Fault Tree Analysis and Diagnostics Development for PI-in-a-Box with the Neurolab Sleep and Respiration Experiment

by

ROBIN LEE SMITH

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Signature of Author: .....
Department of Aeronautics and Astronautics
May 9, 1997

Certified by: .....
Laurence R. Young
Apollo Program Professor of Astronautics
Thesis Supervisor

Accepted By: .....
Professor Jaime Peraire
Chairman, Graduate Office

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ABSTRACT

Principal Investigator-in-a-Box (PI-in-a-Box) is an expert system designed to improve the quality and quantity of data collected in remote laboratory settings. Its role in the Neurolab sleep and respiration experiment is to assist the astronauts with the signal verification process during the sleep instrumentation period. PI-in-a-Box will display the raw signal data in real time and provide state information on the quality of each signal. In addition, PI-in-a-Box will provide diagnostic procedures to assist the astronauts with troubleshooting of the experiment hardware.

A three stage process for developing the PI-in-a-Box diagnostics is presented. A fault tree analysis was performed in order to identify all possible failure modes of the system. Using the experiment hardware and software, each of these failure events was simulated in order to determine the system response. After each failure simulation, the corrective steps required to return the system to its nominal operating state were recorded. Based on these corrective steps, a diagnostic diagram was developed for each system state. These diagnostic diagrams, which were modeled after the malfunction procedure diagrams flown on each NASA space shuttle mission, served as the basis for the development of the PI-in-a-Box diagnostics.

Thesis Supervisor: Laurence R. Young

Title: Apollo Program Professor of Astronautics

Acknowledgments

When I was first presented with the opportunity to work on PI-in-a-Box, it was the idea of helping to develop a system that would fly- *in space!*- that peaked my interest. But when I found out that I would also be coordinating with the sleep experiment, I was hooked. After all, sleep has always been one of my favorite activities.

Working on the PI-in-a-Box project has proven to be my most valuable educational experience in my years at MIT. It has been not only a lesson in science and engineering, but in life as well. I owe a tremendous debt of gratitude to many people, whose advice, friendship, and support have helped be to achieve this goal.

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Chapter 1

Introduction

1.1 Overview

The goal of Principal Investigator-in-a-Box (abbreviated "PI-in-a-Box" or [PI]) is to improve the quality of scientific investigations performed in remote laboratories through the application of knowledge-based systems. On the Neurolab Space Shuttle mission scheduled for April 1998, PI-in-a-Box will be flown in conjunction with a sleep and respiration experiment, a collaborative effort which is being conducted by the Circadian Medicine and Sleep Disorders Section of the Brigham and Women's Hospital and the Physiology Section of the University of California, San Diego. The role of PI-in-a-Box in this experiment will be to assist the astronauts throughout the sleep instrumentation period by graphically displaying all signal data, providing an autonomous evaluation of the signal quality, and guiding the astronauts through the troubleshooting process. The objective of PI-in-a-Box for this experiment is to improve the overall integrity of the sleep and respiration signals, reducing the potential for worthless data collection sessions due to poor signal quality, while decreasing the time required for setup and verification of the sleep and respiration instrumentation.

One of the functions of PI-in-a-Box on this mission is to perform system diagnostics throughout the sleep instrumentation period. In order to develop the set of diagnostics which will

be incorporated into the PI-in-a-Box software, all possible failure scenarios must be identified. This thesis will describe the failure analysis performed for the sleep, respiration, and PI-in-a-Box system. In addition, the process of testing these failure scenarios and developing the appropriate diagnostic procedures will be discussed.

1.2 Background/ Motivation

1.2.1 PI-in-a-Box

In space experiments, physical distance prevents the Principal Investigator (PI) from maintaining direct control over the science experiment. Instead, the astronaut acts for the PI while in space, performing the experiment as well as managing the protocol. However, these astronauts are often performing experiments outside of their field of expertise and, despite operational training, have relatively little experience and knowledge of the experiments compared to the actual Principal Investigators. As a result, the quality and quantity of the scientific results may suffer.

Ideally, the Principal Investigator for each experiment would fly in space along with his or her experiment and perform the experiment protocol him/herself. Obviously, this is not practical. The next best solution would be to develop a system which incorporates both the knowledge and experience of the Principal Investigator and allow this system to accompany the experiment in space. That is the basis for the Astronaut Science Advisor (ASA), informally known as PI-in-a-Box. PI-in-a-Box is a knowledge-based system designed to assist the astronauts in performing space experiments. It successfully accompanied the "Rotating Dome" visual-vestibular interaction experiment on board the Space Life Sciences 2 (SLS-2) Space Shuttle Mission in 1993[1].

[PI]'s role in this experiment consisted of a number of different functions. It provided data collection capabilities. It assisted the astronauts in performing the experimental protocol, monitored the time schedule, and suggested modifications to the protocol accordingly. In addition, PI-in-a-Box was equipped with an "interesting data" filter which was designed to perform a quick-look analysis on the resulting data and to identify variations from the expected results.

A new version of the PI-in-a-Box system is under development which will fly in conjunction with the sleep and respiration experiment on the Neurolab 1998 space shuttle mission. The specific application to this experiment differs considerably from [PI]'s application to the Rotating Dome Experiment. It's functions, capabilities, and user interface have been modified to complement the requirements of the sleep and respiration experiment, with emphasis on the setup phase. However, the fundamental objective of PI-in-a-Box remains unchanged. It is to facilitate the process of performing a science experiment in space, while improving the quality and quantity of data collected.

1.2.2 Neurolab Sleep and Respiration Experiment

The sleep and respiration experiment on the Neurolab mission is a collaborative effort between the Brigham and Women's Hospital / Harvard Medical School and the University of California, San Diego. The Principal Investigators are Dr. Charles Czeisler from BWH and Dr. John West from UCSD. The experiment is entitled "Sleep, Respiration and Melatonin in Microgravity." The two experiments were joined together due to the strong coupling between respiration and sleep. In the sleep portion of the experiment, sleep quality and next-day cognitive performance of

1. Hazelton et al.

the astronauts following melatonin administration will be evaluated to determine whether or not the melatonin doses affect both subjective and objective sleep quality. The respiration portion of the experiment will investigate sleep patterns and disruptions during sleep and their relationships to circadian phase.

During missions in space, the quality of astronauts' sleep is significantly degraded[1]. This could be the result of a number of factors. In the microgravity environment, it is not possible to be physically anchored to a surface by the force of gravity in the same way that we are here on earth. Instead, the astronauts float around much more freely and are sometimes secured by bungee cords or enclosed in sleeping bags. As a result, astronauts sometimes become disoriented or uncomfortable, which may result in poor sleep quality. The excitement and anxiety experienced by the astronauts may be a major contributor to the lack of sleep as well.

Another factor which affects sleep in space is the irregular light / dark schedule experienced in orbit. As the space shuttle orbits the earth, the sun rises and sets with a period of approximately 90 minutes. Thus, it is impossible to rely on cues from the sun in order to determine when to go to sleep. There is also a gradual time shift which occurs throughout the mission which forces the astronauts to shift their sleep schedule by a couple of hours each night. Coupled with this is the fact that for the duration of the mission, the shuttle crew operates on Houston time (CST). Furthermore, in order to maximize efficiency of the use of the crew members' time, the crew is sometimes divided into two shifts, where one team sleeps while the other team works and vice verse. As a result, normal sleep schedules established prior to launch are not maintained and the quality of sleep in space is sacrificed.

1. Santy et al.

Physical activity and workload may play a role in sleep quality as well. On earth, muscles are constantly being used to combat the force that gravity exerts on the human body. The simple act of standing upright requires the use of many of the body's muscles. However, this is not true in the microgravity environment. In space, the muscles and skeleton do not support the body's weight. As a result, the physical exertion experienced during the course of the day in space is significantly less than it is on earth. This reduction in physical activity may result in poor sleep quality.

In response to sleep difficulties in space, many of the astronauts take benzodiazepine hypnotics to try and improve their sleep. However, recognizing that the sleep disturbances may, in large part, be due to shifts in the sleep-wake cycle with respect to the circadian rhythm[1], the concept of using melatonin was introduced. Melatonin is a pineal hormone, naturally produced by the human body during sleep, which has been shown to have hypnotic properties at physiological doses[2]. The sleep experiment will assess the effects of this substance on sleep quality of the astronauts.

Sleep and respiration are strongly coupled. By examining the changes in respiratory control which occur in the microgravity environment, some insight may be gained in the analysis of sleep patterns in space. In order to accomplish this, the respiration experiment has been designed with four objectives. First is to examine the relationship between sleep disruptions and circadian phase. Second is to determine if the pattern of chest motion is altered during sleep in microgravity. Third is to investigate whether or not arterial oxygen desaturation occurs during sleep in

1. Gundel, Polyakov, and Zulley
2. Zhdanova et al.

microgravity. Finally, the respiration experiment will examine the coupling of heart rate and respiration to determine if it is significantly altered by the microgravity environment.

The sleep and respiration experiment will be conducted on eight of the sixteen nights of the Neurolab mission. Subjects will be paired in groups of two, each group performing the experiment on two consecutive nights during the early days of the mission and two consecutive nights toward the end of the flight. Only two subjects will perform the sleep and respiration on any given night of the mission.

1.2.3 Role of PI-in-a-Box with the Sleep and Respiration Experiment

The sleep and respiration instrumentation process has been targeted by PI-in-a-Box for a number of reasons. The goals of both the sleep experiment and PI-in-a-Box are fundamentally very similar. The sleep experiment will examine the effects of melatonin on the subjective sleep quality and cognitive performance of the Neurolab crew members. Ultimately, the objective is to improve the quality of work done by the astronauts during space missions by improving the quality and duration of their sleep periods. Like the sleep experiment, the goal of PI-in-a-Box is to help improve the performance of the astronauts as well, by providing them with assistance in the form of an expert system. Although they use very different means and strategies, the underlying objectives of the sleep experiment and PI-in-a-Box are very much the same.

Time constraints of both mission scheduling and pre-flight training were factors as well in the decision to include PI-in-a-Box in the sleep and respiration experiment. During a mission, sleep time is extremely valuable, and any extra time devoted to donning equipment during the pre-

sleep period results in a loss of available sleep time for the crew members. This in itself defeats part of the objective of the sleep experiment. Another consideration is the limited amount of time devoted to pre-flight training. The process of instrumenting for sleep is a difficult and time-consuming task. Correct placement and skin contact of the electrodes is critical to the quality of the data and the success of the experiment. Even with the use of new sleep recording devices called Sleep*Nets[1], the proper attachment and placement of the electrodes has proven difficult, even for trained sleep technicians.

In ground experiments, the technicians are also required to identify poor signals at a glance, and take the appropriate steps to correct the problem. Despite their training and experience, these technicians frequently experience difficulties in identifying the presence and causes of poor quality signals. Thus, considering the limited training time available and the stresses of space flight, it is unreasonable to assume that the astronauts will be able to perform this signal quality evaluation. Instead, PI-in-a-Box will evaluate the signals electronically during the setup stage, identify bad signals, and suggest corrective measures if necessary. The application of [PI] during this pre-sleep period is especially critical since communication between the astronauts and the Principal Investigators on the ground is generally not permitted during that time.

1.3 Objective

The objective of this thesis is threefold. First, a failure analysis will be performed in order to identify all potential failure modes of the system. Second, a series of tests will be performed to determine the response of the digital sleep recorder, as well as the PI-in-a-Box hardware and soft-

1. The HydroDot^{TM} NeuroMonitoring System is manufactured by Physiometrix, Inc., North Billerica, Massachusetts, USA.

ware, under each set of failure conditions. Finally, for each of these failure scenarios, a set of diagnostic procedures will be developed which will serve as the basis for the diagnostic messages displayed in the PI-in-a-Box diagnostics window.

1.4 Methods

The process leading to the development of the malfunction procedures is depicted graphically in Figure 1.1. In the first step, a failure analysis was performed in order to determine all known failure scenarios for the system. Hardware and software failures, in addition to procedural errors, were considered. These failure modes were identified by performing a fault tree analysis on the system. The failure events may be divided into two categories: "basic" and "undeveloped" events[1]. These event names are based on their roles in fault tree analysis. Basic failure events include equipment malfunctions, software errors, and power-related failures. Since these basic events cannot be simulated, it is impossible to predict the effect such a failure will have on the system. Nevertheless, based on knowledge of the system and its components, an attempt was made to anticipate the "system state" following the occurrence of each basic failure. "System state" information includes operational mode and screen display of the DSR as well as screen and signal activity of the PI-in-a-Box ThinkPad.

Undeveloped failure events include procedural errors in the instrumentation process and improper preparation or application of the equipment or sensors. Unlike the basic failure events, undeveloped failure events can be simulated to determine the exact system response for each individual scenario. Testing was performed in the Sleep Laboratory at the Brigham and Women's

1. Barlow and Fussell

Hospital, with the author as the only subject. Each undeveloped failure event was simulated using the sleep and respiration instrumentation procedures developed for the Neurolab mission. After each simulated failure event, the state of the system was recorded. In addition, the exact procedures required to return the system to its normal operating state were identified. These steps served as the foundation for the development of the diagnostic procedures.

A complete list of system states resulting from the failure simulations was compiled. Each of these system states was common to a number of different failure scenarios. For example, no electrophysiological signals being displayed by PI-in-a-Box could be the result of either the use of the incorrect definition file or the failure to plug the Sleep*Net into the DSR. Thus, the failure events for each system state were prioritized according to likelihood of occurrence. These rankings were entirely subjective. They were established based on observations made in the sleep lab and experiences during the astronaut training sessions. From these prioritizations, diagnostic procedure diagrams were developed for each system state. Finally, diagnostic messages for the PI-in-a-Box diagnostic display window were developed from these diagnostic procedures.

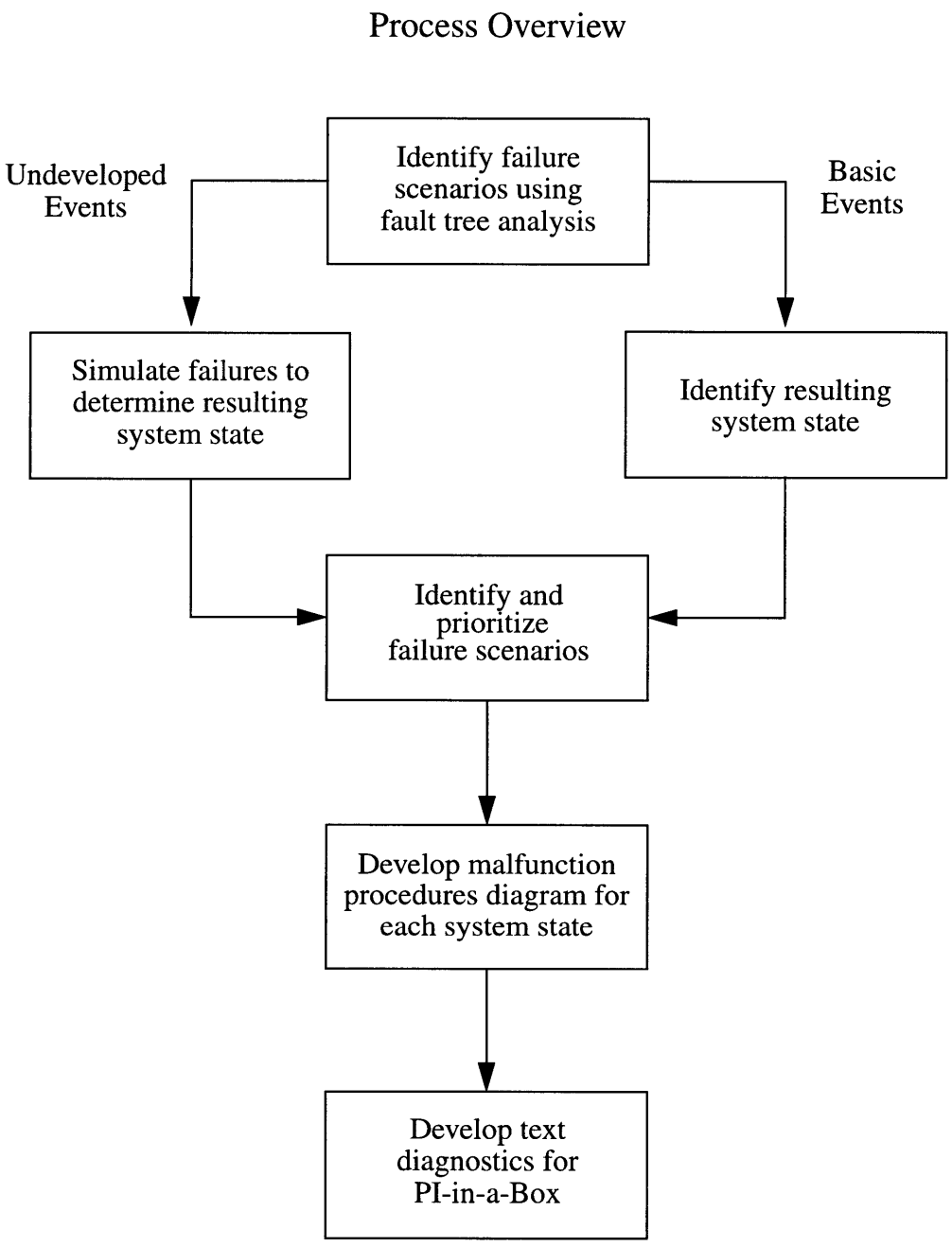

Figure 1.1: Process Overview

Chapter 2

System Overview

2.1 Hardware Requirements

The hardware and equipment required for the testing phase of the project was as follows:

- Vitaport2[1] digital sleep recorder, 4 AA batteries, and 1 Flash RAM data card
- Sleep*Net, Hydrodots[2], adhesive pads, and skin prep sticks
- RIP Suit and Borg Harness
- Pulse oximeter, microphone, nasal thermistor, EKG pads, and event marker
- IBM ThinkPad (486 processor, 50 MHz, 12 MB RAM)
- PI-in-a-Box software (version 2.0)
- RS-232 cable, optically isolated
- Biomedical Function Generator[3]

1. Copyright 1996 Vitaport EDV System GmbH. Distributed by TEMEC instruments BV, the Netherlands.
2. Hydrodots are manufactured by Physiometrix, Inc., North Billerica, Massachusetts, USA.
3. Biomedical Function Generator is manufactured by Medi Cal Instruments, Inc. Reynoldsburg, Ohio.

2.2 Experimental Configuration

The experimental configuration consists of the sleep and respiration hardware, a digital sleep recorder (DSR), and a laptop computer on which the PI-in-a-Box software runs. A schematic of the hardware configuration for the pre-sleep signal evaluation process is illustrated in Figure 2.1.

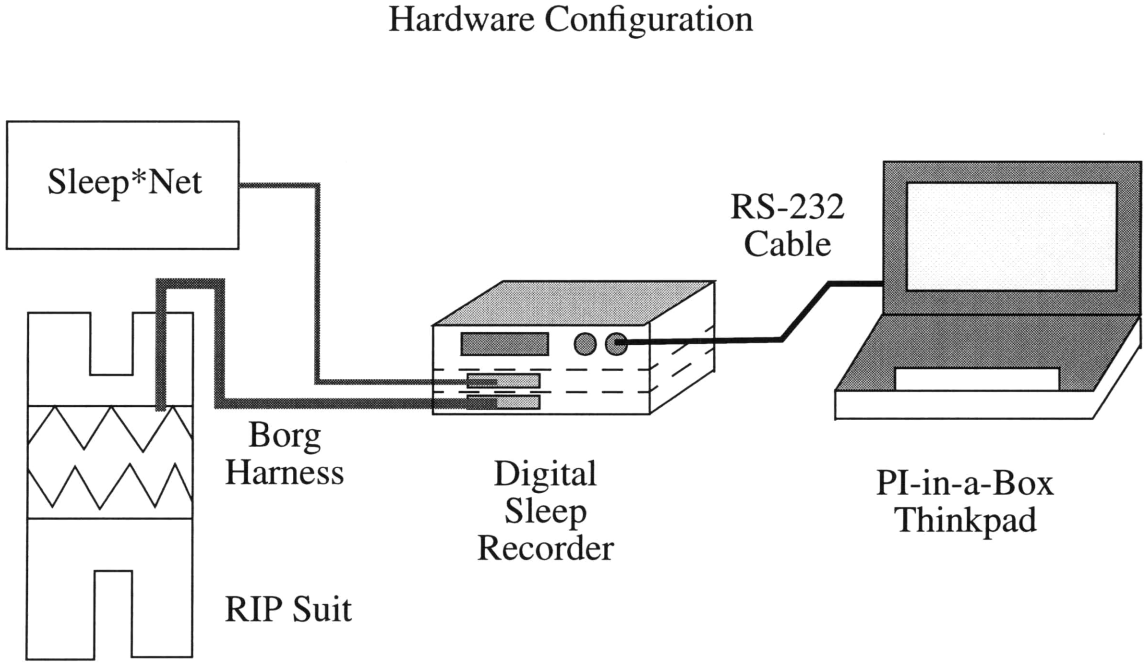

Figure 2.1: Experiment Hardware Configuration

2.3 Sleep Hardware

A recently developed "sleep cap" called the HydroDot^{TM} NeuroMonitoring System (informally referred to as the Sleep*Net) will be worn by the subjects during the sleep recordings to measure the EEG, EOG, and EMG signals. A picture of the Sleep*Net is provided in Figure

2.2. The Sleep*Net consists of a reusable, web-like cap, disposable biosensors which are housed in this cap, and a cable with a 50-pin multiconnector which provides a link from the Sleep*Net to the digital sleep recorder. The Sleep*Net cap provides several advantages over the previous technique of manually applying each individual electrode. Due to its elastic design, the Sleep*Net enables the subject to place the electrodes more consistently in the same location on the scalp for different test sessions. They provide more support to the electrodes and help prevent them from coming unattached as well. In addition, the biosensors consist of a sticky, hydrogel material which adheres to the scalp, providing better surface contact than traditional electrodes. One potential drawback is that the Sleep*Net may be uncomfortable for the subject to wear, resulting in difficulties sleeping. Although this may be a serious concern for the ground experiments, it is less likely to be a problem in the flight experiments, since in microgravity, the subject's head does not rest on any surface during sleep.

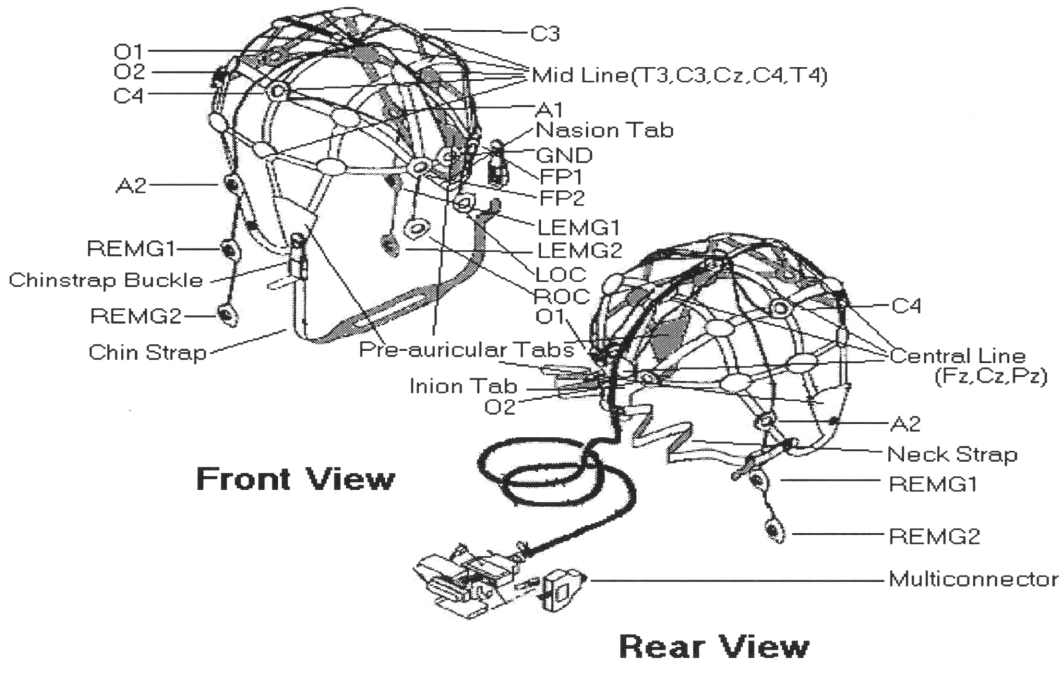

Figure 2.2: Sleep*Net Diagram[1]

1. Diagram provided by Eymard Riel, Center for Circadian Medicine, Brigham and Women's Hospital.

2.4 Respiration Hardware

For the respiration part of the experiment, each subject will don a Respiratory Inductance Plethysmograph (RIP) suit, which consists of two coils embedded in a two-piece black lycra bodysuit. The RIP suit uses inductance measurements to record data on the expansion and contraction of the rib cage during respiration. Measurements are taken on both the abdomen and thorax regions of the chest. In addition to the RIP suit is a "Borg Harness" which is a collection of sensors and electrodes grouped together to form a single, thick cable. The sensors which compose the Borg Harness (BH) include a microphone which detects snoring, an airflow thermistor used to measure temperature of air inhaled and exhaled by the subject, a pulse oximeter which measures the saturation of oxygen in the bloodstream via the tip of the ring finger, and EKG leads which will be used to determine the subject's heart rate. The Borg Harness, which is fastened to the RIP suit using velcro, terminates in a 50-pin multiconnector as well.

2.5 Digital Sleep Recorder

The sleep and respiration signals recorded by the Sleep*Net and RIP suit are recorded using a digital sleep recorder (DSR). Both the Sleep*Net and Borg Harness are connected to the DSR by their 50-pin multiconnectors. The DSR selected for this experiment was the Vitaport2 recording system, illustrated in Figure 2.3. The Vitaport2 is a modular unit that consists of "slices" which may be easily stacked according to the required input capabilities. In the Neurolab sleep configuration, two data input slices are used. The Sleep*Net is plugged into the blue electrophysiological module, which records the electrophysiological data for the sleep experiment. The Respitrace suit is plugged into the black cardiorespiratory module, which records the cardiorespi-

ratory data for the respiration experiment. The modularity of the Vitaport2 allows the sleep and respiration data to be recorded on the same device, while maintaining independence of the hardware and cables for the two different experiments. Included in the Borg Harness is an event marker which plugs into a LEMO port on the DSR. The event marker is activated by the astronaut to indicate significant events in the experimental protocol. The Vitaport2 unit is battery operated, requiring four AA batteries. Mission data will be stored on the DSR using 85 MB FlashRAM data cards. During the flight, "data dumps" will be performed on the mornings following sleep recordings in order to transfer the data to the ground.

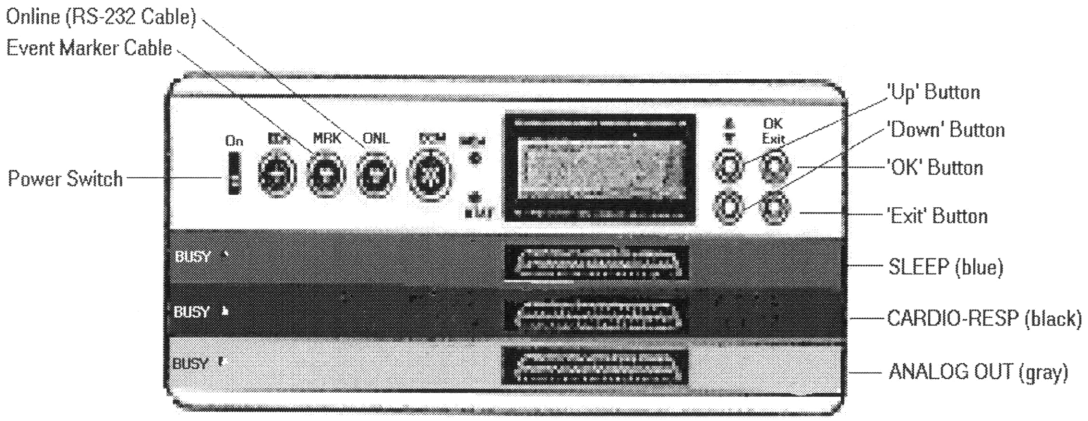

Figure 2.3: Digital Sleep Recorder[1]

2.6 PI-in-a-Box Hardware

On the Neurolab mission, PI-in-a-Box will run on an IBM Thinkpad 755C. The flight computer configuration consists of a 486 processor with 20 MB RAM and a speed of 75 MHz. The ThinkPad is connected to the digital sleep recorder using an optically-isolated RS-232 cable.

1. Diagram provided by Eymard Riel, Center for Circadian Medicine, Brigham and Women's Hospital.

The DSR sends the sleep and respiration data to the ThinkPad through the serial port in real time. PI-in-a-Box displays the raw data on the user interface and analyzes the data to evaluate the quality of the incoming signals. In addition, PI-in-a-Box sends information about its activity back through the serial cable for storage by the DSR on the FlashRAM data card as well. A schematic of the hardware configuration and data flow for the PI-in-a-Box and sleep system is provided in Figure 2.4.

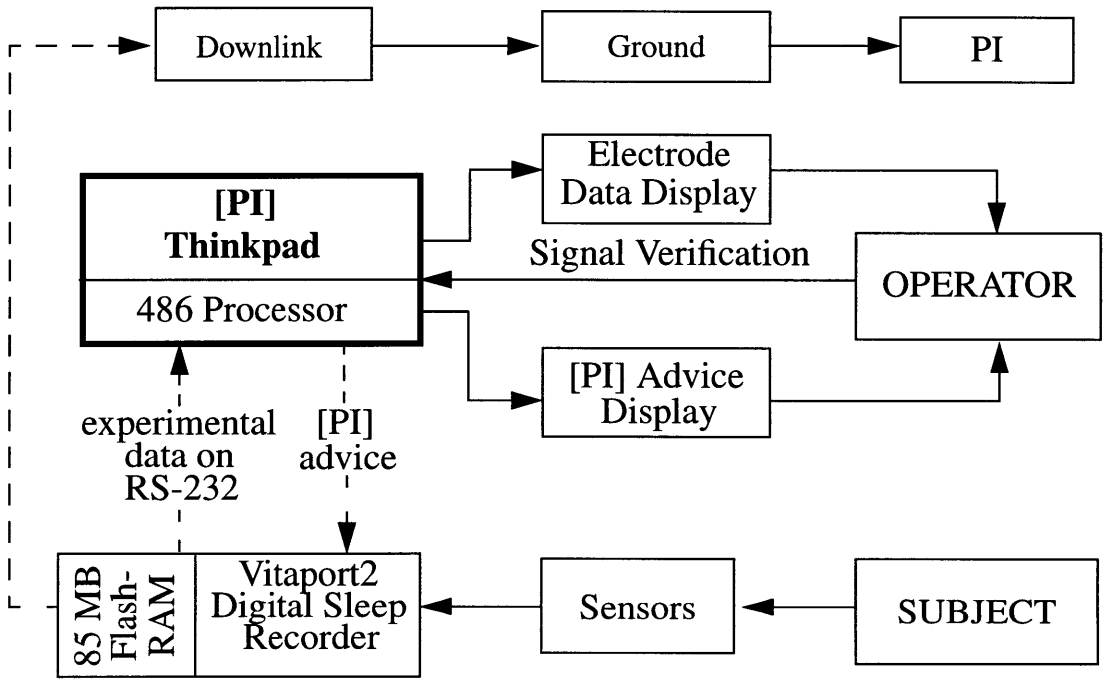

Figure 2.4: Experiment Data Flow[1]

2.7 PI-in-a-Box Graphic User Interface

All of the code for the PI-in-a-Box software was written in C++. The graphic user interface of [PI] consists of two separate screens. One displays the cardiorespiratory (CR) signals and

1. Modified from original version developed in conjunction with NASA Ames PI-in-a-Box Team.

the other displays the electrophysiological (EP) signals. The EP screen is illustrated in Figure 2.5. The raw signal data will be displayed in real time to enable the astronauts to view each individual signal. Each vertical line on the data display represents five seconds of data. The "state" of each signal will be indicated using color-coded LED's, which will enable the astronauts to determine at a glance which signals require attention. In addition, the system will alert the astronauts to any problems in the signal quality using both a graphic and text display. PI-in-a-Box will attempt to diagnose the underlying cause of the problem by performing a troubleshooting analysis. The astronaut will then be provided with suggestions and diagnostic procedures for eliminating the problem and returning the system to its nominal operating state.

