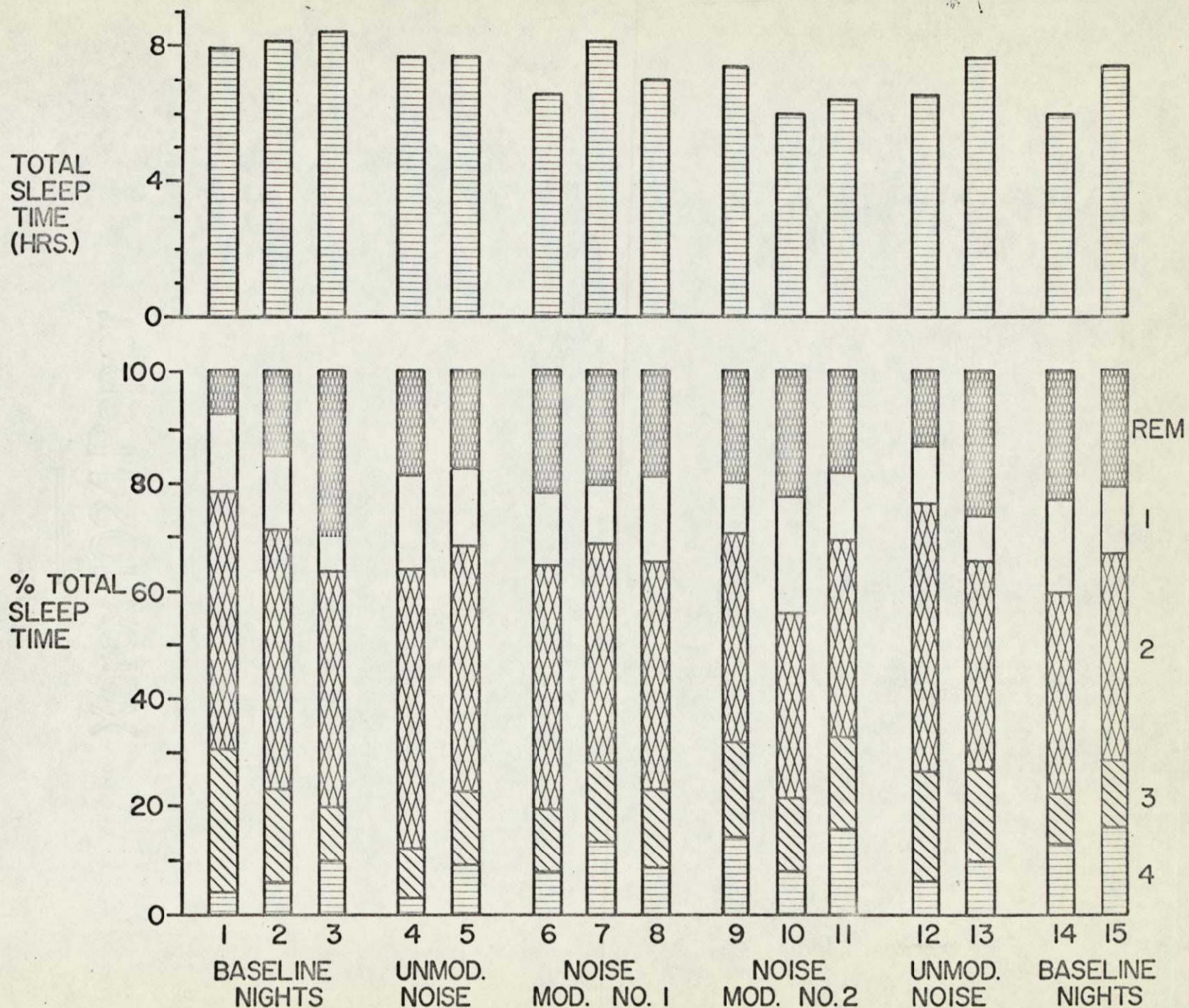


FIG. 9-SUBJECT NO. 2 - TOTAL SLEEP TIME AND % VALUE FOR EACH STAGE

TABLE 2. AVERAGED RESULTS

		Baseline Nights (Av. of 3)	Unmodi- fied Noise (Av. of 2)	Noise Mod. #1 (Av. of 3)	Noise Mod. #2 (Av. of 3)	Unmodi- fied Noise (Av. of 2)	Baseline Nights (Av. of 2)
Total sleep time (hours)	Sub. 1	8.3	8.4	8.3	8.4	8.1	8.0
	Sub. 2	8.2	7.7	7.3	6.7	7.2	6.8
% REM time	Sub. 1	27.1	19.5	22.6	25.6	19.8	27.6
	Sub. 2	19.7	19.5	20.6	20.5	20.6	22.7
% stage 3-4 time	Sub. 1	24.2	19.0	29.0	32.0	38.7	21.3
	Sub. 2	20.8	16.2	23.0	28.2	26.3	24.8
% stage 2 time	Sub. 1	28.4	55.3	44.7	35.9	36.6	43.4
	Sub. 2	46.3	48.7	42.7	36.6	43.9	37.9
% stage 1 time	Sub. 1	20.4	6.4	3.7	6.5	5.1	7.8
	Sub. 2	13.1	15.8	13.5	14.6	9.3	14.9
% stage 3 time	Sub. 1	18.7	16.3	22.2	22.7	26.8	14.1
	Sub. 2	14.5	10.9	13.5	15.9	18.7	10.7
% stage 4 time	Sub. 1	5.4	2.7	6.8	9.3	12.0	7.3
	Sub. 2	6.2	5.4	9.5	12.3	7.6	14.1
Time to fall asleep (stage 2)(min.)	Sub. 1	14.5	8.0	7.6	12.1	13.7	10.3
	Sub. 2	20.6	25.0	35.7	25.7	41.8	46.5
No. of arousals (> 10 sec.)	Sub. 1	5.0	2.0	2.0	2.0	2.5	6.5
	Sub. 2	17.0	15.5	15.6	14.3	15.0	16.5
No. of REM periods	Sub. 1	4.0	4.5	5.0	5.3	3.0	4.5
	Sub. 2	6.3	6.5	6.6	4.0	5.5	6.5

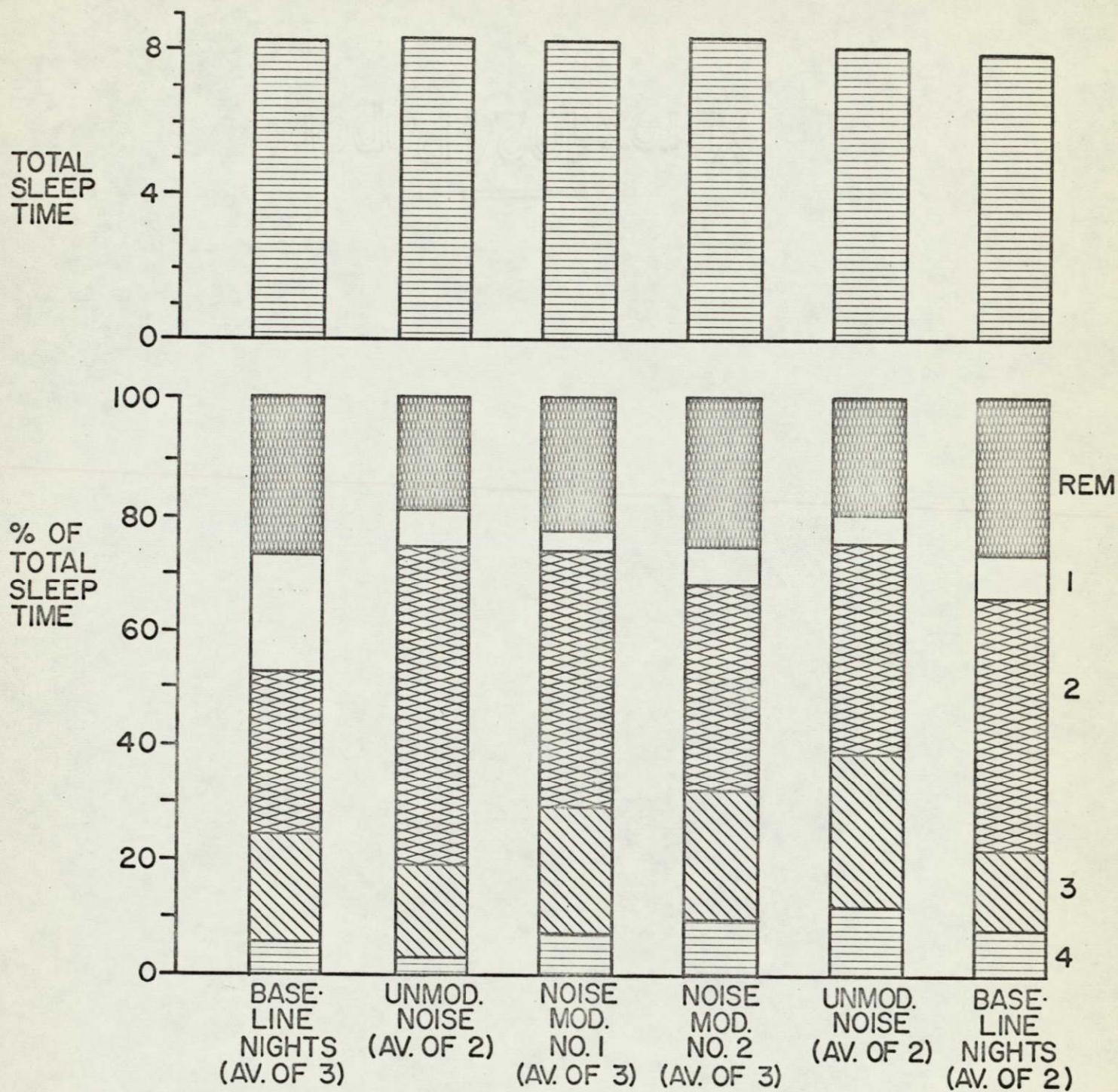


FIG. 10- SUBJECT 1 - AVERAGED RESULTS
TOTAL SLEEP TIME AND % VALUES FOR EACH STAGE

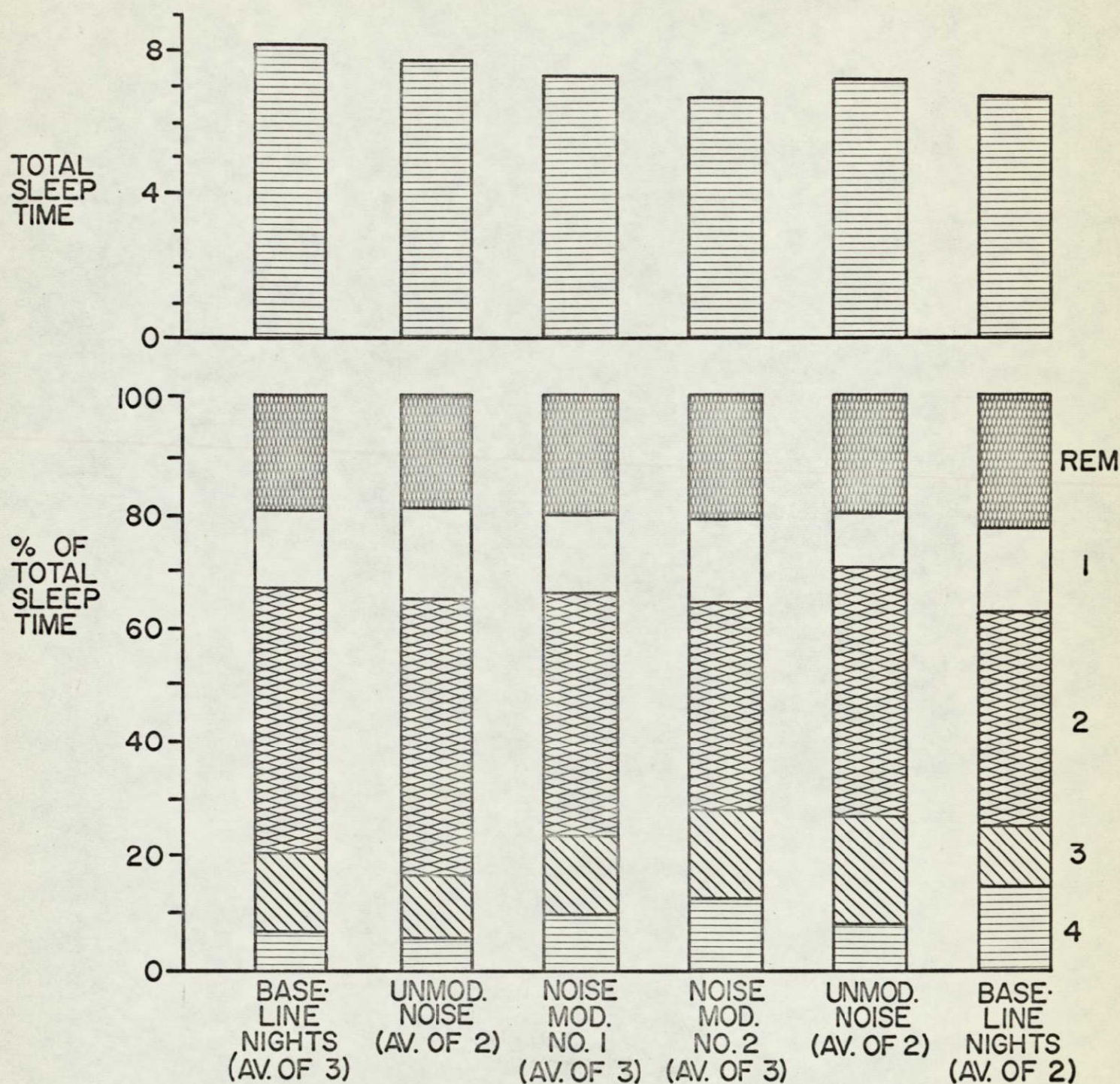


FIG. II- SUBJECT NO. 2 - AVERAGED RESULTS
TOTAL SLEEP TIME AND % VALUES FOR EACH STAGE

Samples of the graphic record for each stage of sleep for each subject are presented in Figs. 12 through 17.

2. Total Sleep Time

This value represents the total amount of time the subject actually slept each night by EEG and EOG criteria. As indicated in Table 1 and displayed in the upper portion of Fig. 8, subject #1, except for the first and last nights of the study, maintained a very constant total sleep time throughout the test period.

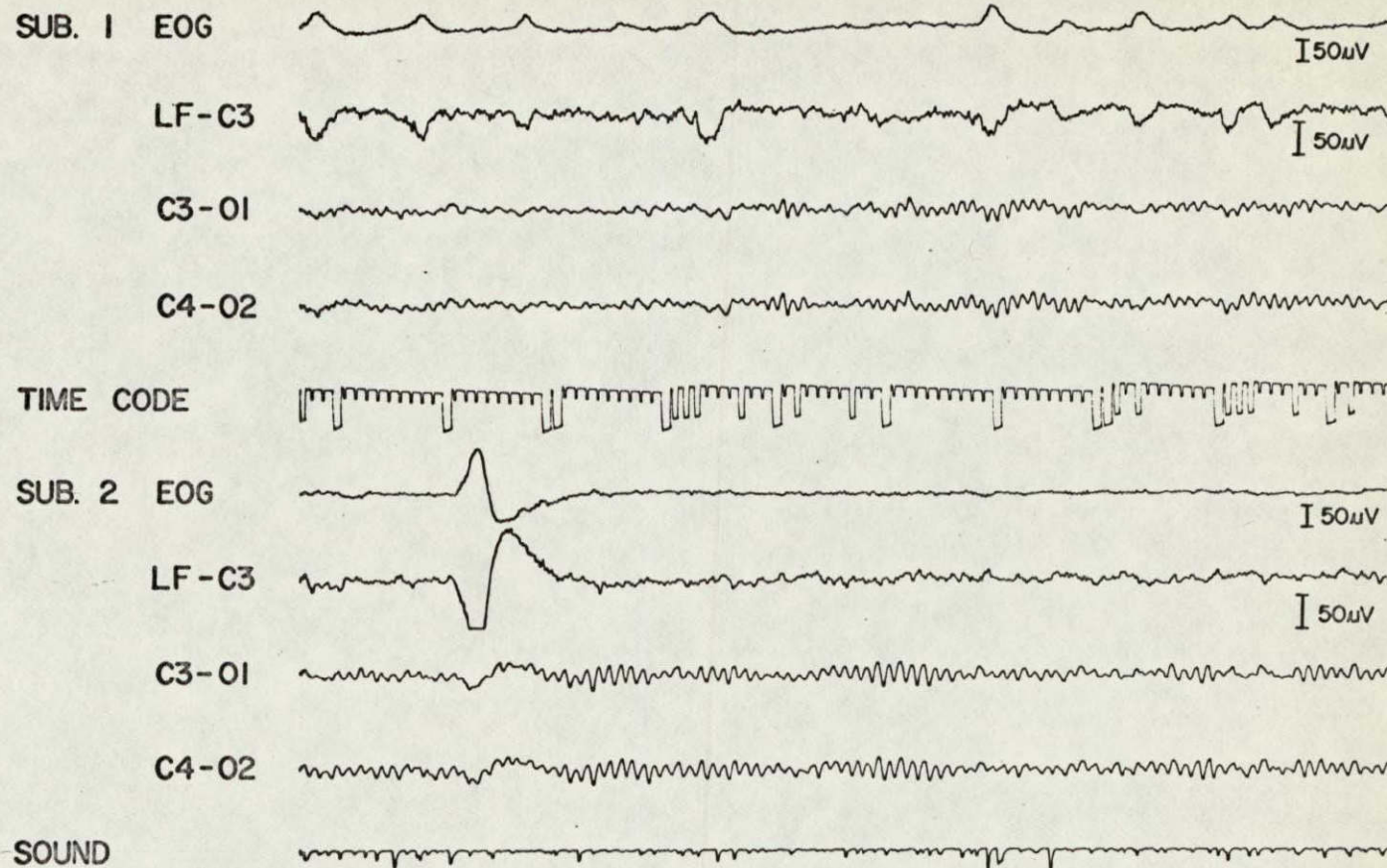
In particular, as demonstrated in Table 2 and the upper portion of Fig. 10, there was no detectable change in this measure which could be associated with either of the two periods of unmodified spacecraft noise or with the two periods of altered noise.

