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APPLICATION OF MODERN NETWORK THEORY TO ANALYSIS OF MANNED SYSTEMS

by John C. Fakan

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Cleveland, Ohio 44135

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16. Abstract

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SUMMARY

The techniques of Modern Network Theory are modified and expanded to provide a generalized methodology for the analysis of systems that contain man as a functioning part.

An approach to the formulation of the systems equations that describe a human subsystem, by characterizing the phenomenological appearance of man in each of his functional roles, is described. The problems associated with metering of the significant human parameters are discussed, and a series of physiological measurements are described which indicate that human heart rate can provide a useful measure of total work output in the engineering sense.

A sample man-machine system modeled after an experience of two men involved in a representative system of this type is presented, along with a series of results which demonstrate the recovery response of this system of stochastic perturbations such as an event which prevents sleep during one of the system "nights."

A FORTRAN IV computer program developed for the analysis of this type of system is included in the appendix.

Further possible uses for the generalized methodology are suggested, including the analysis of urban renewal, finance, and social behavior problems as well as analyses of proposed manned planetary expeditions.

INTRODUCTION

The success of the Apollo Program in landing man on the Moon is most certainly only the first of what will be a series of manned expeditions to the Moon and the planets. Other types of missions which may be considered in the future include in the following:

(1) Manned orbiting research laboratories

(2) Permanent manned lunar scientific bases

(3) Manned operations for the recovery of lunar natural resources

(4) Manned planetary exploration (e.g., to Mars and Venus)

(5) Permanent planetary colony (e.g., on Mars, Venus, and/or Ganymede)

Inherent in every one of these missions is a requirement for determining in advance, and with some degree of reliability, that the mission can actually succeed in the sense not only that will the human subsystem survive but also that the objectives of the mission will be met.

By their very nature, systems that contain man as a functioning part are quite complex. Even the development of basic life-support systems has been so complex that intuition backed up by much previous experience is about all the designer has to work with. When considering a system in which man is not just a "sump" for the life-support subsystem but rather a functioning part of the overall system, the complexity of the system quickly exceeds the intuitive grasp of the human mind. Analytical techniques for studying and designing these missions are therefore not merely desirable, but may be essential.

The most advanced studies of manned missions reported in the literature (e.g., refs. 1 to 3) have employed empirical methods. Although such methods provide computer mission-study compression times of about 1000, and can handle a great number of subsystem functions, they are at present limited to treating man merely as an on-off function. Even astronauts well trained in particular tasks cannot be expected to respond with "design" performance under emergency situations, or when their physiological or psychological state is impaired for medical or other reasons. Furthermore, man has an irrational characteristic of being an unreliable judge of his own capacity for physical or mental tasks, and often exerts himself to the point of critical exhaustion in a heroic spirit. From this brief definition of the analysis problem, it is clear that an adequate methodology for manned-mission analysis must meet these minimum requirements:

(1) Treatment of man as a subsystem in a complex, interrelated, total system

(2) Description of man as a subsystem with variable performance and limited reserve capacity for each task function

(3) Compatibility with medical-diagnostic monitoring information and extensive medical case-history data, to provide accurate projections of task-ability capacity

(4) Adaptability to programming for high-speed digital computers

(5) Fast convergence to optimal solutions for normal base-line missions, for stochastic perturbations of system performance due to internal or external conditions, and for stochastic subsystem failure

(6) Allowance for adaptive reprogramming of the mission during the actual mission, particularly in the event of impairment of crew performance

In addition to meeting these fundamental requirements, the methodology should both express and define a clear basic philosophy for manned-mission analysis, and should have an assured potential for growth. The work to be reported here has shown that Modern Network Theory (hereinafter called MNT) already meets most of these requirements, and that there is every indication that the theory can be augmented and extended to meet the remainder of the requirements.

In initial formulation, the research reported in this report and in reference 4 was envisioned as a primitive step in adapting MNT to the analysis of man-machine systems. It was intended that some progress be made in extending the basics of MNT to encompass systems having man as a subsystem or component.

The results of this research investigation are reported here in a sequence best suited to understanding on the part of readers who have not specialized in network analysis. Discussions of the techniques of MNT is available, to some extent, in the literature, and the reader who desires to review these techniques is directed to references 4 to 6.