2.8 Impedance Check

Neither the DSR nor PI-in-a-Box include any impedance checking capabilities. An impedance check will be performed, independently of PI-in-a-Box, on each of the electrophysiological signals. These impedance checks will provide some initial feedback to the astronauts on the quality of the EP signals. The impedance check will be performed just prior to the activation of PI-in-a-Box. As a result, it will not be included in the PI-in-a-Box diagnostics. Therefore, the impedance checking process was not included in this failure analysis and system testing.

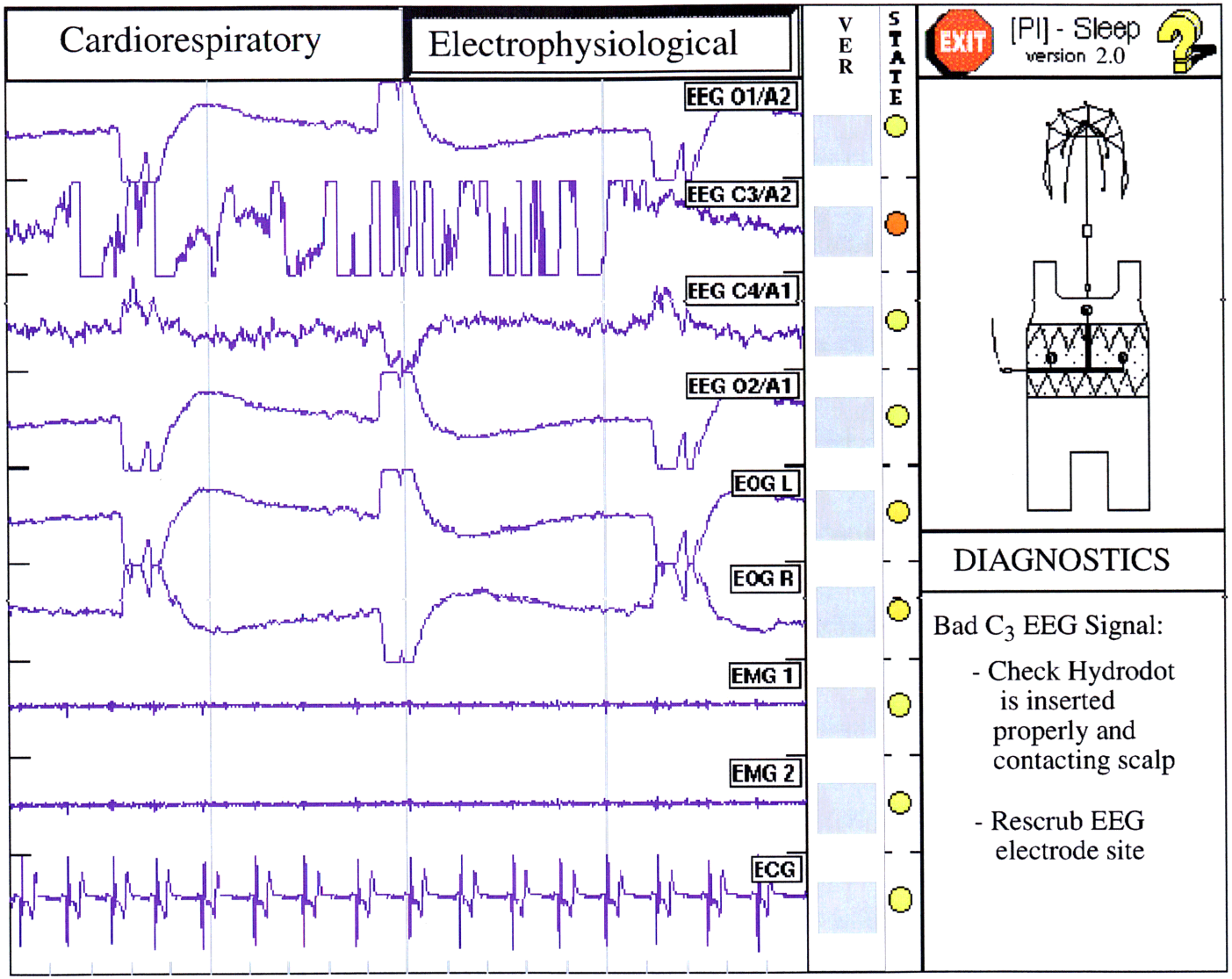

Figure 2.5: PI-in-a-Box User Interface

Chapter 3

Signal Overview

3.1 Signal Summary

During selected sleep periods, a number of different polysomnographic measurements will be recorded. The data consist of two types. The signals are listed in Table 3.1. The first type is cardiorespiratory (CR) data, which will be recorded for UCSD's respiration experiment. The CR signals include respiration (abdomen and rib cage), airflow, microphone, SaO_2, and electrocardiogram (EKG) measurements. The other group of signals which will be recorded is the set of electrophysiological (EP) signals, required for Brigham and Women's sleep experiment. The EP signals consist of the electroencephalogram (EEG), electro-oculogram (EOG), electromyogram (EMG) of the muscles in the jaw, and electrocardiogram.

Table 3.1: Signal Summary

Electrophysiological	Cardiorespiratory
EEG (4)	SaO_2
EOG (2)	Airflow
EMG (2)	Microphone
EKG	RIP-RC
	RIP-AB
	EKG

3.2 Electrophysiological Signals

3.2.1 Polarity of Signal Display

There are a number of conventions which have been adopted in the field of sleep research in an attempt to establish uniformity in all sleep data. One of these conventions is for indicating signal polarity when displaying sleep signals. It is standard to display the signal "negative up," which requires that negative signal voltages are represented by an upward vertical deflection of the signal as it is displayed.

3.2.2 Location of Electrodes

A second convention is the location of each electrophysiological electrode. By applying standard criteria for the placement of the scalp electrodes, variation between different data recording sessions for each subject are minimized. The standard that is used is known as the international 10-20 system of electrode placement[1]. A schematic of this measurement system, highlighting the location of electrodes to be used in the Neurolab recording, is provided in Figure 3.1. Based on the 10-20 system, the subject's scalp is marked at distances of 10 and 20 percent of the total distance between the nasion and inion. The nasion is located at the top of the nose, in the center of the nasofrontal structure, as indicated in Figure 3.1. The inion is the protruding bone located on the back of the head, several inches above the neck. Marks are also made at distances of 10 and 20 percent between the subject's two preauricular points, located behind the ears, as well as around the circumference of the head. Electrodes are then placed at the intersection of these points.

1. Kryger, Roth, and Dement

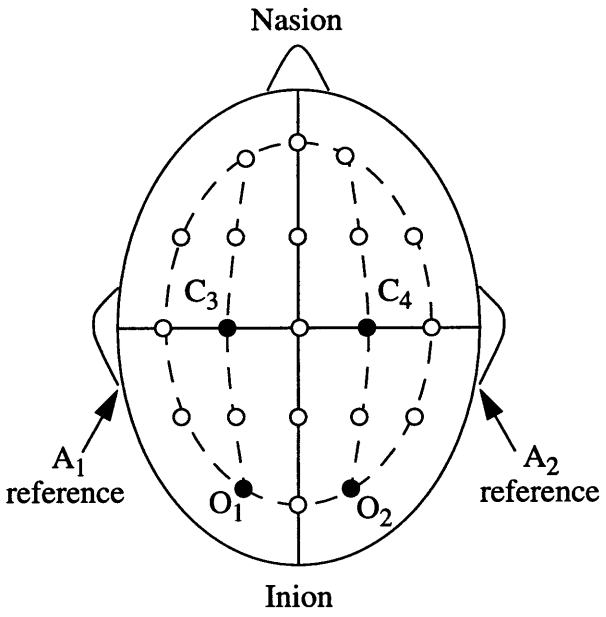

Figure 3.1: International 10-20 System of Electrode Placement[1]

For the Neurolab sleep experiment, the scalp and facial electrodes will be mounted in the Sleep*Net. Each subject will be individually fitted with a personalized Sleep*Net, helping to ensure both comfort and correct placement of the electrodes on the scalp. Use of this Sleep*Net should facilitate the process of applying the electrodes during instrumentation and improve the consistency of their placement from session to session as well.

3.2.3 Notation

Certain letters are generally used to represent specific types of scalp electrodes. "C" denotes a central EEG, "O" represents an occipital EEG, and "A" is used to indicate a mastoid reference electrode. Numbers are also used in conjunction with these letters to identify specific elec-

1. Redrawn from Harner and Sannit

trodes. These numbers are separated by hemisphere with the even numbers corresponding to the right side of the head and odd numbers corresponding to the left.

For this experiment, each electrophysiological electrode was also assigned a number between one and eleven. The electrode sockets were labeled with these numbers, which correspond to their channel assignments on the impedance meter. The PI-in-a-Box interface includes these numbers on the signal labels as well. A complete list of the electrophysiological signals and their corresponding number assignments for the Neurolab study is provided in Table 3.2.

Table 3.2: Electrophysiological Electrode Assignments

Electrode Assignment	Signal Type	Specific Electrode
1	Ground	Ground
2	EEG	C3
3	EEG	C4
4	EEG	O1
5	EEG	O2
6	EOG	LOC
7	EOG	ROC
8	Reference	A1
9	Reference	A2
10	EMG	EMG-L
11	EMG	EMG-R

3.2.4 Differential Signals

The electromyogram and electrocardiogram signals are differential signals. They are produced by measuring the difference in potential between two electrodes. The EMG signals are measures of the potential between two EMG electrodes on the chin separated by a distance of approximately an inch. Similarly, the EKG is a measure of the difference in potential between the two EKG electrodes located in different regions of the abdomen, referenced to a ground electrode located on the lower abdomen. For the sleep and respiration experiment, the EKG is considered to be a cardiorespiratory signal. Therefore, the EKG electrode location is discussed in further detail in the respiration instrumentation section.

3.2.5 Referential Signals

In contrast to the EMG and EKG, the electroencephalogram and electro-oculogram signals are referential signals. They are found by measuring the potential between the EEG or EOG electrode and a designated reference electrode. There are two reference electrodes, each located behind the ear on the contralateral mastoid. Each mastoid reference electrode is shared by one central EEG, one occipital EEG, and one EOG electrode.

3.2.6 Filter Settings

The filter settings for the electrophysiological signals are given in Table 3.3.

Table 3.3: Electrophysiological Signal Filter Settings

Signal	Low Filter Setting	High Filter Setting
EEG	0.3 Hz	35 Hz
EOG	0.3 Hz	35 Hz
EMG	10 Hz	75 Hz
EKG	5 Hz	15 Hz

3.2.7 Electroencephalogram (EEG)

The electroencephalogram (EEG) is the primary polysomnographic measure used in evaluating and scoring sleep data. The four different stages of Non-Rapid Eye Movement (NREM) sleep can be distinguished based on the EEG signal characteristics alone. In general, a minimum of one central and one occipital EEG are recorded in sleep studies. For redundancy, two of each will be recorded on Neurolab.

When the subject is awake and relaxed with eyes open, the EEG is a mixed frequency, low amplitude signal. A standard amplitude range for the EEG signal is 10-200 uV. When the subject's eyes are closed, a rhythmic, higher frequency pattern becomes apparent in the EEG signal. This activity, known as alpha activity, is characterized by a frequency in the 8-12 Hz range. Alpha activity is generally most prominent in the occipital EEG, but is also discernible in the central EEG. An example of EEG data, including alpha activity, is illustrated in Figure 3.2.

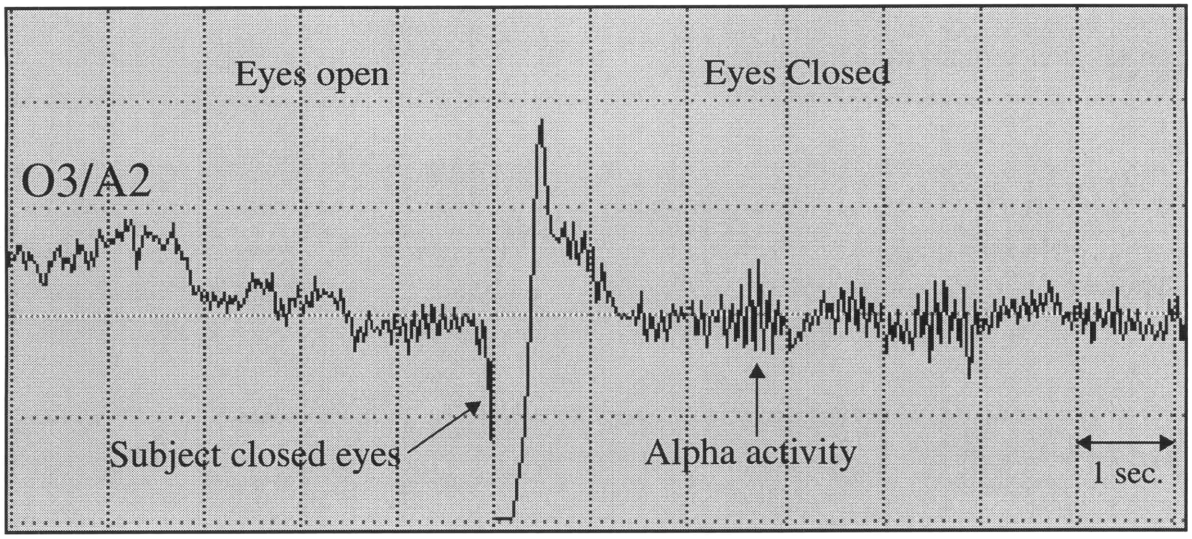

Figure 3.2: EEG Data - Good Quality

A number of different types of noise and artifacts may be present in the EEG signal which reduce the quality of the data. The presence of a poor quality EEG signal may be the result of a Hydrodot which is incorrectly inserted or hair beneath the electrode that prevents the Hydrodot from contacting the scalp. The data artifact which results from poor contact between the scalp and electrode is known as "popping." An example of popping is illustrated in Figure 3.3. Incorrect placement of the electrodes may also result in a poor quality signal. In addition, excess movement of the subject may introduce muscle artifacts into the EEG data. The PI-in-a-Box signal quality evaluation function will be designed to detect the presence of these artifacts in the data. A set of quantitative criteria will be developed and applied to the data in order to characterize the quality of each signal. For example, a Fast Fourier Transform (FFT) analysis will be performed on the EEG signal. The power density of the signal when the subject's eyes are closed will be compared to the power density when the subject's eyes are open. If the quality of the EEG signal is good, the power density in the 8-12 Hz range should increase significantly when the subject's eyes are

closed, due to the presence of alpha activity. This type of qualitative criteria will be developed for each set of electrophysiological signals.

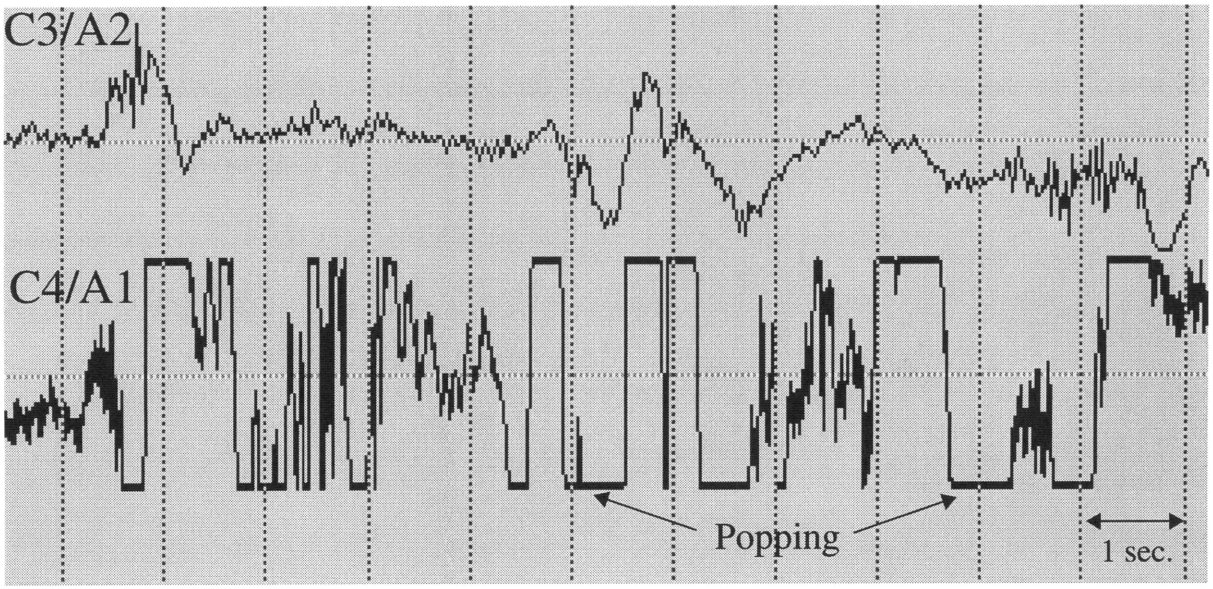

Figure 3.3: EEG Data - Poor Quality

3.2.8 Electro-oculogram (EOG)

The electro-oculogram (EOG) is recorded in sleep studies primarily for the purpose of distinguishing Rapid Eye Movement (REM) sleep from NREM sleep. These two phases of sleep cannot be distinguished easily using the EEG signal alone. Also, in the period just prior to sleep, the EOG signal is characterized by slow, rolling eye movements. In order to identify these characteristics of sleep, the left and right EOG signals are recorded. When the subject is relaxed, the EOG is a relatively mixed frequency, low amplitude signal, with higher amplitudes resulting from movements of the eyes. A normal amplitude range for the EOG signal is 20-500 uV.

The polarity of the EOG signal is the most complex of the electrophysiological signals. One reason for this is that there is a natural potential difference which exists across the human eyeball. The cornea, located in the front of the eye, is positively charged with respect to the retina, which is located in the back of the eye. Coupled with this polarity is the fact that the human eye has more than one degree of freedom. The two relevant movements in the EOG analysis are up and down and right and left movements.

Each EOG electrode is referenced to the mastoid reference electrode located behind the opposite ear. As a result, the movement of both eyes in either the right or left direction within the horizontal plane produces a negative voltage in one eye and a positive voltage in the other. Eye movements to the left result in a downward (positive) deflection of the left EOG signal and an upward (negative) deflection of the right EOG signal. The reverse is true for eye movements to the right. An example of this is illustrated in Figure 3.4. The right and left eye movements produce deflections in each EOG signal which are approximately equal in magnitude, but opposite in polarity.

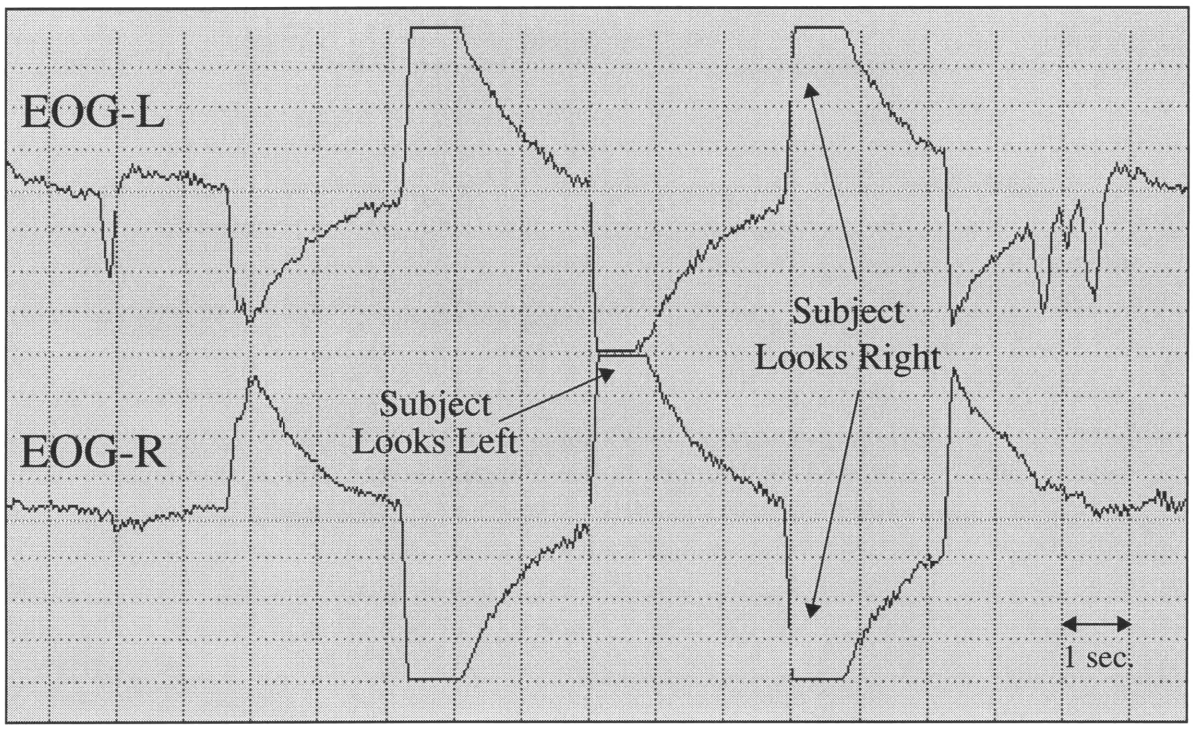

Figure 3.4: EOG Data - Left and Right Eye Movements

Up and down eye movements produce deflections similar to right and left eye movements, but smaller in magnitude. This is a result of the convention of placing the right EOG electrode above the eye and the left EOG below. Because of this difference in electrode location as well as the polarity of the eyeball, up and down eye movements produce deflections in both EOG signals that are similar in magnitude, but opposite in polarity. The magnitude of the right EOG signal is sometimes noticeably greater than the left EOG because, since it is located above the right eye, it also detects movement of the upper eye lid. An upward movement of the eyes corresponds to an upward (negative) deflection of the left EOG signal, and a downward (positive) deflection of the right EOG signal. The reverse is true for downward eye movements. An example of up and down

eye movements is illustrated in Figure 3.5. A summary of EOG signals responses to specific eye movements is given in Table 3.4.

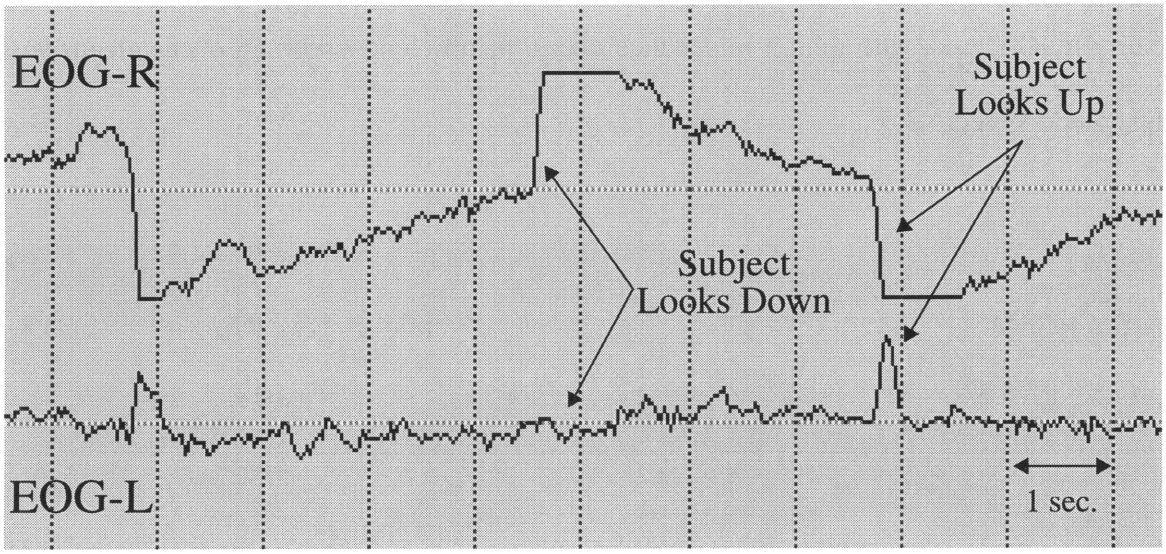

Figure 3.5: EOG Data - Up and Down Eye Movements

Table 3.4: EOG Signal Deflections

Eye Movement	Left EOG Deflection	Right EOG Deflection
Up	Up (negative)	Down (positive)
Down	Down (positive)	Up (negative)
Right	Up (negative)	Down (positive)
Left	Down (positive)	Up (negative)

Many of the artifacts and noise that are common in EEG signals can be present in the EOG signals as well. Correct placement of the EOG electrodes is critical in obtaining a good quality signal. The signal will be weak if the electrodes are placed too far away from the eyes in any direction. However, it is essential that the electrodes are placed at a sufficient distance above and

below the eyes in order to detect up and down eye movements. Like the EEG signal, movement of the subject may also introduce muscle artifacts into the data. In addition, popping or noise may appear in the data if the EOG Hydrodots do not contact the skin properly. An example of a poor quality EOG signal, with a high impedance due to insufficient scrubbing of the electrode site, is illustrated in Figure 3.6.

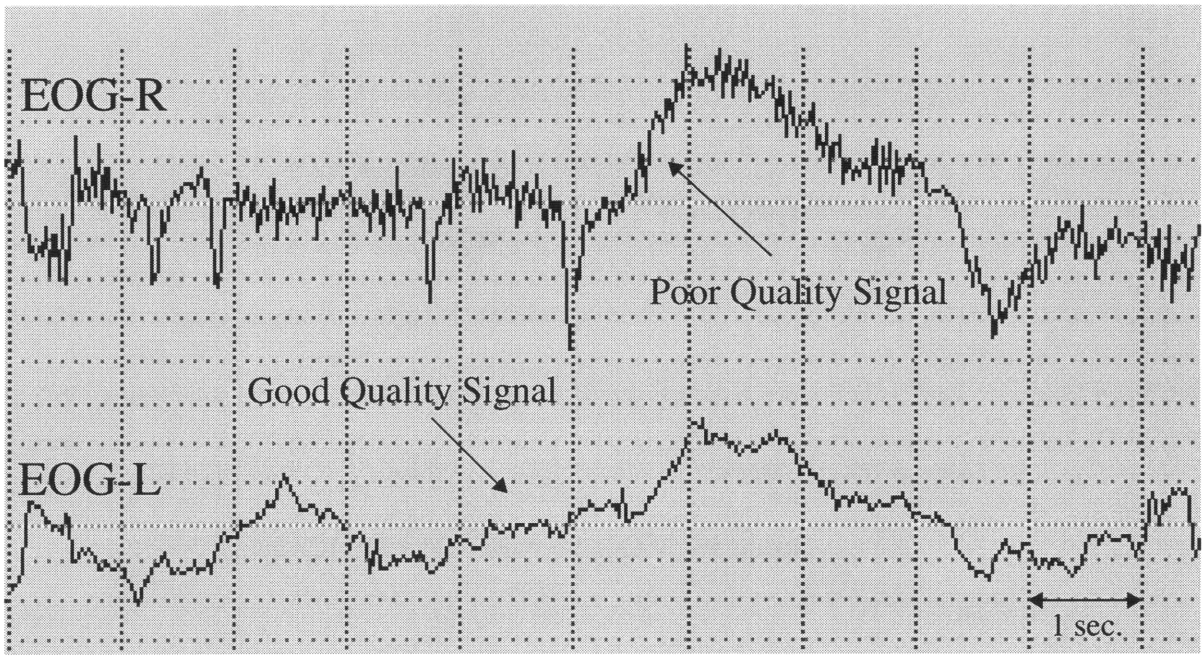

Figure 3.6: EOG Data - Poor Quality

3.2.9 Electromyogram (EMG)

One of the defining characteristics of REM sleep, in addition to the rapid eye movements after which it is named, is a loss of muscle tone. In order to detect this, the electromyogram (EMG) records muscle activity in the chin, providing information supplemental to the EOG concerning the onset and duration of REM sleep. The EMG is a higher frequency signal than the EEG and EOG, and it varies in amplitude from 20-300 uV. Movements of the chin and jaw muscles

dramatically increase the amplitude and frequency of the EMG signal. An example of this is illustrated in Figure 3.7. In general, one EMG signal is required, and a second may be recorded as a backup. On Neurolab, two chin EMG signals will be recorded.

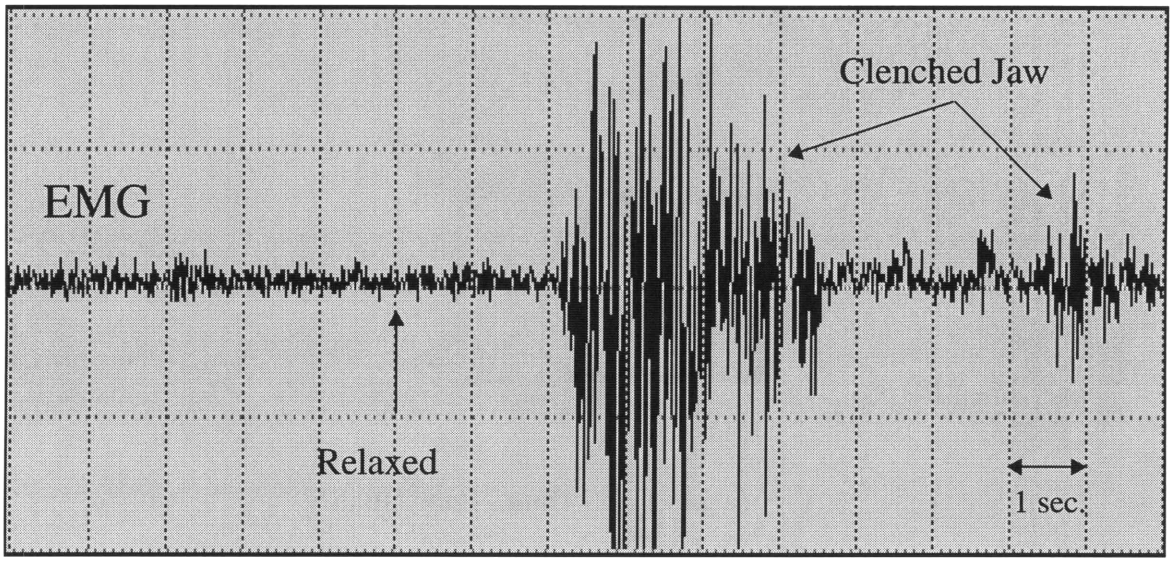

Figure 3.7: EMG Data - Good Quality

Many of the same artifacts and noise which produce poor quality EEG and EOG signals may affect the EMG signal as well. The presence of noise in the EMG signal may me detected by the absence of a significant amplitude increase in the signal when the subject talks or clenches his jaw. Proper placement of the electrodes below the jaw bone is necessary in order to produce a good quality signal. Proper skin contact with the Hydrodot is also essential. If the electrode does not maintain good contact with the skin, noise may be introduced into the data or the signal may not be detected. The EMG data in Figure 3.8 illustrates a poor quality EMG-L signal due to a loose EMG electrode. In comparison, the quality of the EMG-R signal in Figure 3.8 is good.