Subject #2 showed considerably more variation in total sleep time (Table 1), and, as is evident in Fig. 9, there was, in general, a progressive decline in this measure over the period of the study. But the averaged results (Table 2 and Fig. 11) indicated no effect which could be specifically attributed to any of the noise conditions. Thus, while the average total sleep time during each of the four periods of noise was less than the average of the first three baseline nights, the average of the last two baseline nights was less than any of the unmodified noise periods and the period of noise modification #1.

3. Sleep-Stage Characteristics

Although Table 1 and Figs. 8 and 9 indicate a considerable amount of night-to-night variation in the relative time spent in each sleep stage for both subjects, this variation is not unusual and tends to average out to typical values over several nights. Fig. 2 is the output of the automatic sleep analyzer for subject #1 and illustrates a typical night of sleep for this subject. The characteristic cyclic nature of the sleep pattern is evident, as is the relative increase in length of REM periods and decrease in amount of stage 4 time as the night progresses. Fig. 3 shows a similar plot for subject #2, and while it too exhibits the cyclic pattern of sleep stages, it also illustrates a fairly long period when the subject was awake early in the morning, followed by a return to stage 2-3 sleep. This was a typical observation in this subject, and, together with a somewhat longer time required to fall asleep (see below), it accounts for the generally shorter and more variable total sleep time of subject #2.

Table 2 and Fig. 18 illustrate the only sleep-stage feature which appeared to be consistently influenced by the presence of the spacecraft noise.



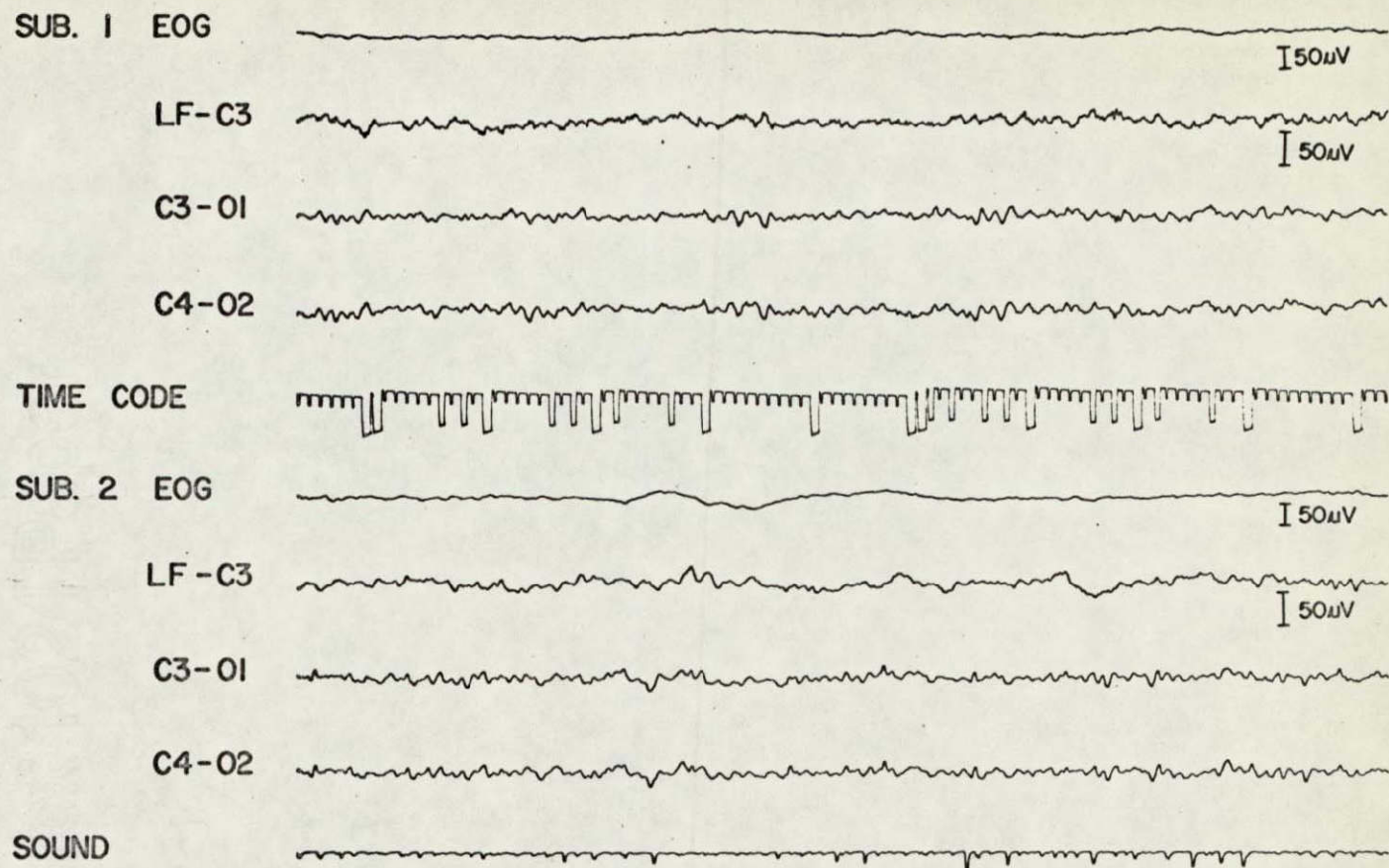
AWAKE, EYE BLINKS, SUB. 1 and 2
1/16-17/70