MAN AS A SUBSYSTEM

Whenever man employs any agent as a tool to mediate the accomplishment of a task, a man-machine system exists. This definition is so broad that, in general, all of man's works can be listed under the heading of man-machine systems. Even in such an abstract idea as the message an artist attempts to pass on to the viewers of his work is contained all the essentials of a man-machine system. In this case the system functions through an interplay between the device produced by the artist and those characteristics of man that relate how he "sees" and interprets the inputs to his senses.

In the less abstract man-machine systems (e.g., manned interplanetary missions systems), the main problem is to reduce the system to a mathematically defined set of interrelated subsystems. The "machine" part of these systems does not constitute a problem in itself.

The problems associated with the mathematical treatment of man are many and, with the exception of a few simple situations, have appeared insurmountable. The principal reason for this lies in the apparently overwhelming complexity of man. It seems quite clear that no device produced by man to date even begins to approach the human being in overall complexity. Nonetheless, various phases of human performance can be understood to some degree, as evidenced, for example, by the science of anthropometrics as applied to the design of the many machines which are constructed for use by man, and by the very significant amount of work that has been done on the measurement of particular characteristics of man. A large amount of progress has also been made in the technique of treating man as a black-box feedback element in various servosystems.

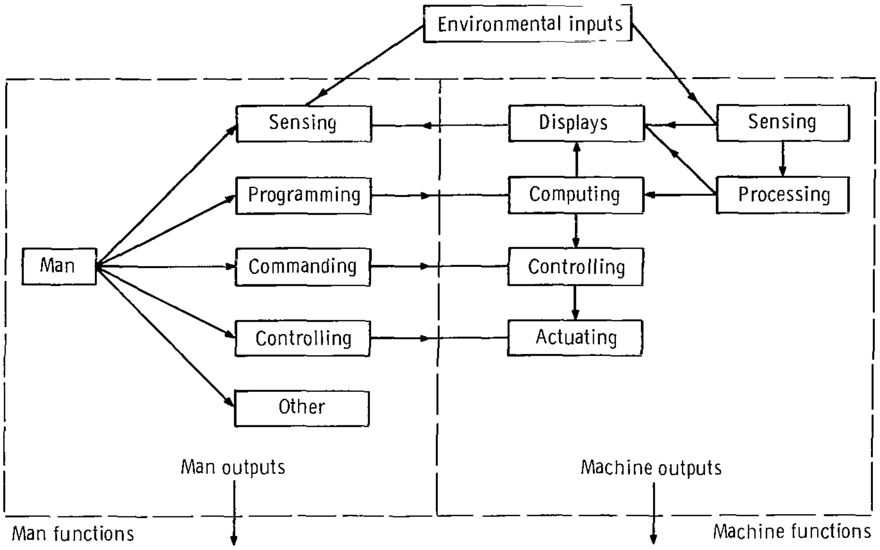


Figure 1. - Block diagram of typical man-machine system.

Man's role as a subsystem in modern day complex space systems has developed from both empirical and scientific considerations. In early man-machine flight systems, man carried out the guidance function and, in general, stabilized the system. In the development of present day space-flight systems, man's role has evolved from that of a stabilizing feedback element to that of a systems manager and a task-performing entity. Figure 1 is a block diagram as modified from reference 7 that may be helpful in visualizing man's role in a functioning man-machine system. A possibility for an approach to the human subsystem is suggested by block diagrams of this type. In every instance, man appears as a set of subsystems each coupled with other subsystems of the set of machine subsystems. This is, of course, an overly simplified picture since the human subsystems are also interconnected, but it does allow for the formulation of an approach (and the human interaction can also be included eventually). In other words, if man is considered as a set of task-performing subsystems each of which is describable phenomenologically, an MNT analysis will be possible. The formulation of the human subsystems will be suggested by each of the various roles that man assumes as a part of the overall system.

Approach

The methodology that will produce a mathematically analyzable human subsystem must be based upon knowledge of the characteristics of that subsystem and how it depends upon other human and/or machine subsystems. Consider, for instance, man in the role of a physical-task-performing subsystem. Involved in this case are man's structural, muscular, and metabolic characteristics.