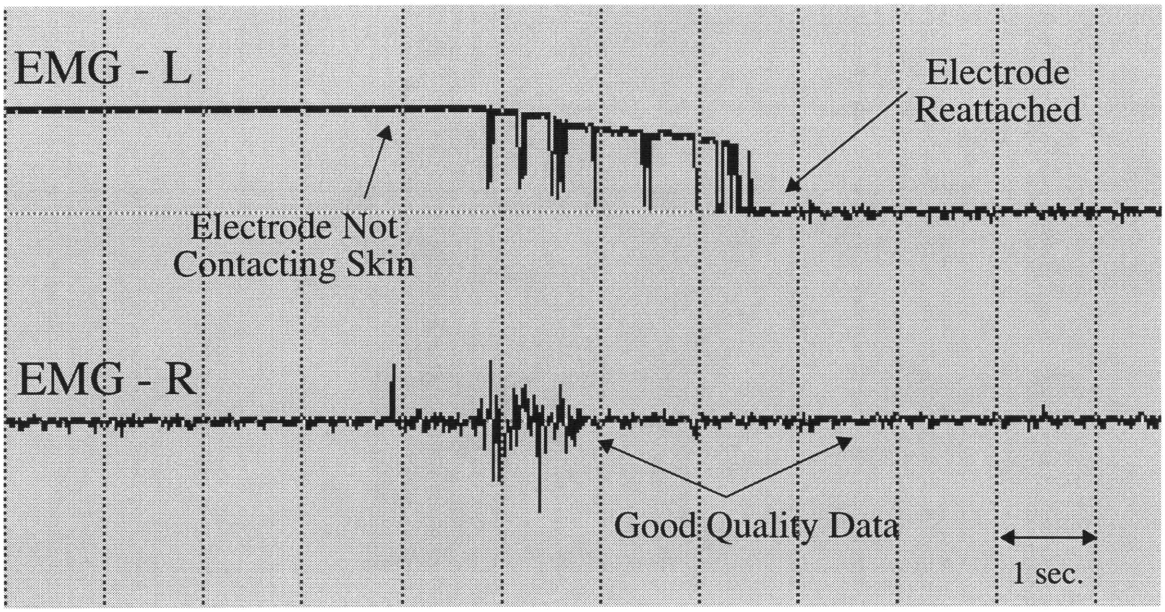

Figure 3.8: EMG Data - Poor Quality

3.2.10 Electrical Ground

A common ground electrode is used for all of the electrophysiological signals. It is housed in the Sleep*Net and located on the forehead of the subject.

3.3 Cardiorespiratory Signals

3.3.11 Respiratory Inductance Plethysmograph (RIP) Suit

The RIP Suit is a two piece black lycra suit which records data on the subject's respiration. Embedded in the suit are two inductance coils which encircle the subject's chest and abdomen. The top coil measures the expansion and contraction of the thorax region of the chest, while the lower coil measures the expansion and contraction of the abdominal region. The RIP signals fol-

low a sinusoidal pattern when the subject is breathing normally. When breathing stops, chest volume remains constant, and the RIP signals become flat. Thus, these respiration data can be used to identify sleep apnea.

3.3.12 Electrocardiogram (EKG)

Each EKG electrode is mounted on a disposable adhesive pad. In the center of the pad is the EKG sensor, which is held securely to the skin by the adhesive surrounding. On the back of each pad is a snap which allows each EKG sensor to be attached to the EKG wires on the Borg Harness.

There are three EKG electrodes in total, each color-coded to coordinate with a velcro flap on the RIP Suit indicating the electrode's proper location. The three electrodes are arranged in a triangular pattern as illustrated in Figure 3.6. The positive electrode is located in the upper right region of the chest, near the subject's shoulder. The negative electrode is located in the lower left region of the abdomen. The ground EKG electrode is located in the lower right region of the abdomen, in the same horizontal plane as the negative EKG electrode. This particular electrode pattern is required in order to produce a signal with the correct polarity.

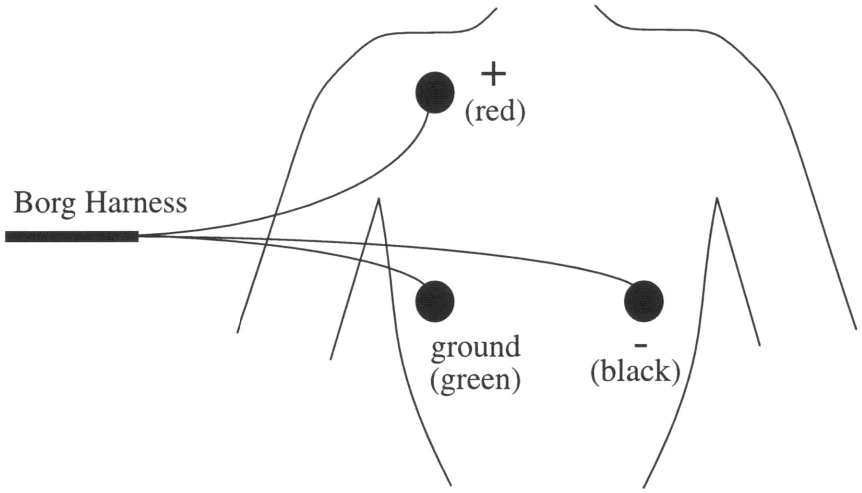

Figure 3.9: Location of EKG Electrodes
(Redrawn from Neurolab Sleep Instrumentation Procedures)

The EKG signal is characterized by a wave pattern known as the "QRS" complex. This QRS wave pattern is illustrated in Figure 3.10. The QRS spike provides a graphical display of heart activity. Heart rate data can be derived from the EKG signal. The QRS wave has a much greater amplitude than the electrophysiological signals, reaching amplitudes of up to 5 mV.

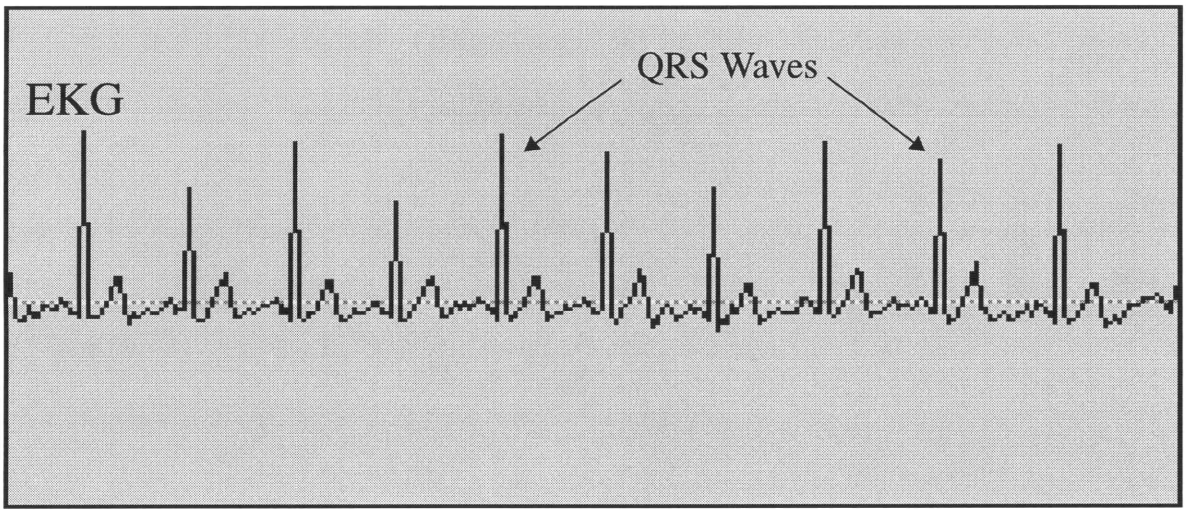

Figure 3.10: EKG Data

3.3.13 Microphone

The microphone sensor is part of the Borg Harness. It measures vibrations in the throat to detect snoring during sleep. The sensor is applied to the subject's throat using an adhesive pad.

3.3.14 Airflow

The airflow sensor is a thermistor worn just below the nose which measures the temperature of the air inhaled and exhaled by the subject. These temperature readings provide information which supplements the RIP data on the respiration patterns of the subject. Like the respiration signals recorded by the RIP Suit, the airflow signal should vary sinusoidally as the subject inhales and exhales.

3.3.15 Oxygen Saturation (SaO_2)

The pulse oximeter measures the saturation of oxygen in the blood stream. The sensor selected for the Neurolab study is worn on the finger. A red beam of light is transmitted from one side of the sensor, through the tip of the finger, and received by the other side of the sensor. The resulting signal is a DC signal, indicating the percentage of oxygen in the bloodstream. SaO_2 values for normal subjects are generally between 95 and 100 percent.

Chapter 4

Instrumentation and Crew Procedures

4.1 Sleep Instrumentation

Setup for the sleep portion of the experiment consists of a pair of subjects assisting one another with the preparation and donning of their Sleep*Nets. Each subject performs the initial Sleep*Net preparation procedures on his or her Sleep*Net as instructed in the instrumentation procedures. After cleansing the forehead, nasion, temple, and chin regions of the face with alcohol pads, the EOG and EMG electrodes are applied to the appropriate facial locations using adhesive pads. The back end of a cleansing swab is then used to separate the hair of the subject beneath each EEG electrode socket, exposing the scalp. The skin at each Sleep*Net electrode site is cleansed using the cotton end of the prep swab. The swabs for the Neurolab mission will be pre-prepared with a mildly abrasive cream in order to facilitate the cleansing process. After each site has been scrubbed, a Hydrodot is inserted into each electrode socket, until it is flush with the top surface of the socket. These Hydrodots contain a conductive gel which contacts the scalp and provides an electrical link between the scalp and Sleep*Net.

4.2 Respiration Instrumentation

A diagram of all cardiorespiratory sensor locations is provided in Figure 4.1.

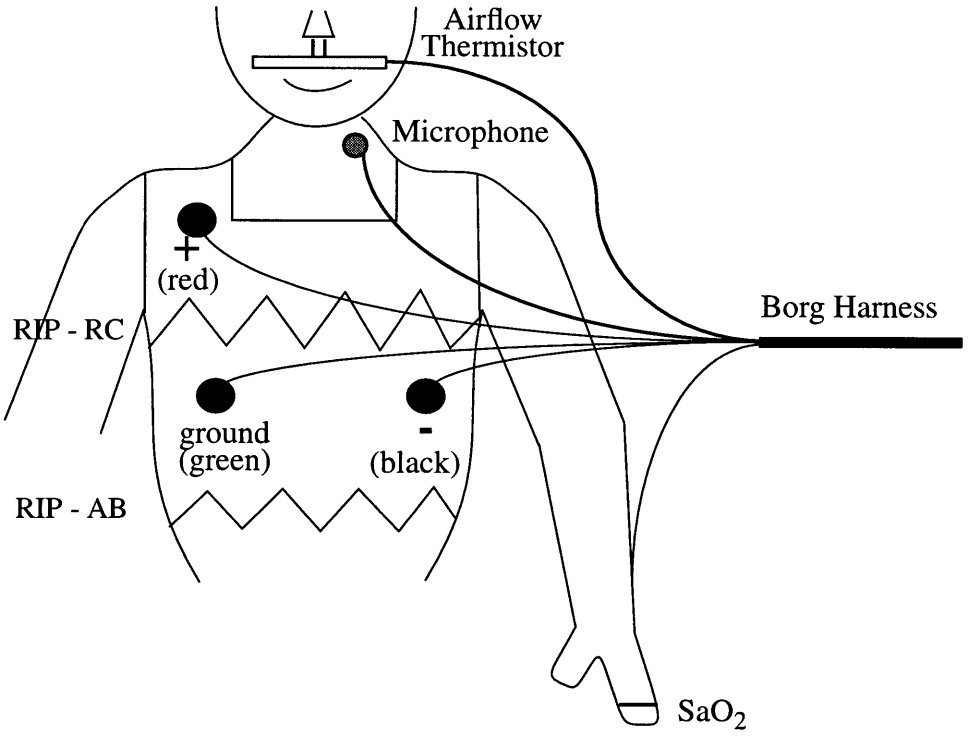

Figure 4.1: Location of Cardiorespiratory Sensors

4.2.1 Respiratory Inductance Plethysmograph (RIP) Suit

Each subject dons a black lycra RIP suit. The top and bottom of the suit are fastened together using velcro strips. The length of the suit top may be adjusted using the velcro tabs located on the shoulders. Attached to the RIP suit is a connector which plugs into the Borg Harness.

4.2.2 EKG

The subject applies the three EKG electrode pads to the chest and abdomen. The EKG wires in the Borg Harness are attached to the EKG pads using snaps. The wires are color-coded with the RIP Suit to correspond with the correct EKG pad location.

4.2.3 Microphone

The microphone is applied to the subject's neck using an adhesive socket pad. The subject determines an appropriate location by placing two fingers on his or her neck and humming. The sensor is placed in a region of the neck where vibrations are the strongest, generally just below the jaw bone, displaced by several centimeters laterally in either direction from the center of the throat. Due to the stiffness of the wire, a piece of tape is used to secure the microphone and wire to the subject's neck. Since the microphone cable is part of the Borg Harness, the subject is not required to plug in the microphone sensor.

4.2.4 Airflow Thermistor

Prior to applying the airflow thermistor, the end of the sensor is plugged into the Borg Harness. As packaged, the airflow sensor is mounted on an adhesive strip. After removing the plastic backing, the thermistor is placed on the upper lip of the subject. The two prongs of the sensor point toward the subject's nostrils.

4.2.5 Pulse Oximeter

The pulse oximeter is applied to the ring finger on the subject's non-dominant hand. The sensor is placed on the tip of the finger, and secured with a Velcro strip which encircles the finger. There is a wire connected to the pulse oximeter which the subject must plug into the Borg Harness.

4.3 DSR Activation

Subjects are required to replace the four AA batteries and insert a new FlashRAM data card into the digital sleep recorder before the start of each recording session. This will eliminate the possibility of losing battery power on the DSR or running out of storage space on the data card during the sleep session. The Sleep*Net, Borg Harness, and an event marker are plugged into the DSR. After the DSR has been powered on, the subject follows the procedures to begin recording data. Subjects must identify themselves by selecting their designated patient identification number on the DSR. Subjects must also verify that the correct definition file has been selected. When this has been completed, the subject begins the recording.

4.4 PI-in-a-Box Activation

It is critical that the subject does not plug the serial RS-232 cable into the DSR until the recording has begun. If the DSR has been connected to the ThinkPad before the recording has started, the DSR automatically goes into "online" mode. In this mode, it is possible to remotely view the signals using PI-in-a-Box without recording any data. However, once the DSR has been placed in online mode, a recording cannot be started on the DSR.

After the recording has been started, the DSR is connected to the ThinkPad using the RS-232 serial cable. The ThinkPad is powered on, and the PI-in-a-Box program is activated. The default screen of the [PI] graphic user interface appears and displays the electrophysiological signals. The subject evaluates the quality of each EP and CR signal. If the quality of any signal is poor, indicated by a red state light on PI-in-a-Box, the subject follows the troubleshooting proce-

dures, provided in the [PI] diagnostics window. When the quality of each electrophysiological and cardiorespiratory signal is acceptable, the subject confirms that each signal is good by clicking on the signal verification boxes on both screens of the PI-in-a-Box interface. The RS-232 cable is then disconnected from the DSR and the subject exits the PI-in-a-Box program. The first subject then assists the second subject with the sleep and respiration instrumentation process. After both subjects have completed the signal checking process, the ThinkPad is powered off and the subjects may go to sleep. The detailed instrumentation procedures developed for the Neurolab mission are provided in Appendix A.

Chapter 5

Fault Tree Analysis

5.1 Fault Tree Overview

A fault tree analysis was performed for the sleep and respiration instrumentation process, including the use of PI-in-a-Box. The first step in the analysis was to identify a number of top-level, undesirable events which could potentially occur as the result of some failure event in the instrumentation process. Each top-level failure event can be broken down in order to identify the possible sources of the failure.

Four primary failure events were identified for this analysis. They are as follows:

1. The DSR is not recording.
2. The DSR recording is unacceptable.
3. No signals are present on PI-in-a-Box.
4. Not all signals are present on PI-in-a-Box.

The first two events describe scenarios in which the objectives of the sleep experiment would not be satisfied. A failure of the DSR to record the data would be catastrophic to the sleep and respiration study. There are also a number of scenarios in which the DSR is recording, but the

recording is unacceptable. These scenarios include events such as selecting the wrong definition file, entering the wrong patient identification number, or recording poor quality signals.

In addition to these two scenarios, a number of other failure scenarios have been identified which involve PI-in-a-Box. The third and fourth failure events are closely related to the first two, containing several identical subsets of failure scenarios. Nevertheless, failures which affect the DSR recording and PI-in-a-Box are not mutually exclusive. PI-in-a-Box adds an additional computer, cable, and software program to the sleep and respiration configuration. In addition to failures with the sleep hardware or DSR, a failure associated with any of the PI-in-a-Box items may result in an apparent [PI] failure as well. Therefore, separate fault tree analyses were also required for the third and fourth top-level failure events involving PI-in-a-Box.

Failures may result from many combinations of events. They may be caused by hardware malfunctions, software loading problems, or procedural errors made by the subject. In developing the fault trees, an attempt was made to identify all potential failure scenarios which may occur in the instrumentation process.

5.2 Fault Tree Notation

Standard symbols are used in fault tree analyses to represent different types of failures[1]. There are three primary symbols which represent different types of failure events. The first symbol is a circle, used to indicate a "basic" event. A basic event is a failure of the system or of any system element which results from internal causes. The second type of symbol is shaped like a

1. Barlow et al.

diamond. These diamonds represent "undeveloped" events. They are referred to as "undeveloped" because although they do not describe the primary cause of a failure, they are intentionally not developed any further in the fault tree analysis. Many of these undeveloped events involve human error. Each branch of the fault tree terminates in either a basic event or an undeveloped event.

The remaining events in the fault trees are "fault" events, indicated by rectangular boxes. Fault events describe abnormal system states. However, unlike basic and undeveloped events, they must be broken down further to identify their potential causes. A branch of a fault tree never terminates in a fault event. Some fault events in this analysis are indicated by dashed rectangular boxes. The dashed rectangle is not a conventional symbol used in fault tree analysis. This symbol was added to indicate that further development of that particular failure event was performed in a separate fault tree on a different page. This was done in an attempt to minimize clutter in the diagrams and to prevent subsets of certain fault trees from being duplicated.

In addition to the event symbols, "and" and "or" logic gates are used to describe the relationship between certain events. The complete list of symbols used in this failure analysis is depicted in Figure 5.1.

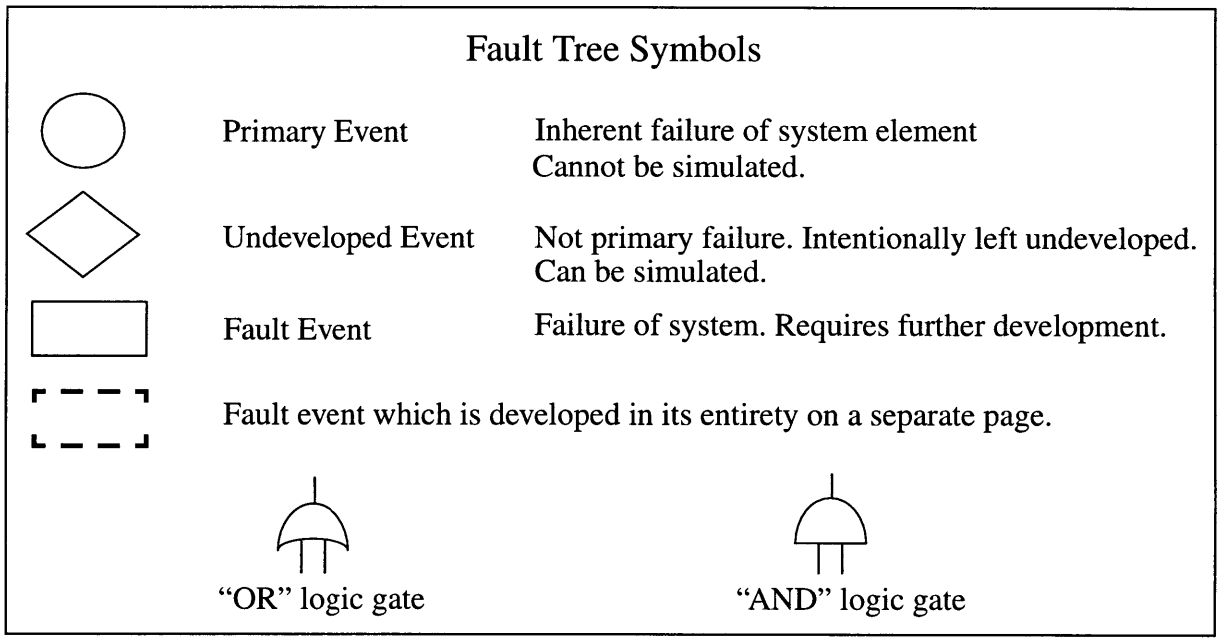

Figure 5.1: Fault Tree Symbol Summary

5.3 Results

The fault trees are provided in Figures 5.2 - 5.10.