SUB. 1 ANALYZER

1 SECOND

SUB. 2 ANALYZER

FIG. 12



STAGE 1, SUB. 1 and 2

1/16-17/70

SUB. 1 ANALYZER

1 SECOND

SUB. 2 ANALYZER

FIG. 13

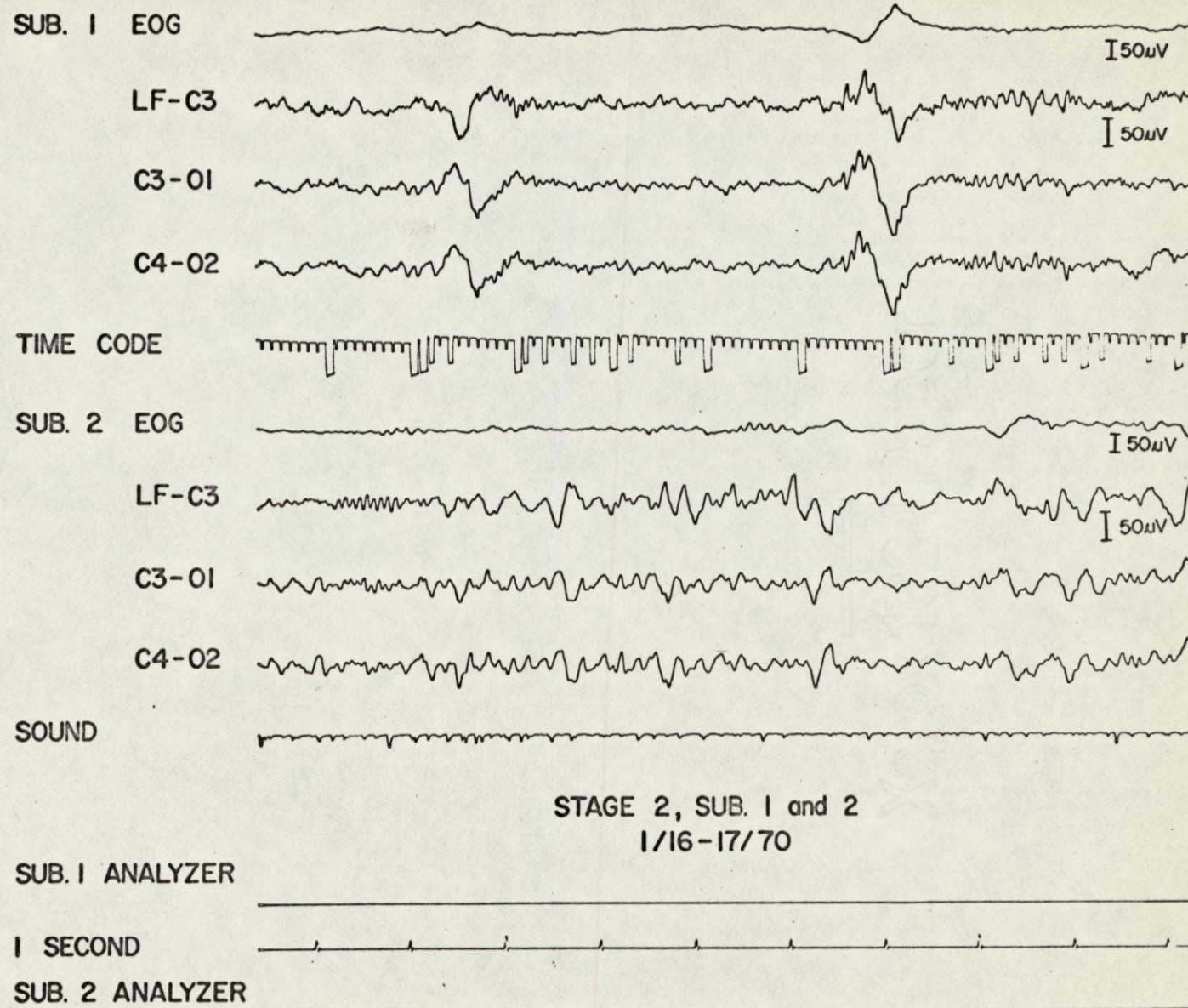


FIG. 14

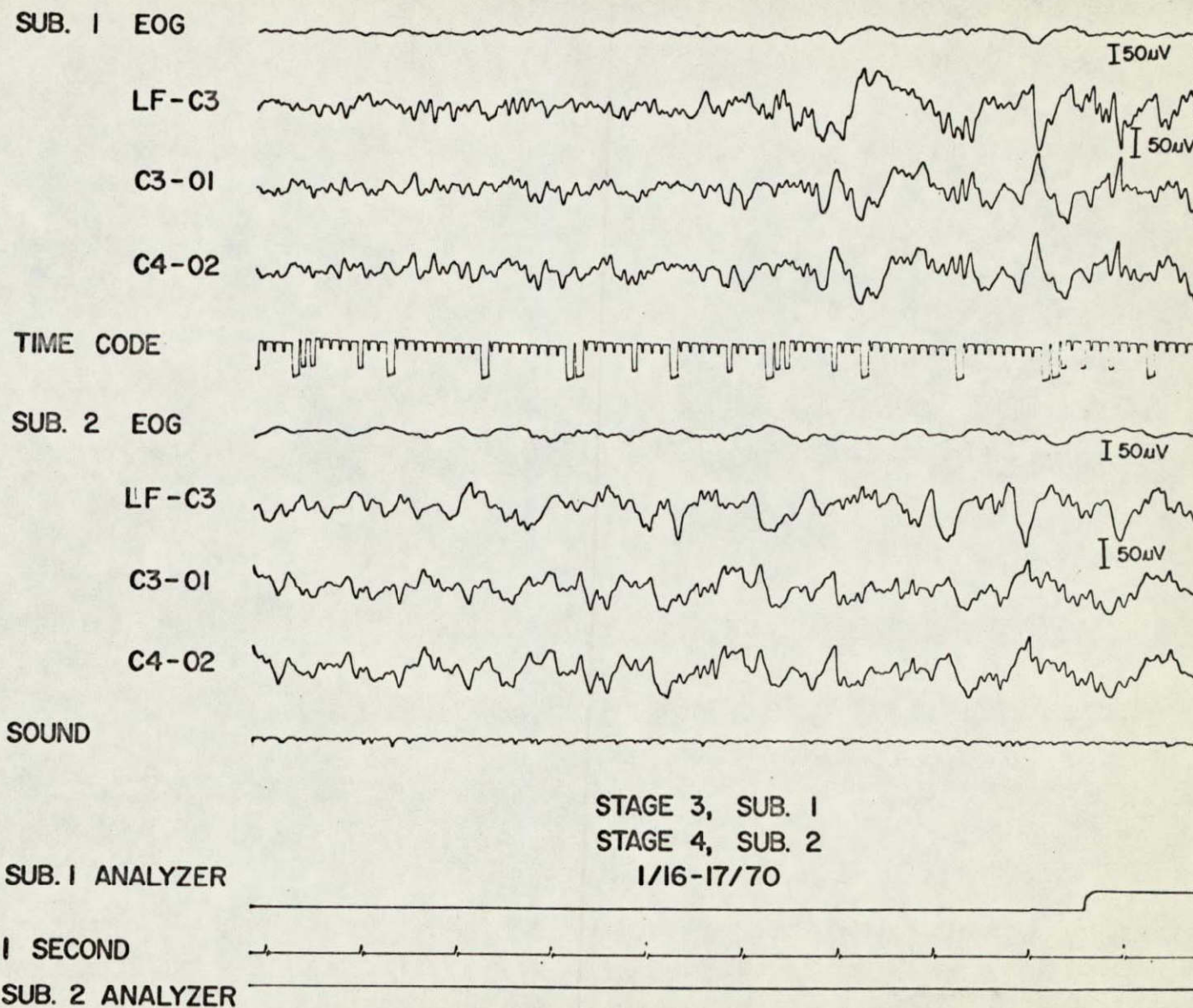


FIG. 15A

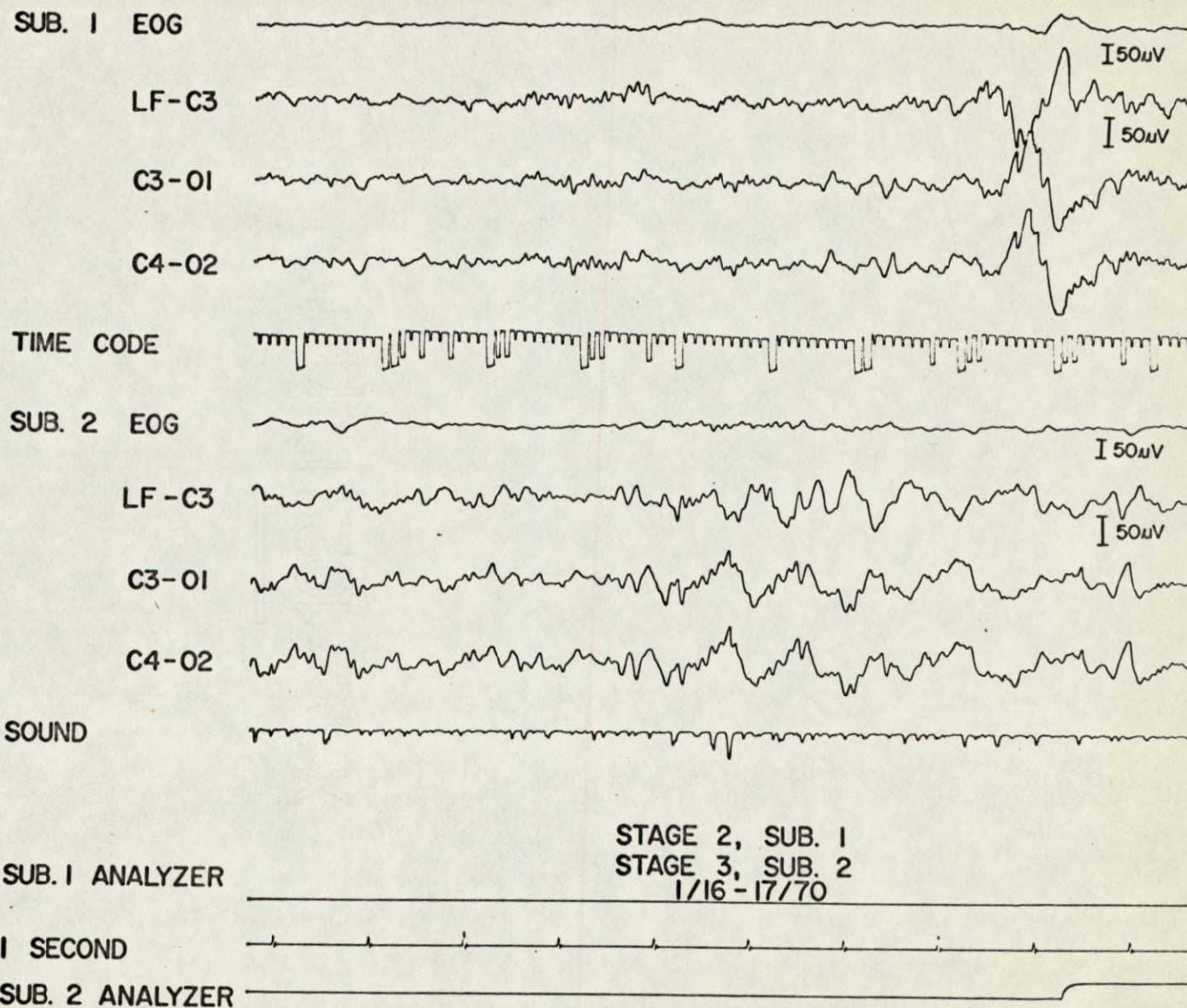


FIG. 15B

SUB. 1 EOG

LF-C3

C3-O1

C4-O2

TIME CODE

SUB. 2 EOG

LF-C3

C3-O1

C4-O2

SOUND

STAGE 4, SUB. 1 and 2
1/16-17/70

SUB. 1 ANALYZER

1 SECOND

SUB. 2 ANALYZER

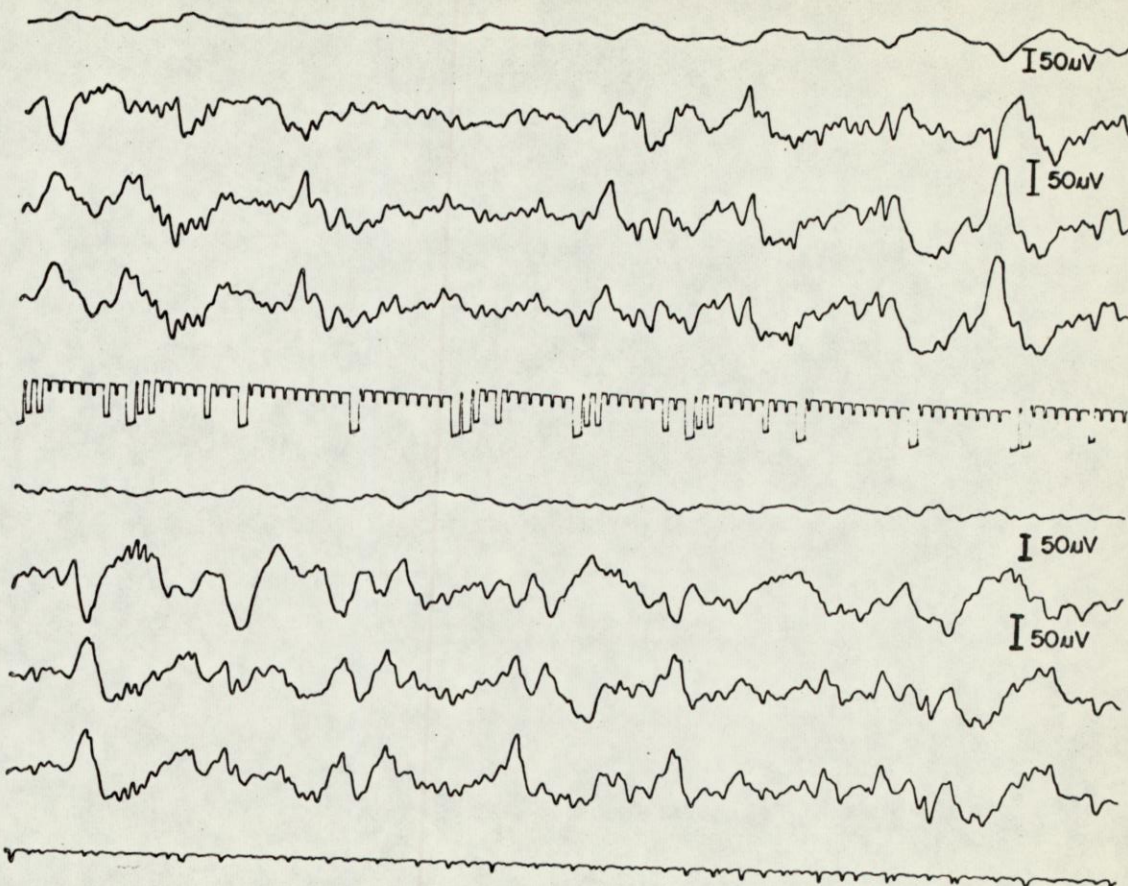


FIG. 16

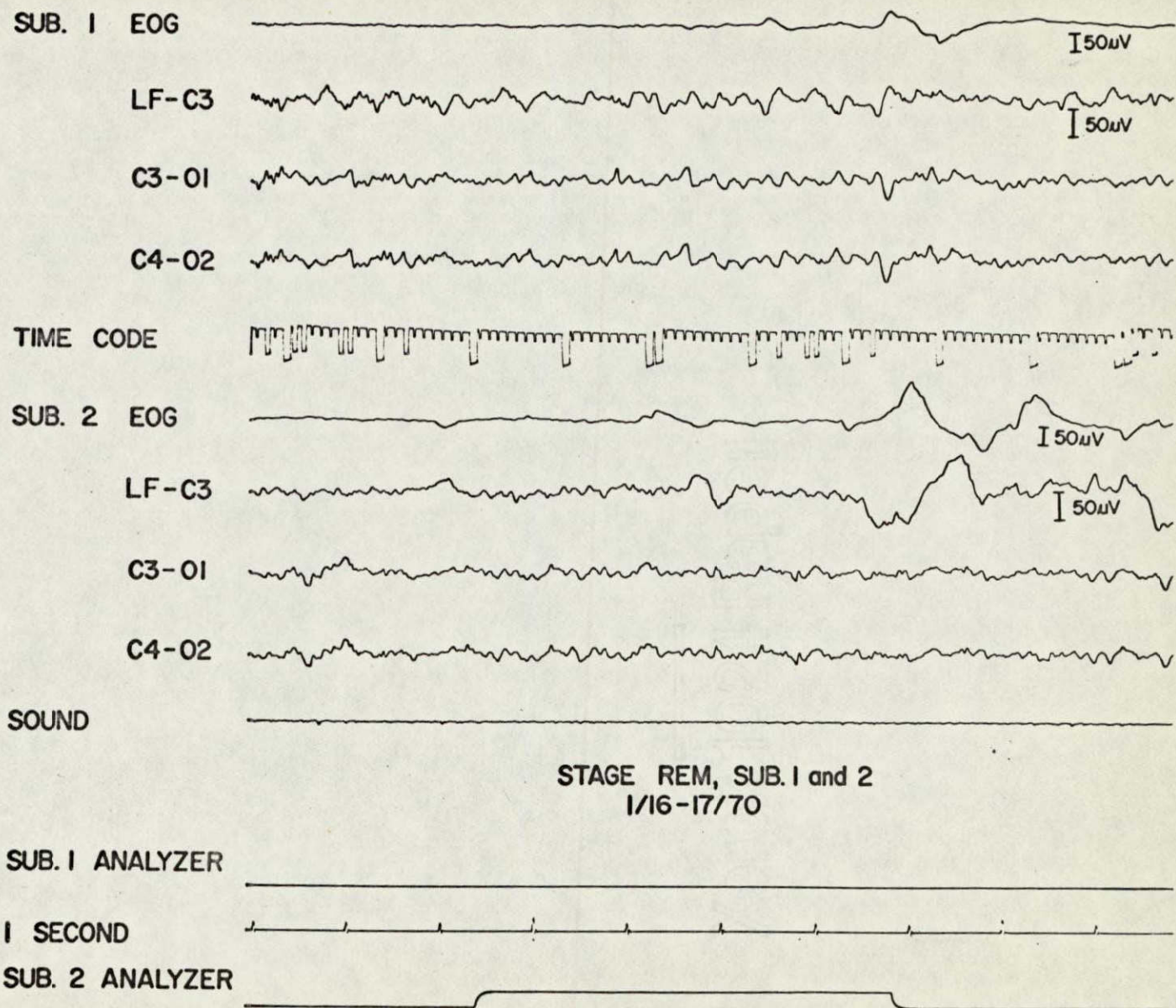


FIG. 17

REM TIME
AS % OF
TOTAL SLEEP
TIME

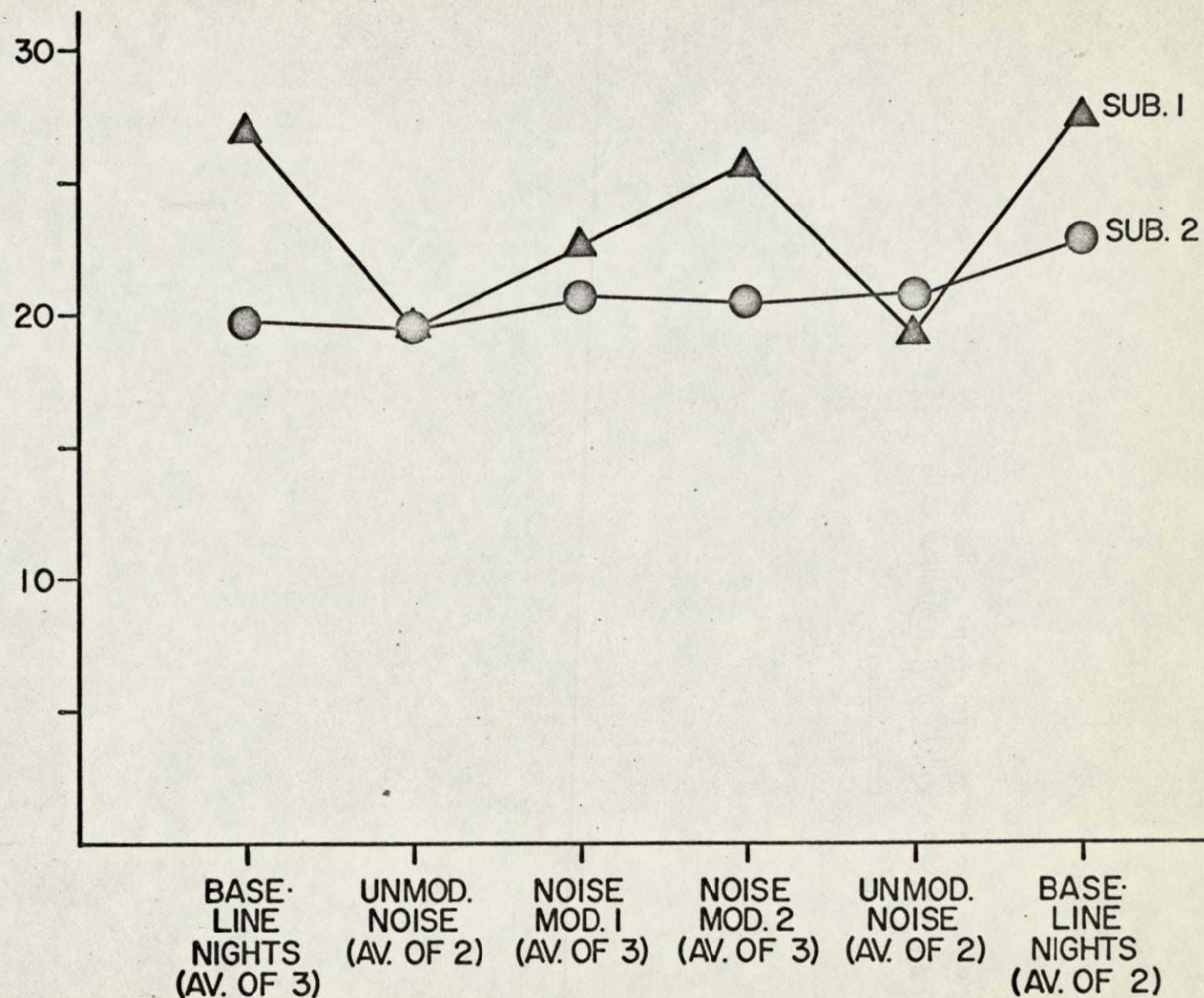


FIG. 18
AVERAGE % REM TIME

Subject #1 showed a noticeable reduction in average percent stage REM time during both periods of the unmodified noise, and a lesser reduction during the two periods of modified noise as compared to either the first or last baseline periods. A similar trend is suggested in the data from subject #2, but the change is not considered to be significant.

4. Time to Fall Asleep

Subject #1 went to sleep first in every instance (Table 1) and never required longer than 22 minutes (range, 5-22 minutes). Subject #2 ranged between 16 and 69 minutes. The presence or absence of the various noise conditions appeared to have no consistent influence on this measure in either subject (Table 2; Fig. 19).

5. Number of Arousals (awake periods longer than approximately 10 seconds)

Subject #1 consistently had fewer arousals throughout the night than did subject #2 (Table 1). Both subjects exhibited a reduction in the average number of arousals during all periods of the spacecraft-noise exposure (Figs. 20 and 21) in spite of the sporadic tape-recorder transients. ("Subarousals," i.e., brief EEG shifts to a lighter stage of sleep but not reaching wakefulness, were not tabulated.)

6. Number of REM Periods

Although, as noted above, the percent REM time appeared to be influenced by the presence of the noise conditions, no influence on the number of REM periods was evident (Figs. 22 and 23). Thus, since the total sleep time was relatively consistent in subject #1, the reduction in percent REM time must be attributed to a shortening of the REM periods rather than to a reduction in their number.

7. Analysis of the Waking Alpha Rhythm

Each 5-minute period of waking activity preceding the sleep time was subjected to computer analysis^{5, 6} in order to obtain a quantitative measure of the stability of each subject's alpha activity and to detect any possible effects related to the noise study which might occur over a period of days. The "modal alpha wavelength," which is plotted in Figs. 24 and 25, is a quantitative measure which correlates well with the reciprocal of alpha-frequency estimations made by an electroencephalographer. The "mean alpha wavelength" and its standard deviation provide a measure of the "constancy" of the alpha rhythm.

TIME TO
ATTAIN
STAGE 2
(MIN.)

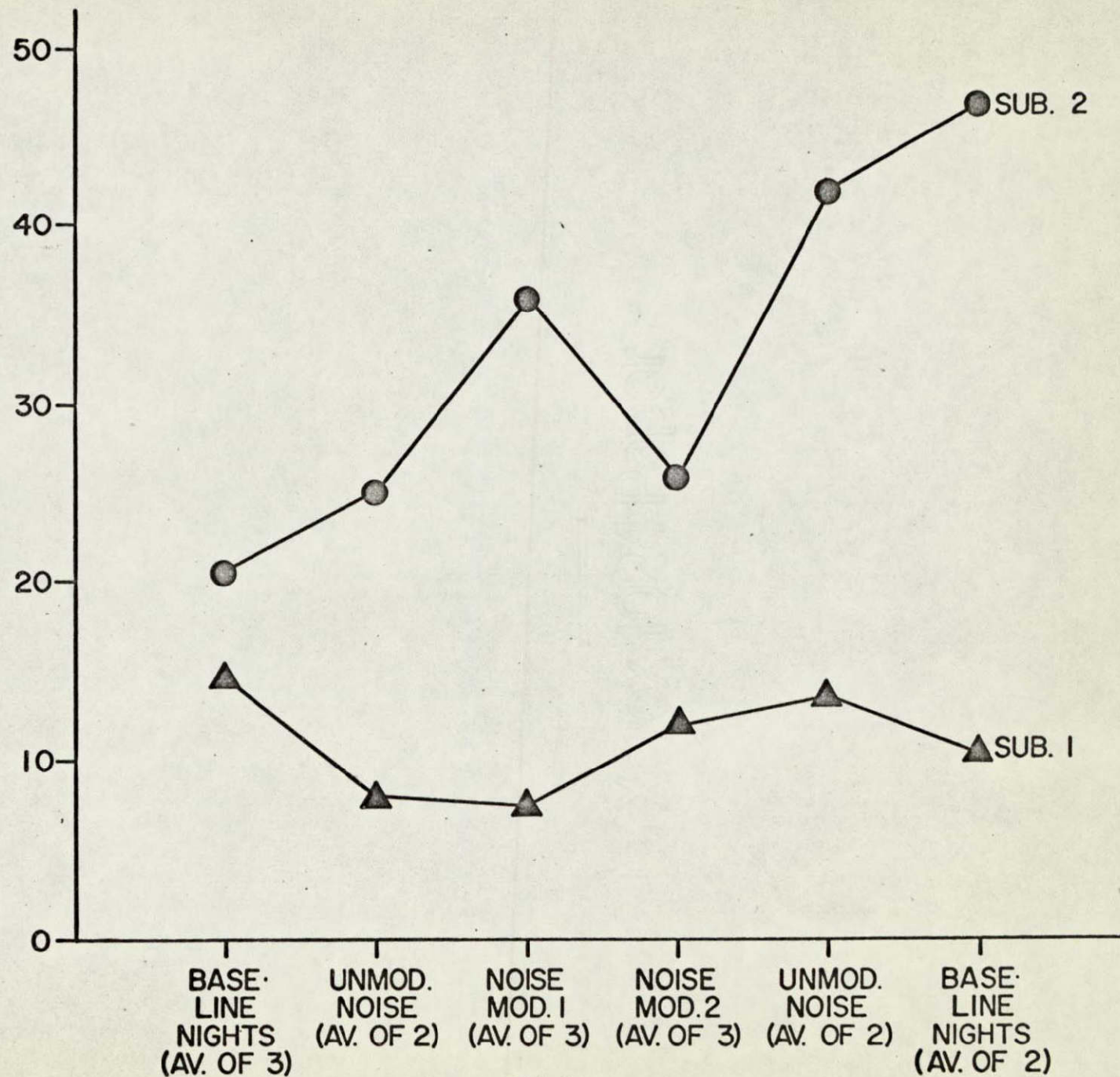


FIG. 19

AVERAGE TIME TO FALL ASLEEP (STAGE 2 SLEEP)