As is pointed out in reference 4, a pair of variables must be defined for each subsystem for MNT analysis, and further, the variables need not represent the actual classical variables which have been historically affixed to man's characteristics. Because of the freedom allowed by this point, it was felt that a good choice of variables would be ones that were heretofore unencumbered by formal definition but still within possible reach of a set of realistic measurement (metering) techniques. The through-variable chosen for use in this subsystem is called Q and is defined as "the ability to perform tasks." (While in some circumstances "task" might appear to be "work," it should not be so read.) The across-variable chosen is called M and is defined as "the motivation or driving force that relates to the flow of Q through an elemental representation of a task." Note that by "motivation" the author does not mean to imply the specific definitions associated with the term by psychologists and others, but rather a more general idea that may become more clear in the later discussion.

Because the Q and M parameters are pure inventions of the author, they may be defined in any way whatever that fits the overall requirements of the MNT techniques. Thus it can be assumed that the requirements relating to subsystem variable pairs are met by definition, and that what remains is to define the components that make up the subsystem and to determine metering techniques that will allow measurement of the variables in a manner consistent with the summation requirements on variable pairs (ref. 4).

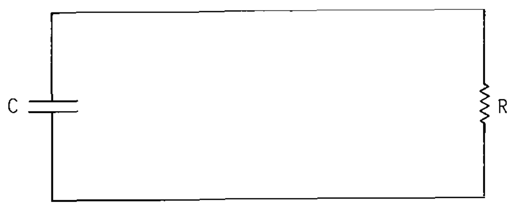
Formulation of a Model

In the case of man in the role of a physical-task-performing subsystem, it would be expected that certain assumptions can be made to facilitate the formulation of the model used to represent this subsystem. First of all, it will be assumed that man as a Q storage device is not unlike other energy storage devices. (For the case of physical task performance, Q will have the characteristics of energy.) That is to say, the gain and loss of Q in the human subsystem will behave according to an exponential law. Secondly, it is clear that for many types of tasks the "flow" of Q through that task element will be independent of M over some range. The implication here is that for these tasks the human element, or Q storage device, will have more ability than that required to just perform the task.

These characteristics are not unlike certain types of response found in many other subsystems, and because of a background in electrical engineering it is difficult for the author to avoid comparisons with a similarly behaving electrical analog which will be used as an aid in establishing the system analysis program for a sample man-machine system. This sample was used to test the ideas presented herein and further to establish the fidelity which could be achieved by a simple attempt at an analysis of a nonsimple problem. There is no intended implication that physical task performance in a man-machine system can be analoged to an electrical subsystem. The electrical circuitry to follow is used only as an aid to thought in the formulation of the model.

Consider that man in the role of a Q storage device resembles somewhat the electrical capacitor in the role of a charge storage device. Similarly, the flow of electrical charge through an electrical resistance and the resultant dissipation of electrical energy (after transformation to thermal energy) can be thought to resemble the "flow" of Q through a representative task with a resultant dissipation, or using up, of this task-performing ability. (Note that the variable Q is not otherwise related to the q that will stand for electrical charge.)

A highly simplified example of a man-machine system in the form of one man and one simple task might resemble the following schematic sketch of an electrical circuit:



where C is a capacitor and R a resistor. The electrical system equation for this arrangement would be

$$q(t) = q_o \exp\left(- \frac{t}{RC}\right) \tag{1}$$

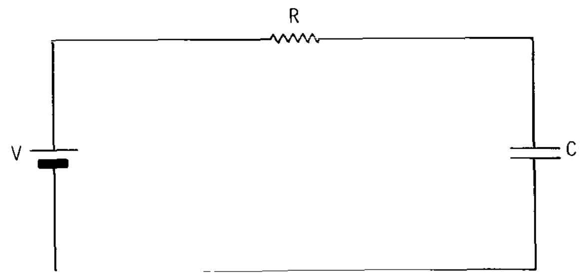
where $q(t)$ is charge remaining in the capacitor at time t, q_o is the initial charge (at $t = 0$), C is the value of the capacitor, and R the value of resistance.

The voltage $V(t)$ across the resistor at any time t is given by

$$V(t) = \frac{q_o}{C} \exp\left(- \frac{t}{RC}\right) \tag{2}$$

The intended implication is that Q and M of the man-machine system will behave similarly to the q and V of the electrical circuit. Thus, by considering the general properties of a man-machine system in the light of similar arrangements of electrical circuitry, a set of mathematical relations may be evolved that can be utilized for the analysis of such man-machine systems, provided that the proper parameter values for man can be determined and included in the relations.