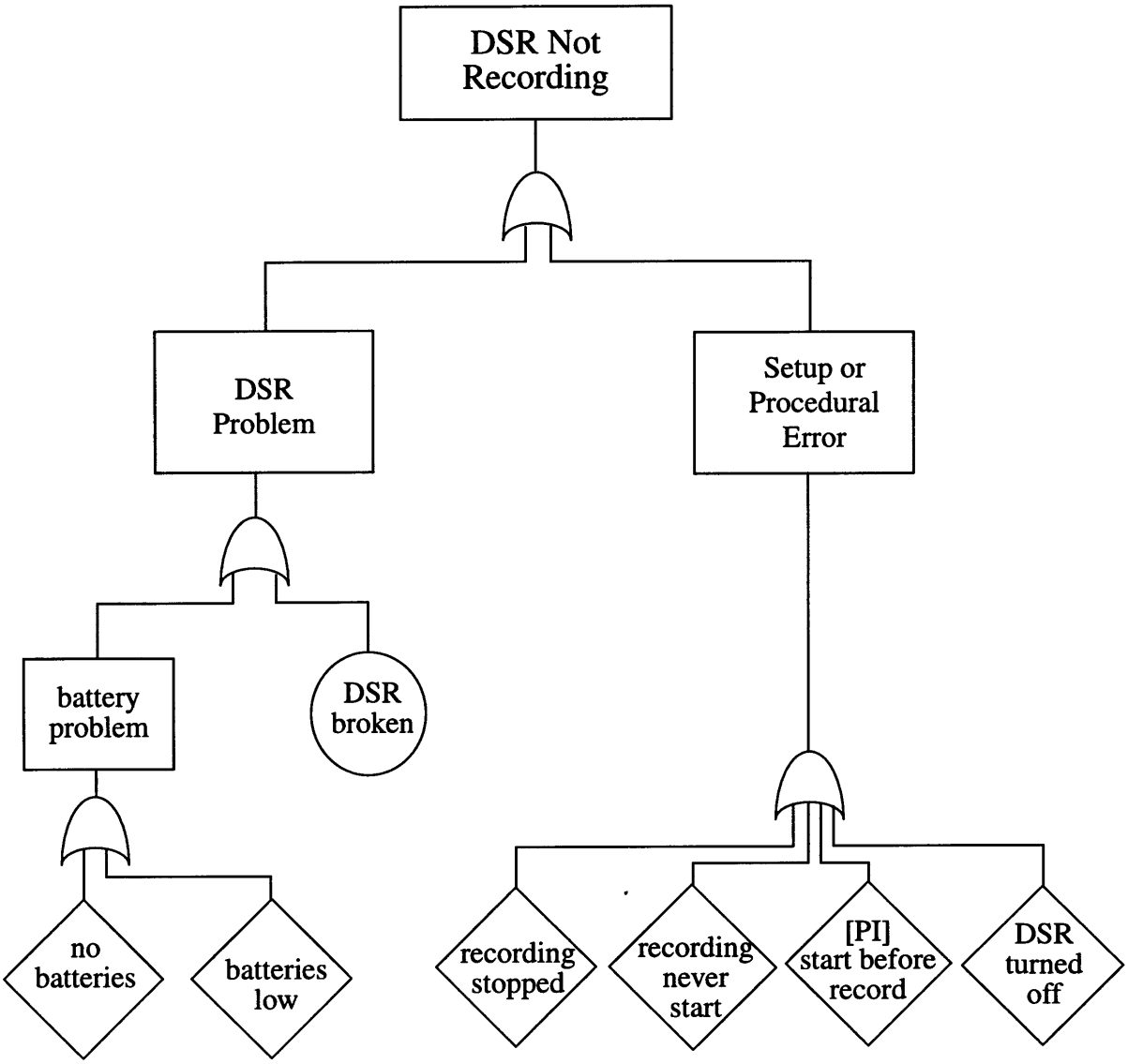

Figure 5.2: Fault Tree Diagram - DSR Not Recording

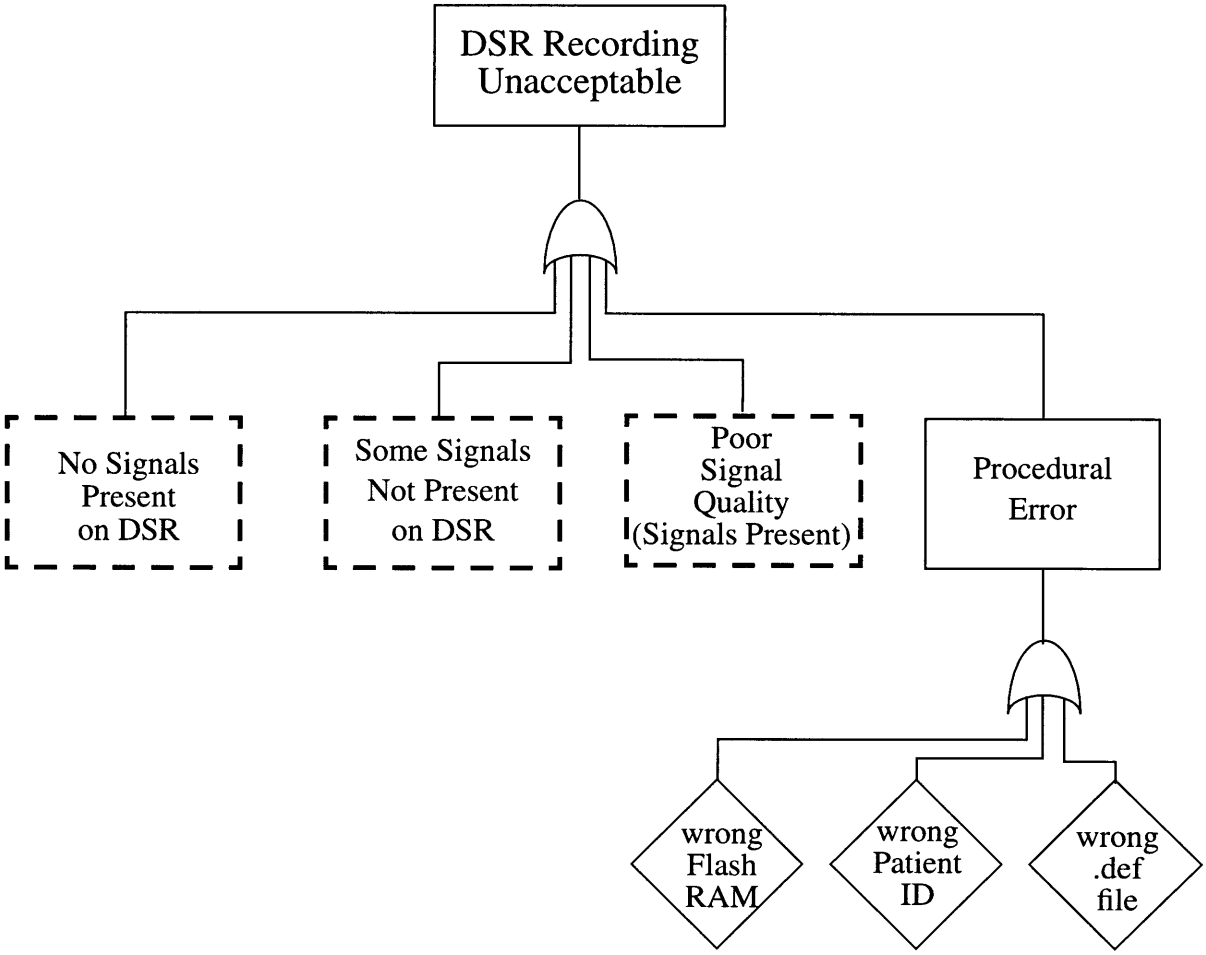

Figure 5.3: Fault Tree Diagram - DSR Recording Unacceptable

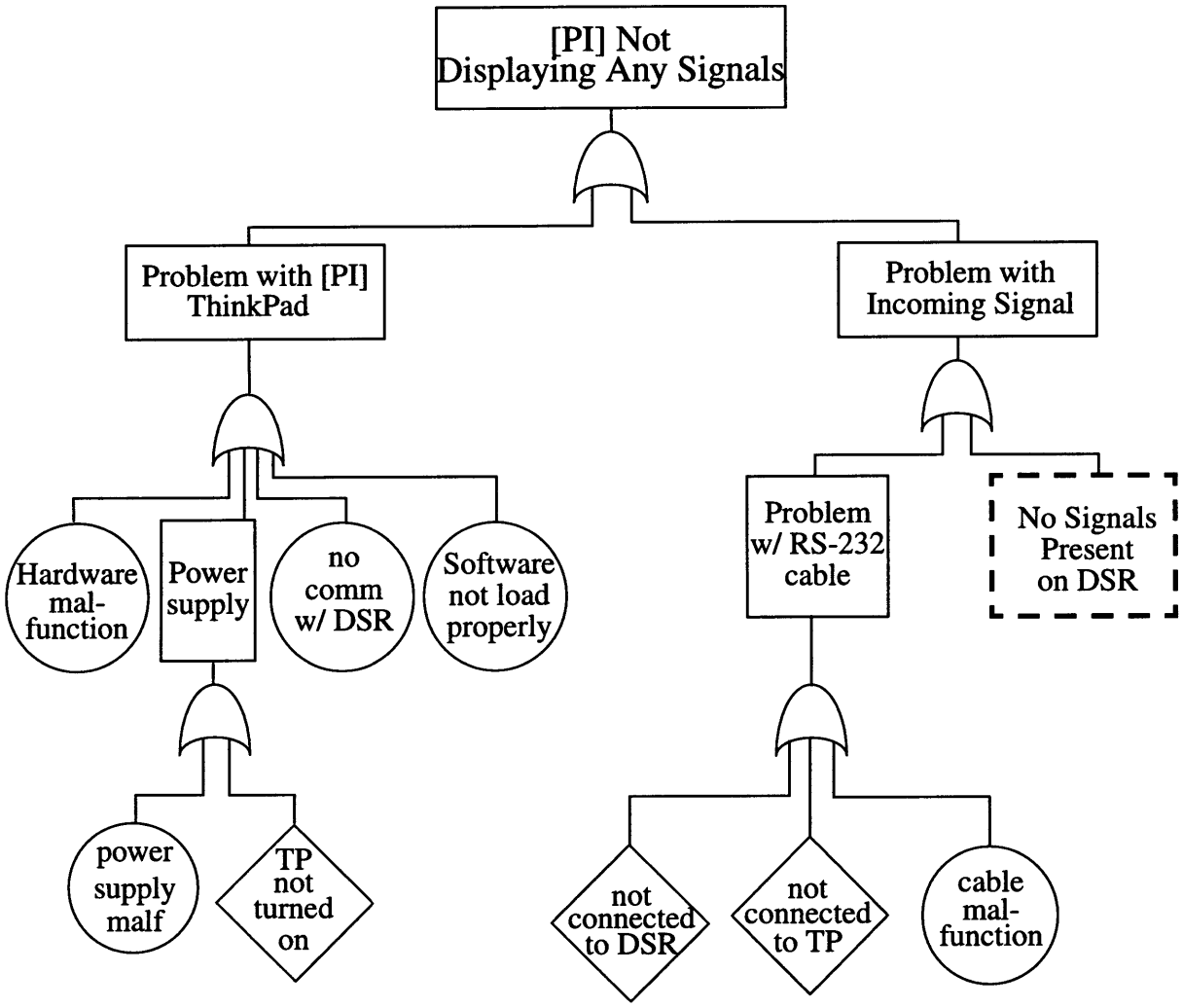

Figure 5.4: Fault Tree Diagram - No Signals on PI-in-a-Box

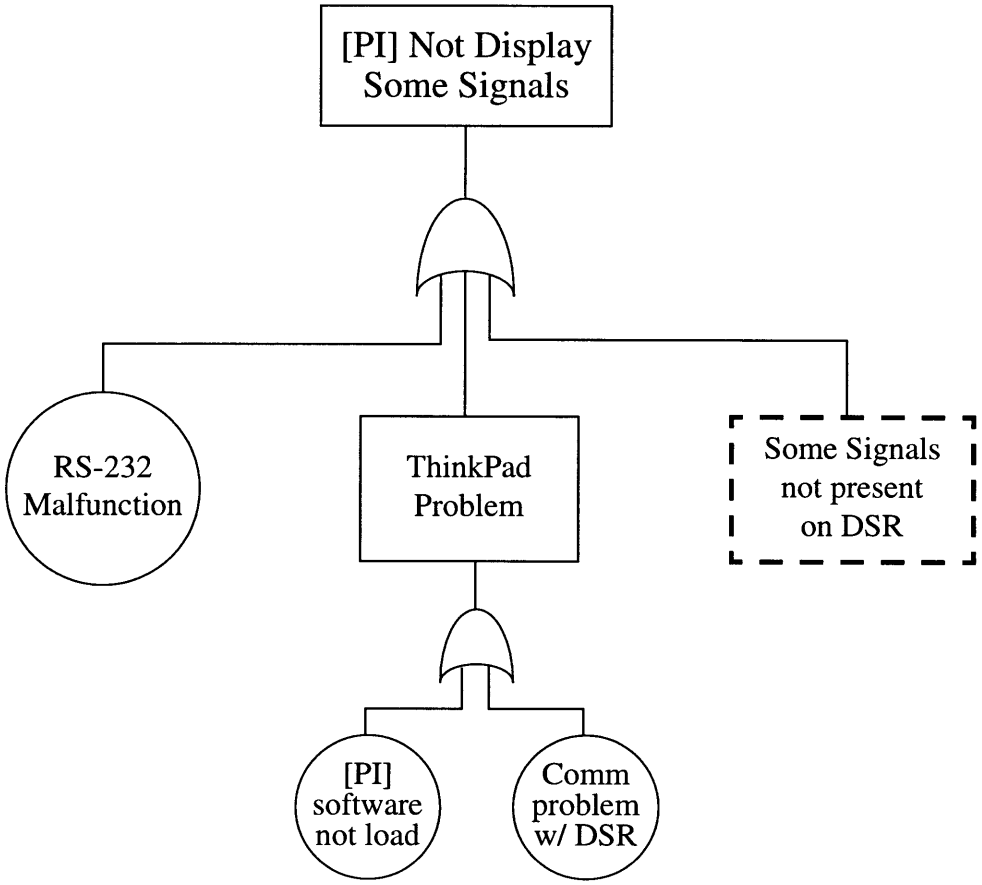

Figure 5.5: Fault Tree Diagram - Some Signals Missing on PI-in-a-Box

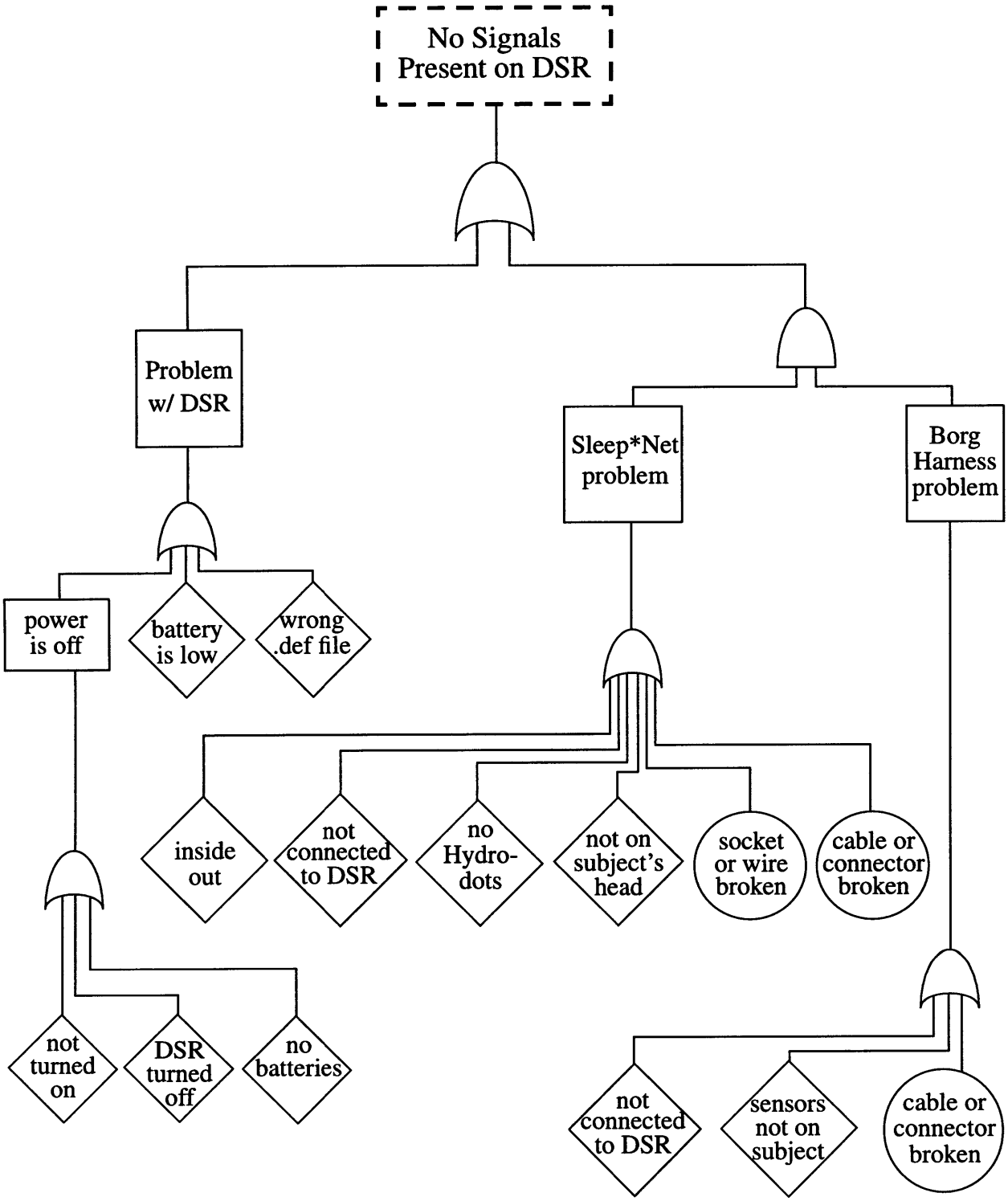

Figure 5.6: Fault Tree Diagram - No Signals on DSR

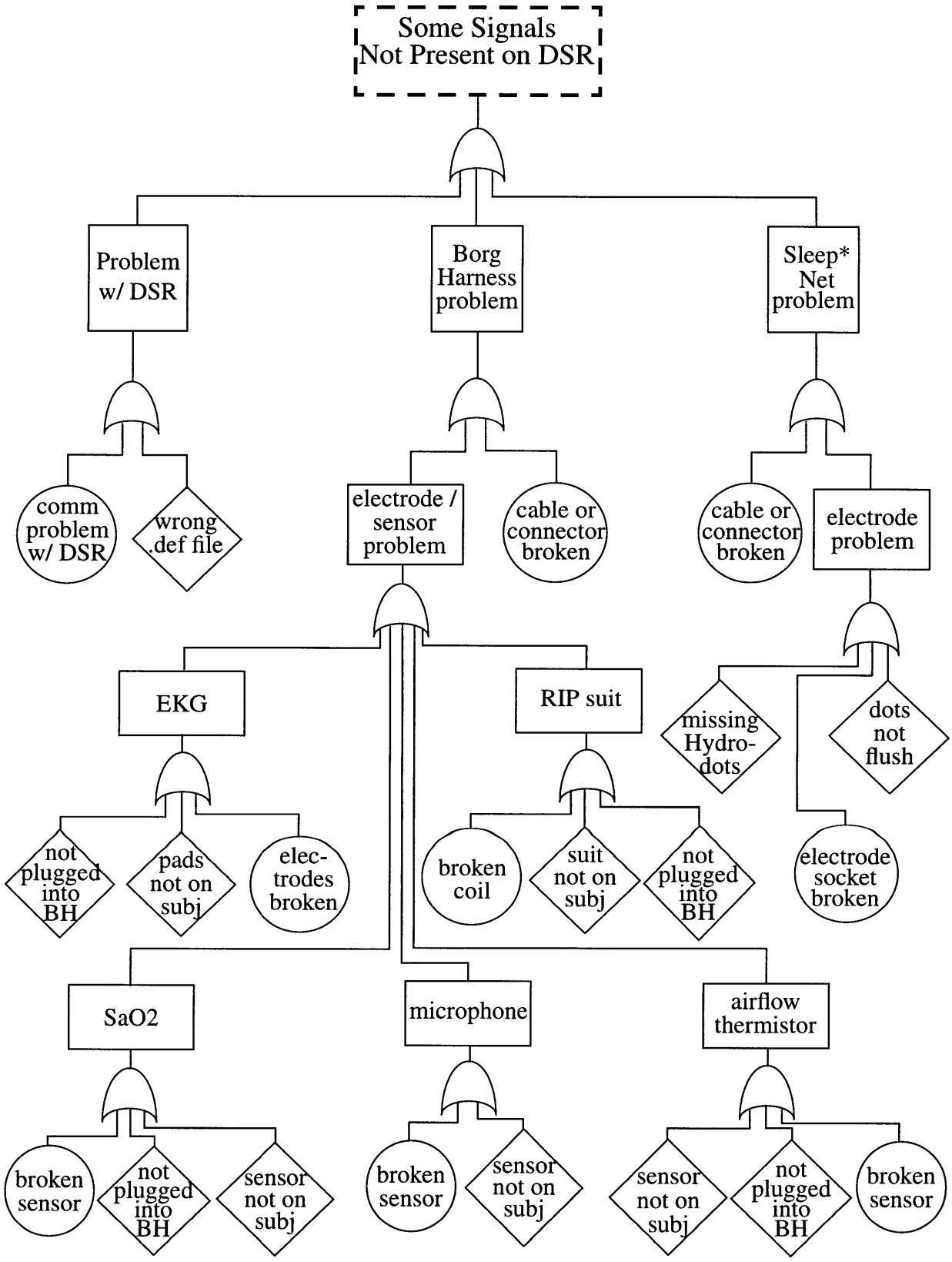

Figure 5.7: Fault Tree Diagram - Some Signals Missing on DSR

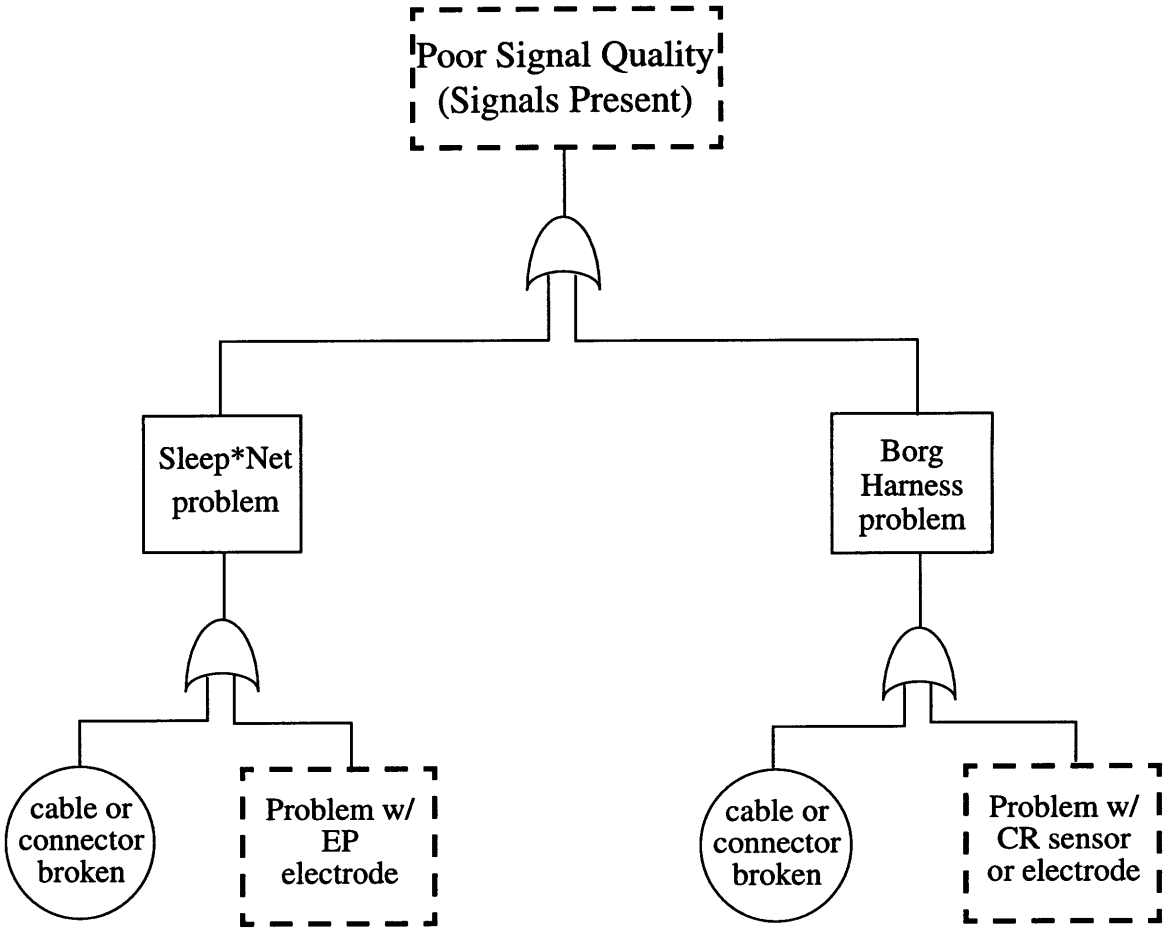

Figure 5.8: Fault Tree Diagram - Poor Signal Quality

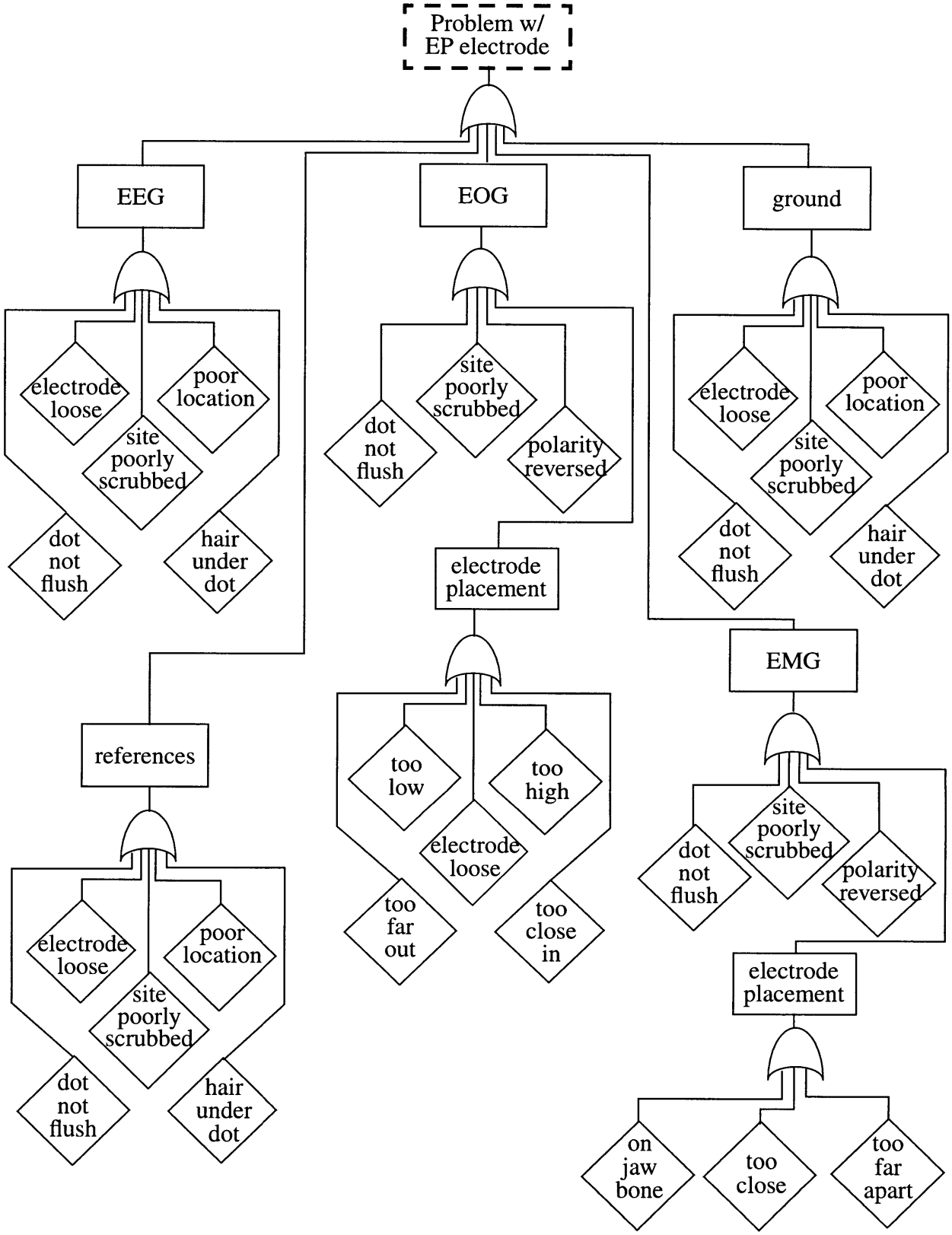

Figure 5.9: Fault Tree Diagram - Problem with EP Electrode

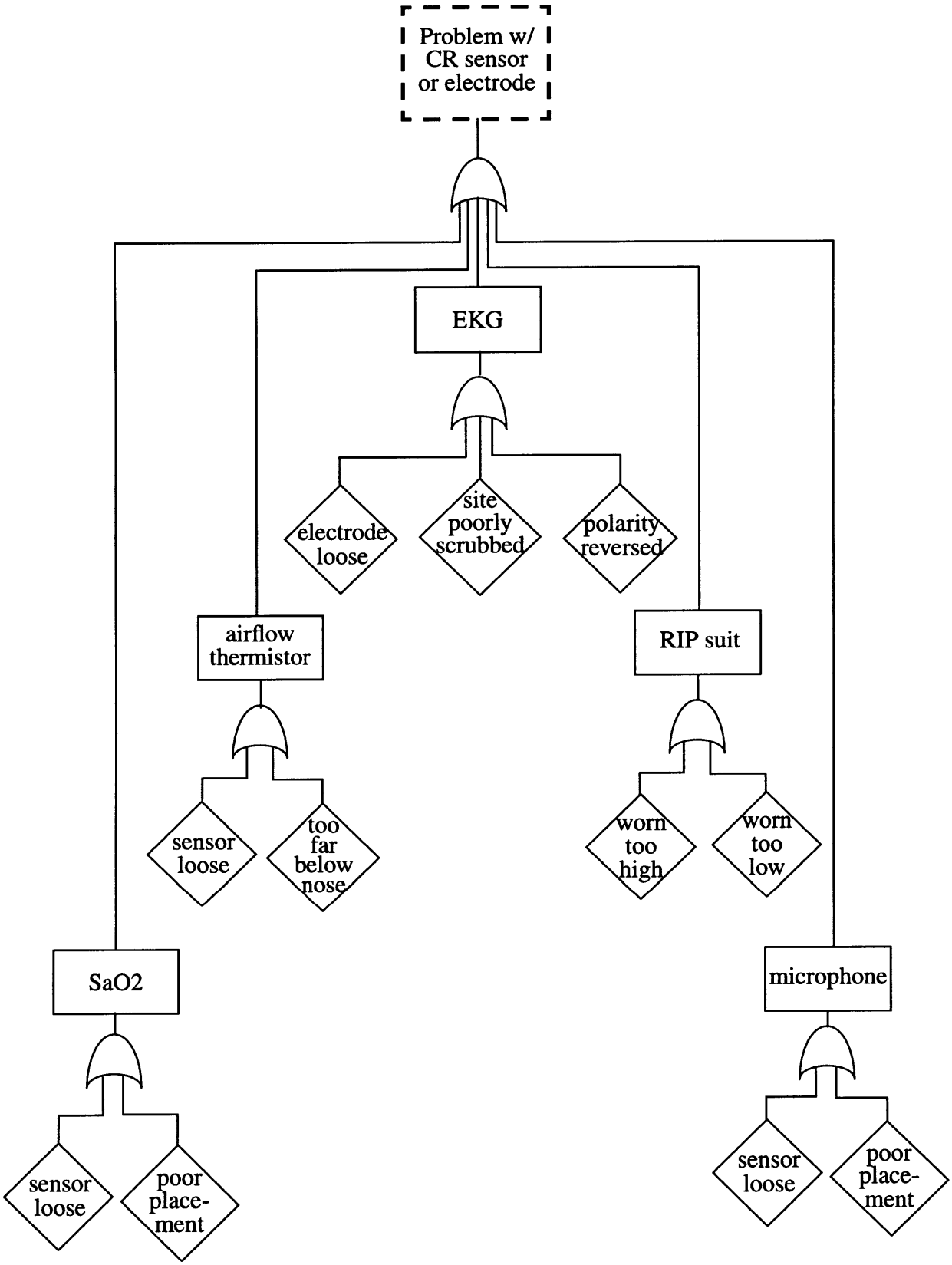

Figure 5.10: Fault Tree Diagram - Problem with CR Sensor or Electrode

Chapter 6

Testing

6.1 Test Process

The fault trees illustrate potential events leading to some top-level failure. The events at the lowest level of the tree can be divided into two categories, and are distinguishable by their graphic symbols. The first type of bottom-level fault, a basic event, is a failure which occurs as a result of an event which could not be anticipated or prevented. Examples of basic events are hardware malfunctions and software errors. Because these events can not be controlled, they are not included in the failure simulation tests. The second type of bottom-level failure is an undeveloped event. These are failures which can be controlled and occur as the result of a preventable error. The list of failure scenarios used for testing was constructed from these undeveloped events.

The testing process was designed to simulate each undeveloped event and to determine the response of the system. The system states resulting from these simulations served as the starting points for performing the troubleshooting analysis. After each failure scenario was simulated, the steps required to return the system to its normal operational state were recorded. These steps were determined on a trial and error basis. In some cases, the corrective steps were obvious, from experience operating the hardware. However, in other cases, there was more than one possibility for returning the system to its nominal operating state. For example, if the incorrect patient ID is

entered, the subject has the option of scrolling through the DSR menu to reset the patient ID, or powering off the DSR and beginning again. Both procedures will produce the same result. In cases with more than one option for troubleshooting procedures, the simplest option was selected. This selection was entirely subjective. Options which required powering off the DSR were avoided whenever possible. After the troubleshooting procedures were identified, they were repeated in order to verify their accuracy. Based these troubleshooting procedures, the PI-in-a-Box diagnostic procedures were developed.

Tests were performed by following the sleep instrumentation procedures provided in Appendix A. For each test, all procedures were followed as listed, with the exception of the simulated failure. After each simulation, the state of the system was recorded. This state information includes details of both the DSR and PI-in-a-Box screen displays.

6.2 Test Conditions

Since the ThinkPads which will be used on Neurolab (model 755C) are no longer manufactured by IBM, testing of the PI-in-a-Box software could not be done on a computer identical to the flight hardware. Instead, tests were performed on a laptop computer at BWH which is slower and has less memory than the ThinkPad which will run PI-in-a-Box on the Neurolab mission. The laptop computer used for testing was an IBM ThinkPad with 12 MB RAM and a 50 MHz, 486 Processor. Version 2.0 (date) of the PI-in-a-Box software was run for all tests.

The DSR used in the testing was the Vitaport2 NASA configuration.[1] On the DSR, there were four definition files. One of these files was "Sleep_022697.def", the default definition file

and montage which will be used in the flight sleep and respiration study. This was the definition file used throughout the failure simulation testing. A second definition file on the DSR was "Awake_022697.def", a definition file which will be used in a different Neurolab respiration study. This definition file was used in testing only when simulating selection of the wrong definition file by the subject. The two other definition files on the DSR were master definition files. They were not used at any time during the testing. One FlashRAM data card and four Lithium AA batteries were used with the DSR for all tests.

6.3 Results

6.3.1 Undeveloped Failure Events

Simulations were performed for each undeveloped failure event. These individual failure events were designated by diamond-shaped borders in the fault tree diagrams. The failure analysis test data are provided in Table 6.1.

1. The Vitaport2 NASA configuration consists of one blue electrophysiological slice, one black cardiorespiratory slice, and one silver slice which functions as an analog out converter for the awake respiration studies.

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
1. Wrong .def-file	Wrong .def-file displayed on DSR or No EP, airflow, or microphone signals	Using wrong DSR, default .def-file wrong, wrong .def-file selected	Press "exit" to stop DSR recording. Press "ok" to confirm. Unplug RS-232 cable from DSR. DSR displays: "Start recording?" Press down arrow 1x to "Select def-file?" Press "ok" to select. Use up and down arrows to scroll to "Sleep" def file. Press "ok". Press "ok" to start recording.	No EP, microphone, or airflow data recorded
2. No batteries in DSR	No DSR screen display	Step omitted in procedures	Power off DSR. Remove DSR battery cover & insert new batteries. Replace DSR batter cover. Power on DSR and continue.	No data recorded
3. Batteries in DSR wrong	No DSR screen display	Batteries inserted incorrectly	Power off DSR. Remove DSR battery cover and take out batteries. Insert batteries according to DSR label. Replace DSR batter cover. Power on DSR and continue.	No data recorded
4. Recording stopped	[PI] signal display freezes, DSR displays "Recording Stoppd"	Subject stopped DSR recording	Unplug RS-232 from DSR. Press "ok". DSR displays: "Start recording?" Press "ok" and append to data. Plug RS-232 back into DSR.	Loss of data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
5. DSR turned off	No DSR display, [PI] signal display freezes	DSR power switch turned off	Unplug RS-232 cable from DSR. Power on DSR and start recording. When recording, plug RS-232 into DSR. Press "ok" on [PI] pop-up window.	Loss of data
6. DSR never turned on	No DSR display	Step omitted in procedures	Unplug RS-232 cable from DSR. Power on DSR and continue.	No data recorded
7. No FlashRAM card in DSR	DSR displays: "No card in slot"	Step omitted in procedures	Insert correct FlashRAM card into slot in DSR. Continue procedures to begin DSR recording.	No data recorded
8. Wrong FlashRAM card used	FlashRAM label wrong and/or DSR displays: "Card not empty"	Wrong FlashRAM card selected or wrong FlashRAM card used a in previous recording	Press "exit" TWICE on DSR to cancel recording. When DSR displays: "Start Recording?", remove FlashRAM and replace with empty card. Label new card with correct Patient ID and session number. Press "OK" to start DSR recording.	Loss of data from another session or data labelled incorrectly
9. Wrong or no Patient ID entered	functions normally	Entered wrong or incorrect ID selected	When DSR displays: "Start Recording?", press down arrow 4x to option: "Set Patient ID?". Press "OK" and enter correct Patient ID. Press "OK" when entered. DSR displays: "Start Recording?". Press "OK" to start rec.	Patient and session # cannot be identified

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
10. RS-232 cable plugged into DSR when try to start recording	DSR displays: "Remote control" or "Remote View Amp"	Procedures performed out of order	Unplug RS-232 cable from DSR. DSR displays: "Start recording?" Use up and down arrows to select patient ID and .def-file Press "ok" to start recording.	No data recorded
11. RS-232 cable not connected to or disconnected from DSR	No signals displayed on [PI] or signals freeze; DSR displays: "Remote View rec" or "Recording data"	Cable not plugged in or was disconnected from DSR	Verify DSR is recording. Plug RS-232 cable into DSR and continue.	No signals displayed on [PI]
12. RS-232 cable not connected to ThinkPad	No signals displayed on [PI] or signals freeze; DSR displays: "Remote View rec" or "Recording data"	Cable not plugged in or was disconnected from ThinkPad	Plug RS-232 cable into ThinkPad and continue.	No signals displayed on [PI]
13. ThinkPad not powered on	No power or display on ThinkPad screen	TP powered off or step omitted in procedures	Power on ThinkPad. Start PI-in-a-Box and continue.	No signals displayed on [PI]

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
14. Sleep*Net not connected to DSR	EP signals on [PI] are only noise (except EKG), no response of EP sigs to physiological cals	Step omitted in procedures, or Sleep*Net connector disconnected from DSR	Plug Sleep*Net connector into blue DSR slice.	No EP signal data recorded
15. Borg Harness not plugged into DSR	No CR signals displayed on [PI], DSR displays: "Remote View Rec"	Step omitted or Borg Harness connector was disconnected from DSR	Plug Borg Harness into DSR. Wait approximately 20 seconds for signal display.	No CR signal data recorded
16. BH plugged into EP slice of DSR	EP signals not present or poor quality	Followed procedures incorrectly	Unplug BH from blue EP slice. Plug BH into black CR slice.	No EP and CR data recorded
17. Sleep*Net plugged into CR slice of DSR	CR signals appear as flat lines	Followed procedures incorrectly	Unplug Sleep*Net from CR slice. Plug into blue EP slice.	No EP and CR data recorded
18. Recording started with neither Sleep*Net nor BH plugged into DSR	[PI] displays no CR or EP signals	Steps omitted	Plug Sleep*Net into blue EP slice and BH into black CR slice of DSR.	No data recorded

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
19. Both Sleep*Net and Borg Harness unplugged from DSR during recording	DSR displays: "Remote View Rec"; No EP and CR signals on [PI]	Cables unplugged from DSR.	Plug Sleep*Net into blue EP slice and BH into black CR slice of DSR.	Loss of EP and CR data
20. Hydrodots not in Sleep*Net or not flush with electrode sockets	Electrophysiological signals poor quality or not present	Step omitted in procedures	Scrub electrode sites. Insert Hydrodot into each socket until flush with top of socket.	Poor quality or no EP data
21. Sleep*Net not on subject's head	Only noise in EP signals	Step omitted in procedures	Unplug Sleep*Net from DSR. Don Sleep*Net. Check impedances. Plug into DSR and continue.	No EP data recorded
22. CR sensors not on subject	No CR signals displayed on [PI]	RIP Suit instrumentation section omitted in procedures	Follow RIP Suit and Borg Harness instrumentation procedures.	No CR data recorded
23. Some Hydrodots missing	Some EP signals not present or poor quality	Step not completed in setup procedures	Scrub electrode sites. Insert Hydrodot into each socket until flush with top of socket.	Loss of EP data
24. EKG pads not plugged into EKG cables on Borg Harness	Flat EKG signal on [PI]	Step omitted in procedures	Connect EKG cables to appropriate color-coded EKG pad.	No EKG data recorded