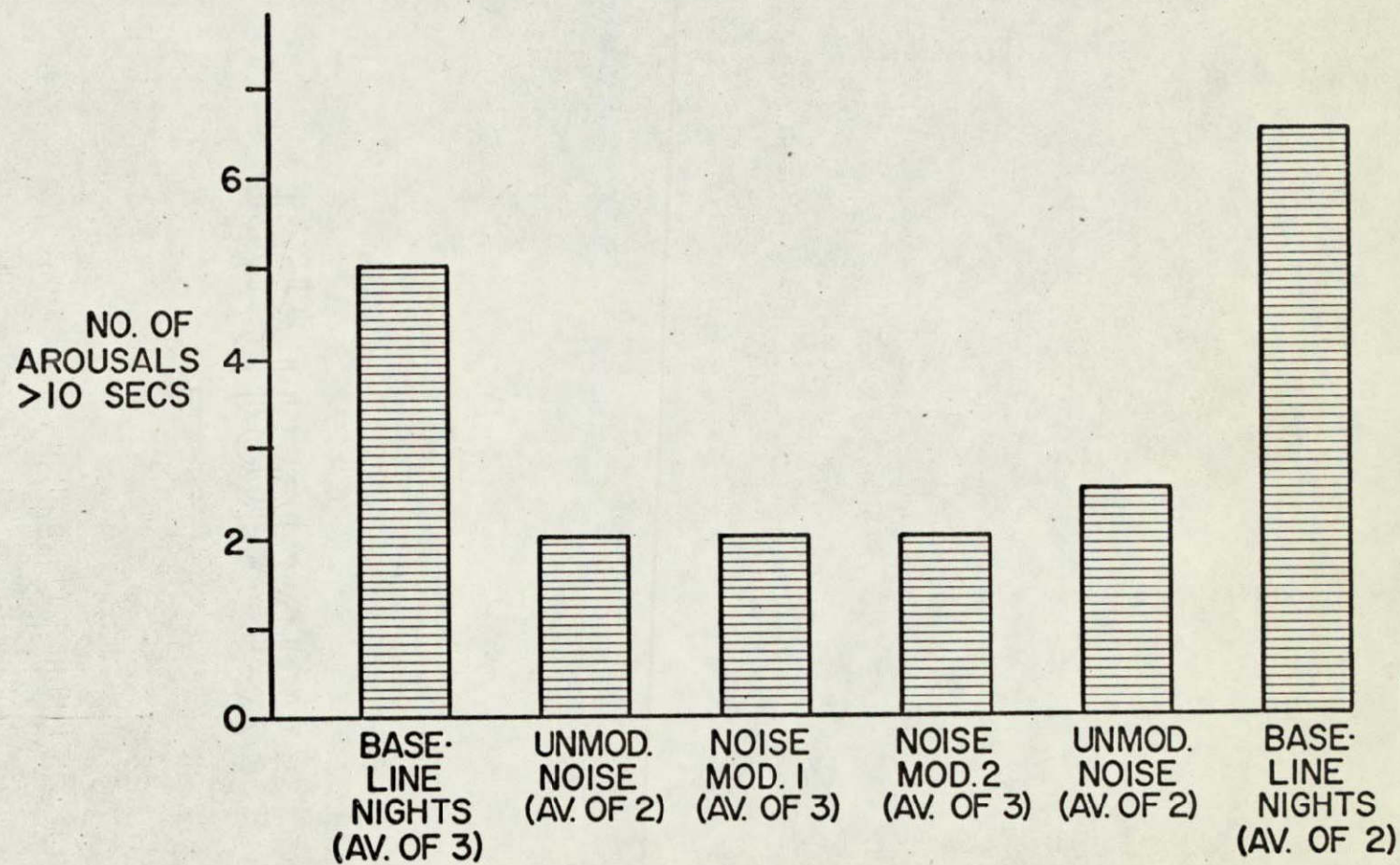


FIG. 20

SUBJECT 1 - AVERAGE NO. OF AROUSALS

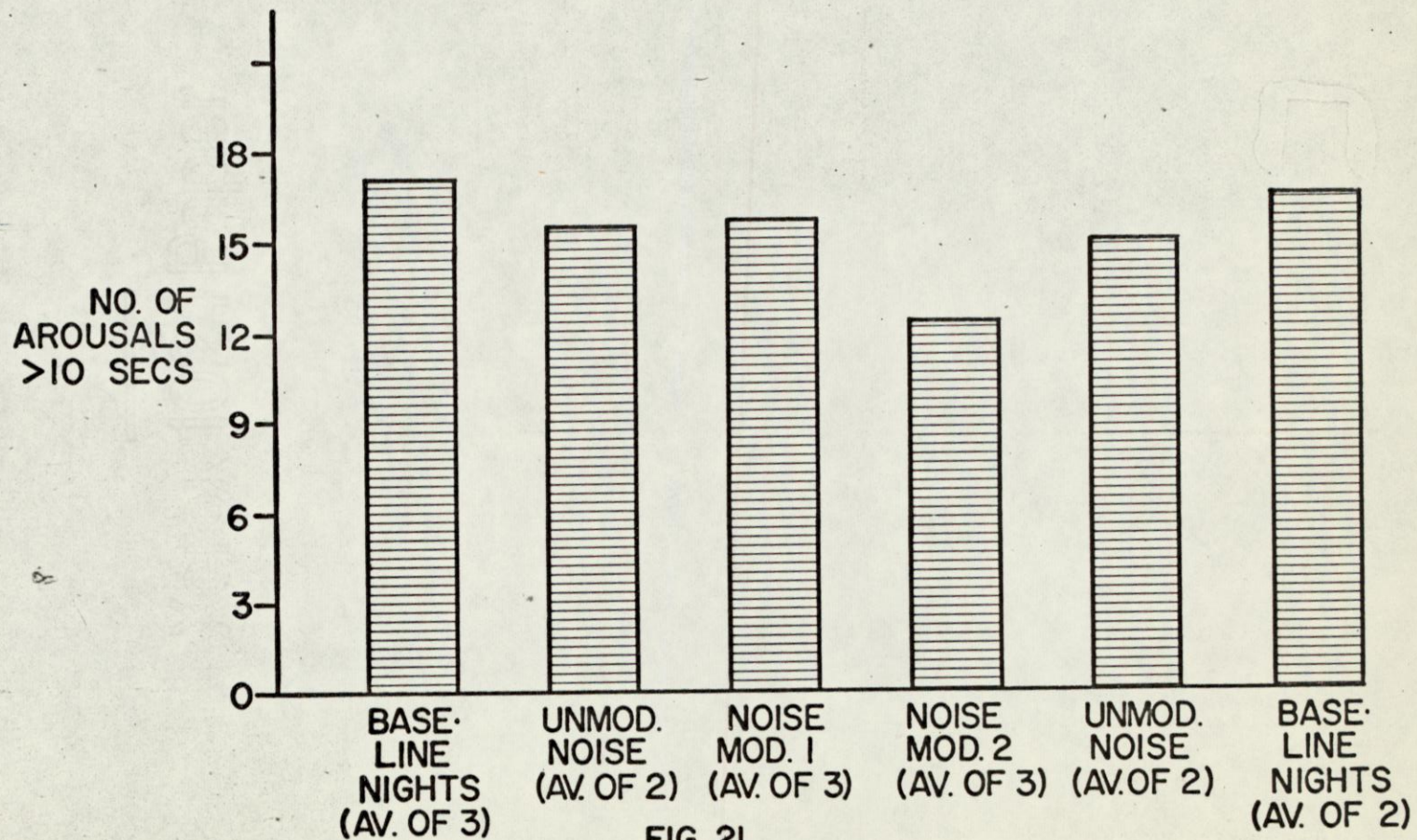
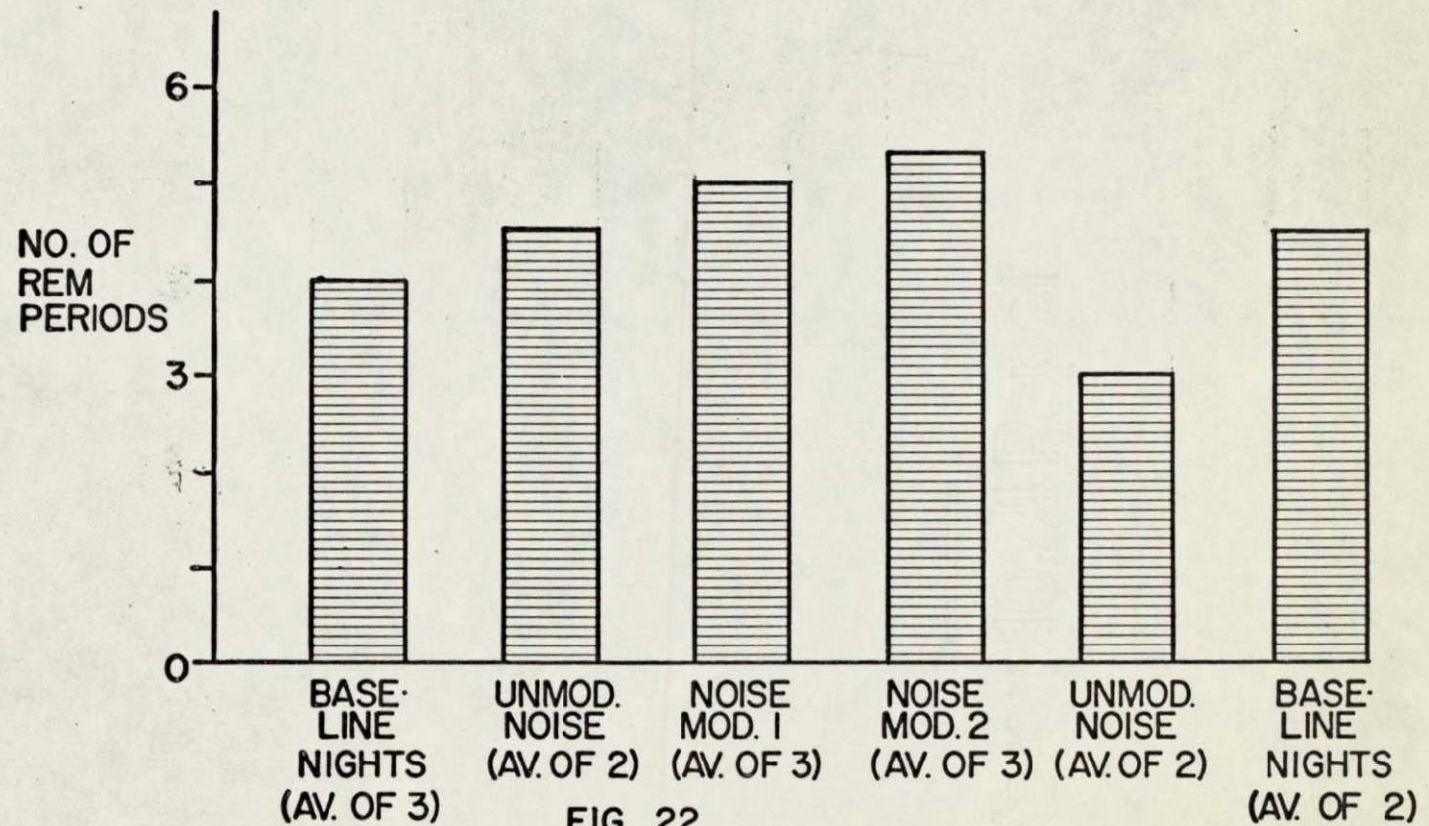