The previous capacitor-resistor network was to demonstrate the equation form for a "task performance" situation. Another role to be played by man in the same type of system is one wherein man would reacquire Q (through sleep or rest). Consider the following schematic sketch whereby the capacitor is being charged by the combination of a charge source with voltage V (a battery, for example) and an electrical resistor R:



The value of charge contained in the capacitor at any time t (assuming no initial charge) is given by

$$q(t) = \frac{V}{R} \int_0^t \left[\exp\left(-\frac{t}{RC}\right)\right] dt \tag{3}$$

which becomes upon integration

$$q(t) = CV \left[1 - \exp\left(-\frac{t}{RC}\right)\right] \tag{4}$$

The basic form of either equation (3) or (4) can be used to represent the resting or sleeping state for man, where the equivalent values of V and R would be those appropriate for each man (one set for sleep and another for rest).

The very first circuit in this set of examples was intended to resemble man in the role of performing a task. However, the task represented by this circuit is not at all the usual type of task that man would address himself to, since the implication is that all of the man's M is required by the task and he is thus working at a maximum and ever

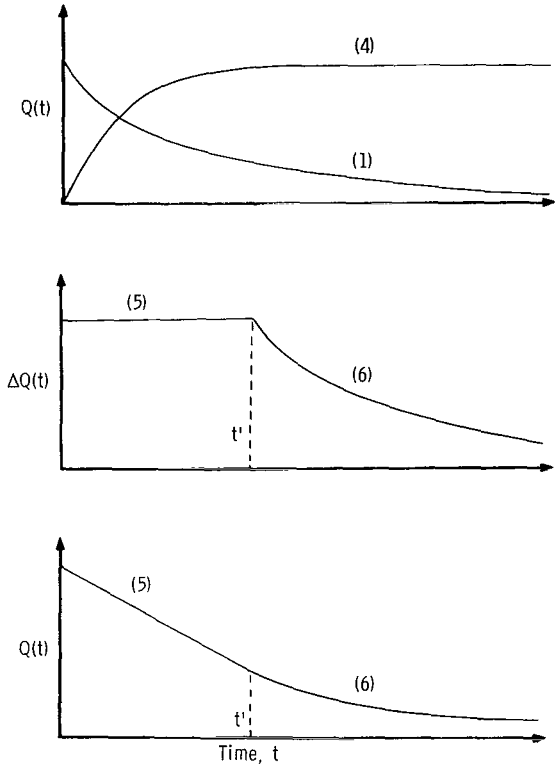
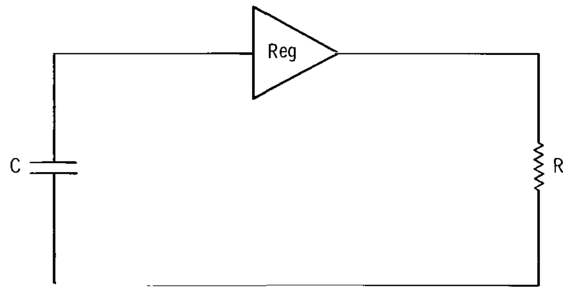


Figure 2. - Plots of the functions. The numbers refer to the equation numbers that apply to each region.

decreasing rate (i. e., the V across the capacitor and the resistor are the same and the flow of charge is at a maximum and ever decreasing rate).

A more normal situation is one where a man would initially have more than sufficient M for a given task and would perform at a constant rate until such time as he would become "tired" and would then slow down as in the first case.

A similarly behaving electrical example would be the following:



where REG is a regulator that maintains a constant current j so long as the capacitor voltage V_C exceeds $jR \equiv V^*$. The equations for such an arrangement are

$$q(t) = CV_o - \frac{V^*t}{R} \qquad \text{for } V_C > V^* \tag{5}$$

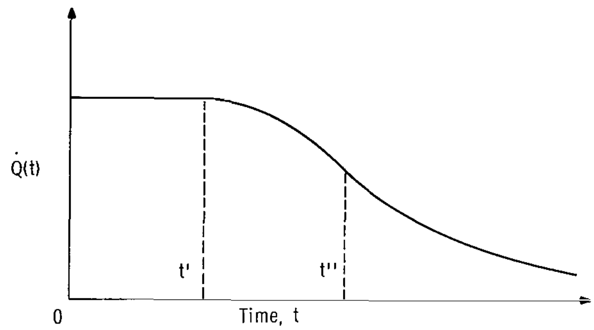
and

$$q(t) = CV^* \left[\exp\left(\frac{t' - t}{RC}\right)\right] \qquad \text{for } V_C \leq V^* \tag{6}$$