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
25. Microphone not donned	Microphone signal is flat	Step omitted in procedures	Apply adhesive pad to sensor. Place sensor on neck.	No microphone data recorded
26. SaO_2 sensor not donned	SaO_2 signal poor quality or not present	Step omitted in procedures	Apply sensor to ring finger. Plug sensor into BH.	No SaO_2 data recorded
27. SaO_2 not plugged into Borg Harness	SaO_2 value is zero on [PI]	Step omitted in procedures or SaO_2 sensor came disconnected from BH	Connect SaO_2 sensor to Borg Harness. Wait approximately 20 seconds for signal to be displayed.	No SaO_2 data recorded
28. RIP suit not plugged into Borg Harness	RIP-AB and RIP-RC signals on [PI] are flat lines	Step omitted in procedures or RIP Suit came disconnected from BH	Plug RIP Suit into Borg Harness. Wait several seconds for signal to be displayed.	No RIP data recorded
29. RIP suit not donned	RIP-AB and RIP-RC signals are flat lines on [PI]	Step omitted in procedures	Don RIP Suit. Plug RIP Suit into Borg Harness.	No RIP data recorded
30. Airflow thermistor not donned	Airflow signal is flat	Step omitted in procedures	Plug airflow sensor into BH. Apply sensor to upper lip.	No airflow data recorded

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
31. Thermistor not plugged into BH	Airflow signal on [PI] is a flat line, or only noise; no discernible sine wave pattern	Step omitted in procedures	Plug airflow thermistor into BH. Wait approximately 20 seconds for signal to be displayed.	No airflow data recorded
32. EEG electrode comes loose	EEG signal not present or poor quality	Sleep*Net not secure	Tighten chin and neck straps on Sleep*Net.	Poor quality EEG data
33. poor EEG electrode placement	EEG signal not present or poor quality	Sleep*Net not positioned correctly	Subject's partner adjusts Sleep*Net alignment and location of EEG electrodes.	Poor quality EEG data
34. Insufficient scrubbing of EEG site	EEG signal not present or poor quality	New swab not used when cleansing site, or site not scrubbed adequately	Lift electrode off scalp. Rescrub site using a new prep swab. Replace electrode in proper location.	Poor quality EEG data
35. Hair beneath EEG Hydrodot	EEG signal not present or poor quality	Hair not sufficiently cleared away from site during electrode site preparation	Partner removes hair from electrode site using back end of prep swab.	Poor quality EEG data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
36. EEG Hydrodot not flush with Sleep*Net	EEG signal not present or poor quality	Hydrodot not properly inserted into EEG electrode socket or Hydrodot comes loose	Press Hydrodot into EEG electrode socket until it is flush with the top of the socket.	Poor quality EEG data
37. EMG Hydrodot not flush with Sleep*Net	EMG signal not present or poor quality	Hydrodot not properly inserted into EMG electrode socket or Hydrodot comes loose	Press Hydrodot into EMG electrode socket until it is flush with the top of the socket.	Poor quality EMG data
38. Insufficient scrubbing of EMG site	EMG signal not present or poor quality	New swab not used when cleansing site, or site not scrubbed adequately	Lift electrode off skin. Rescrub site using a new prep swab. Replace electrode in proper location.	Poor quality EMG data
39. Loose EMG electrode	EMG signal not present or poor quality	Adhesive circle comes off skin or EMG electrode socket	Press electrode against skin and hold for 5 seconds. If still not adhere, replace adhesive circle.	Poor quality EMG data
40. EMG electrode placed on jaw bone	EMG signal not present or poor quality	EMG electrode improperly placed	Remove EMG electrode. Replace electrode below jaw bone.	Poor quality EMG data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
41. EMG socket upside down	EMG signal not present or poor quality or adhesive circle on thick side of electrode socket	Electrode not placed according to diagram in procedures	Remove adhesive circle from socket. Place a new adhesive circle on the thin side of the socket. Press socket to skin and hold for 5 seconds.	Poor quality EMG data
42. Insufficient scrubbing of EOG site	EOG signal not present or poor quality	New swab not used when cleansing site, or site not scrubbed adequately	Lift electrode off skin. Rescrub site using a new prep swab. Replace electrode in proper location.	Poor quality EOG data
43. EOG Hydrodot not flush with Sleep*Net	EOG signal not present or poor quality	Hydrodot not properly inserted into EMG electrode socket or Hydrodot comes loose	Press Hydrodot into EOG electrode socket until it is flush with the top of the socket.	Poor quality EOG data
44. EOG electrode loose	EOG signal not present or poor quality	Adhesive circle comes off skin or EOG electrode socket	Press electrode against skin and hold for 5 seconds. If still not adhere, replace adhesive circle.	Poor quality EOG data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
45. EOG electrode too far from eye	No significant change in EOG-L signal when subject moves eyes	Left EOG electrode improperly placed	Replace EOG-L electrode closer to the outside of the eye.	Poor quality EOG data
46. LOC too low	No significant change in EOG-L signal when subject looks up and down	Left EOG electrode improperly placed	Replace Left EOG electrode closer to horizontal plane of the eyes.	Poor quality EOG-L data
47. LOC too high	No significant change in EOG-L signal when subject looks up and down	Left EOG electrode improperly placed	Replace Left EOG electrode below horizontal plane of the eyes.	Poor quality EOG-L data
48. ROC too low	No significant change in EOG-R signal when subject looks up and down or blinks	Right EOG electrode improperly placed	Replace Right EOG electrode above horizontal plane of the eyes.	Poor quality EOG-R data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
49. ROC too high	No significant change in EOG-R signal when subject looks up and down or blinks	Right EOG electrode improperly placed	Replace Right EOG electrode closer to horizontal plane of the eyes.	Poor quality EOG-R data
50. EOG polarity reversed	Signals deflect in opposite direction than indicated in signal verification table	Right EOG applied below eye and Left EOG applied above eye	Remove both EOG electrodes. Replace electrodes with Right EOG above eye and Left EOG below eye.	EOG data difficult to interpret
51. Reference electrode loose	Corresponding EEG's, EOG, and EMG signals bad or not present	Sleep*Net not secure	Tighten chin and neck strap on Sleep*Net.	Corresponding EEG's and EOG poor quality
52. Insufficient scrubbing of reference site	Corresponding EEG's and EOG signal bad or not present	New swab not used when cleansing site, or site not scrubbed adequately	Lift electrode off scalp. Rescrub site using a new prep swab. Replace electrode in proper location.	Corresponding EEG's and EOG poor quality

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
53. Hair beneath reference Hydrodot	Corresponding EEG's and EOG signal bad or not present	Hair not sufficiently cleared away from site during electrode site preparation	Partner removes hair from electrode site using back end of prep swab.	Corresponding EEG's and EOG poor quality
54. Poor reference electrode placement	Corresponding EEG's and EOG signal bad or not present	Sleep*Net not positioned correctly	Subject's partner adjusts Sleep*Net alignment and location of reference electrodes.	Corresponding EEG's and EOG poor quality
55. Reference Hydrodot not flush with Sleep*Net	Corresponding EEG's and EOG signals bad or not present	Hydrodot not properly inserted into reference electrode socket or Hydrodot comes loose	Press Hydrodot into reference electrode socket until it is flush with the top of the socket.	Corresponding EEG's and EOG poor quality
56. Hair beneath ground Hydrodot	EP signals not present or poor quality	Hair not sufficiently cleared away from site during electrode site preparation	Partner moves hair away from electrode site using back end of prep swab.	Poor quality EP data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
57. Insufficient scrubbing of ground site	EP signals not present or poor quality	New swab not used when cleansing site, or site not scrubbed adequately	Lift electrode off forehead. Rescrub site using a new prep swab. Replace forehead pad in proper location.	Poor quality EP data
58. Ground hydrodot not flush with Sleep*Net	EP signals not present or poor quality	Hydrodot not properly inserted into ground electrode socket or Hydrodot comes loose	Press Hydrodot into ground electrode socket until it is flush with the top of the socket.	Poor quality EP data
59. Poor location of ground electrode	EP signals not present or poor quality	Sleep*Net not positioned correctly	Subject's partner adjusts Sleep*Net alignment and location of ground electrodes.	Poor quality EP data
60. Ground electrode loose	EP signals not present or poor quality	Forehead pad not properly adhere to forehead	Press electrode against skin and hold for 5 seconds. If still not adhere, replace forehead adhesive pad.	Poor quality EP data
61. Insufficient scrubbing of EKG site	EKG signal not present or poor signal quality	Insufficient scrubbing before applying EKG pads	Remove EKG pads. Scrub sites with prep wipes. Replace EKG pads. Connect pads to correct color-coded cable of BH.	Poor quality EKG data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
62. EKG electrode loose or comes off	EKG signal not present or poor signal quality	EKG pad not properly adhere to skin	Replace EKG pad. Reattach to Borg Harness.	Poor quality EKG data
63. EKG polarity reversed	QRS-wave inverted on [PI] signal display	Incorrectly wired to Borg Harness	Disconnect from Borg. Harness. Reconnect EKG pads to correct color-coded wires.	Inverted QRS wave
64. Airflow thermistor too far below nose	No clear sine wave pattern on [PI] display	Airflow sensor not properly placed	Remove airflow sensor. Reapply sensor closer to nose.	Poor quality airflow data
65. Airflow thermistor loose	Erratic signal, or sensor not adhere properly to upper lip	Sensor not adhere properly to upper lip	Remove airflow sensor and unplug from BH. Plug new sensor into BH. Apply new sensor to upper lip. Press firmly to lip for 5 seconds.	Poor quality airflow data
66. Poor placement of pulse oximeter, or sensor upside down on finger	Very low SaO_2 value (below 95)	Sensor not placed properly on finger	Remove sensor from finger. Reapply sensor with cable on palm side of finger. Tighten with velcro.	Poor quality SaO_2 data
67. Pulse Oximeter loose	Signal not stable	Sensor not secure on finger	Remove sensor. Replace adhesive tabs and replace sensor. Tighten well with velcro strip.	Poor quality SaO_2 data

Table 6.1: Failure Simulation Results

Failure Event	System State	Reason Why Occur	Troubleshooting Procedures	Consequence if Not Corrected
68. Poor placement of microphone	Microphone signal flat	Sensor placed too far from voice box	Remove sensor. Replace adhesive circle. Place fingers on neck and hum to find good location and reapply microphone.	Poor quality microphone data
69. Microphone loose	Microphone signal flat	Socket pad not adhere to socket or skin	Replace socket pad and reapply microphone. Secure microphone wire to neck with medical tape.	Poor quality microphone data

6.3.2 Basic Failure Events

Since basic failure events are generally due to a hardware or software malfunctions, these events cannot be simulated. Nevertheless, for each basic event, the resulting system state was estimated, based on knowledge of the system and its functions. The diagnostic procedures for each basic event will consist of replacing the malfunctioning hardware with the backup hardware. The basic failure events and their anticipated system responses are provided in Table 6.2.

Table 6.2: Basic Event System Responses

Failure Event	System State	Consequence if Not Corrected
TP Power Source Malfunction	DSR ok ThinkPad power off	No [PI] signal display
TP Malfunction	DSR ok TP no signal display or no screen display	No [PI] signal display
No Communication Between DSR and TP	DSR ok TP no signal display or no screen display	No [PI] signal display
RS-232 Cable Malfunction	DSR ok [PI] interface ok, but no signals	No [PI] signal display
[PI] Software Not Load Properly	DSR ok [PI] display no signals or signals freeze	No [PI] signal display
DSR Malfunction	No DSR display or incorrect message [PI] display no signals	No data recorded
Sleep*Net Cable or Connector Broken	DSR ok Some or all EP signals missing on [PI]	No EP data recorded
Sleep*Net Electrode Socket or Wire Broken	One or more EP signals not present	Loss of EP data
Borg Harness Cable or Connector Broken	DSR ok Some or all CR signals missing from [PI]	No CR data recorded

Table 6.2: Basic Event System Responses

Failure Event	System State	Consequence if Not Corrected
Sleep*Net and Borg Harness Cables or Connectors Broken	DSR ok CR and EP signals not present or poor quality on [PI]	No data recorded
EKG Cable or Electrode Broken	EKG signal not present or poor quality	No EKG data recorded
RIP Coil, Cable or connector Broken	RIP signal not present or poor quality	No RIP data recorded
SaO_2 Sensor or Cable Broken	No red light on sensor when plugged into DSR or no SaO_2 signal	No SaO_2 data recorded
Mic Sensor or Cable Broken	Microphone signal not present or poor quality	No microphone data recorded
Airflow Sensor or Cable Broken	Airflow signal not present or poor quality	No airflow data recorded

Chapter 7

Diagnostics

7.1 Process Overview

Many of the system states identified in the failure simulation process were common to more than one failure event. That is, several different types of procedural errors or hardware malfunctions may result in the same system state. For example, an RS-232 cable malfunction would result in a failure of PI-in-a-Box to display any signals. However, the absence of a signal display on [PI] could result from a number of other failure events as well, including turning off the DSR or forgetting to plug both the Borg Harness and the Sleep*Net into the DSR. Therefore, in order to correct this system state, the subject is required to proceed through a list of potential failure events until the problem is identified. After the failure event has been discovered, the subject performs the diagnostic procedures designed to return the system to its nominal operating state. Based on the results of the failure event simulations, a list of system states was compiled. They are listed in Table 7.1.

Table 7.1: List of System States

State #	System State
1	No Signals Displayed on [PI]
2	Signals on [PI] Display Freeze
3	EP Signals on [PI] are Poor Quality or Not Present
4	CR Signals on [PI] not Present
5	All EP and Some CR Signals Not Present on [PI]
6	EEG Not Present or Poor Quality
7	EMG Not Present or Poor Quality
8	EOG Not Present or Poor Quality
9	RIP Signal Not Present or Poor Quality
10	SaO_2 Signal Not Present or Poor Quality
11	Airflow Signal Not Present or Poor Quality
12	Microphone Signal Not Present or Poor Quality
13	EKG Not Present or Poor Quality
14	DSR Displays: "No card in slot"
15	DSR Displays: "Remote control"
16	DSR Displays: "Card not empty"
17	Patient ID Incorrect
18	EOG Polarity Reversed
19	EKG Polarity Reversed

7.2 Prioritization of Failure Events

For each system state, all possible failure events leading to each of these states were identified. For example, all potential failure events leading to system state #1, no signals displayed by PI-in-a-Box, were determined. These failure events were then prioritized according to their likelihood of occurrence. The rank assigned to each failure event was based on observations made in the sleep laboratory as well as experience in the astronaut training sessions. Events that occur frequently in the laboratory, such as procedural errors and insufficient site preparation for the electrodes, were assigned high rankings. Uncommon occurrences, such as hardware malfunctions and software loading errors, were assigned low priorities. All of the rankings were completely subjective. They are shown in Tables 7.2 - 7.20.

Table 7.2: Failure Event Prioritization - System State #1

System State	Sub-State	Possible Failure Events	Priority Rank
No Signals Displayed on PI-in-a-Box	DSR is on ThinkPad has no power	TP not turned on	1
		TP power not connected	2
		Power supply malfunc	3
		TP malfunction	4
	DSR is on ThinkPad is on	RS-232 cable not conn to DSR or TP	1
		Sleep*Net & BH not plugged into DSR	2
		[PI] software error	3
		RS-232 cable malfunction	4
		Sleep*Net & BH cables broken	5
	No DSR display ThinkPad is on	DSR power off	1
		DSR batteries not in or in wrong	2
		DSR malfunction	3

Table 7.3: Failure Event Prioritization - System State #2

System State	Possible Failure Events	Priority Rank
Signals on PI-in-a-Box Display Freeze	RS-232 was disconnected from DSR or ThinkPad	1
	DSR was turned off	2
	DSR recording stopped	3
	RS-232 cable malfunction	4
	[PI] software error	5

Table 7.4: Failure Event Prioritization - System State #3

System State	Possible Failure Events	Priority Rank
Electrophysiological Signals on [PI] are Poor Quality or Not Present	Sleep*Net connected to wrong slice or not connected at all to DSR	1
	Wrong definition file	2
	Sleep*Net not donned	3
	No Hydrodots in Sleep*Net	4
	Hydrodots not flush with Sleep*Net	5
	Ground electrode missing or not contacting skin properly	6
	Sleep*Net cable or connector malfunction	7
	EP slice of DSR malfunction	8

Table 7.5: Failure Event Prioritization - System State #4

System State	Possible Failure Events	Priority Rank
No Cardiorespiratory Signals on PI-in-a-Box	BH or Sleep*Net not plugged in or plugged into wrong slice of DSR	1
	CR sensors not on subject	2
	BH cable or connector malf	3
	CR slice of DSR malfunc	4

Table 7.6: Failure Event Prioritization - System State #5

System State	Possible Failure Events	Priority Rank
All EP and Some CR Signals Not Present on [PI]	Wrong definition file	1
	Sleep*Net not plugged into DSR and some sensors not on subj or plugged into BH	2

Table 7.7: Failure Event Prioritization - System State #6

System State	Possible Failure Events	Priority Rank
EEG Signal Not Present or Poor Quality	Hydrodot not inserted or not flush or not contact scalp	1
	Hair beneath Hydrodot	2
	Site not properly scrubbed	3
	Sleep*Net placement poor	4
	Reference electrode loose	5
	Broken wire or socket	6
	EP slice of DSR malfunction	7

Table 7.8: Failure Event Prioritization - System State #7

System State	Possible Failure Events	Priority Rank
EMG Signal Not Present or Poor Quality	Hydrodot not inserted or not flush or not contact scalp	1
	Poor electrode placement	2
	Site not properly scrubbed	3
	Socket upside down	4
	Broken wire or socket	5
	EP slice of DSR malfunction	6

Table 7.9: Failure Event Prioritization - System State #8

System State	Possible Failure Events	Priority Rank
EOG Signal Not Present or Poor Quality	Hydrodot not inserted or not flush or not contact scalp	1
	Poor electrode placement	2
	Site not properly scrubbed	3
	Reference electrode loose	4
	Socket upside down	5
	Broken wire or socket	6
	EP slice of DSR malfunction	7

Table 7.10: Failure Event Prioritization - System State #9

System State	Possible Failure Events	Priority Rank
RIP Signal Not Present or Poor Quality	RIP not plugged into BH	1
	Suit not on or positioned too high or too low	2
	RIP coil, cable, or connector broken	3
	EP slice of DSR malfunction	4

Table 7.11: Failure Event Prioritization - System State #10

System State	Possible Failure Events	Priority Rank
SaO_2 Signal Not Present or Poor Quality	Sensor loose or not donned	1
	Sensor upside down	2
	SaO_2 not plugged into BH	3
	Sensor, cable, or connector broken	4
	CR slice of DSR malfunc	5

Table 7.12: Failure Event Prioritization - System State #11

System State	Possible Failure Events	Priority Rank
Airflow Signal Not Present or Poor Quality	Sensor not on or not adhere properly	1
	Sensor too far from nose	2
	Not plugged into BH	3
	Wrong definition file	4
	Sensor or cable broken	5
	CR slice of DSR malfunc	6

Table 7.13: Failure Event Prioritization - System State #12

System State	Possible Failure Events	Priority Rank
Microphone Signal Not Present or Poor Quality	Sensor loose or not on	1
	Poor placement	2
	Wrong definition file	3
	Sensor or cable broken	4
	CR slice of DSR malfunc	5

Table 7.14: Failure Event Prioritization - System State #13

System State	Possible Failure Events	Priority Rank
EKG Signal Not Present or Poor Quality	Pads not on or not adhere properly	1
	Pads not plugged into BH or not wired correctly	2
	Site poorly scrubbed	3
	Cable or sensor broken	4
	CR slice of DSR malfunc	5

Table 7.15: Failure Event Prioritization - System State #14

System State	Possible Failure Events	Priority Rank
DSR Displays: "No card in slot"	FlashRAM card improperly inserted	1
	No FlashRAM card in DSR	2
	DSR malfunction	3

Table 7.16: Failure Event Prioritization - System State #15

System State	Possible Failure Events	Priority Rank
DSR Displays: "Remote control"	RS-232 plugged into DSR when attempt start recording	1
	DSR malfunction	2

Table 7.17: Failure Event Prioritization - System State #16

System State	Possible Failure Events	Priority Rank
DSR Displays: "Card not empty"	Wrong FlashRAM card used	1
	DSR malfunction	2

Table 7.18: Failure Event Prioritization - System State# 17

System State	Possible Failure Events	Priority Rank
Patient ID Wrong	Wrong Patient ID entered	1
	DSR malfunction	2

Table 7.19: Failure Event Prioritization - System State #18

System State	Possible Failure Events	Priority Rank
EOG Polarity Reversed	Electrode positions reversed	1
	[PI] display polarity wrong	2

Table 7.20: Failure Event Prioritization - System State #19

System State	Possible Failure Events	Priority Rank
EKG Polarity Reversed	Incorrect electrode wiring	1
	[PI] display polarity wrong	2

7.3 Diagnostic Diagrams

Based on the failure event rankings, a set of diagnostic procedures was developed for each system state. Each diagnostic diagram begins with one system state, or malfunction, and outlines the troubleshooting procedures for returning the system to its nominal state. The order of the troubleshooting procedures was determined based on the prioritizations presented in the previous section. The diagnostic diagrams are modeled after the malfunction procedures flown on each space shuttle mission. They are illustrated in Figures 7.1 - 7.22.