FIG. 21

SUBJECT 2 - AVERAGE NO. OF AROUSALS



SUBJECT 1 - AVERAGE NO. OF REM PERIODS

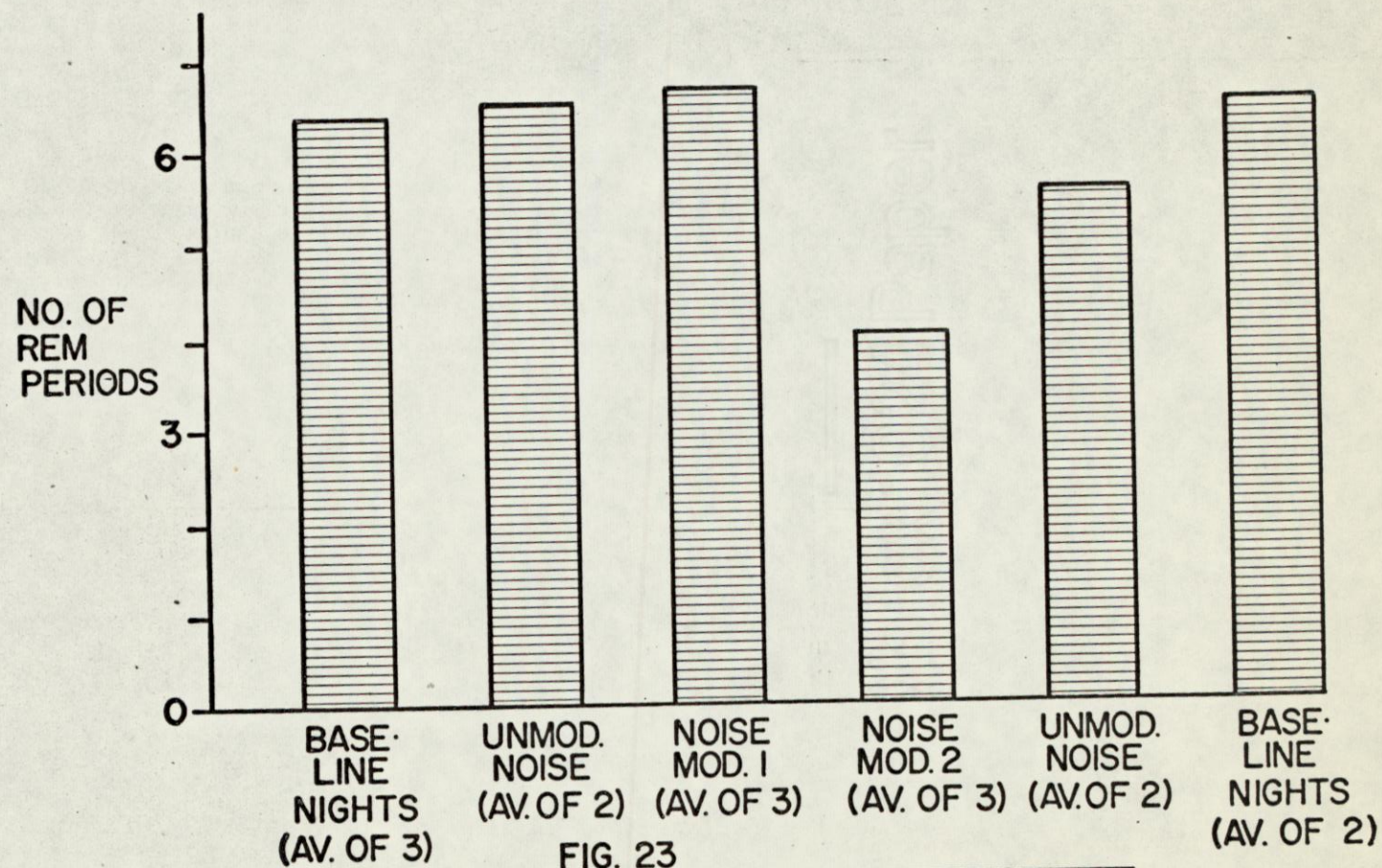


FIG. 23

SUBJECT 2 - AVERAGE NO. OF REM PERIODS

- MEAN ALPHA WAVELENGTH
- MODAL ALPHA WAVELENGTH
- | STANDARD DEVIATION AROUND MEAN

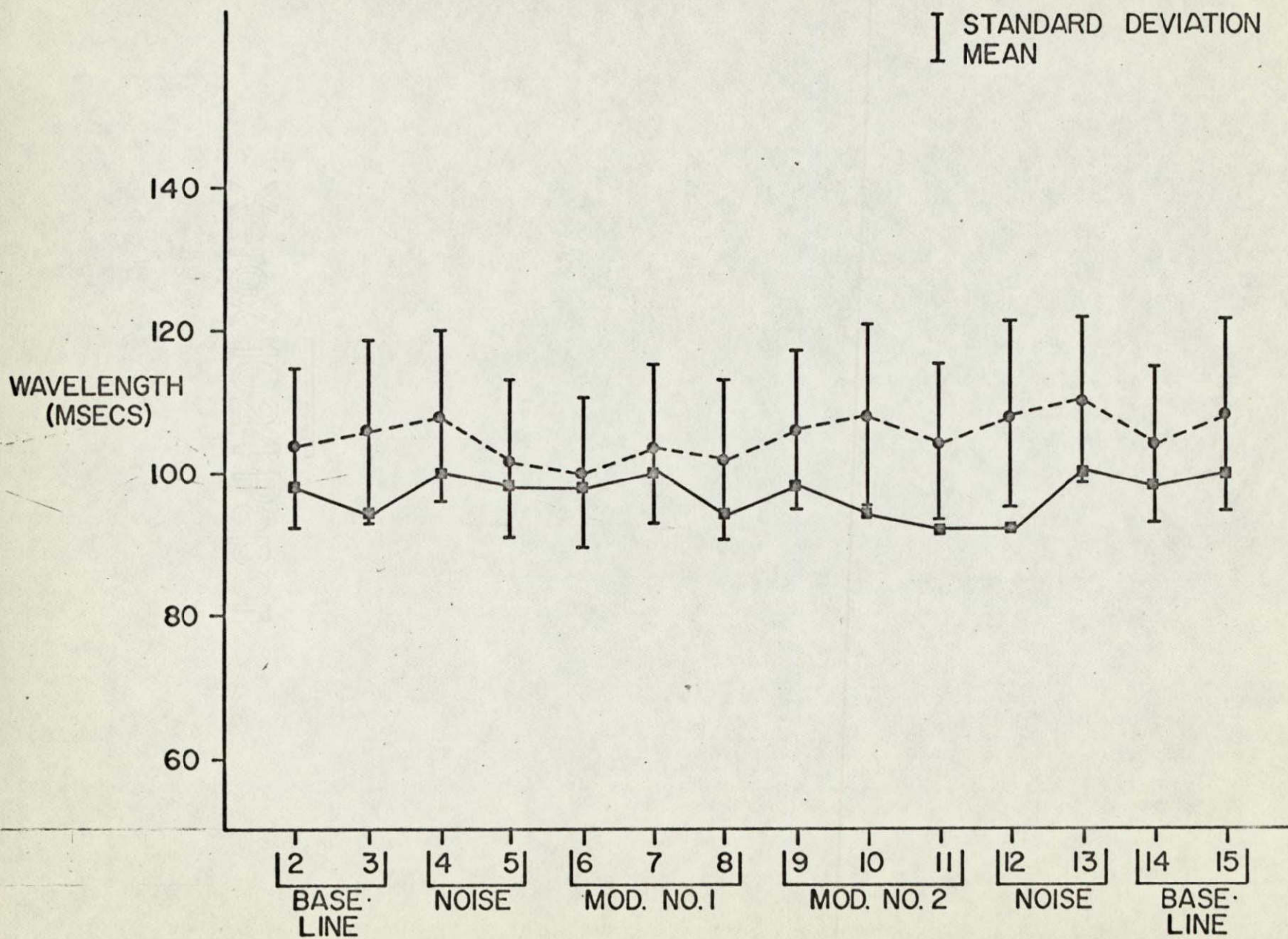


FIG. 24
SUB. 1, ALPHA WAVELENGTH CHARACTERISTICS

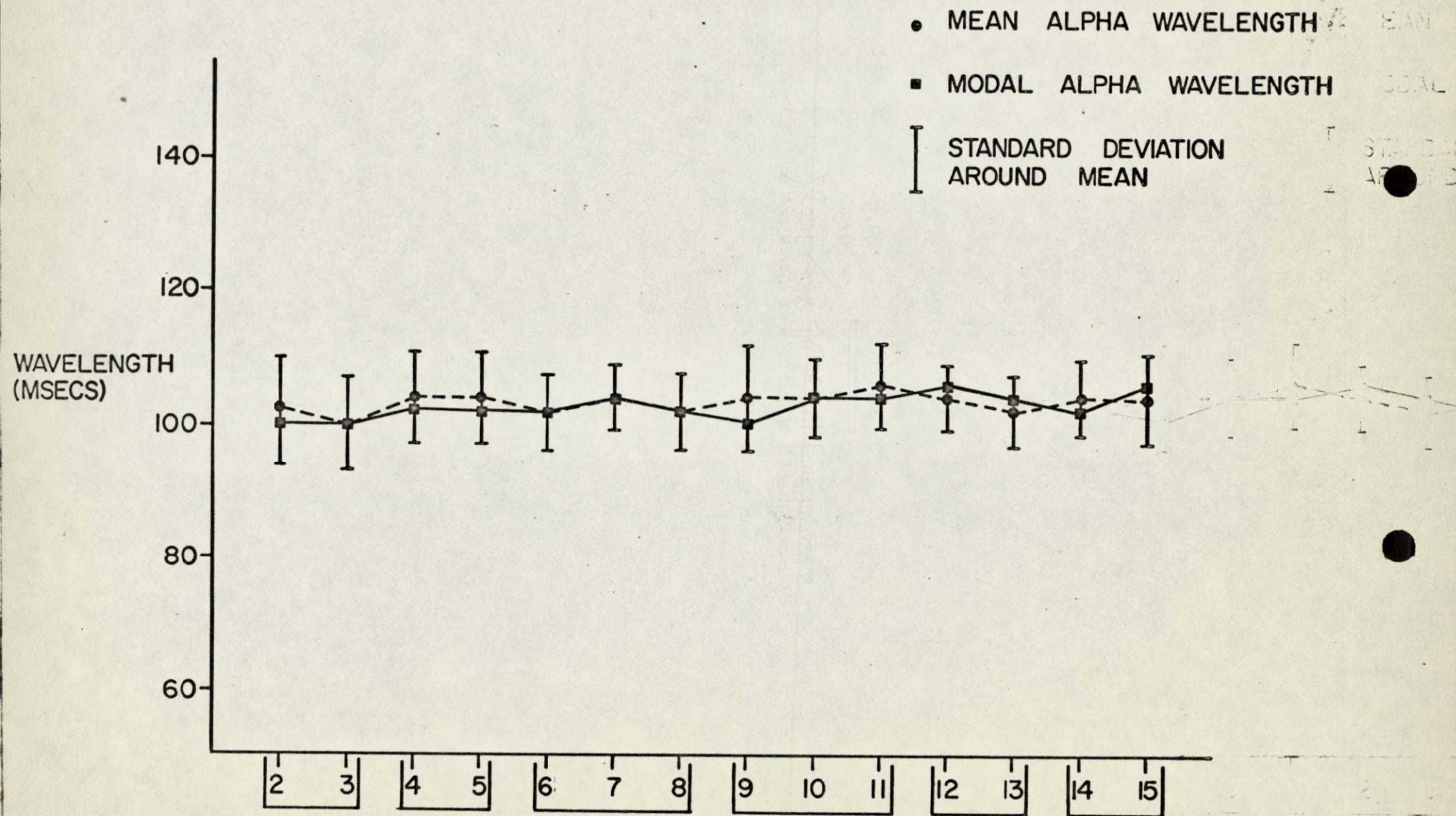


FIG. 25

SUB. 2, ALPHA WAVELENGTH CHARACTERISTICS

Figs. 24 and 25 illustrate that while each subject presented a different set of alpha characteristics (i. e., subject #1 had a slightly lower modal wavelength and a more dispersed and skewed distribution than did subject #2), the individual characteristics remained relatively consistent over the 14-day observation period (nights 2-15), and the minimal fluctuations noted could not be related to the specific noise conditions.

C. Comparison of Subjective and Objective Estimates

Table 3 is a tabulation of the subjects' own estimates of certain sleep characteristics. Figs. 26 and 27 compare the subjective and actual results for subject #1 and subject #2, respectively.

Both subjects tended to underestimate their total sleep time, but in general the estimates followed the actual trend (i. e., low actual sleep values were usually correctly identified by a low estimate). The estimates of subject #1 ranged from a maximum underestimate of 1 hour to an overestimate of 0.2 hour, with an average error of 0.5 hour over the 15-day period. Subject #2 had a maximum underestimate of 2.8 hours and a maximum overestimate of 0.8 hour, with an average error of 0.8 hour.

The estimates of both subjects tended to be closer to the actual values during the central portion of the study (i. e., during the various noise-exposure periods) than they were during the baseline nights (subject #1: average error on baseline nights = 0.55 hour, average error during all noise conditions = 0.42 hour; subject #2: average error during baseline nights = 1.3 hours, average error during all noise conditions = 0.52 hour).

Estimates of the time required to fall asleep also tended to parallel, in general, the actual values. Subject #1 usually overestimated this characteristic (maximum overestimate = 60 minutes, maximum underestimate = 6 minutes, average error = 12.4 minutes), while subject #2 was more variable in over- or underestimating but more accurate in overall agreement (maximum overestimate = 27 minutes, maximum underestimate = 33 minutes, average error = 10.6 minutes). Subject #1 made his best estimates on the nights with the unmodified spacecraft noise present (average of nights #4, #5, #12, #13 = 6.3 minutes error), while subject #2 made his worst estimates on these same nights (average error on nights #4, #5, #12, #13 = 19.6 minutes).

Subject #1, who in most instances had relatively few arousals throughout the night, did quite well in estimating this aspect, again tending to be more accurate during the central portion of the study. Subject #2, who always had more arousals, underestimated the actual number in every case and showed no obvious differences

TABLE 3. SUBJECTIVE ESTIMATES

		Baseline Nights			Unmodi- fied Noise		Noise Mod. #1			Noise Mod. #2			Unmodi- fied Noise		Baseline Nights	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Total sleep time	Sub. 1	7.0	7.5	8.8	7.8	8.0	8.0	8.0	7.8	7.8	8.0	8.0	8.0	7.5	8.0	7.0
(hours)	Sub. 2	5.0	7.0	8.0	5.0	7.5	5.5	7.8	7.5	7.5	5.0	7.0	7.5	7.0	4.0	7.3
Time to fall asleep	Sub. 1	75	30	15	15	20	20	15	30	40	20	5	15	10	10	40
(min.)	Sub. 2	30	45	20	60	25	60	20	25	20	45	30	20	20	60	20
Number of	Sub. 1	4	3	1	2	1	2	2	3	1	0	2	1	4	2	3
arousals	Sub. 2	3	4	4	7	4	3	5	4	4	5	4	3	4	6	4
Number of	Sub. 1	0	0	0	0	0	0	0	0	1	0	2	0	0	1	0
dreams	Sub. 2	0	1	0	0	4	0	1	3	0	2	0	1	2	2	0
Length of time	Sub. 1	0	0	0	0	0	0	0	0	?	0	7.0	0	0	10.0	0
dreaming (min.)	Sub. 2	0	5.0	0	0	30.0	0	5.0	60.0	0	10.0	0	10.0	20.0	10.0	0

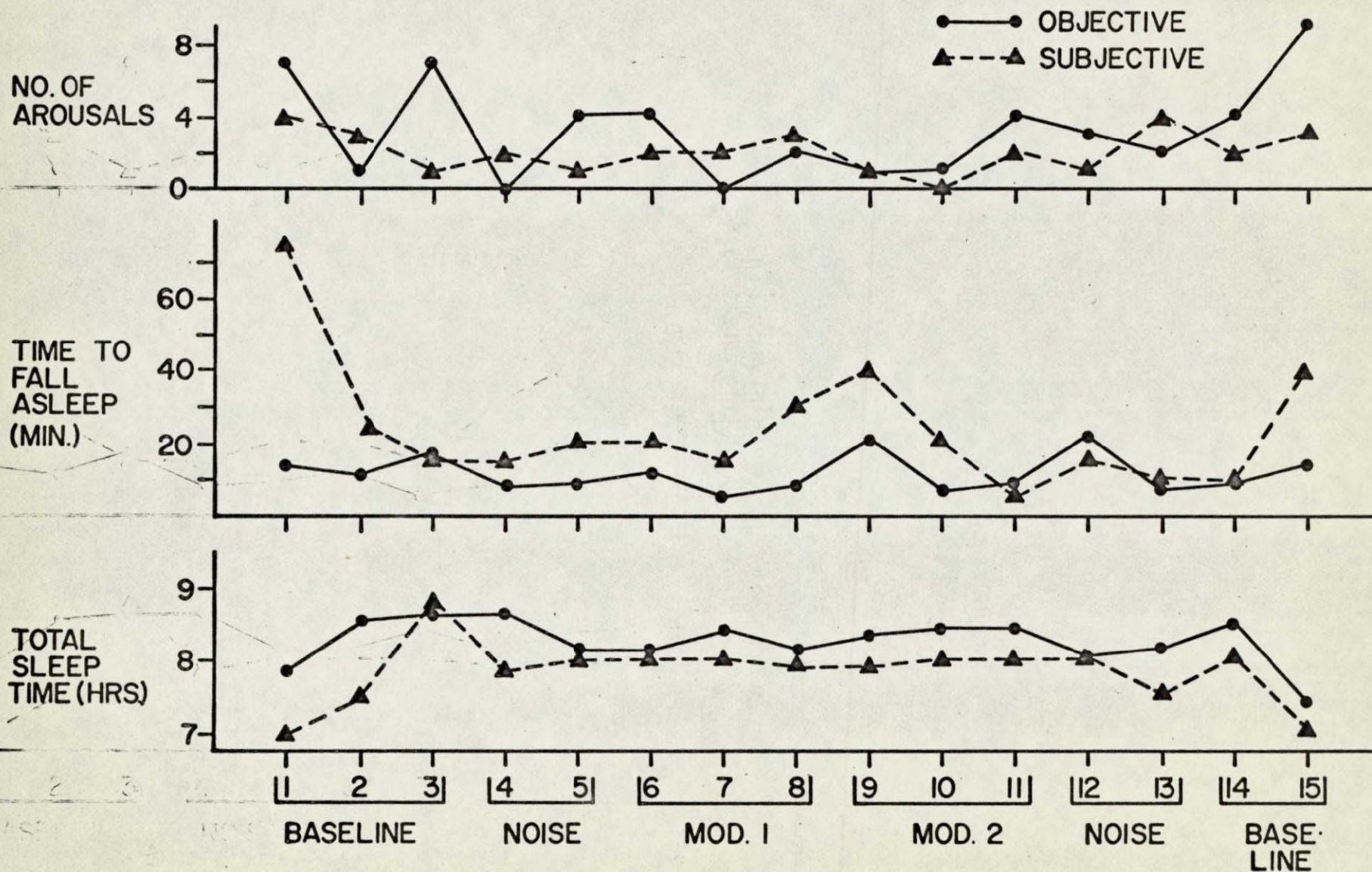


FIG. 26

SUBJECT 1 - SUBJECTIVE ESTIMATES VS ACTUAL VALUES FOR SELECTED SLEEP CHARACTERISTICS

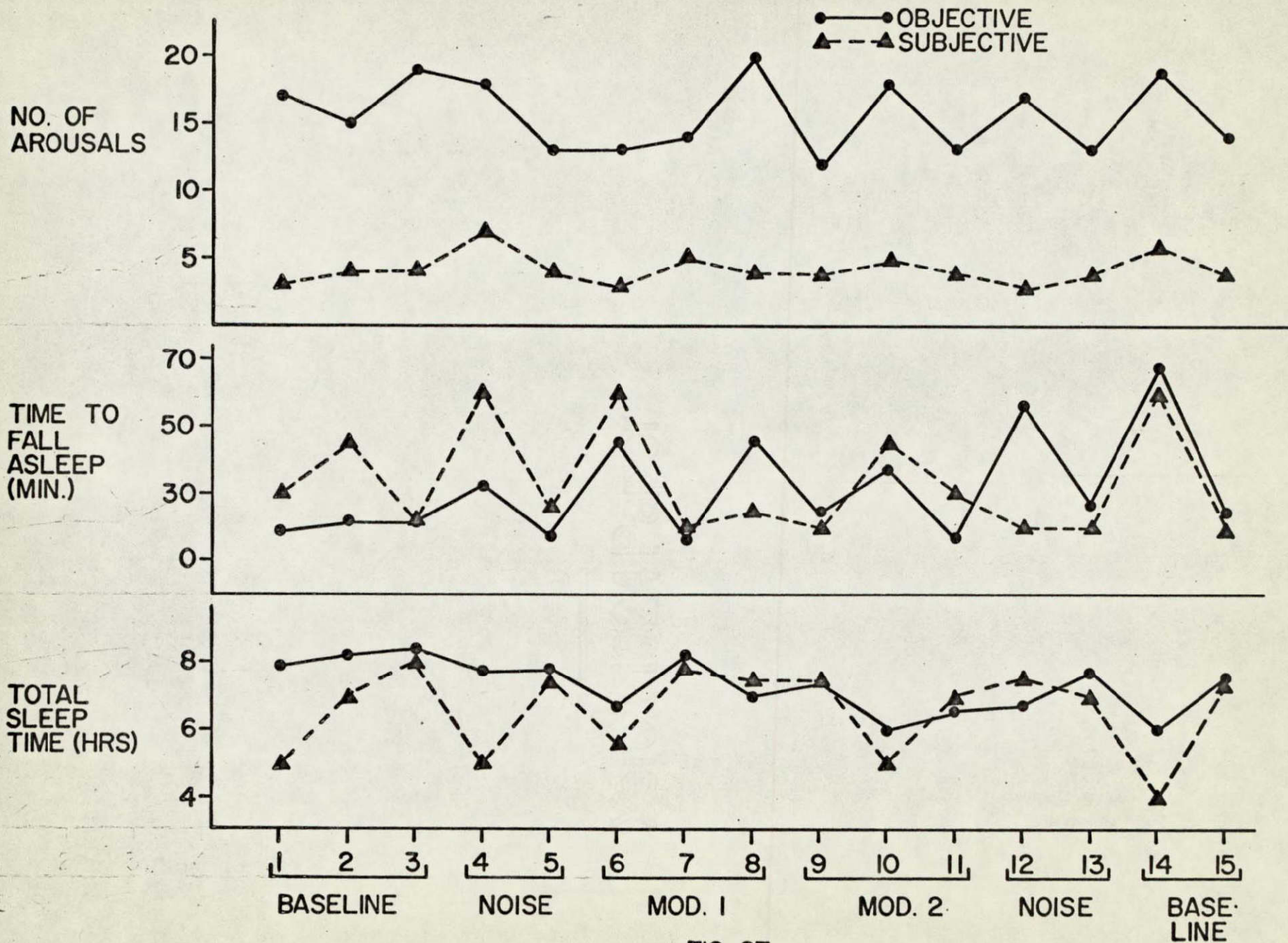


FIG. 27

SUBJECT 2 - SUBJECTIVE ESTIMATES VS ACTUAL VALUES FOR SELECTED SLEEP CHARACTERISTICS

in accuracy in association with the noise conditions.