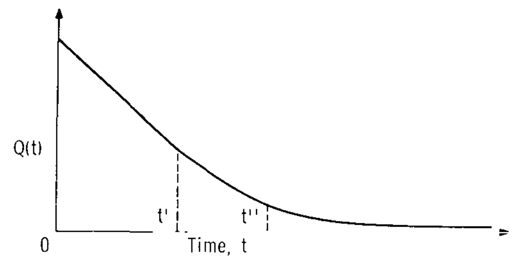
where V_o is the initial value of capacitor voltage and t' is the time at which V_C become equal to V^*.

Plots of the various function relations discussed so far in this section are given in figure 2.

It may well be that the simple RC (resistive-capacitive) functions do not adequately match the response characteristics of the human subsystem. Thus it may be that other less usual relations are required. For example, the author's experience would predict that a more descriptive plot of $\dot{Q}(t)$ (rate of flow of Q) against time would include a transition region and have the form



with the resulting Q(t) against t relation:



where the functions for $t' < t < t''$ could be simulated in a number of ways; as, for example, if the parameter equivalent to the electrical C were allowed to vary as a function of time. The response in the regions $0 < t < t'$ and $t > t''$ would still be as given by the relations in equations (5) and (6), respectively.

In this manner, a simplified schematic for a man-machine physical-task-performance system might be as shown in figure 3 where the depicted components represent the man-machine equivalent components rather than the usual electrical components. The arrows drawn through the components indicate that they may be varied either as a function of time or as a function of some other parameter.

The ability to vary the value of the so-called capacitor representing the Q storage device in the figure allows for the simulation of a number of characteristics that can be important in a man-machine system. For instance, if a subject is performing a task for a sufficiently long period that he does not have sufficient M to perform at the desired level and an emergency situation suddenly arises, a decrease of the equivalent C of the Q storage device will cause an increase in M which may well be sufficient to increase $\dot{Q}$ to the desired level. However, after the value of M again falls to the level required, the subsequent falloff of $\dot{Q}$ will be at a higher rate than before the emergency. In the author's experience, this is not unlike the response attributed to the release of

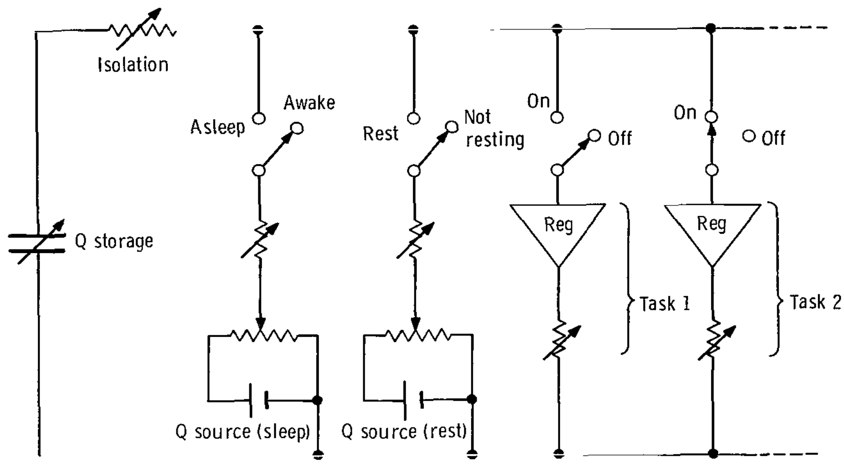


Figure 3. - Schematic representation of one man in a simple man-machine system. Condition shown: Performance of Task 2.