State #1

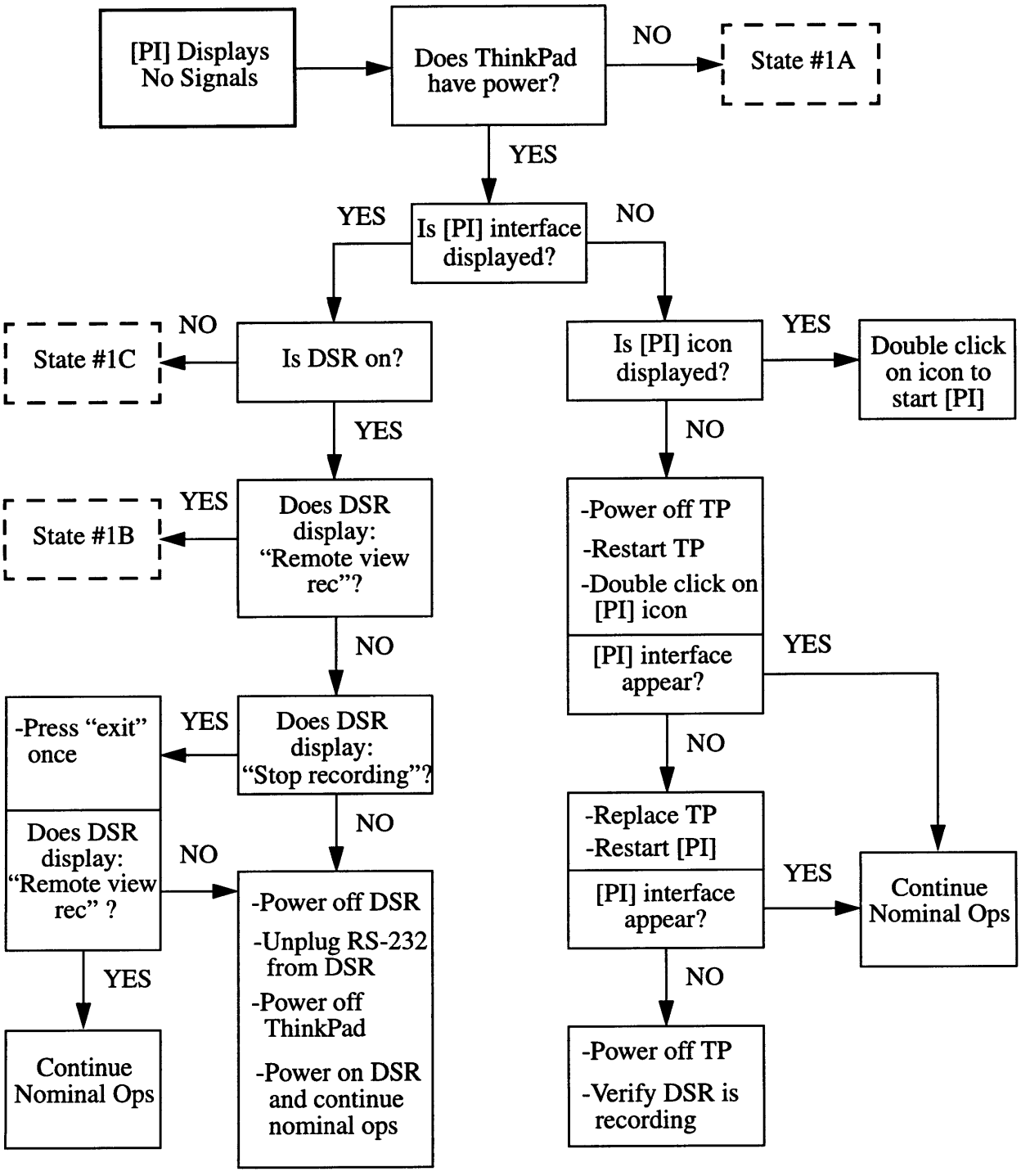

Figure 7.1: Diagnostic Diagram - State #1

State #1A

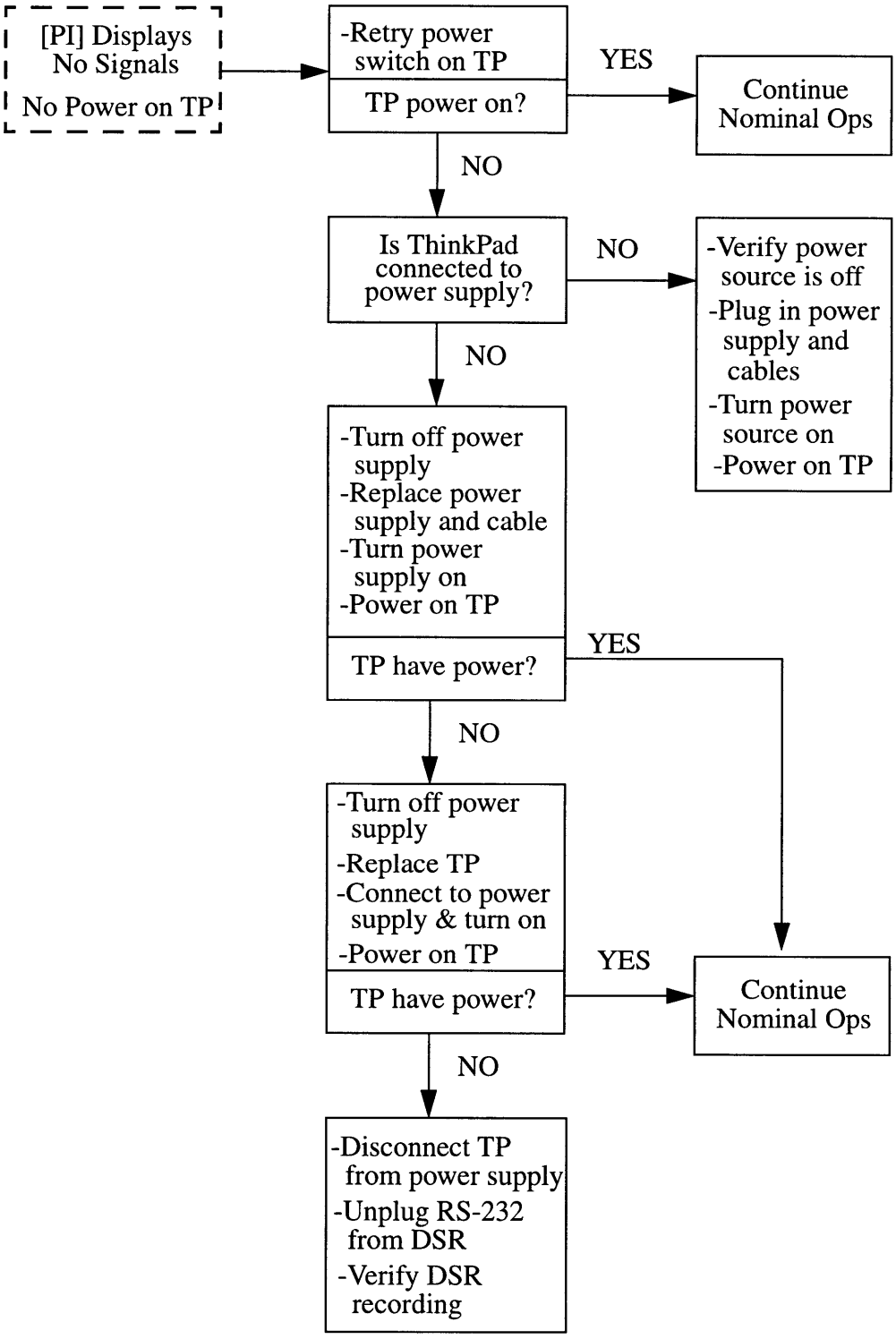

Figure 7.2: Diagnostic Diagram - State# 1A

State #1B

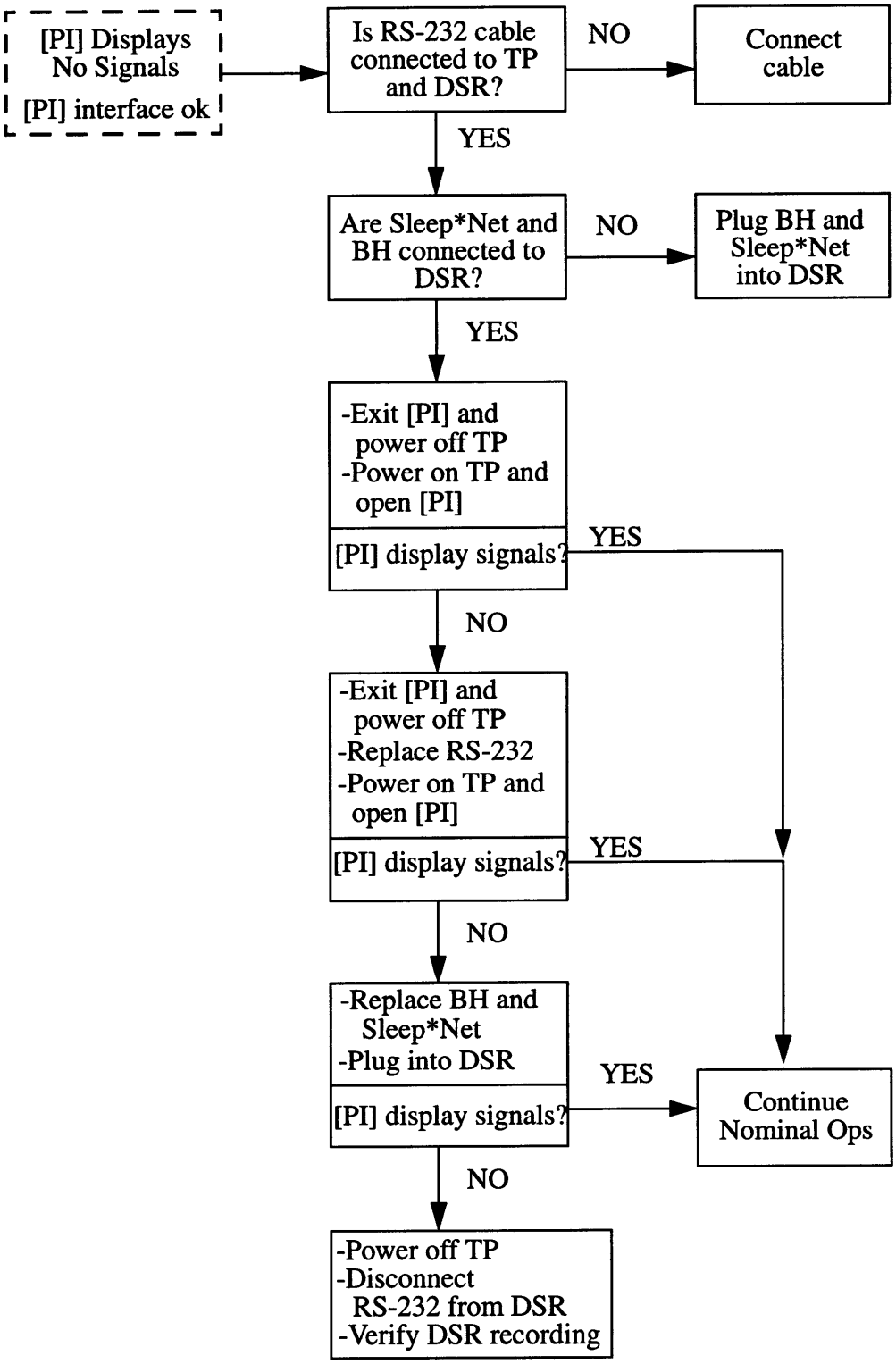

Figure 7.3: Diagnostic Diagram - State #1B

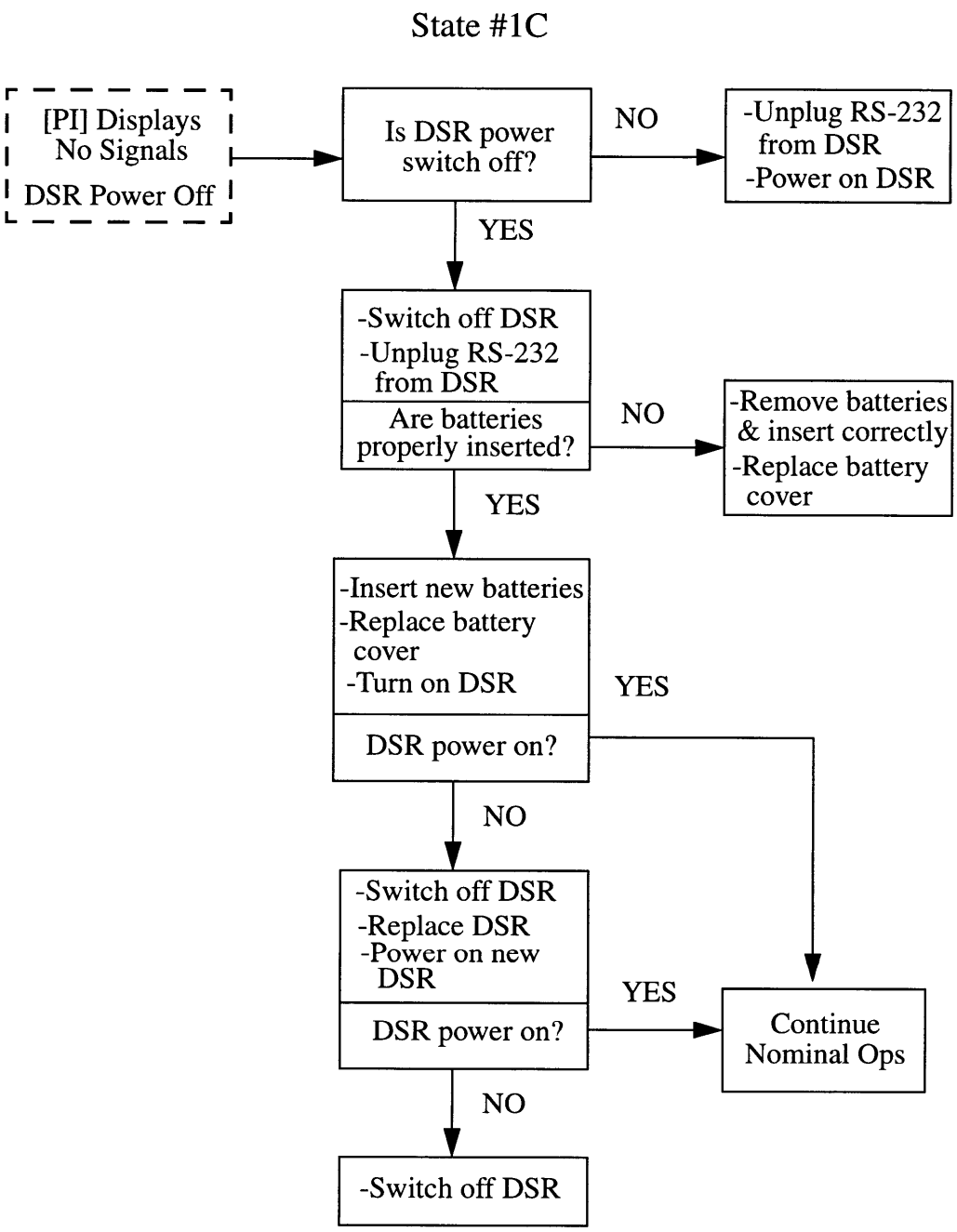

Figure 7.4: Diagnostic Diagram - State #1C

State #2

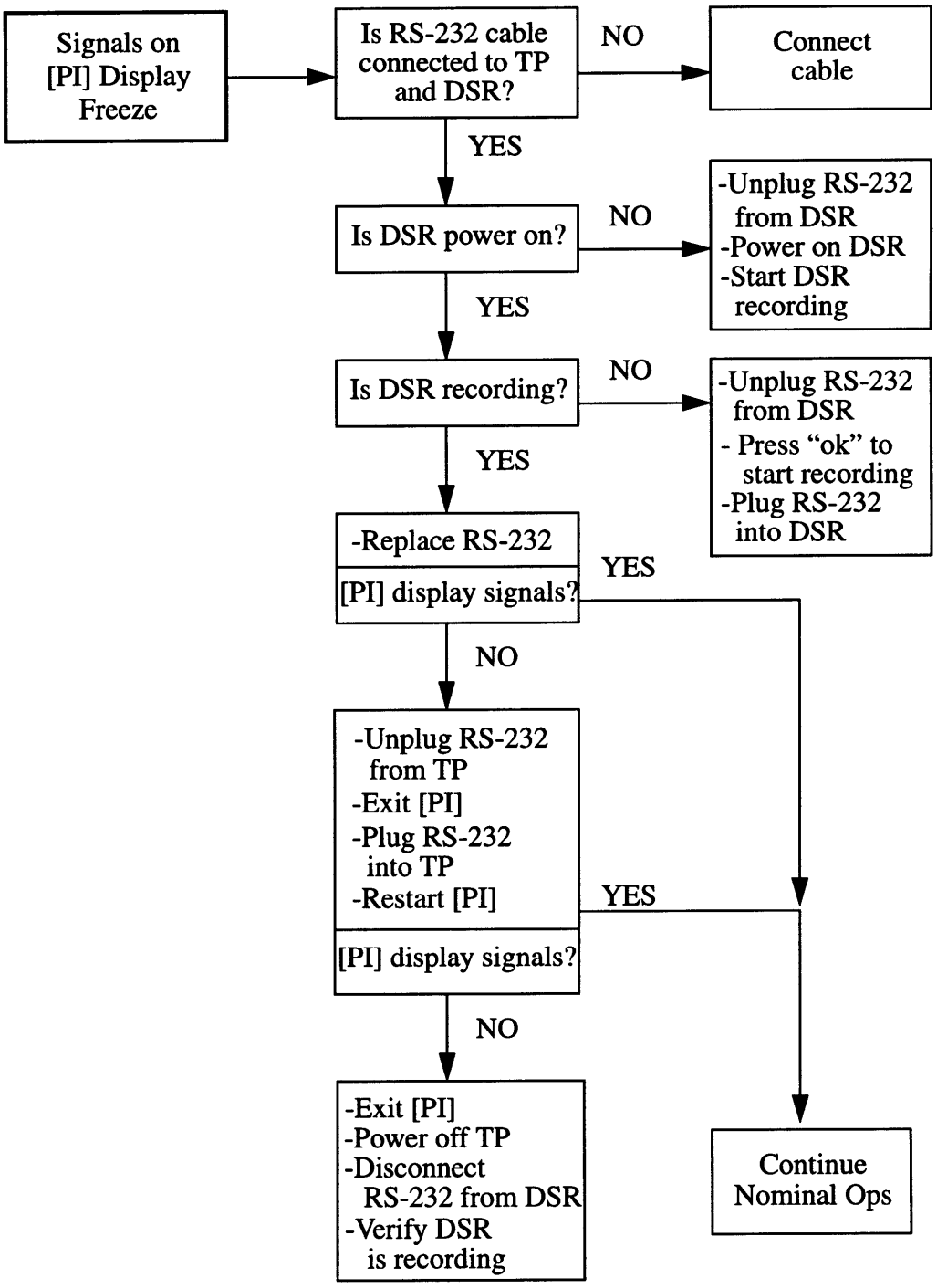

Figure 7.5: Diagnostic Diagram - State #2

State #3

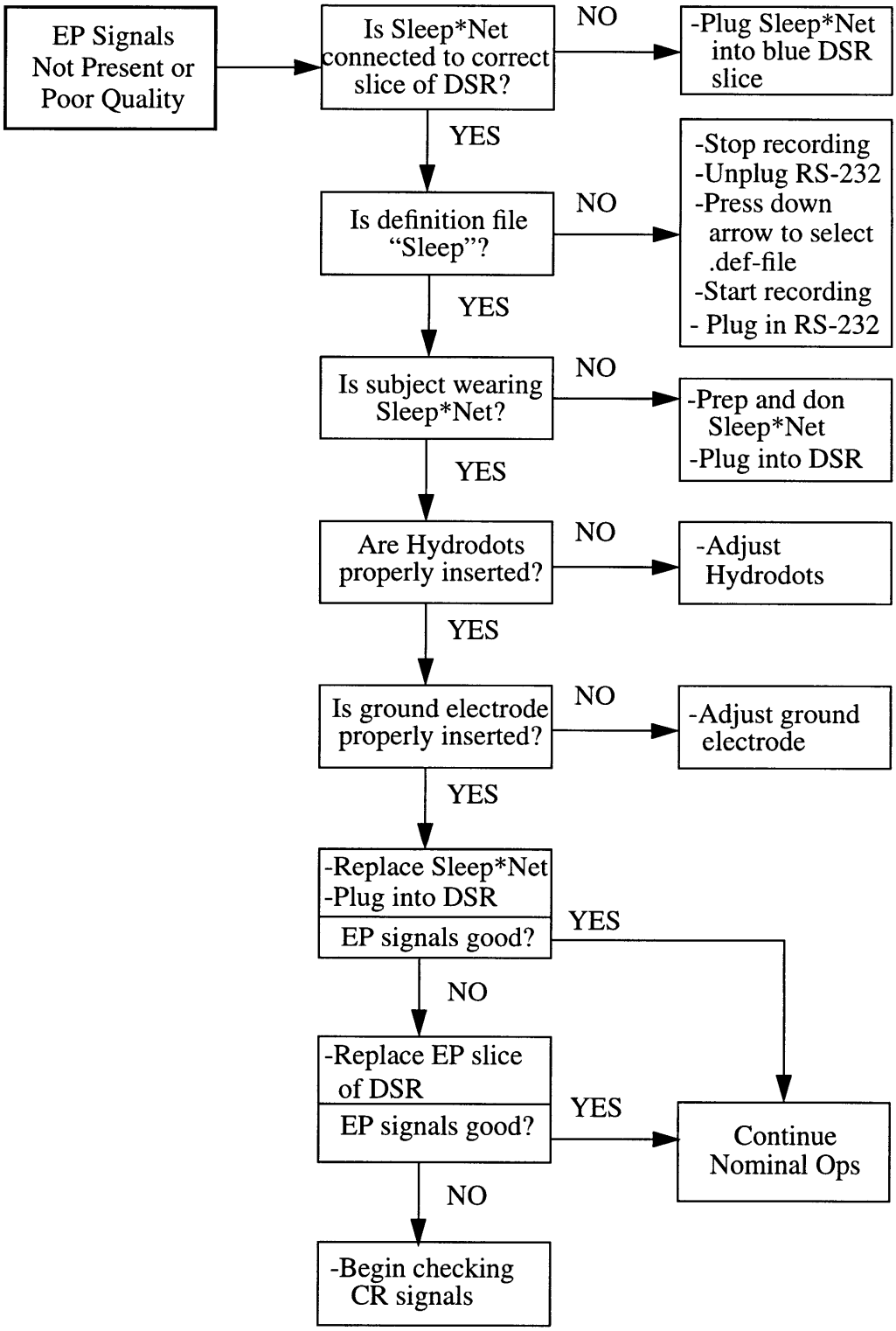

Figure 7.6: Diagnostic Diagram - State #3

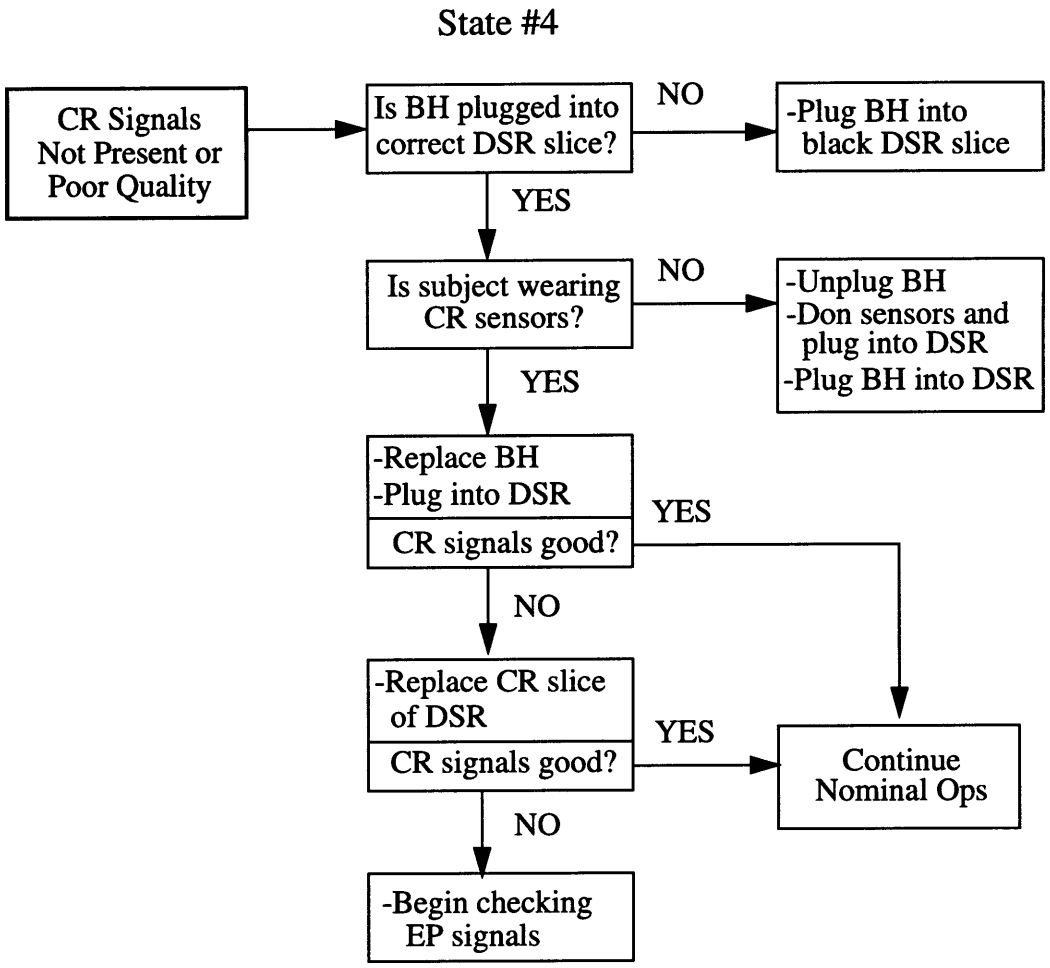

Figure 7.7: Diagnostic Diagram - State #4

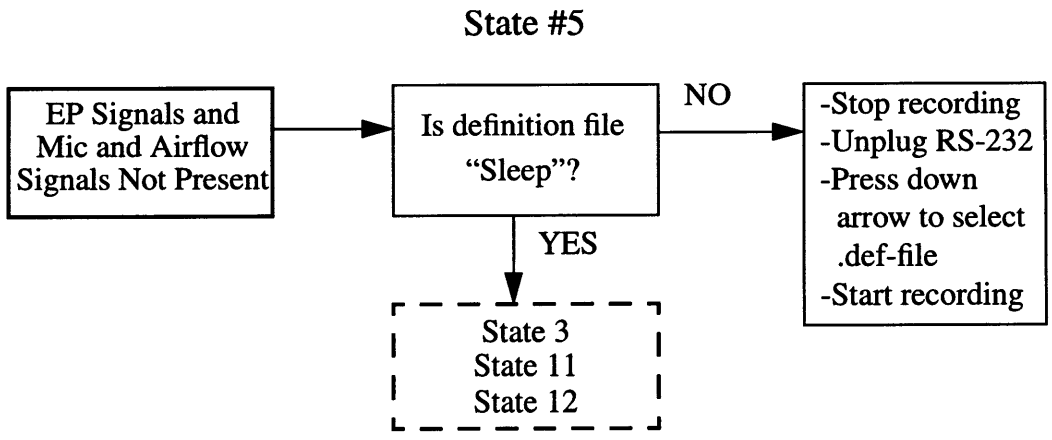

Figure 7.8: Diagnostic Diagram - State #5

State #6

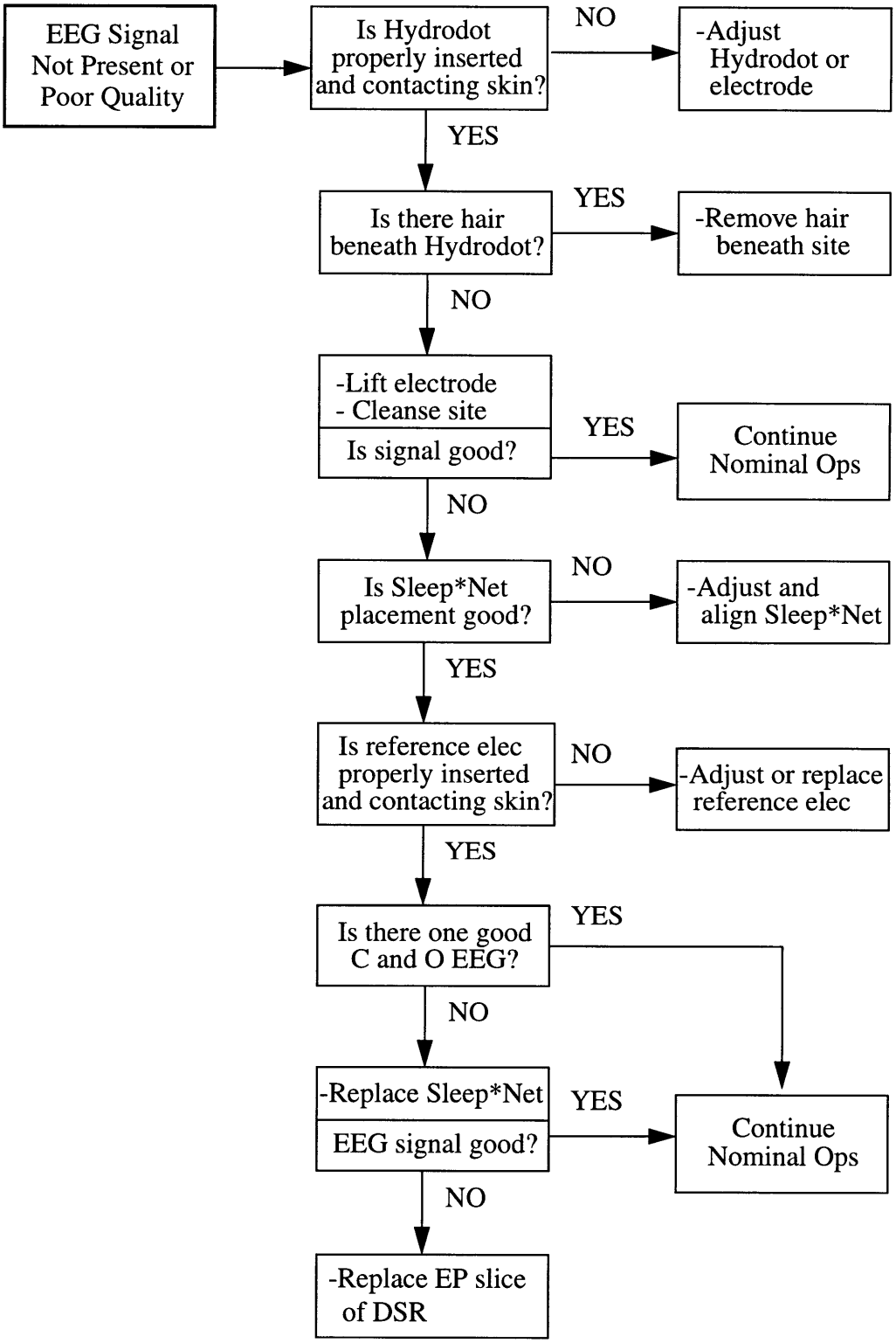

Figure 7.9: Diagnostic Diagram - State #6

State #7

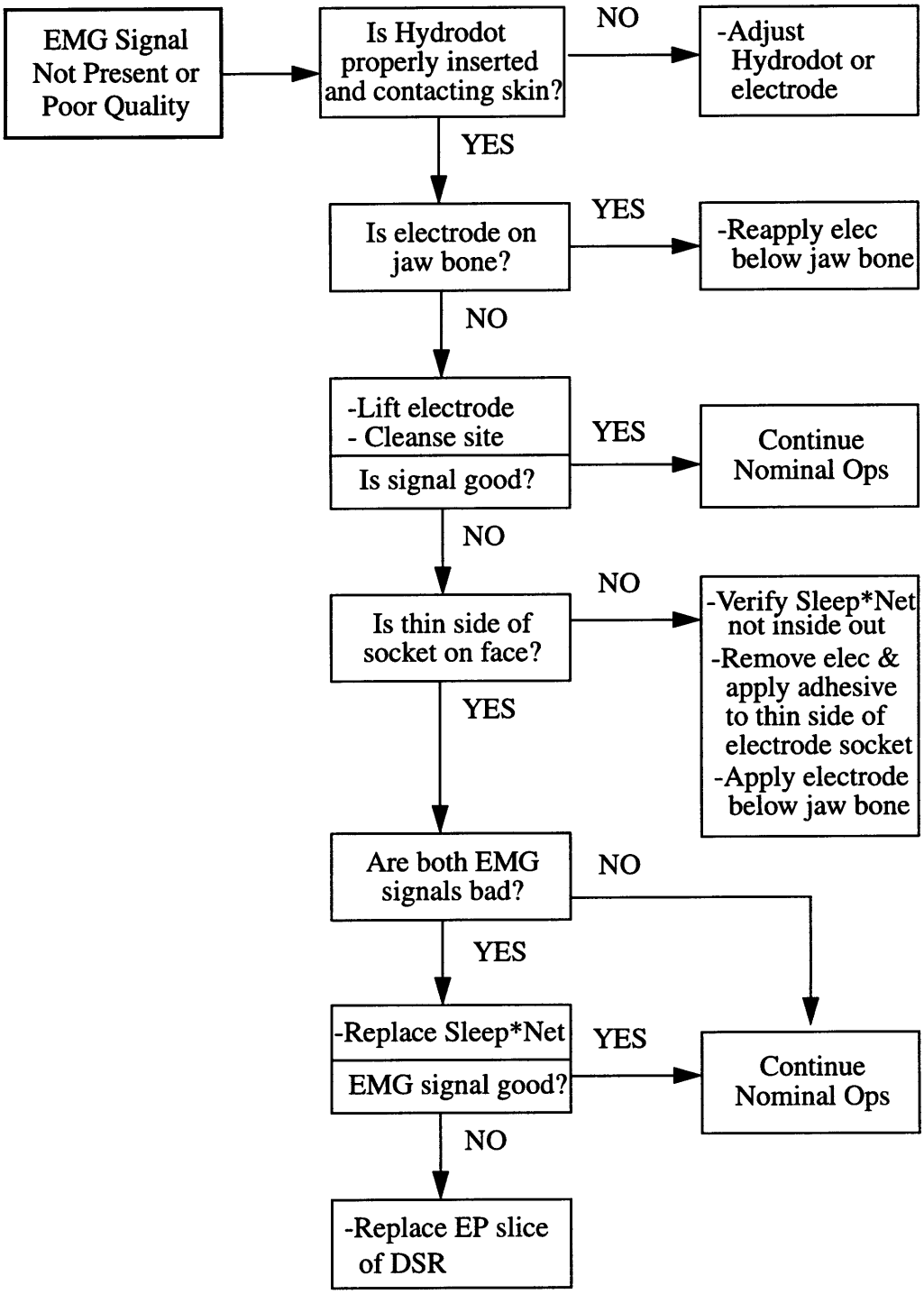

Figure 7.10: Diagnostic Diagram - State #7

State #8

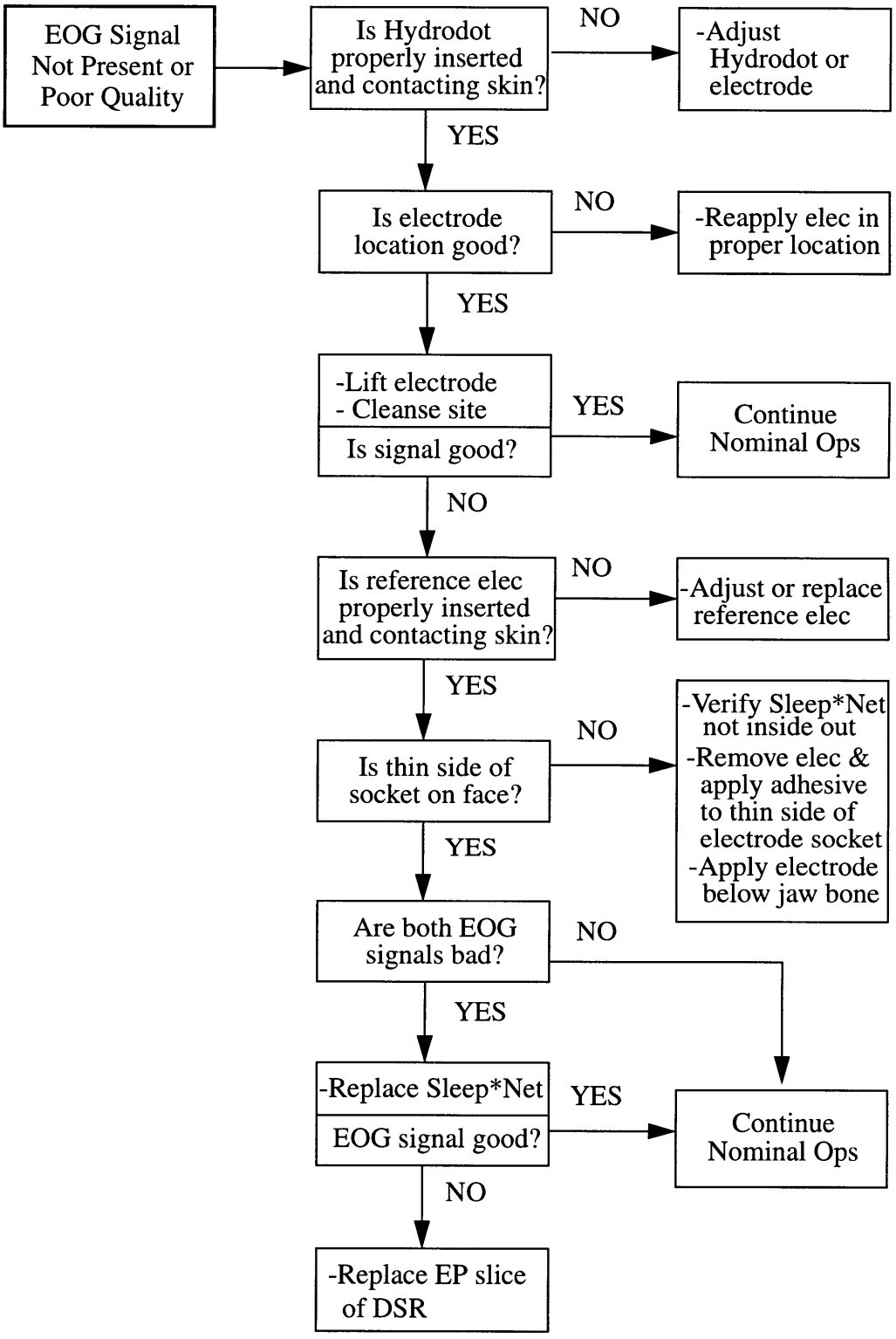

Figure 7.11: Diagnostic Diagram - State #8

State #9

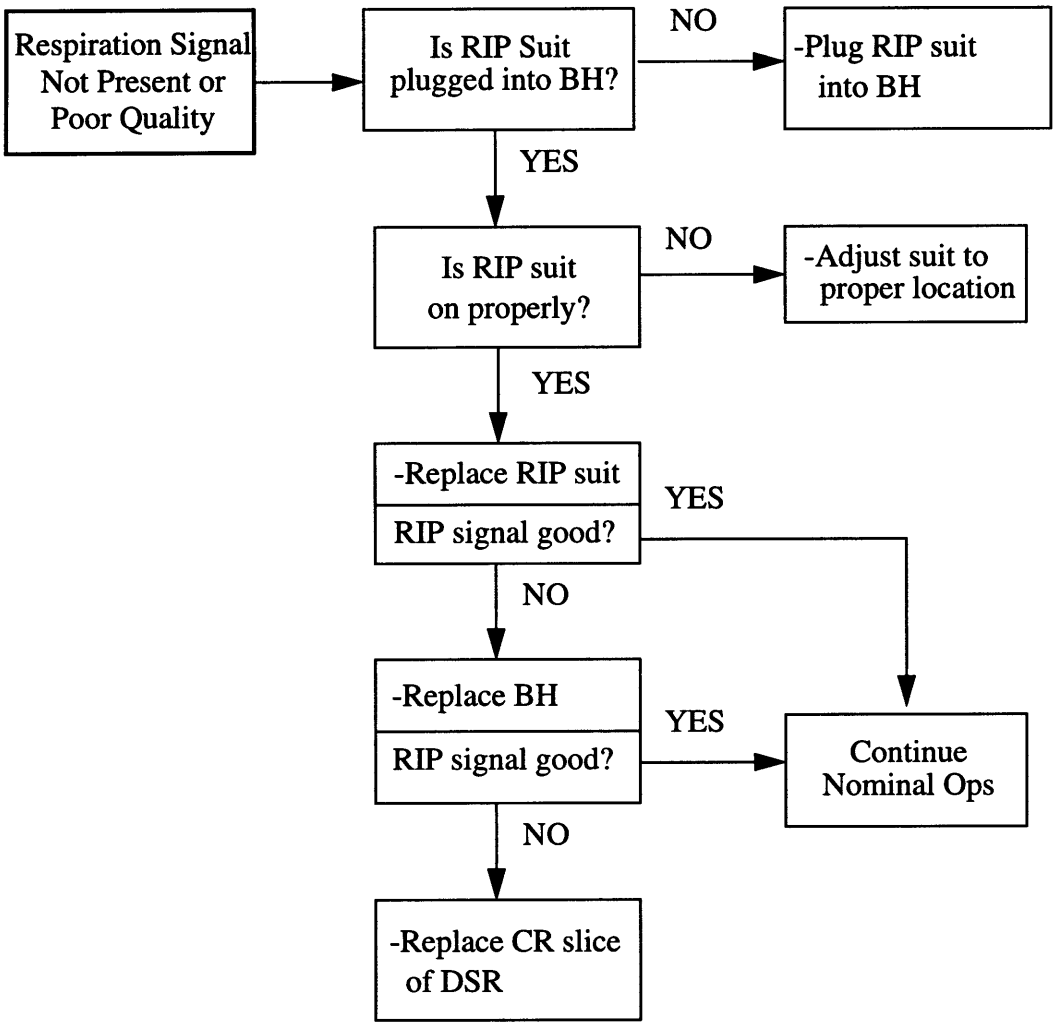

Figure 7.12: Diagnostic Diagram - State #9

State #10

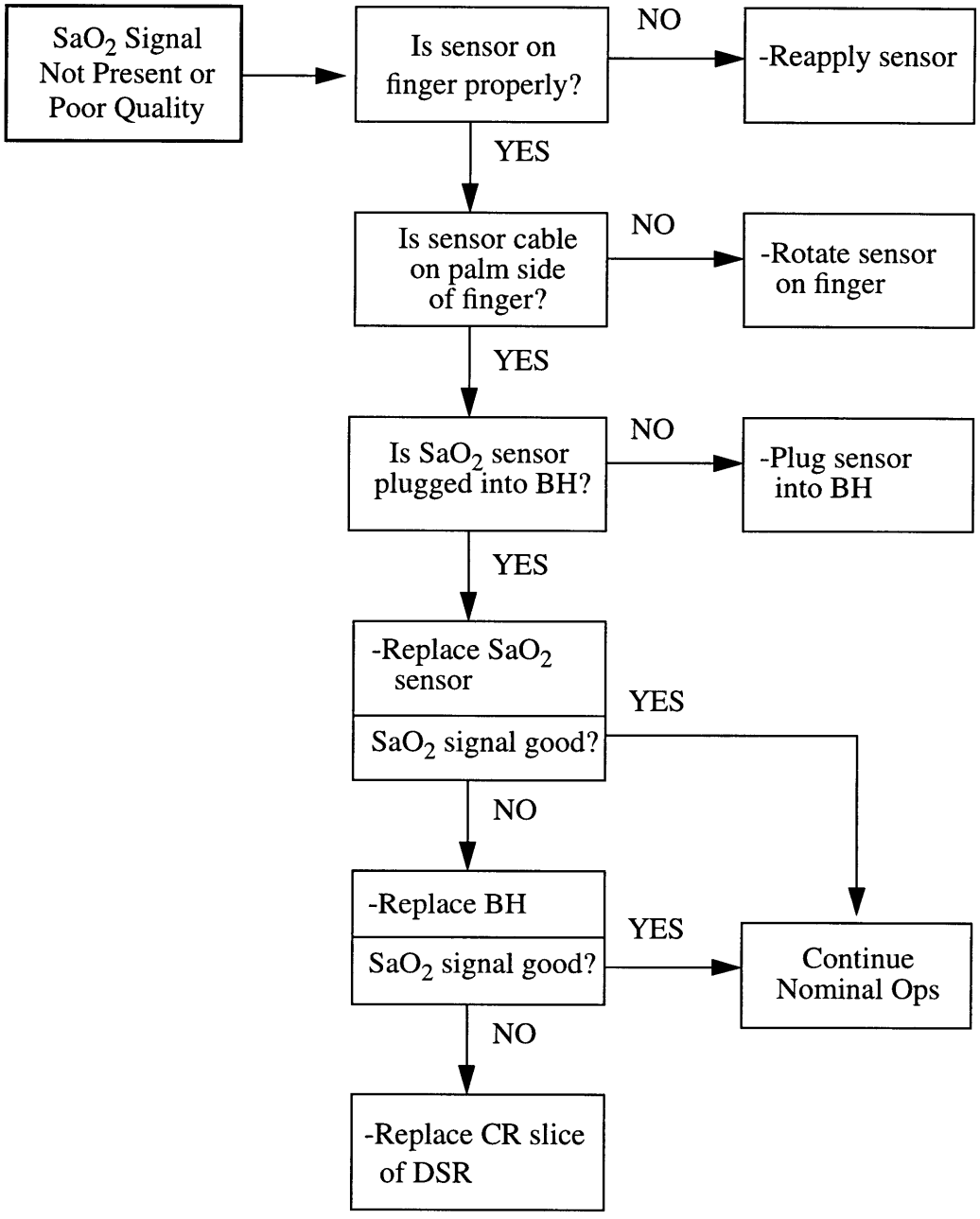

Figure 7.13: Diagnostic Diagram - State #10

State #11

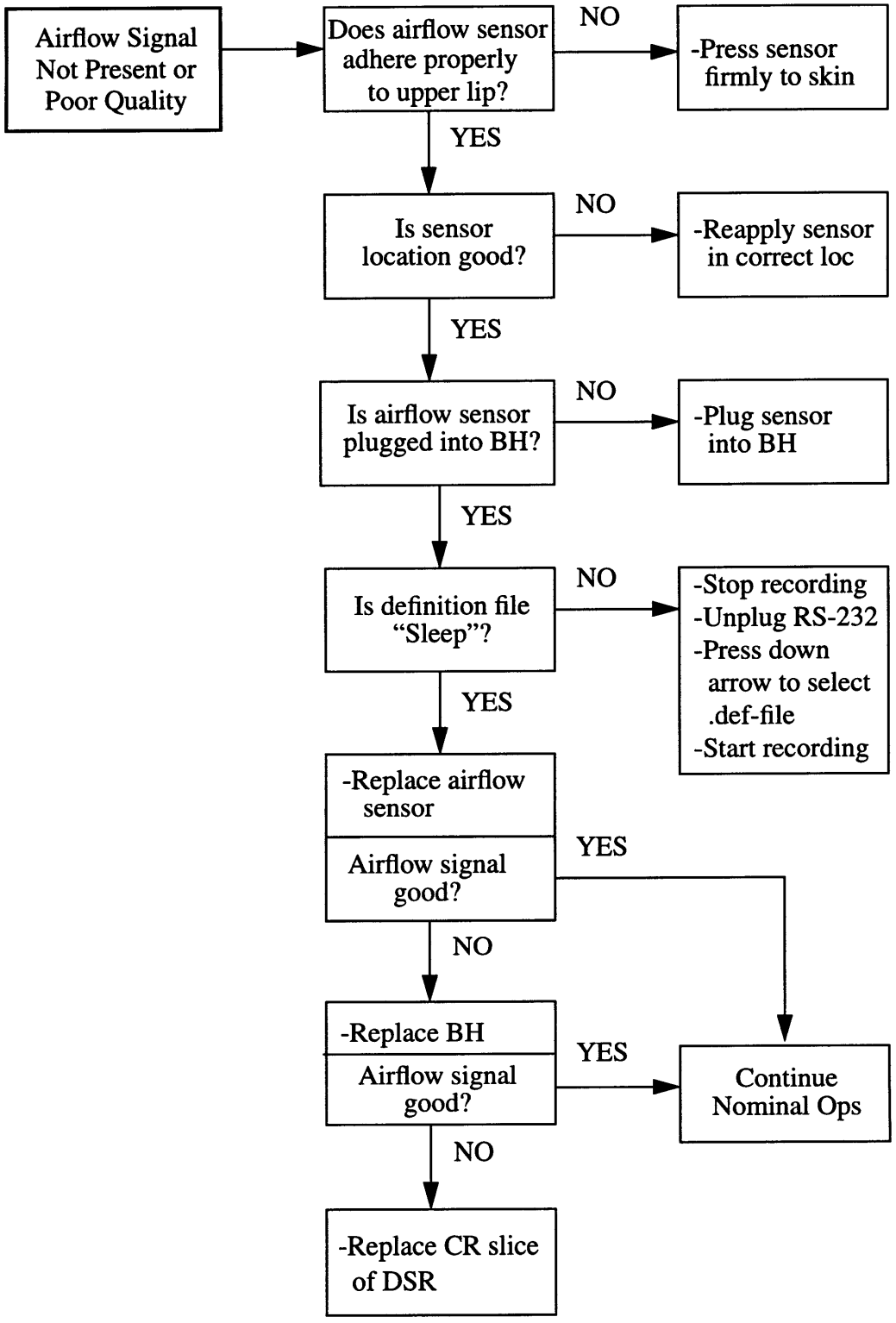

Figure 7.14: Diagnostic Diagram - State #11

State #12

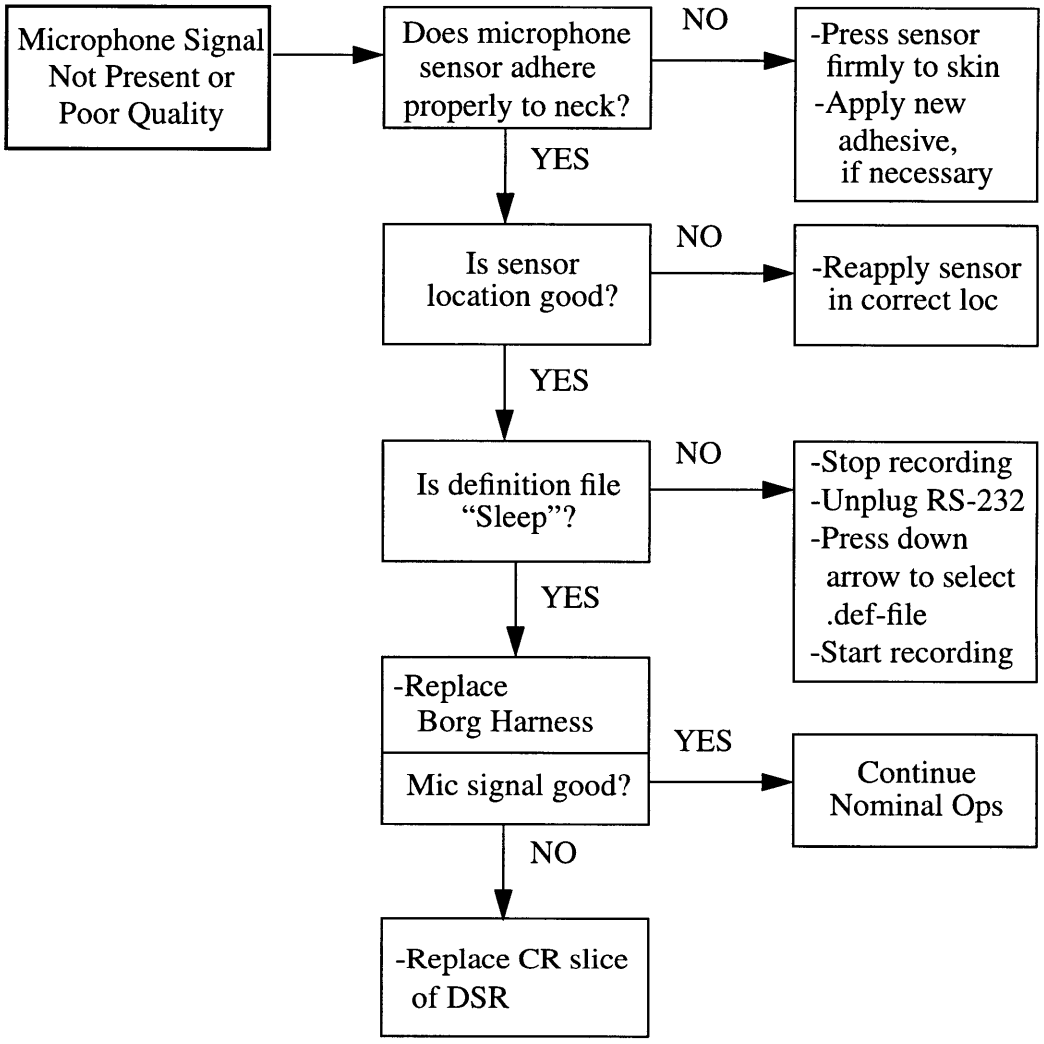

Figure 7.15: Diagnostic Diagram - State #12

State #13