As expected, neither subject recalled many dream periods (Table 3), and, except for subject #2 on night #8, all estimates of total dream time were far below the objective measure of total stage REM time (Table 1).

D. Tests of Hearing Function⁷

The hearing function of each subject was monitored by Békésy audiometry and impedance audiometry. The following measures were obtained on each ear:

- 1) Threshold audiogram for pulsed sound (2.5 ips) over the frequency range from 250-8K Hz.
- 2) Minimal hearing level, in dB, necessary to elicit stapedius reflex, at frequencies of 500, 1K, 2K, and 4K Hz.
- 3) Impedance (reactive component) in the plane of the eardrum.

All measures were accomplished on three different dates, as follows:

1/9/70	3:00-4:00 p. m.
1/13/70	7:00-8:00 a. m.
1/21/70	3:00-4:00 p. m.

Fig. 28 shows the threshold audiogram and reflex hearing levels for the left ear of subject J. E. Both audiometric thresholds and stapedius reflex levels are expressed in Hearing Threshold Level (dB re audiometric normal, ISO-64).

Subject J. E.'s left ear is normal and there is no significant change over the 12-day observation period.

Fig. 29 shows results for the right ear of subject J. E. The audiogram shows a mild, permanent, sensorineural loss above 2K Hz, but there is no change over the 12-day observation period.

Fig. 30 shows the results for the left ear of subject G. K. The audiogram shows a severe, permanent, sensorineural loss above 2K Hz, but no significant change in the loss over the 12-day observation interval.

Fig. 31 shows results for the right ear of subject G. K. Again, there is a severe, permanent, sensorineural loss above 2K Hz, but no change over the 12-day observation interval.

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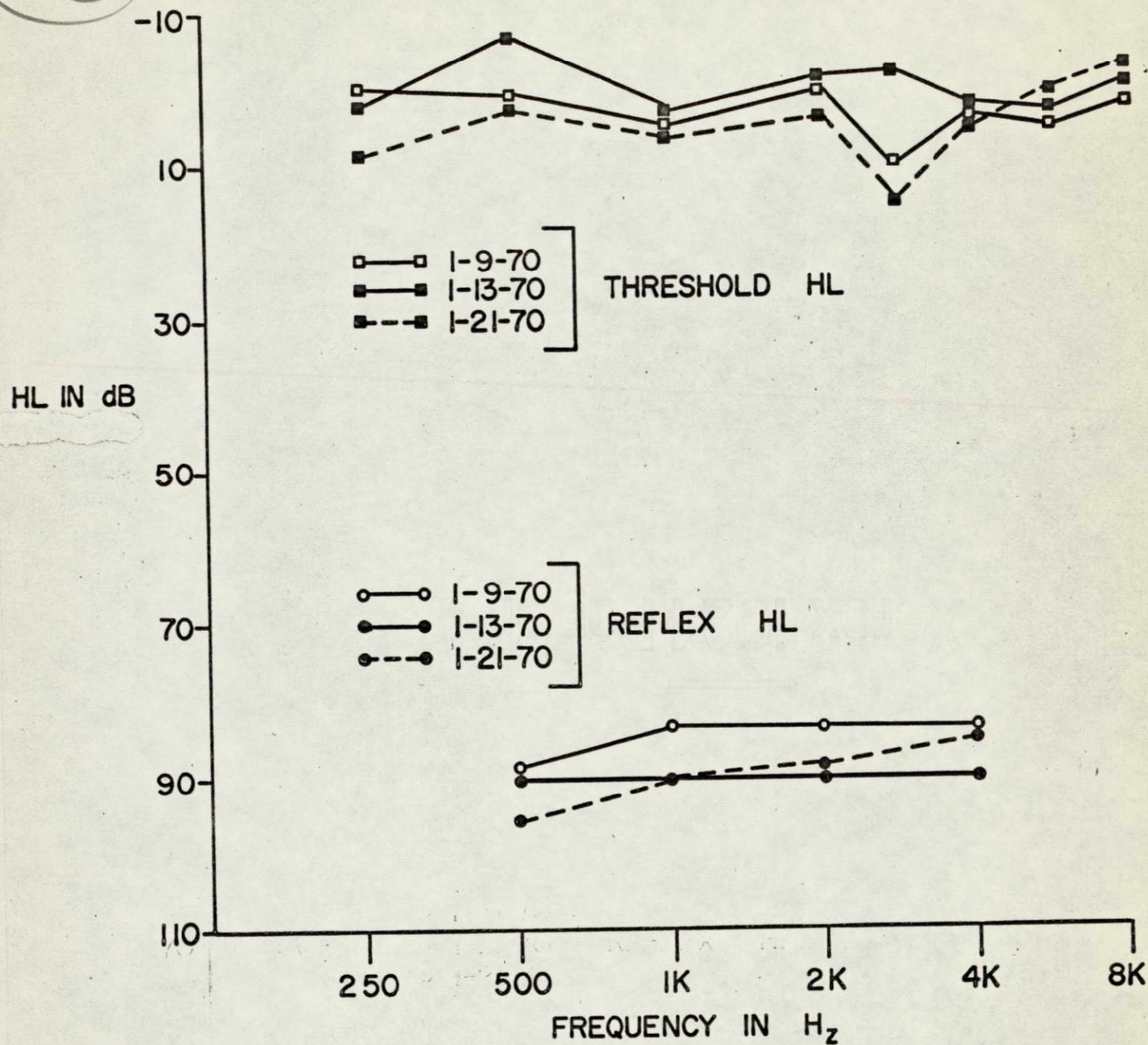


FIG. 28 - SUB. I, AUDITORY FUNCTION, LEFT EAR

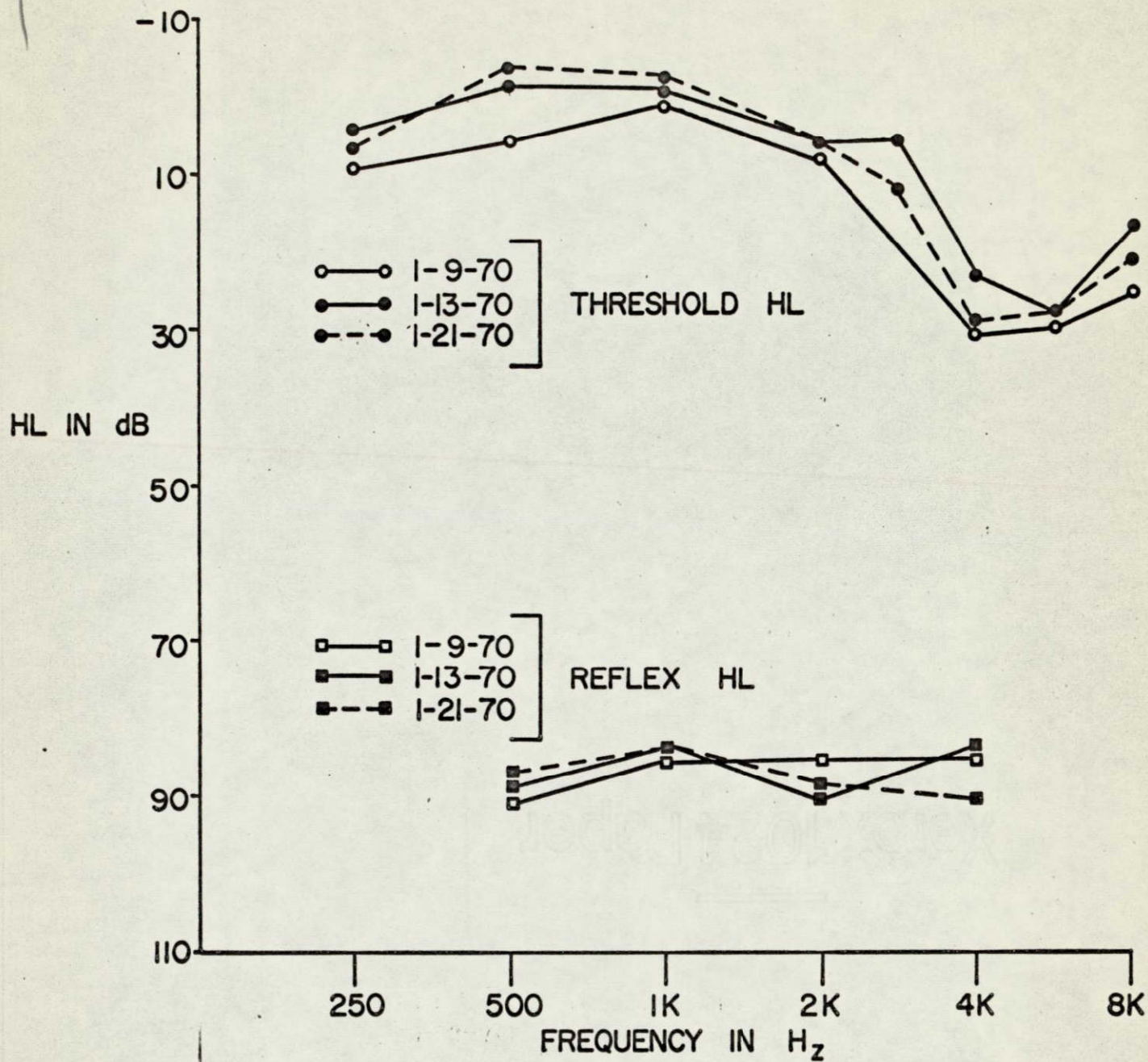


FIG. 29-SUB. I, AUDITORY FUNCTION, RIGHT EAR

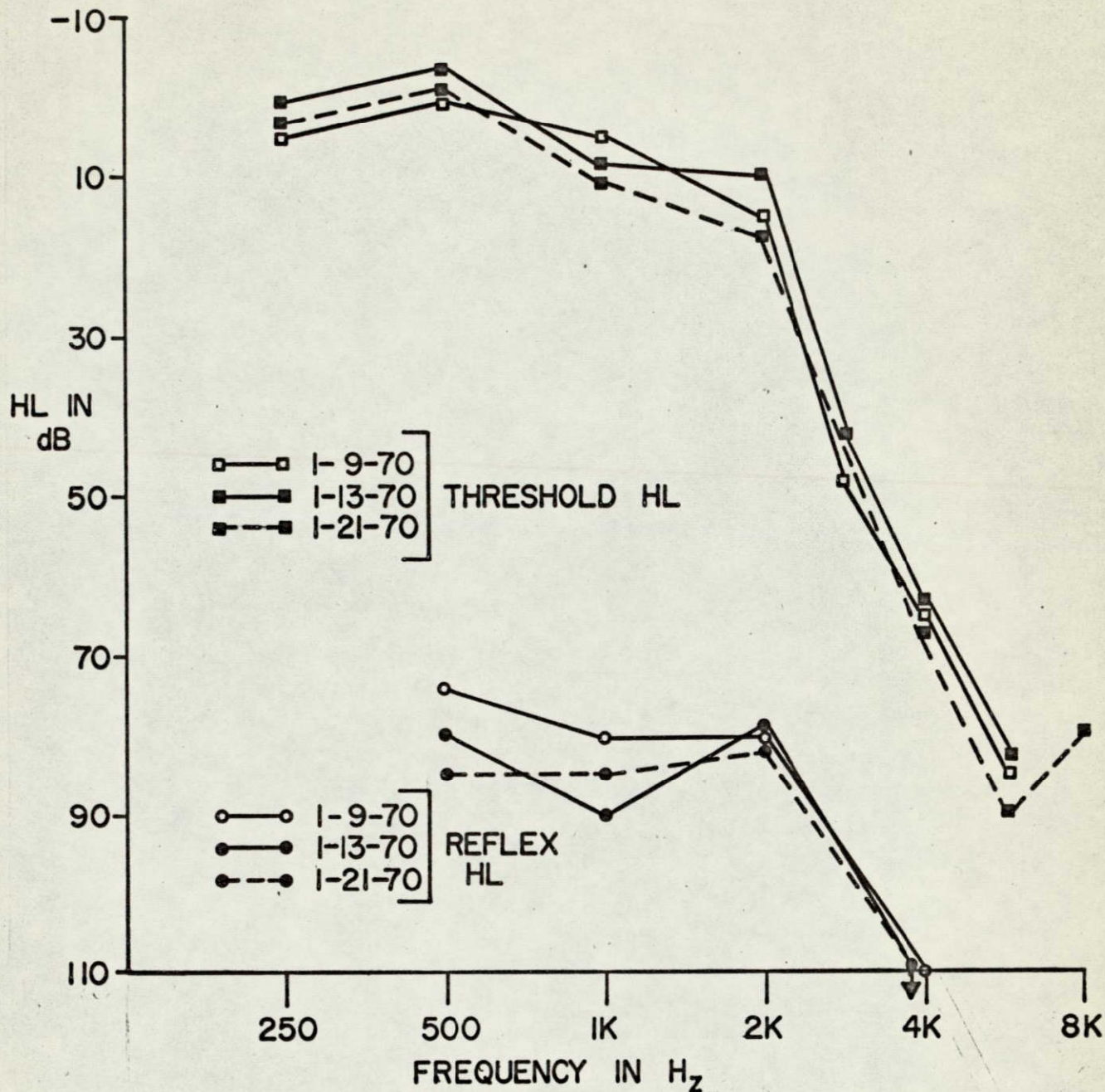


FIG. 30-SUB. 2, AUDITORY FUNCTION, LEFT EAR

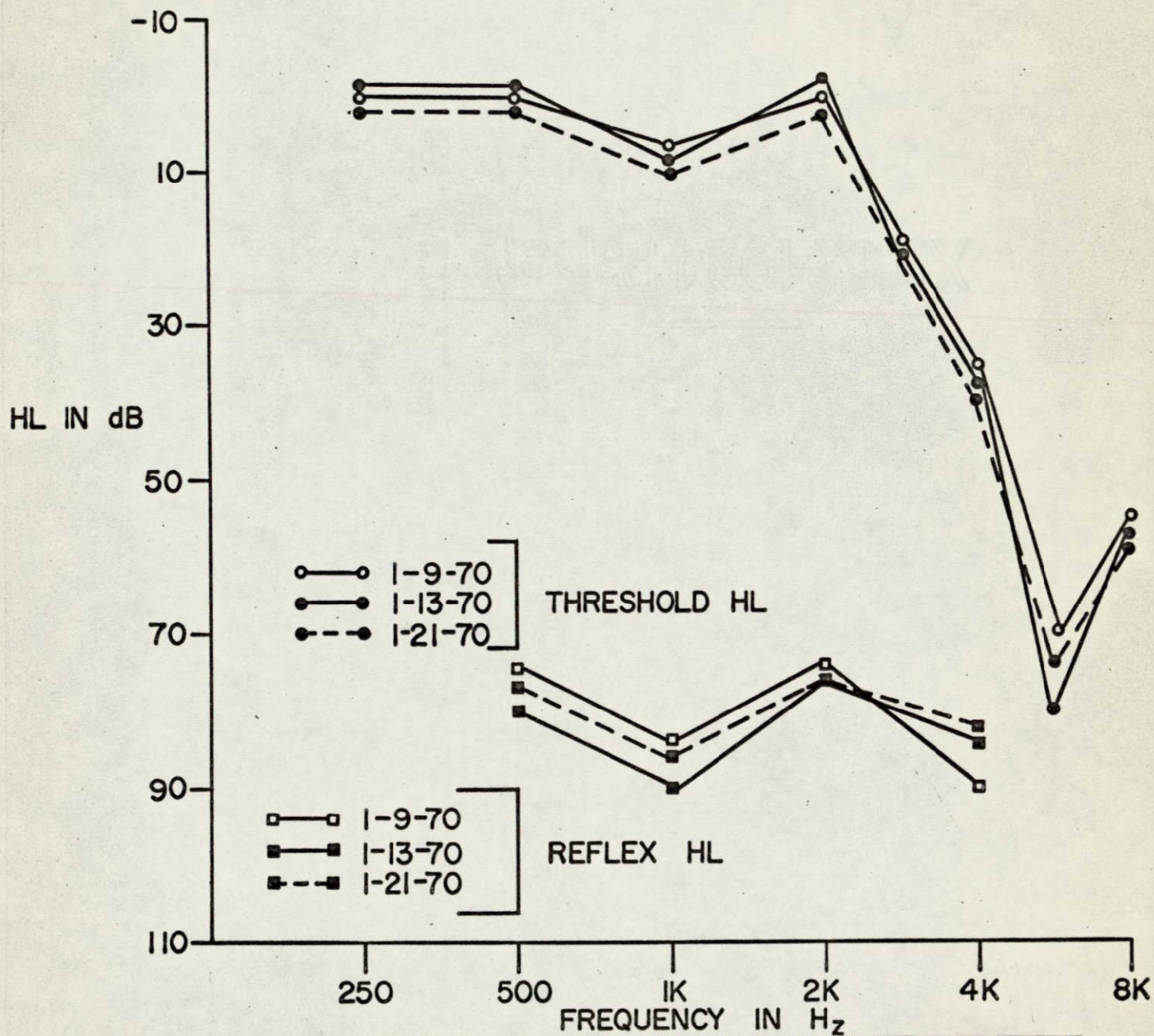


FIG. 31-SUB.2, AUDITORY FUNCTION, RIGHT EAR

Fig. 32 shows middle-ear impedance data for both ears of each subject at each test date. All variation is within expected limits of test-retest error, and all measured impedances are within the normal range (1000-3000 ohms).