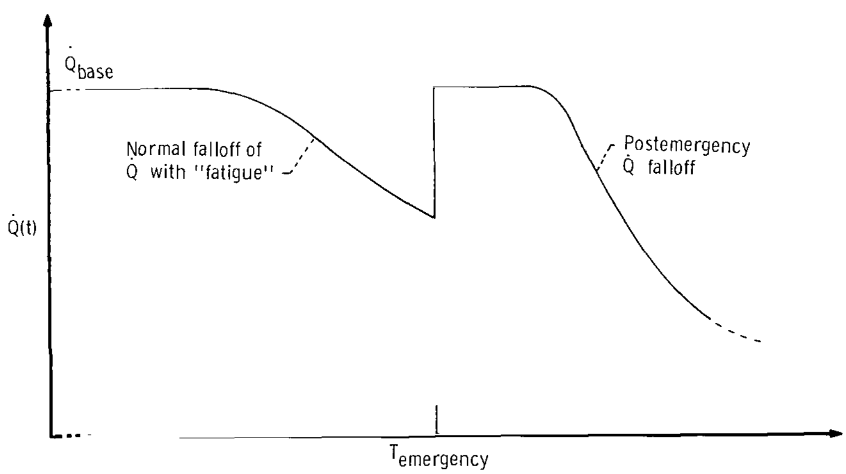


Figure 4. - Response of simulated man-machine system to an emergency situation.

adrenalin in a subject faced with this type of problem. A plot of the response just described is shown in figure 4.

Parameter Values

With the relations established in the preceding section and with the MNT techniques as described in reference 4, it would now be possible to establish a system equation set for the analysis of a given man-machine system. However, without appropriate values for the various parameters involved, nothing much could be accomplished by an attempted analysis.

Most certainly, parameter values for human subsystems must come from actual measurements made on human subjects. As was pointed out earlier, a large amount of such measuring has already been done and is available for use, although not always in a form suitable for the analysis of man-machine systems from an engineering approach to an actual system. However, much can be gained from a study of a general set of situations that would then be applicable to more specific situations which would later arise in the analysis of actual systems.

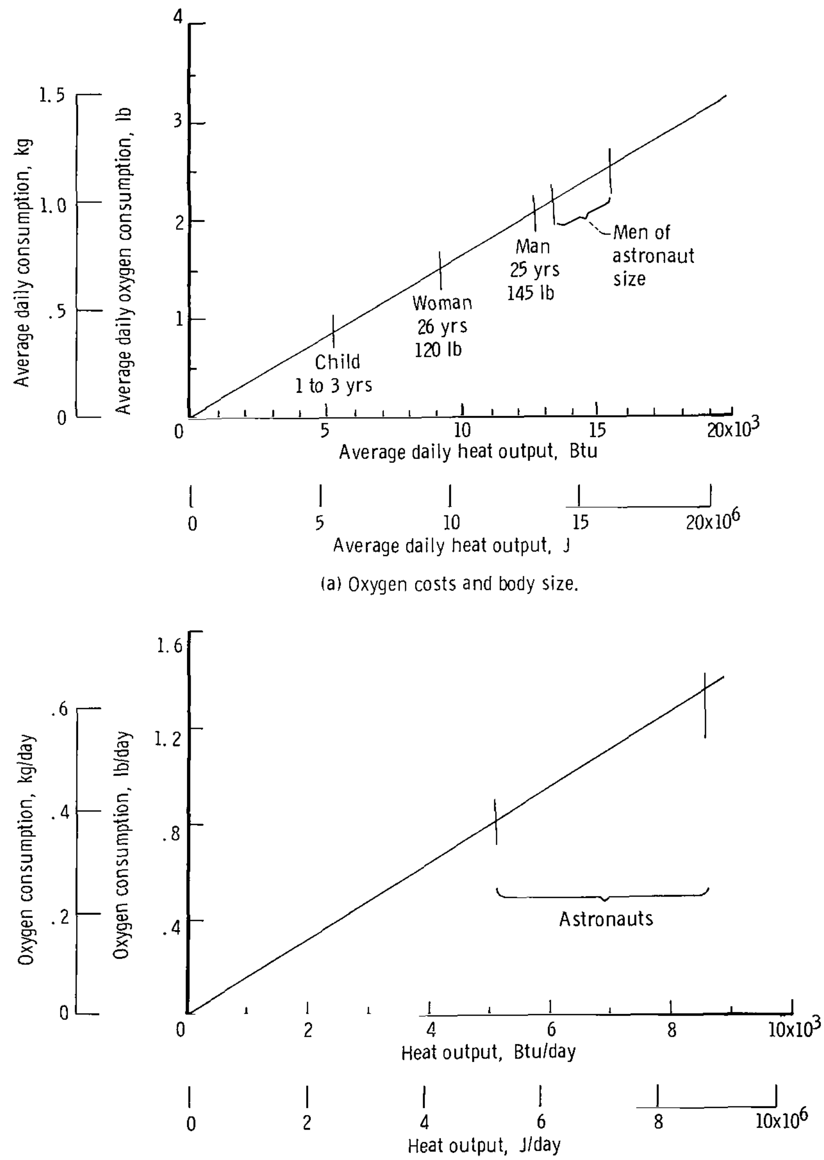
Consider, for example, the type of human performance data available in reference 8 that pertains to the energy costs involved in the performance of various tasks, as determined by a measurement of the oxygen consumption of various subjects during the performance of these tasks, of which table I is an example. Since the values given are