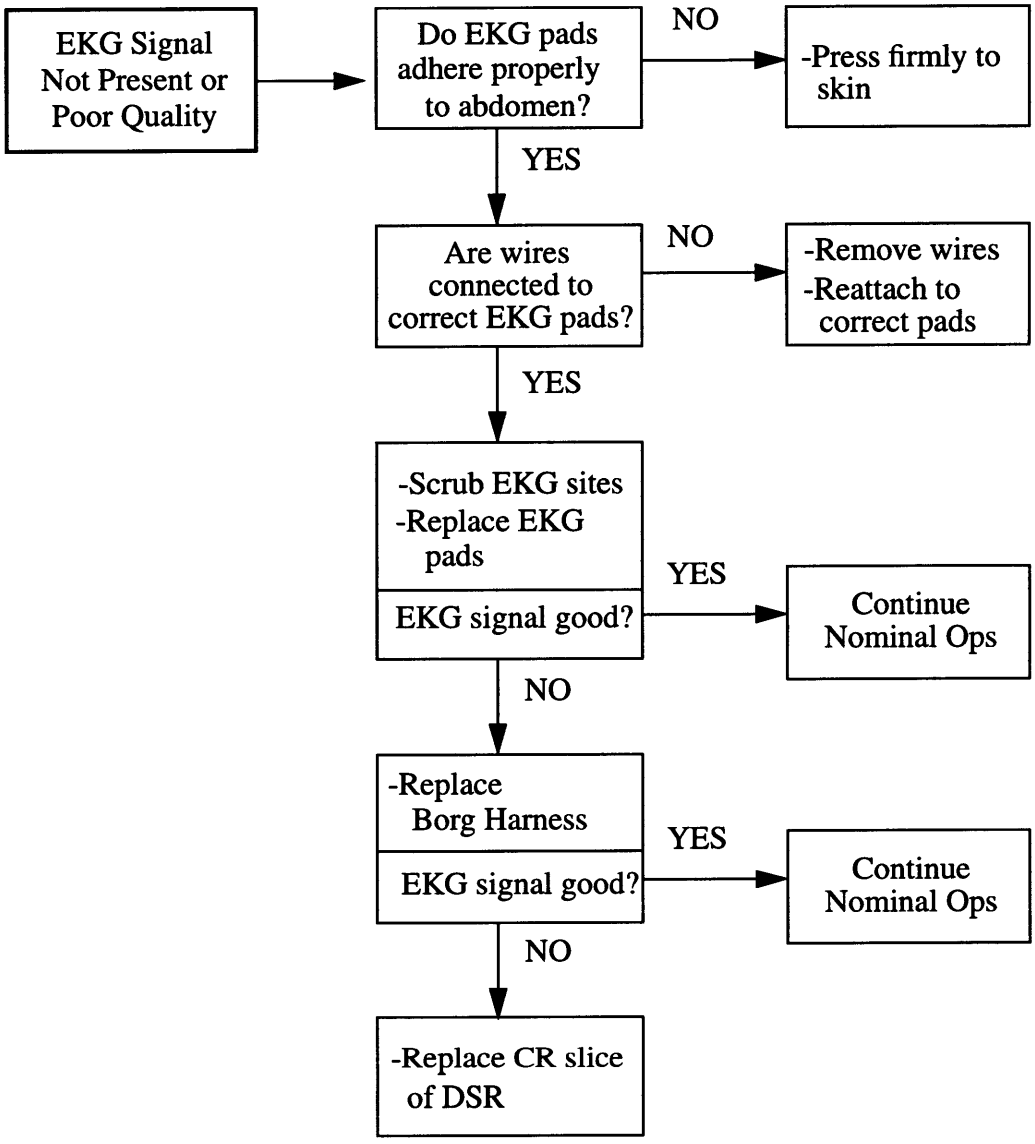

Figure 7.16: Diagnostic Diagram - State #13

State #14

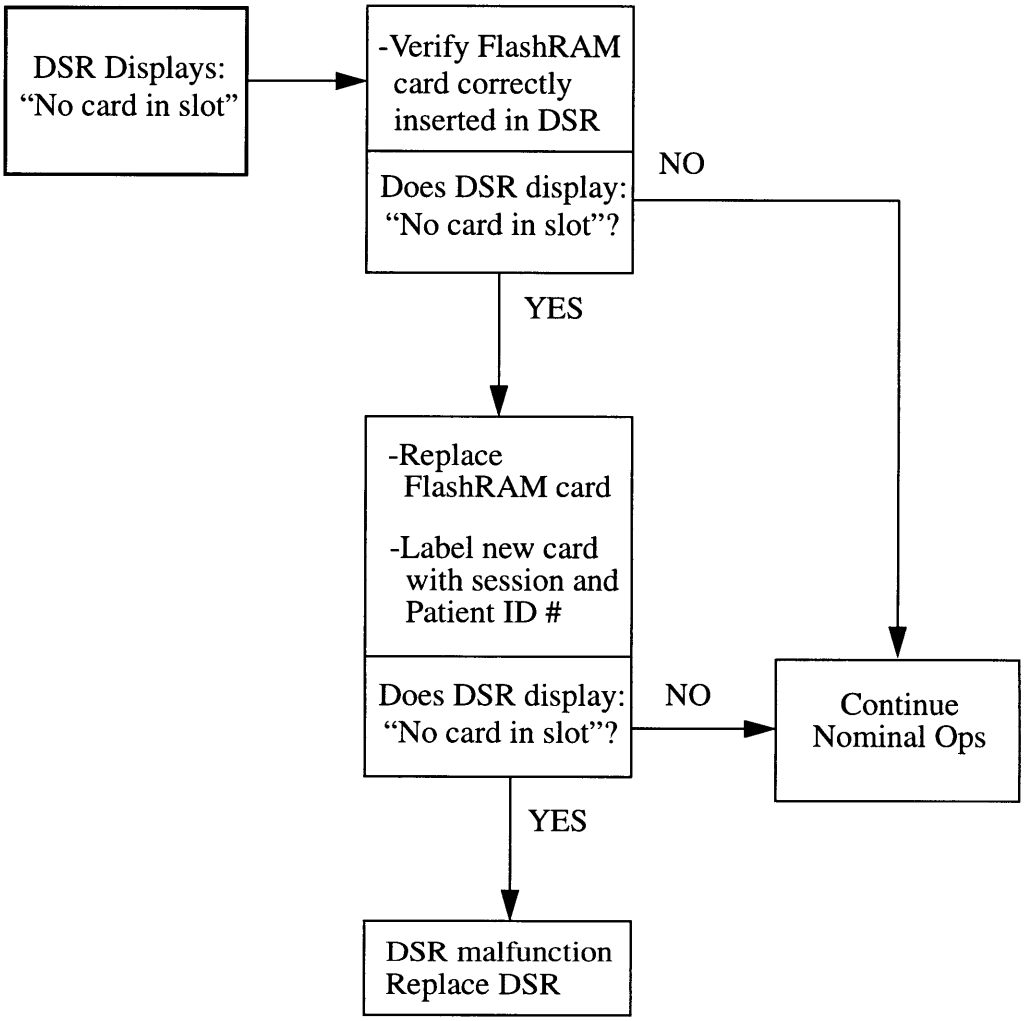

Figure 7.17: Diagnostic Diagram - State #14

State #15

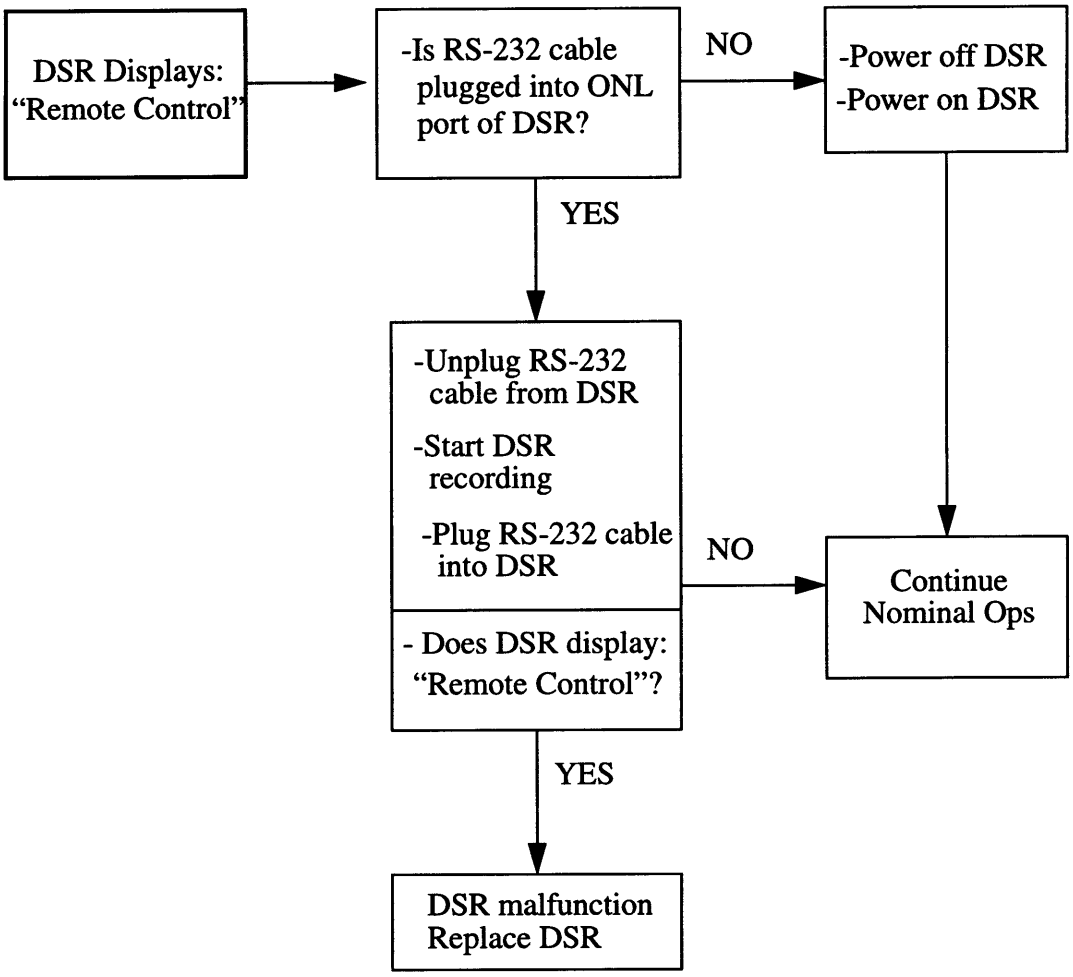

Figure 7.18: Diagnostic Diagram - State #15

State #16

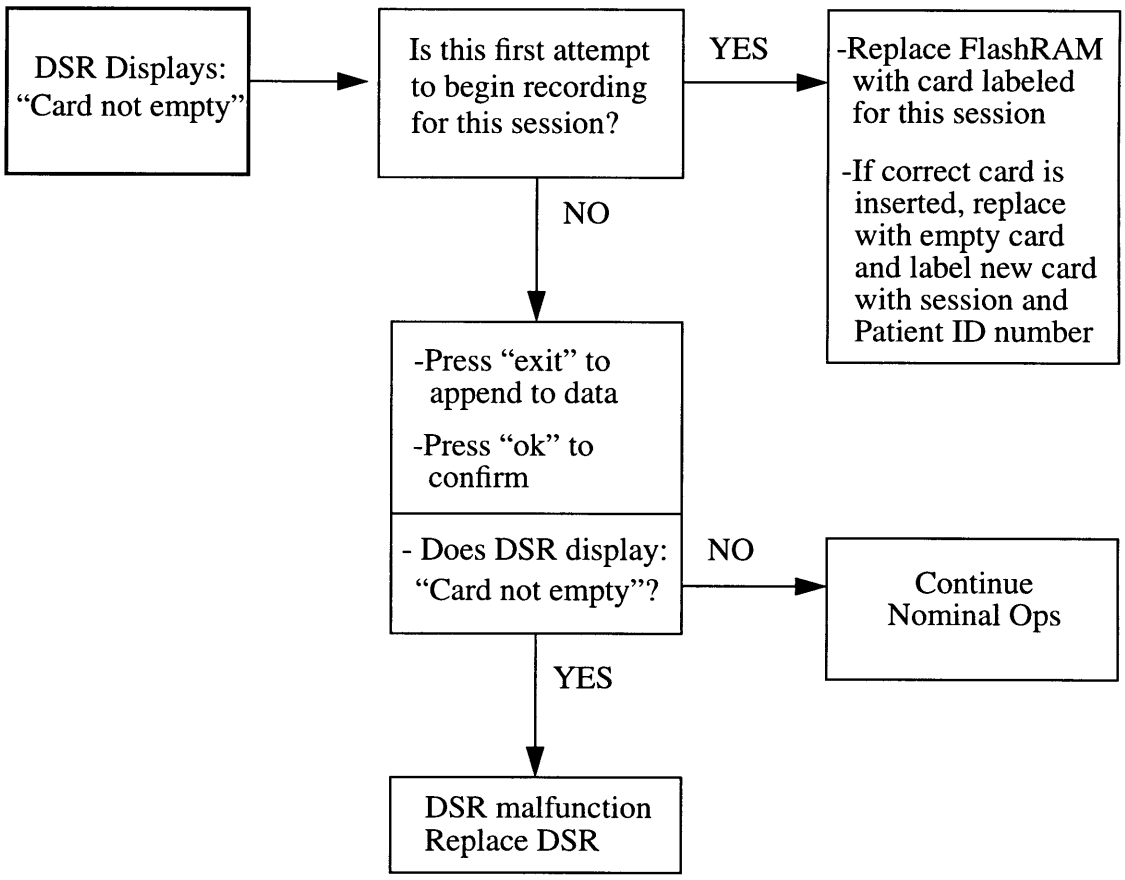

Figure 7.19: Diagnostic Diagram - State #16

State #17

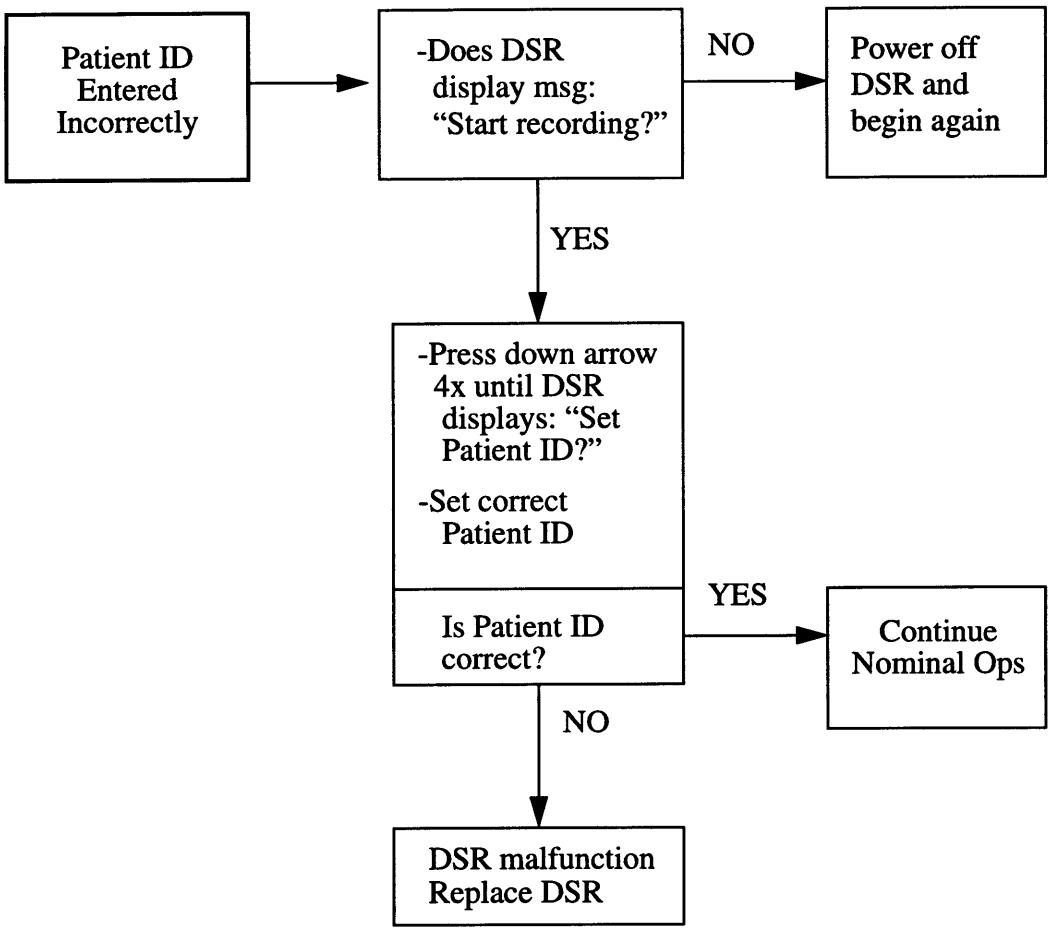

Figure 7.20: Diagnostic Diagram - State #17

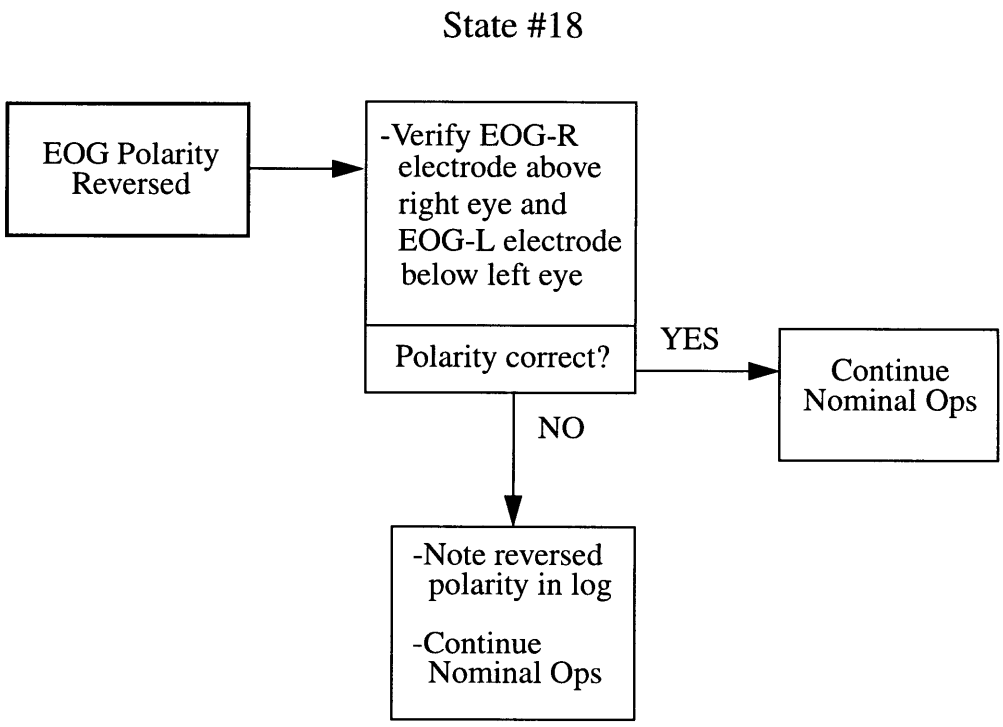

Figure 7.21: Diagnostic Diagram - State #18

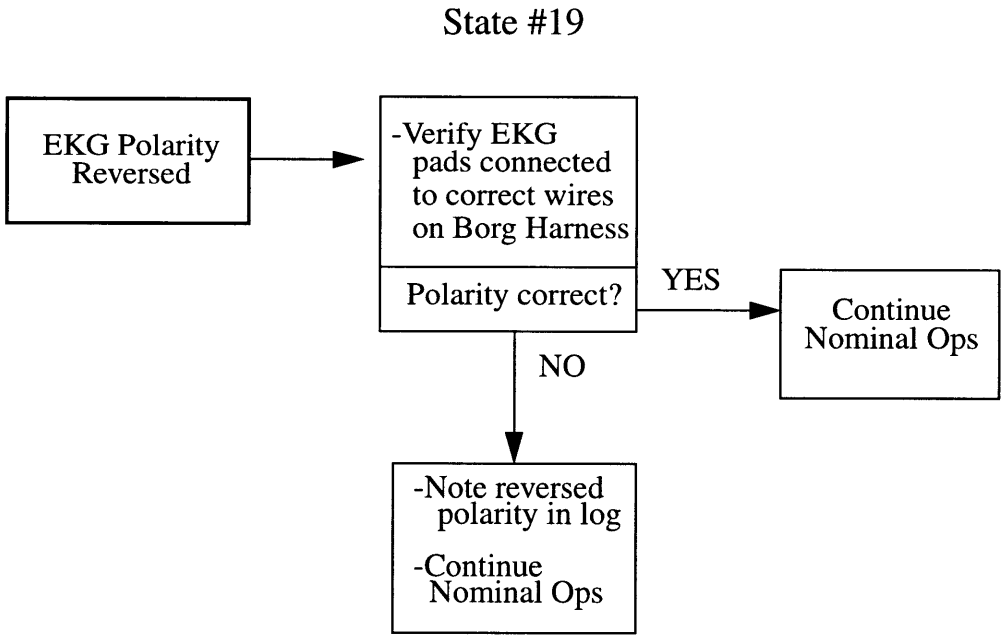

Figure 7.22: Diagnostic Diagram - State #19

7.4 PI-in-a-Box Diagnostics

For each space shuttle mission, the astronauts are provided with a notebook of malfunction procedures similar to the diagnostic diagrams presented in the previous section. Although these hardcopy diagrams can be useful in diagnosing a failure in an experiment, a great deal of additional time is required to locate the binder and the applicable malfunction procedures. In response to this, one of the functions developed for PI-in-a-Box on the Neurolab mission is a diagnostics and troubleshooting function which will diagnose problems and provide the astronauts with procedures for returning the system to its nominal operating state. These procedures will be displayed on the [PI] screen, eliminating the need for the astronauts to search for the malfunction procedures.