In summary, all results indicate unchanged auditory status during the 12-day observation interval. There was no evidence of either temporary or permanent change in auditory function on any test data.

Conclusions

The results of this study indicate that none of the three spacecraft-noise environments which were tested resulted in a significant abnormality in either subject's sleep characteristics. Under the controlled conditions in the laboratory, the few changes in sleep patterns which could be causally related to the noise were of only minimal degree and could not be considered to have truly disrupted the sleep profiles.

Since the laboratory environment in which these studies were carried out did not simulate the other, both demanding and stressful, features of spaceflight, the results must be interpreted with some caution. The relatively small observed influence of the noise condition on sleep could conceivably become a more significant factor under the actual spaceflight conditions.

The slight reduction in percent stage REM time observed during the two periods of exposure to unmodified spacecraft noise, particularly in subject #1, did not result in an abnormal sleep pattern; i. e., the percent stage values were still within a normal range. However, the possibility exists that this process could become accentuated under more stressful conditions, and in this case it might become a significant factor and eventually influence the subject's performance. For this reason, it is concluded that the noise-reduction devices which were tested offer a potential advantage over the unmodified-noise condition.

The general decline in total sleep time over the period of the study which was observed in subject #2 did not appear to be directly related to the noise conditions, particularly since it continued into the final baseline period. While it could represent a type of cumulative effect of the noise, it seems more likely that the high values of total sleep time during the first baseline period were unusual for this subject, perhaps representing a "rebound" effect due to partial sleep deprivation in the days preceding the study or an effect associated with the change in environment. In support of this view is the subject's estimate of 6 to 6 1/4 hours for his usual total sleep time at home.

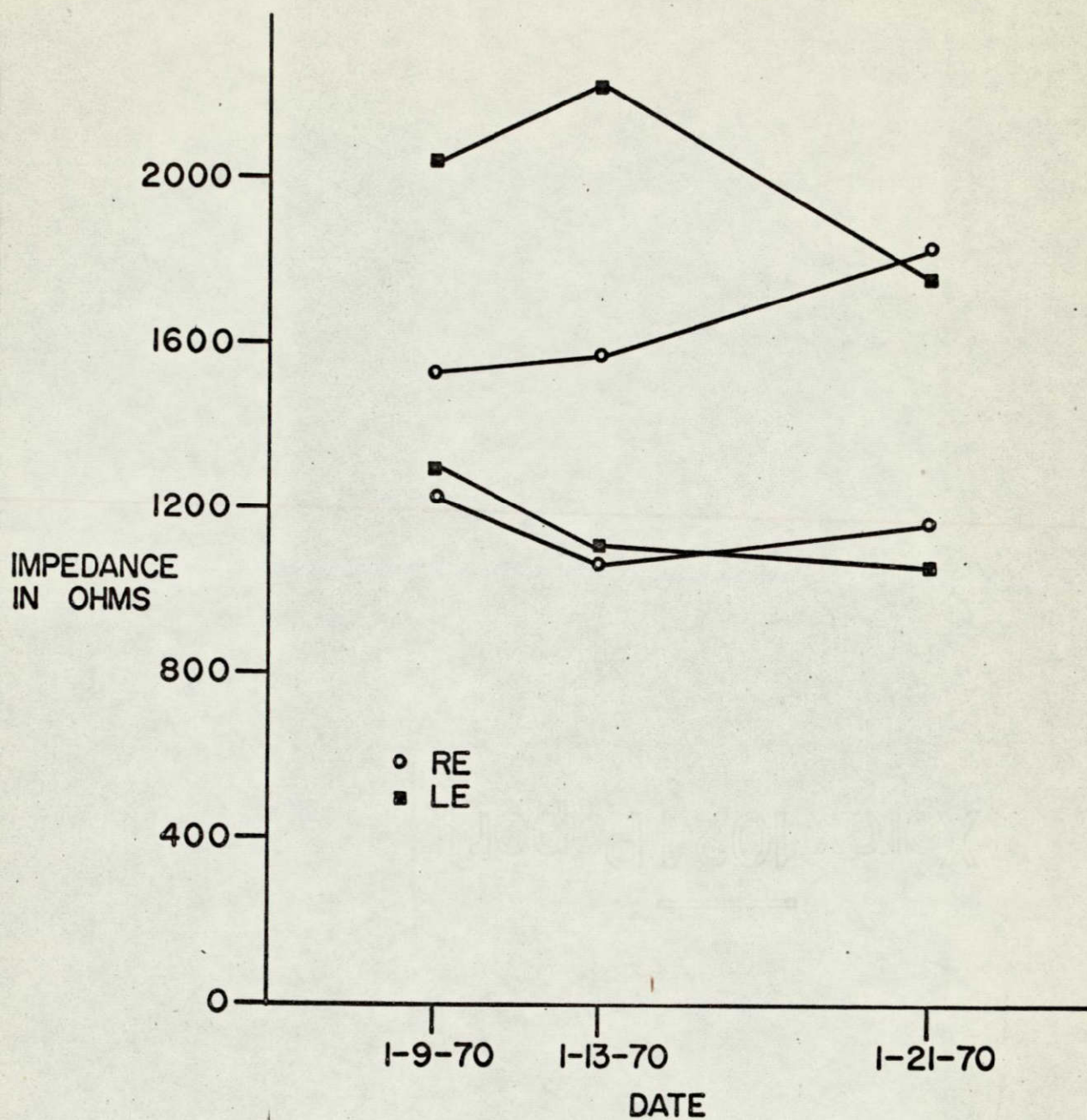


FIG. 32
SUB. 1 and 2, MIDDLE EAR IMPEDANCE

A possibly beneficial effect of all spacecraft-noise conditions tested was the reduction in average number of awakenings during the night. This is probably due to the masking of transient environmental sounds (e. g., movements or snoring of the other subject, extraneous noises) by the relatively continuous spacecraft noise. In addition, both subjects tended to more accurately estimate their sleep characteristics during the periods of noise exposure. While the validity and significance of this observation are beyond the scope of this study, it does emphasize the difficulties inherent in subjective evaluations of sleep, particularly under changing environmental conditions.

Summary

Spacecraft noise of the type tested in this 15-night study did not, under otherwise normal conditions, cause a significant disruption of the sleep characteristics of two test-pilot subjects. A slight reduction in the percent stage REM time was consistently associated with the unmodified-noise condition in one subject, and a similar trend was suggested in the other subject. It is proposed that this effect could be more significant under actual spaceflight conditions, and for this reason the reduction in noise intensity offered by modifications #1 and #2 appears to be a potential improvement in spaceflight environmental control.

Recommendations

1. Noise-reduction devices which are at least as effective as those tested in this study should be incorporated into the design of future spacecraft.
2. Additional evaluation of the effects of spacecraft noise on sleep is needed and should include tests carried out under overall environmental conditions which approach those of spaceflight, with respect to both scheduling of work-rest periods and simulation of the demands and stresses of an actual mission.

References and Notes

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6. Carrie, J. R. G. The modal alpha wavelength. Electroenceph. Clin. Neurophysiol. 27: 703, 1969. (See copy in Appendix).
7. Audiometric testing was performed by Dr. James Jerger, Division of Audiology and Speech Pathology, The Methodist Hospital, Houston, Texas.

APPENDIX

TN 4-15A 3010.69

OCT 30 1969

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AN AUTOMATIC SLEEP ANALYZER¹

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ACCEPTED FOR PUBLICATION

¹Supported in part by Grants No. NGR-44-003-025 from the Manned Spacecraft Center, NASA, and HE 05435 from USPHS, and by NASA Contract NAS 9-9418.

Running Title:

AUTOMATIC SLEEP ANALYZER

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The methods proposed for processing EEG sleep records automatically have usually been based upon measurement of derived features of the original voltage-time tracing (for example, for spectral analysis: Knott et al. 1942; Kaiser et al. 1964; Hord et al. 1965; Johnson et al. 1967; Walter et al. 1967; Lubin et al., in press; for average amplitude: Maulsby et al. 1966; Agnew et al. 1967; Fink et al. 1967; Itil et al. 1969; for frequency/voltage ratio: Riehl 1961), and precise agreement with the levels specified by visual scoring criteria has not yet been achieved. Other techniques approach more closely the way in which the electroencephalographer treats the EEG (Burch 1959; Burch et al. 1964; Fink et al. 1967; Smith et al. 1968; Itil et al. 1969; Roessler et al., personal communication; Viglione et al., personal communication), and although these techniques have sometimes yielded results very close to those of visual scoring, they require the use of a large digital or special-purpose computer.

The method described here is based on criteria similar to those considered by the electroencephalographer as proposed by Dement and Kleitman (1957), and utilizes a small, portable, completely self-contained, analog-digital device which operates in real time, requires one channel of EEG and one of EOG, and is not biased excessively by occasional artifacts. Because of its compact size (approximately

1 cu ft, including EEG and EOG preamplifiers) this analyzer can be used outside the laboratory in situations where continuous assessment of a subject's sleep status is desired.

The analyzer provides a six-level output voltage, with each step corresponding to a clinical assessment of wakefulness or sleep stage based upon EEG criteria: awake, drowsy (stage 1), light sleep (stage 2), moderately deep sleep (stage 3), deep sleep (stage 4), and abnormal state (e.g., coma). These levels are also indicated by the illumination of one of six panel lamps. The analyzer does not distinguish rapid eye movement (REM) sleep from stage 1 sleep, but this difficulty is resolved by passing an EOG channel through a bandpass filter, amplitude discriminator, and logic gate and indicating the times of occurrence of REMs during stage 1 on a graphic recorder, along with the EEG analyzer output.

METHOD

Operation of the device is summarized in Fig. 1. As detailed below, the EEG analyzer is essentially an amplitude-weighted, dominant-frequency meter for the 0.7-13 c/sec EEG band, with the output restricted to six discrete levels.

Activity from the two scalp EEG electrodes (central to occipital derivation) is amplified by the preamplifier, then passed through the

filter circuit. This step greatly attenuates most electrode, movement, and muscle artifacts, yet enough information is retained to allow accurate determination of sleep stages.

The signal next enters three level detectors, each set to indicate a different EEG amplitude (see Fig. 2). Level 3 is greatest, arbitrarily called 100%. Level 2 is at 20% of the distance from the baseline to level 3, and level 1 is at 1%, just above the noise level of the system. The gain of the preamplifier is adjusted for each subject such that only the greatest amplitude, negative-going waves in his closed-eyes waking EEG exceed level 3, with the majority of the peaks falling between levels 2 and 3. Thus the higher voltage activity during sleep will frequently cross the 3rd level, whereas the low voltage activity during stage 1 will exceed only levels 1 and 2.

The logic circuitry (Fig. 1, bistable circuit, logical AND gate) associated with the level 1 and 2 detectors triggers a negative-pulse generator if, and only if, level 1 and level 2 are crossed successively in a negative-going direction (e.g., Fig. 2, a-e, i, j). Fluctuations about either level 1 or 2 alone are ineffective (Fig. 2, e, f). As a result, the number of pulses produced by the negative-pulse generator is proportional to the dominant frequency of the EEG and independent of minor variations or inflections. Each pulse from the negative

generator is of a constant amplitude and duration.

The level 3 detector operates in a straightforward fashion, triggering the positive-pulse generator each time it is exceeded (Fig. 2, g, h). The output of the positive-pulse generator is of the same duration as that of the negative generator, but of opposite polarity and one-half the amplitude. The pulses from the two generators enter the mixer amplifier, which supplies a composite pulse train to the integration circuit (see lower tracing, Fig. 2).

The integrator is a buffered RC circuit with a 15-sec time constant for both rise and decay. The output is consequently a voltage level that is dependent upon the number and polarity of pulses received during the preceding approximately 15 sec.

If only levels 1 and 2 are exceeded by the fluctuating EEG input voltage, then the integrator's output is proportional to the dominant frequency. However, each time level 3 is exceeded (one-half amplitude, positive pulse), the integrator loses one-half the value previously added by a level 1-2 pulse (negative pulse). In actual operation on a complex input signal, waves which exceed only levels 1 and 2 have the highest value in terms of increasing the output, whereas high voltage waves, exceeding level 3, have only half the value, and very low voltage waves (below level 2) have no value.

The output of the analyzer will have its highest value when the subject is awake and alert. At this time, the basic EEG rhythm is relatively low in voltage but is high enough to cross levels 1 and 2 and is high in frequency. Thus, a high rate of negative pulses will be supplied to the integration circuit. As the subject relaxes and closes his eyes, the alpha rhythm becomes higher in voltage, which causes more frequent crossings of level 3 and results in the addition of positive pulses to the integrator and eventually in a slightly lower output level of the integrator. When the subject becomes drowsy and enters stage 1, the EEG amplitude again drops such that only levels 1 and 2 are crossed, but in addition the alpha is replaced by a slower, 5-7 c/sec irregular activity. As a result, there are fewer negative input pulses to the integrator and the output decreases to a lower level.

High voltage vertex transients during stage 2 result in crossings of level 3, which, together with a somewhat slower background, result in a further lowering of the output. During stage 3 sleep, the dominant frequency becomes still slower, and more waves reach level 3, both resulting in reduction of the output. Stage 4, with its very slow and high voltage activity, causes the output to reach its lowest normal value, since levels 1 and 2 are crossed relatively few times and level 3 is crossed almost as frequently.

Certain abnormal conditions can produce even lower levels, for example, the oscillations of deep coma, and if the EEG becomes flat, the lowest possible level (0 V output) is reached, since no pulses will be supplied to the integration circuit.

The EEG state of the individual is therefore expressed as a voltage level at the output of the integrator: the awake EEG is associated with the highest output voltage, and progressive stages of sleep are accompanied by correspondingly lower output values.

Since it is customary to assess sleep clinically in several discrete steps rather than in the continuous, or analog, manner of the integrator output, the remaining circuitry of the analyzer (Fig. 1) compares the integrator output voltage with previously determined voltage ranges (Fig. 1, five voltage-comparator circuits) and provides the most appropriate of six discrete output-voltage levels, each one corresponding to a stage (awake, stage 1, stage 2, stage 3, stage 4, or abnormal state).¹ In addition, an indicator lamp is provided for

¹Initial setting of the potentiometers is accomplished by determining empirically the output voltages from the integrator that correspond to the transition points between EEG sleep stages. This is most easily accomplished by running a sleep record simultaneously on a conventional EEG machine and on the analyzer. As the subject passes from one stage to another by visual scoring criteria, the appropriate potentiometer is set to the current value of the integrator output voltage. This procedure is necessary only during the initial calibration of the instrument and does not have to be performed for each subject.

each stage, and it is illuminated as long as the integrator output remains within that voltage range. Thus, a glance at the device tells the observer the current EEG level, and a step-like graph is produced by recording the discrete output-voltage levels on a graphic recorder.

Eye movement is recorded from two electrodes, one near the outer canthus and the other in the center of the forehead, which permits detection of both left-right and up-down excursions. The amplified activity from this pair enters a narrow bandpass filter (2-3 c/sec) which provides the best amplitude separation of REMs and background activity. REMs that exceed a preset amplitude in either direction are detected by the dual-comparator circuit (Fig. 1), which in turn triggers a pulse generator. The output of this pulse generator is permitted to pass to the graphic recorder only if the EEG analyzer is in stage 1 (Fig. 1, AND gate). Thus, an indication is produced on the graphic record whenever an REM of sufficient amplitude occurs when the subject is in stage 1.

An example of the analysis is shown in Fig. 3, with the analog output of the integrator above, the discrete-level output of the EEG analyzer and REM indicator in the center, and the result of visual interpretation of the same EEG tracing below.