Since the space available on the PI-in-a-Box interface is limited, it is not possible to display the full malfunction diagrams on the [PI] screen. Instead, text versions of these diagrams will be provided in the PI-in-a-Box diagnostics window. These text diagnostics are condensed versions of the diagnostic diagrams presented in the previous section. The elaborate steps in the diagnostic diagrams were reduced to a list of items for the astronauts to verify and procedures for correcting the problem. The diagnostic messages developed for the PI-in-a-Box diagnostics window are provided in Tables 7.21 - 7.37.

In the following tables, PI-in-a-Box diagnostic procedures are not provided for states #16 and #17. Both of these states involve failure events which, if they occur, would take place prior to PI-in-a-Box activation in the instrumentation protocol. As a result, the PI-in-a-Box diagnostics

window will not be accessible if these failure events occur. Therefore, no diagnostics were developed for these two system states.

Table 7.21: PI-in-a-Box Diagnostics - State #1

No Signals Displayed on PI-in-a-Box
Check RS-232 connected to DSR and ThinkPad
Check DSR is on
Check DSR batteries
Check Sleep*Net and BH plugged into DSR correctly
Restart PI-in-a-Box
Replace RS-232
Replace DSR

Table 7.22: PI-in-a-Box Diagnostics - State #2

Signals Freeze on PI-in-a-Box Display
Check DSR is on
Check DSR is recording
Check RS-232 connected to DSR and ThinkPad
Restart PI-in-a-Box
Replace RS-232
Replace DSR

Table 7.23: PI-in-a-Box Diagnostics - State #3

Electrophysiological Signals Not Present or Poor Quality on PI-in-a-Box Display
Check Sleep*Net plugged into blue DSR slice
Check .def-file on DSR is "Sleep"
Check Sleep*Net position
Check Hydrodots
Check forehead ground electrode
Replace Sleep*Net
Replace EP slice of DSR

Table 7.24: PI-in-a-Box Diagnostics - State #4

Cardiorespiratory Signals Not Present or Poor Quality on PI-in-a-Box Display
Check BH plugged into black DSR slice
Check CR sensors are donned
Replace Borg Harness
Replace CR slice of DSR

Table 7.25: PI-in-a-Box Diagnostics - State #5

Electrophysiological Signals, Airflow and Microphone Signals Not Present on PI-in-a-Box Display
Check .def-file on DSR is "Sleep"
Check Sleep*Net plugged into DSR
Check airflow and mic sensors donned
Check airflow sensor plugged into BH
Replace EP slice of DSR

Table 7.26: PI-in-a-Box Diagnostics - State #6

EEG Signal Not Present or Poor Quality
Check Hydrodot
Remove hair from site and rescrub
Check Sleep*Net placement
Check reference electrode behind opposite ear
Replace Sleep*Net
Replace EP slice of DSR

Table 7.27: PI-in-a-Box Diagnostics - State #7

EMG Signal Not Present or Poor Quality
Check Hydrodot
Check electrode location
Rescrub site
Check thin side of socket applied to skin
Replace Sleep*Net
Replace EP slice of DSR

Table 7.28: PI-in-a-Box Diagnostics - State #8

EOG Signal Not Present or Poor Quality
Check Hydrodot
Check electrode location
Rescrub site
Check reference electrode behind opposite ear
Check thin side of socket applied to skin
Replace Sleep*Net
Replace EP slice of DSR

Table 7.29: PI-in-a-Box Diagnostics - State #9

RIP Signal Not Present or Poor Quality
Check RIP suit plugged into BH
Check suit is on properly
Replace RIP suit
Replace Borg Harness
Replace CR slice of DSR

Table 7.30: PI-in-a-Box Diagnostics - State #10

SaO_2 Signal Not Present or Poor Quality
Check sensor securely on finger
Check sensor cable on palm side of finger
Check sensor plugged into BH
Replace sensor
Replace Borg Harness
Replace EP slice of DSR

Table 7.31: PI-in-a-Box Diagnostics - State #11

Airflow Signal Not Present or Poor Quality
Check sensor securely on upper lip
Check sensor tabs point toward nose
Check sensor plugged into BH
Check DSR .def-file is "Sleep"
Replace sensor
Replace Borg Harness
Replace EP slice of DSR

Table 7.32: PI-in-a-Box Diagnostics - State #12

Microphone Signal Not Present or Poor Quality
Check sensor securely on neck
Check sensor location
Check DSR .def-file is "Sleep"
Replace Borg Harness
Replace EP slice of DSR

Table 7.33: PI-in-a-Box Diagnostics - State #13

EKG Signal Not Present or Poor Quality
Check sensor securely on chest
Check wiring to BH
Rescrub sites and replace pads
Replace Borg Harness
Replace EP slice of DSR

Table 7.34: PI-in-a-Box Diagnostics - State #14

DSR Displays: "No card in slot"
Check FlashRam inserted in DSR
Unplug RS-232 from DSR and begin recording
If not successful, Replace DSR

Table 7.35: PI-in-a-Box Diagnostics - State #15

DSR Displays: "Remote control"
Unplug RS-232 from DSR and start recording
If not successful, Replace DSR

Table 7.36: PI-in-a-Box Diagnostics - State #18

EOG Polarity Reversed
Check right electrode above eye and left electrode below
If electrodes correct, note reversed polarity in log

Table 7.37: PI-in-a-Box Diagnostics - State #19

EKG Polarity Reversed
Check wiring to BH
If wiring correct, note reversed polarity in log

Chapter 8

Discussion and Recommendations

8.1 Hardware Issues

One of the primary obstacles encountered in the development of PI-in-a-Box has been the inability to develop and test the software on the flight computer configuration. The 755C model ThinkPads which will be flown on Neurolab are no longer manufactured by IBM. As a result, all software development at NASA Ames has been performed using a laptop computer with a pentium processor, faster than the 486 processor on the flight computer. In an attempt to address the potential problems associated with this, all testing was performed using a slower computer than the computer which will be flown on Neurolab. The available RAM memory on the test computer was considerably less than the RAM on the flight computer as well.

On the test computer, there was a delay of several seconds associated with the PI-in-a-Box data display. After a failure simulation was performed, the corresponding signal on the PI-in-a-Box interface did not respond for several seconds. In addition, there was a delay when switching between the electrophysiological and cardiorespiratory screens. These delays may have been due to insufficient memory and/or the speed of the test computer. Such delays would be unacceptable on the flight hardware. In order for the astronauts to perform the signal verification process efficiently, all signals must be displayed in real time.

For a number of the crew training sessions, the PI-in-a-Box software was run on the flight hardware. Based on the performance of PI-in-a-Box during those sessions, there appears to be no delay associated with the [PI] display on the flight computer.

Some initial testing has been performed on PI-in-a-Box with the flight computer. The [PI] software was tested for stability, speed, and consistency. In order to test the stability of the [PI] software on the flight computer, a sine wave signal produced by a function generator was input into the digital sleep recorder and displayed on the PI-in-a-Box screen. The signal was displayed for a period of forty minutes without any loss of data or [PI] software errors. The total run time for PI-in-a-Box during any of the sleep sessions on Neurolab should not exceed forty minutes.

The second test performed on the flight computer was designed to verify that the speed of the flight computer is sufficient to run the PI-in-a-Box software. Using the function generator, a sine wave signal was displayed on the PI-in-a-Box interface. The amplitude and frequency of the input signal were varied to determine the response time of the signal displayed by PI-in-a-Box. There was no delay associated with the [PI] signal display on the flight computer.

A final test performed on the flight computer was designed to verify the consistency of the PI-in-a-Box software with results of tests performed on other laptop computers at Brigham and Women's Hospital. Approximately ten of the failure simulations which were performed for this thesis were simulated on the flight computer. The results were identical to those of the tests performed on the ThinkPad at BWH.

As changes are made to the PI-in-a-Box software, additional testing should be performed. The final version of [PI] should be tested extensively to assure both stability and correct functionality of the software on the flight computer.

8.2 Recommendations for Future Work

8.2.1 Modifications to Diagnostics

The diagnostic messages presented in this thesis are intended to provide a methodical approach to diagnosing and correcting any failure event which may occur during the sleep and respiration instrumentation process. However, modifications to these diagnostics may be necessary based on available space in the [PI] diagnostics window. Another consideration is the method for displaying these diagnostic messages. One possibility is to display all diagnostic procedures simultaneously, allowing the subject to proceed down the list of troubleshooting procedures. A second possibility is to display one diagnostic procedure at a time, according to the prioritizations presented in this thesis. This method would enhance clarity in the diagnostics display window. However, in this case, all diagnostic messages should be made accessible to the subject through the use of a scroll bar in the [PI] diagnostics window.

Changes made to the PI-in-a-Box software and the sleep and respiration instrumentation procedures may require the PI-in-a-Box diagnostics to be modified as well. Although version 2.0 of the PI-in-a-Box software was used for all of the failure simulations, changes have been made to the software since the development of the diagnostic procedures. As a result, some of the diagnos-

tic procedures provided in this thesis may require modifications in order to remain applicable to the final software version.

One significant modification to the PI-in-a-Box software currently being implemented is the addition of a "Reset" button on the [PI] interface. The button is designed to enable the user to disconnect and reconnect to PI-in-a-Box without any communication difficulties between the ThinkPad and the DSR. This reset feature will facilitate the process of switching between different subjects in the same instrumentation session. Users will no longer be required to restart PI-in-a-Box prior to performing the [PI] signal verification on a new subject. As a result, the diagnostic procedures must be updated to include the use of the reset button.

Another modification to the PI-in-a-Box interface currently under development is the addition of one signal to the cardiorespiratory screen of PI-in-a-Box. The new signal will be a "P-wave" signal, associated with the pulse oximeter. Since no additional equipment will be necessary, no additional diagnostic procedures for donning the sensor will be required. Nevertheless, the characteristics of the P-wave signal must be determined and troubleshooting procedures must be developed for the case of a poor quality signal.

8.2.2 Ground-Based Studies

In addition to the Neurolab flight experiment, PI-in-a-Box will be incorporated into the ground-based sleep studies. In order to do this effectively, several modifications to the PI-in-a-Box software will be required.

Subjects in the ground-based studies participate on a voluntary basis. Unlike the astronauts in the flight-based study who have medical backgrounds, most of the subjects in the ground-based study will have relatively little knowledge about electrophysiological and cardiorespiratory signals. Therefore, these subjects will require enhanced signal quality evaluation capabilities by PI-in-a-Box.

Instrumentation time for the ground studies will not be as critical as it is in flight. Therefore, a detailed set of subject calibrations will be incorporated into the setup procedures. These formal subject calibrations are traditionally performed to assist the technicians with the signal verification process. In addition, the information from these calibrations serves as a reference point in analyzing the sleep data. For the ground-based studies, PI-in-a-Box will monitor the subject calibrations, evaluating the quality of each signal throughout the calibration process.

8.2.1 Operational and Acceptance Testing

Operational and acceptance testing will be required for both the flight and ground-based versions of PI-in-a-Box. This testing will be performed in order to verify that the PI-in-a-Box software functions properly and that it satisfies the initial design requirements defined by the sleep and respiration teams. The test plans for the flight-based and ground-based versions of [PI] will vary slightly.

Operational testing will be a performed in a collaborative effort between the PI-in-a-Box teams at MIT and NASA Ames Research Center. The objective of these tests will be to verify the technical functionality of the PI-in-a-Box software. For example, the functionality of the "exit"

and "help" buttons on the [PI] interface will be evaluated. If a "reset" button is incorporated into the interface, it will be tested for proper functionality as well. The raw signal display will be evaluated for both speed and stability. Finally, the ability of the PI-in-a-Box software to determine the quality of each signal will be evaluated.

The objective of testing PI-in-a-Box's signal quality evaluation function is to determine whether or not PI-in-a-Box is able to accurately identify both good and bad quality signals. In order to test this, PI-in-a-Box will evaluate data samples of known quality. The data samples used for these tests will be collected from subjects at both the Brigham and Women's Hospital (BWH) and the University of California, San Diego (UCSD). The PI-in-a-Box software must be able to identify good quality data as well as data which contains artifacts and various types of noise.

The first step in collecting data samples is to identify all possible types of noise and artifacts which may be introduced into the data in the experiment environment. Since the actual testing environment is different in space than it is on earth (i.e. 60 Hz noise is present on the ground but not in space), the data samples required for testing the two versions of [PI] will be different. Each of the artifacts will be simulated using subjects at BWH and UCSD. These data samples, as well as samples of data containing no artifacts, will be recorded using the Vitaport digital sleep recorder. These samples will be input into PI-in-a-Box in order to test [PI]'s ability to determine the quality of each signal.

Subjects will be required to perform calibration procedures for the ground experiments. Therefore, the ground-based test protocol must be designed to evaluate [PI]'s ability to characterize the quality of the subject calibrations as well. This process is similar to [PI]'s signal quality

evaluation testing. All possible artifacts and subject errors associated with the subject calibration process must be identified. An example of a data artifact is poor quality data resulting from incorrect electrode placement. An example of subject error is performing the calibration procedures out of order. Data samples must be recorded for each scenario. As in the signal quality evaluation testing, the ability of PI-in-a-Box to identify the quality of each calibration data sample will be verified.

Acceptance testing of PI-in-a-Box will be performed by BWH and UCSD after the operational testing has been completed. Unlike the operational tests, which verify the technical functionality of the software, the acceptance tests are designed to test whether or not PI-in-a-Box satisfies the science requirements of the sleep and respiration experiment. The sleep and respiration teams will verify the ability of [PI] to display each of the signals correctly, with an appropriate time and amplitude scale. Furthermore, the ability of the PI-in-a-Box software to determine the quality of both good and bad signals will be tested. As in the operational testing, the criteria for evaluating PI-in-a-Box may vary for the ground-based and flight-based applications.

Appendix A

Instrumentation Procedures[1]

RIP SUIT AND SLEEP*NET SETUP

1. Unstow:
   RIP suit
   Sleep Kit

2. Don RIP suit & apply ECG pads (in sleep kit).

   Note:
   a. Each subj performs Sleep*Net prep, face prep, dons Sleep*Net, applies face biosensors.
   b. Yellow side of pads to Sleep*Net.
   c. Socket pads to thin ring of electrode sockets (see Figure A.1).

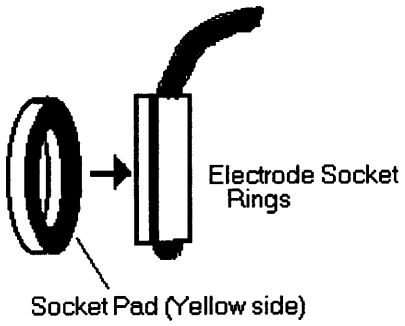

Figure A.1: Electrode Socket

3. Apply frontal pad, socket pads (6) to appropriate sites on Sleep*Net.

4. Loosen chin, neck straps. Disconnect chin strap buckle from one side of Sleep*Net.

5. Prep forehead, mastoids (2), face sites (6) w/ alcohol prep pad (2 sites per pad).

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1. Modified from original version written by Eymard Riel, Center for Circadian Medicine, Brigham and Women's Hospital

6. Don Sleep*Net over top of head w/ nasion tab centered above bridge of nose and flipped up to expose frontal pad.

7. Verify that central line is centered between left, right hemisphere and midline is straight, perpendicular to central line.

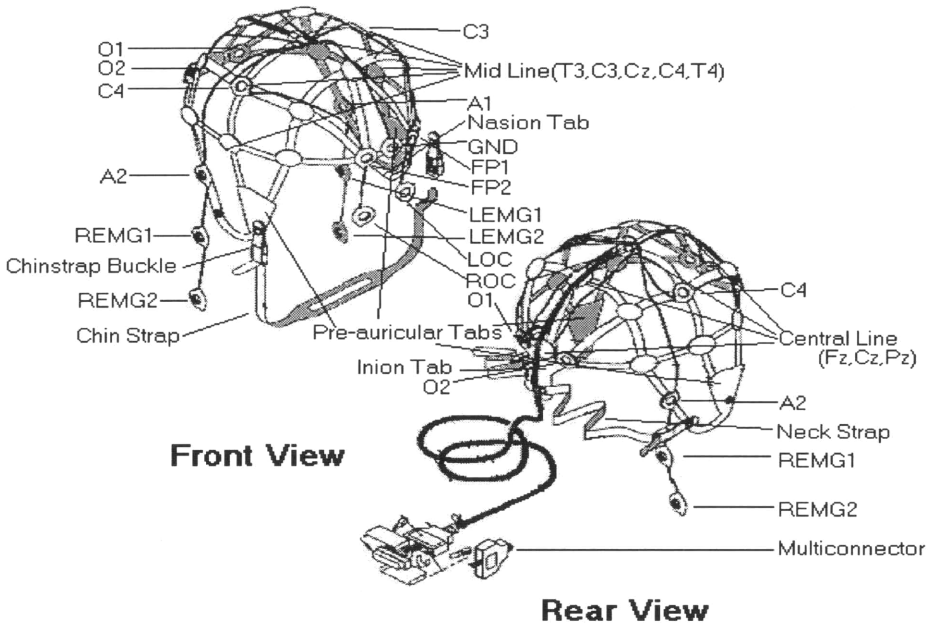

Figure A.2: Sleep*Net

SLEEP*NET

8. Remove adhesive backing on frontal pad, apply pad to nasion region.

9. Verify that frontal pad is centered on nasion region and straight.

10. Holding nasion tab in place, pull down inion tab until hole in tab aligned w/ inion.

11. Connect chin strap.

12. Align side tabs of Sleep*Net w/ right & left pre-auricular points.

Note: Do not over-tighten straps. Discomfort results if too tight, or electrode sights misaligned.

13. Center and tighten chin and neck straps until Sleep*Net firmly in place.

14. Apply face electrodes to skin sites. Press firmly in place.

15. Prep face sites w/ Nuprep swab, 2 sites per swab.

16. Assure inion & nasion tabs, central & mid lines of Sleep*Net over head have remained in correct position. Loosen and/or tighten chin & neck straps to readjust if necessary.

15. Using back of Nuprep swab, clear hair below 4 scalp sites & mastoid site on each side (A1 & A2).

16. Prep 4 scalp, 2 mastoid, 6 face & Ground sites (Ground is middle socket on nasion tab) by swirling Nuprep swab inside each sensor socket (1 swab/2 sites).

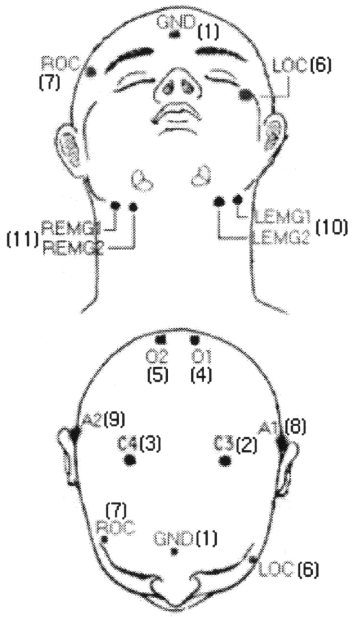

Figure A.3: Electrode Sites

17. Clear hair below sites if they go back under sockets during site preps.

18. Insert 1 Biosensor into each electrode site. Top of Biosensor should be flush w/ top of its socket. Slight side-to-side rocking motion can assist in insertion. Biosensors must touch scalp and not lie entirely on hair for good conduction of EEG signals.

BORG HARNESS SETUP

19. Unstow:

Borg Harness
Nasal Airflow Sensor
Pulse Ox Sensor

Subjs can help each other to speed up procedures & to insure proper placement of sensors.

20. Secure Borg Harness to RIP suit via velcro loops.

21. Attach socket pad to flat side of Microphone & adhere to lower left of larynx by applying pressure for ~5 sec.

22. Plug Airflow sensor into Borg Harness cable.

23. Apply sensor below nose w/ 2 tabs directed towards each nostril, secure lead w/ tape.

24. Connect Pulse Ox sensor into Borg Harness.

25. Apply Pulse Ox adhesive dot to left ring finger nail & another to finger pad.

26. Attach Pulse Ox sensor LED (distal button on Flex Probe) to finger nail of left ring finger. Attach sensor photodetector button to pad of same finger. Verify light source & photodetector are aligned.

27. Wrap Flex probe around finger & tape Pulse Ox cable to finger. Route cable up left arm securing w/ velcro loops on RIP suit.

28. Connect RIP suit connector to Borg Harness.

29. Connect 3 ECG leads to ECG pads by matching colored dots on RIP suit.

DIGITAL SLEEP RECORDER ACTIVATION

30. Unstow:

Digital Sleep Recorder
flash RAM card
AA Battery Kit

Steps 31-46, Subjs will activate own DSR.

31. Remove battery compartment cover on DSR w/ self-retaining thumbscrew. Remove 4 AA alkaline cells & discard in appropriate container. Insert fresh AA alkaline cells from Sleep Kit. Replace battery compartment cover on DSR.

32. Insert correctly labeled, unused flash RAM card into slot on DSR. Flash RAMs will be labeled w/ code identifying Subj and particular recording.

Note:

Imperative that label on flash RAM card corresponds to Subj & that subj's particular recording.

33. Connect Sleep*Net cable to sleep connector (blue "slice") & Borg Harness to Borg Harness connector (black "slice") of DSR.

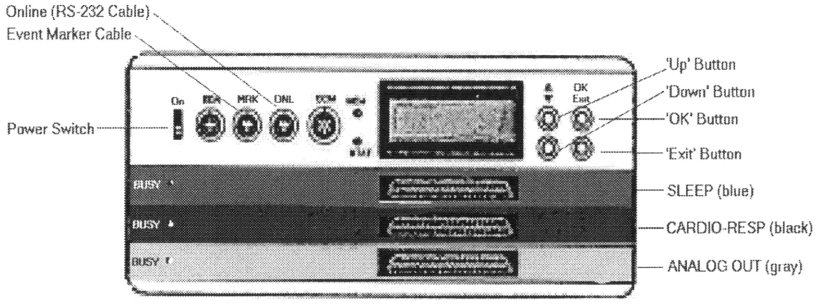

Figure A.4: Digital Sleep Recorder

34. Connect Event Marker cable to LEMO plug labeled MRK of DSR (Event Marker cable attached to Borg Harness). Check red dot on cable aligns w/ red dot on DSR.

35. Power on DSR. Chirping sound w/ screen flashing "Vitaport 0175-56", "Copyright 1996", "No card in slot"(if flash Ram not inserted) or "Harddisk: 85 MB"(if flash RAM properly inserted).

36. LCD will display "Set Patient ID?" and "Battery: <?> V". If battery readout is lower than 6.0V then redo step 40. If battery readout is 6.0V or higher then go to step 46.

37. Press 'OK' button to set patient ID. There is a quick beep every time a button is pressed.

38. LCD will display five 0's on lower half of screen w/ cursor under "0" on far right. Press 'up' button to change digit above cursor, 'down' button to move cursor to next digit. Make sure that numbers on screen matches assigned numbers for this particular DSR recording.

39. Press 'OK' after patient ID has been verified. The screen will now display "Start recording?" and "def-file (i.e. Sleep .def)".

40. Verify the def-file (i.e.: Sleep.def, Wake.def). To change, press 'down' arrow once to display "VITAPORT-II MENU, Select def-file?". Press 'OK' to display "Current def-file" and def-file that is currently loaded (i.e. Sleep.def). Press 'up' or 'down' arrow to select correct def-file. There are 4 possible choices, only Sleep.def or Wake.def will be used. Press 'OK' to display "Start recording?" and def-file.

41. Press 'OK'. MEM light will flash followed by STAT light flashing then BUSY light on each slice that is in use will turn on at the same time screen displays "Setting up amps!" "Stay

relaxed!" followed by beeping sound with screen display "'OK' to start?", def-file flashing once, and "Time: hh:mm:ss".

42. Press 'OK', MEM will flash once. DSR now recording & saving data on flash RAM when top of screen displays "Recording data" and "Time: hh:mm:ss". Ready for sleep recording. Follow PI-in-a-Box setup procedures.

43. In step 50, if DSR beeps continuously & top of screen displays "Card not empty!" date, time, "O:OverW E:Append", check DSR has correct unused flash RAM.

44. If flash RAM not correct (label do not correspond to recording), press 'OK'. Screen will display "Overwrite data?", "T-Time: hh:mm:ss", press 'EXIT'. DSR stops beeping and screen will flash "Process Canceled", "T-Time: hh:mm:ss", When top of screen displays "Start recording?" and def-file, power down DSR & replace correct flash RAM.

45. If flash RAM correct (label correspond to recording but screen displays "Card not empty!"), then this flash RAM was used in a previous recording. (i.e. during recording 3 you need flash RAM 3 but this card is not empty. Then flash RAM 1 or 2 should be empty. Use empty flash RAM. Re-label flash RAMs so they match recordings).

46. After flash RAM is replaced, redo steps 35-42.

PI-IN-A-BOX ([PI]) SETUP

47. Unstow:
    [PI] ThinkPad
    DSR RS-232 Cable

Subj B does steps 48-62 while Subj A relaxes.

48. After DSR is acquiring data, connect DSR RS-232 cable to ThinkPad serial port.

49. Connect DSR RS-232 cable to DSR ONL port. (Check red dots are aligned.)

50. Power on [PI] ThinkPad. Wait for completion of boot sequence.

51. Double-click on [PI]-Sleep icon to activate PI-in-a-Box program. Verify [PI] user interface opens. If at anytime [PI] program crashes or cable accidentally unplugged, do not power down ThinkPad. Check connections, re-plug cable then reactivate [PI] program. If DSR has to be restarted, unplug [PI]. Restart recording of DSR, plug [PI] into DSR and restart [PI] program.

52. Verify DIAGNOSTICS window (bottom right of screen) reads
    "DSR<->ThinkPad comm.
    Initiating...."

indicating to initiate communication w/ DSR.

53. If DSR<->ThinkPad communication not established ("FAILURE to initiate" message displayed), follow troubleshooting procedures displayed in DIAGNOSTICS window.

54. If DSR<->ThinkPad communication established, "VERIFIED" message displayed. Verify DSR screen displays:

"remote view rec"

55. Verify [PI] displays the electrophysiological signals in [PI] Plot window (left side of screen).

May view either electrophysiological or cardiorespiratory signals by selecting appropriate button at top of [PI] window.

56. In [PI] window, immediately to right of each signal & listed under heading "STATE", [PI] uses color coded 'lights' to display status of each signal's quality state. Default/initial color AMBER, indicating "unknown". Wait approx. 20 sec. for [PI] to collect enough signal data to determine quality of each signal.

57. Signal's light displayed under "STATE" heading turns RED if signal quality unacceptable. Follow troubleshooting procedures displayed in DIAGNOSTICS window.

58. Signal's light displayed under "STATE" heading turns GREEN if signal quality acceptable. When quality of each signal acceptable (GREEN), follow procedures for physiologic calibrations.

59. Next to "STATE" column, there is an empty box next to each signal. These boxes should be checked as you verify signal quality and changes corresponding to subj cals.

60. Unplug LEMO connector of RS-232 cable from ONL port of DSR.

61. Subjs switch roles; exit PI-in-a-Box and connect RS-232 cable to other DSR that should already be recording data. Start step 51.

62. When finished, select 'EXIT' button (upper right of screen). Wait until [PI] program closes. Power off [PI] ThinkPad. Unplug serial connector of RS-232 cable from serial port of ThinkPad.

63. Stow:

[PI] ThinkPad
DSR RS-232 Cable

64. Verify DSR is recording.

65. Press event marker to mark beginning of sleep period.

References

Barlow, Richard .E. and Jerry B. Fussell. Conference on Reliability and Fault Tree Analysis, University of California, Berkeley, 1974. Chapter 1. Society for Industrial and Applied Mathematics, Philadelphia, Pennsylvania, 1975.

Bloch, Heinz P. and Fred K. Geitner. Machinery Failure Analysis and Troubleshooting. Volume 2. Gulf Publishing Company, Houston, Texas, 1983.

Faulkenberry, Luces M. Systems Troubleshooting Handbook. John Wiley and Sons, Inc., New York, NY, 1986.

Gundel, A., V. V. Polyakov, and J. Zulley. "The Alteration of Human Sleep and Circadian Rhythms During Spaceflight." *Journal of Sleep Research.* Vol. 6, pp. 1-8, 1997.

Harner, P.F. and Sannit, T. A Review of the International Ten Twenty System of Electrode Placement. Grass Instrument Co., Quincy, MA, 1974.

Hazelton L.R., N. Groleau, R.J. Franier, M.M. Compton, S.P. Colombano, and P. Szolovits. "PI in the Sky: the Astronaut Science Advisor on SLS-2", Proceedings of the Sixth Annual Space Operations and Research Conference, Houston, TX, August 1993.

Kryger, M.H., T. Roth, and W.C. Dement. Principles and Practice of Sleep Medicine. Second Edition, Chapter 89. W. B. Saunders, Philadelphia, PA, 1994.

National Aeronautics and Space Administration, Space Shuttle and Space Station Freedom Payloads Projects Office and Mission Management Office. Payload Malfunction Procedures: SLS-2. July 16, 1993.

Pate, Elisabeth M. Choice of Tools in Reliability Analysis: Fault Trees and Event Trees. Massachusetts Institute of Technology Energy Laboratory Working Paper, Cambridge, MA, 1981.

Polyakov, V.V., Posokhov, S.I., Ponomaryova, I.P., Zhukova, O.P., Kovrov, G.V. and Vein, A.M. "Sleep in Spaceflight" *Aerospace Environmental Medicine.* Vol. 28, pp. 4-7, 1994.

Rechtschaffen, A. and Kales, A. "A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects" UCLA BIS/BRI, Los Angeles, CA, 1968

Santy, Patricia A., M.D., M.S., Heidi Kapauka, M.D., M.P.H., Jeffrey R. Davis, M.D., M.P.H., and Donald F. Stewart, M.D., M.P.H. "Analysis of Sleep on Space Shuttle Missions" *Aviation, Space, and Environmental Medicine*. Vol. 59. pp. 1094-1097, November 1988.

Zhdanova, Irina V., Richard J. Wurtman, Claudia Morabito, Veronika R. Piotrovska, and Harry J. Lynch. "Effects of Low Oral Doses of Melatonin, Given 2-4 Hours Before Habitual Bedtime, On Sleep in Normal Young Humans" *Sleep*. Vol. 19, Number 5, pp. 423-431, 1996.