Since the device considers essentially the same criteria as those

used in visual scoring, namely a combination of dominant frequency and amplitude, the results are generally in close agreement with human interpretation. When discrepancies occur, they are most commonly associated with a borderline situation, for example, where the human may indicate stage 3 where the analyzer shows stage 4, or with sections of the EEG record that are contaminated by prolonged movement artifact. An example of such a discrepancy is indicated by point M, Fig. 3. However, during preliminary testing trials, the number of such discrepancies has not appeared to exceed that noted between different human observers interpreting the same record, or even the same observer rescoring a previous interpretation.

It is thought that the importance of this type of device for sleep research is that it provides a means of obtaining consistency of interpretation not only for a given interpreter but between interpreters. Thus the stages could be calibrated (set) to a specific and pre-determined standard agreed upon by the various sleep laboratories, and the only inter-subject adjustment which would be required would be an amplification correction determined by the individual subject's EEG voltage characteristics.

SUMMARY

A small, portable, special-purpose device is described which accomplishes automatic on-line evaluation and graphing of a subject's sleep status. The instrument performs EEG analysis as an amplitude-weighted, dominant-frequency meter to define stages awake through stage 4 sleep and also considers EOG information to permit detection of the REM state.

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Figure Legends

Fig. 1

Automatic sleep analysis system.

Fig. 2

Operational scheme for levels 1, 2, and 3 amplitude comparators.

Fig. 3

Analysis of $2\frac{1}{2}$ h sleep record. Upper tracing: Output of integration circuit. Center tracing: Discrete-level output of EEG analyzer and REM indicator. M indicates a portion of the original record that was contaminated by movement artifact. Lower tracing: Visual classification of sleep stages.

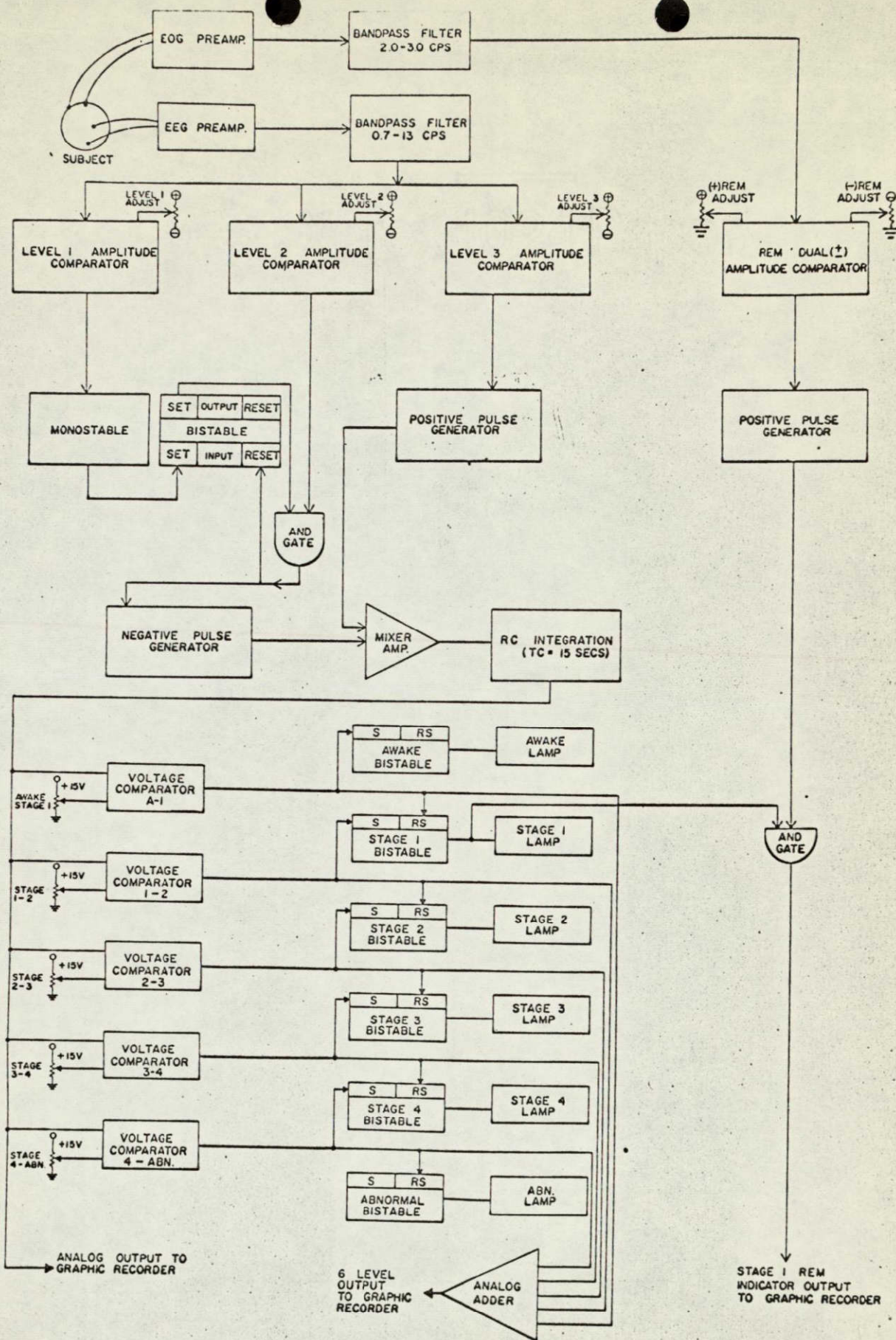


Fig. 1

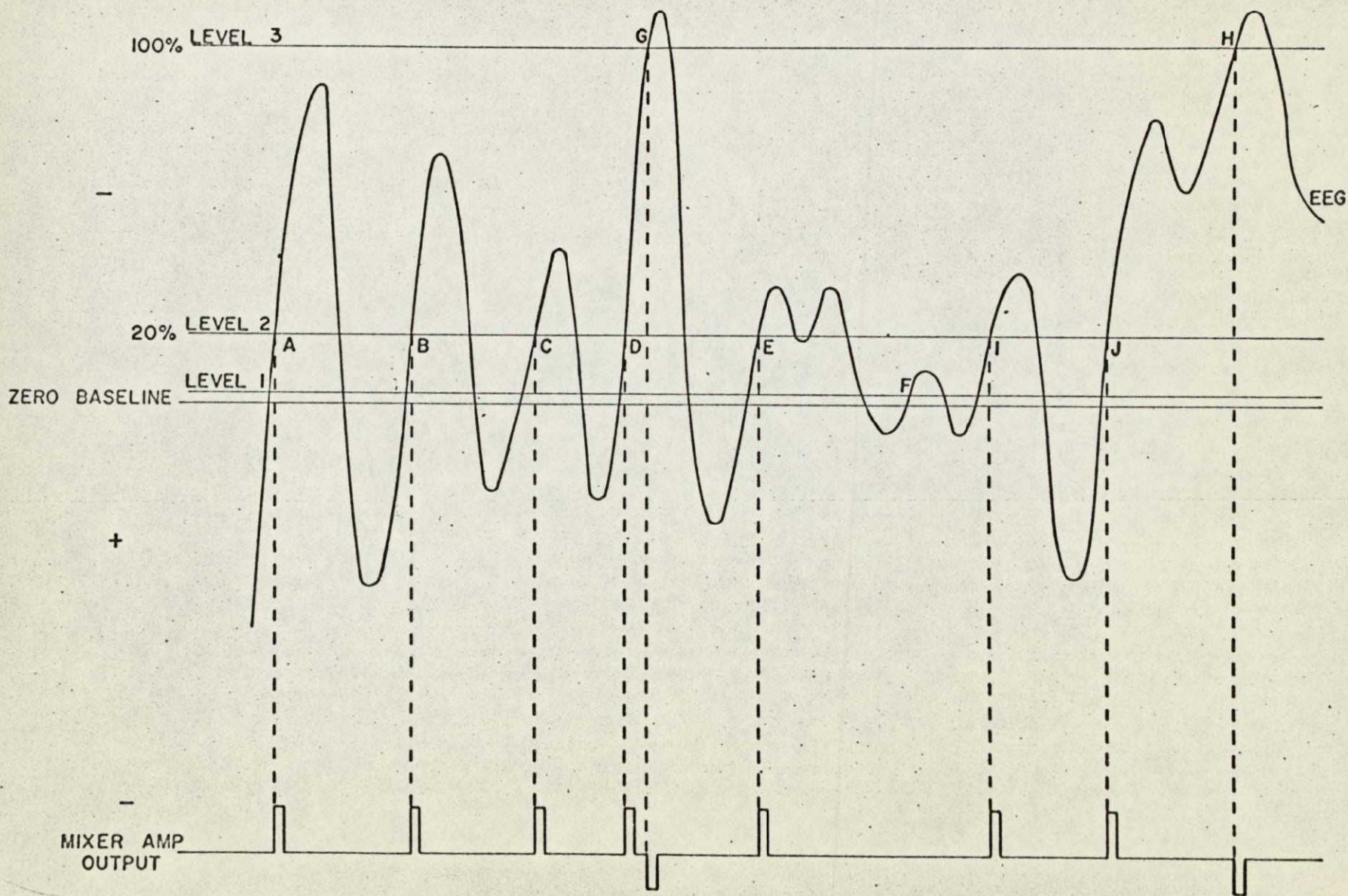
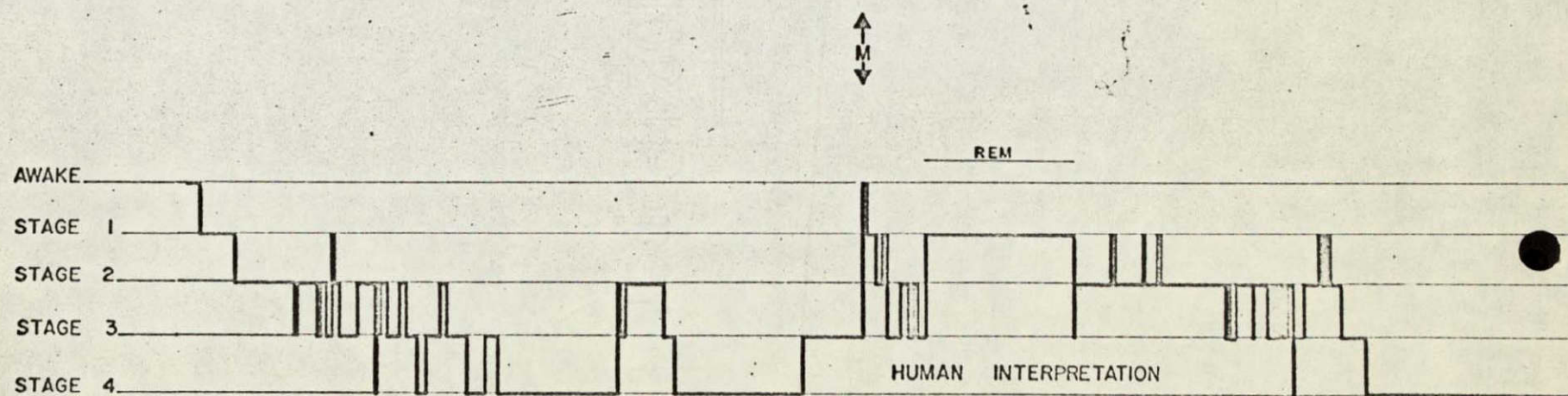
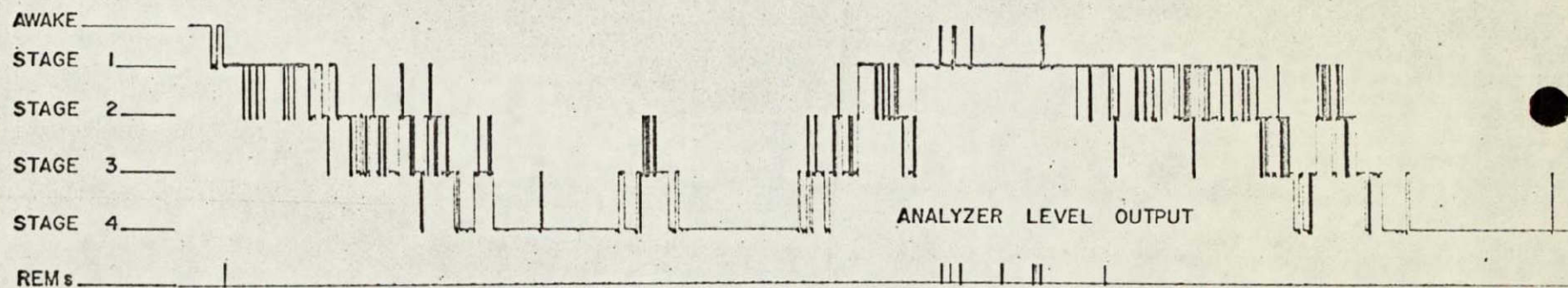
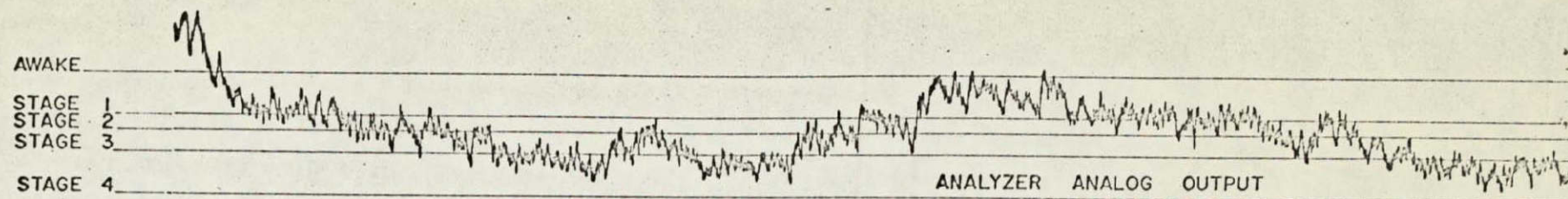


Fig. 2



0 30min. 60min. 90min. 120min.

Fig. 3

(Abstract)

James D. Frost, Jr. Houston, Texas, U.S.A. Wavelength Analysis of the EEG — The Alpha Profile. Electroenceph. clin. Neurophysiol., 1969, 27: 702-703.

Clinical EEG reports usually include some statement regarding alpha frequency and often a comment about its constancy or stability. An on-line computer method is described which automatically quantifies these aspects. The scheme treats EEG frequency in a manner independent of amplitude, and is somewhat similar to Tecce and Mirsky's (1967) technique but differs in that a precise wavelength measurement is made and activity outside the alpha range is excluded.

Filtered occipital activity (6-14 cps) enters an electronic circuit which determines wavelengths by measuring the time interval between successive positive-going baseline crosses (cf. Burch, 1959). Each measurement is checked to determine if it falls within the "alpha range" of 56-174 msec (6-17 cps), and, if not, this value is discarded. If the measurement meets this requirement, a count of one is added at a particular computer-memory location which corresponds to the measured wavelength. Sixty memory locations are used, each representing one of the possible wavelength values between 56 and 174 msec (2-msec resolution). These locations are thus used to "keep score" of the number of waves which fall into different wavelength categories. Analysis continues until a total of 1000 counts are

contained in memory, indicating consideration of 1000 alpha waves. Total time required to complete the analysis is recorded, since it depends upon the average frequency of the alpha activity and the percentage of time it is present, and consequently provides a measure of the "alpha index."

Memory contents are plotted in the form of a histogram, or alpha profile, providing a quantitative measure of the range of alpha activity, with the abscissa corresponding to wavelength and the ordinate to the number of waves in each category. The mode correlates with the electroencephalographer's "alpha frequency" determination, while the spread of the distribution can be a quantitative measure of alpha variability (see Carrie, 1969).

(Abstract)

J. R. G. Carrie Houston, Texas, U.S.A. The Modal Alpha Wavelength.

Electroenceph. clin. Neurophysiol., 1969, 27: 703.

Occipital EEG signals were detected in 67 subjects under standardized experimental conditions. Histograms (profiles) showing the frequency of occurrence of waves of different duration in a sample of 1000 consecutive waves in a pass-band which included the alpha range were derived using the technique developed by Frost.

No correlation was found between modal height and the wave length at which the mode was located. There was significant positive correlation (+0.80) between the location of the mode and the alpha frequency as assessed by visual inspection and manual measurement of the ink-written EEG record. With a technique having this degree of temporal resolution (2-msec separation of the histogram ordinates), the maximum representation of the modal alpha component in the 67 subjects was 16.6% of the sample of 1000 oscillations; the minimum modal representation was 2.5%; the average modal representation was 5.7%.

Since the height of the profile mode is one indicator of the stability or monorhythmicity of the most prominent alpha component, it was predicted that there would be a correspondence between this profile characteristic and the relevant elements in the verbal reports based on visual assessment. An experienced

electroencephalographer wrote verbal reports on each EEG recording without knowledge of the type of analysis to which his assessments would be subjected. It was found that the verbal reports could be divided into four categories with regard to content describing the alpha-activity stability. The average magnitudes of the modes in the corresponding four groups of EEG histogram profiles differed from one another. These differences were highly significant when the groups categorized as showing poorly sustained or uncountable alpha rhythms on visual assessment were compared statistically with the group whose alpha frequency was stated without any comment on the alpha-waveform stability.