TABLE I. - OXYGEN COSTS OF ACTIVITIES

Activity	Oxygen consumption, kg/hr	Energy expenditure		Work rate, W
		Btu/hr	J/hr	
Asleep:				
Sleeping, men over 40	0.018	260	76.2	76.2
Sleeping, men aged 20 to 40	.023	280	82.0	82.1
Sleeping, men aged 15 to 20	.023	300	87.9	87.9
Resting:				
Lying fully relaxed	.023	290	85.0	85.0
Sitting at rest	.032	400	117.2	117.2
Very light activity - seated:				
Writing	.032	430	126.0	126.0
Typing	.041	550	161.2	161.2
Light activity - standing:				
Washing clothes	.068	890	260.8	260.9
Scrubbing	.082	1130	331.1	331.2
Moderate activity:				
Rowing for pleasure	.091	1190	348.7	348.8
Cycling at 8 to 11 mph	.100	1360	398.5	398.6
Chopping wood	.109	1480	433.6	433.8
Army drill	.127	1690	495.2	495.3
Heavy activity:				
Swimming breast stroke at 1.6 mph	.145	1950	571.4	571.5
Digging	.159	2120	621.2	621.4
Rowing with two oars at 3.5 mph	.195	2620	797.0	767.9

constants, it is clear that they represent only the steady-state case for constant-rate task performance and not the general case where the performance would be as shown in the last section. Also, it is seen that no indication of any idea such as "recovery" of task-performance ability is given by such data. We can, however, through energy balance techniques, determine a suitable set of Q-cost and Q-gain rates from the data given. A first assumption will be that given sufficient dietary intake the ability to perform physical tasks will be a unique function of the work-rest-sleep history of a subject.

The plots of figure 5 (as modified from ref. 8) show that men of astronaut size can



(a) Oxygen costs and body size.

(b) Cost of tissue maintainence.

Figure 5. - Metabolic parameters for humans.

be expected to expend about 15 000 Btu's of energy per day, of which about half is expended to maintain the body. This basal rate of energy expenditure will be assumed to take place over the entire 24 hours of every day. Its value on a per-hour basis will thus be about 290 Btu per hour. The light activity that might be performed continuously over an 8 hour work day has a value of approximately 1000 Btu per hour (table I). If, for the sake of simplicity, in this type of task performance we assign a scale to Q such that one unit of Q corresponds to 1 Btu of energy, then the total expenditure of Q in a typical day for a typical subject of astronaut size and weight would be as follows:

$$
\begin{array}{lrl}
\text{24 Hours at 290 units/hr} \cong & 7\,000 & \text{units/day} \\
\text{8 Hours at 1000 units/hr} = & \underline{8\,000} & \text{units/day} \\
\text{Total } Q \text{ expenditure} \quad = & 15\,000 & \text{units/day}
\end{array}
$$

Since all of this Q must be regained through sleep and rest, it is now possible to estimate the average ΔQ values for these two functions. If the typical subject is assumed to sleep for 8 hours each day leaving 8 hours for rest,

$$8 \times \Delta Q_{sleep} + 8 \times \Delta Q_{rest} = 15\,000 \text{ units/day}$$

If, for the sake of a unique solution, the sleep rate is assumed to be twice the rest rate,

$$\Delta Q_{sleep} = 1250 \text{ units/hr}$$

and

$$\Delta Q_{rest} = 625 \text{ units/hr}$$

The Q balance required over a full day to maintain a steady-state condition is thus satisfied; that is,

$$\sum_i \Delta Q_i H_i + \sum_i \Delta Q_j H_j = 0$$

where ΔQ_i is the rate for tasks performed, ΔQ_j is the rate for sleep and rest, and H_i and H_j are the hours of time each event is performed. All ΔQ_i will be negative since they represent a loss of Q from the subject.

Metering

In order to analyze a subsystem, it is most desirable to be able to determine the values of the various variables of the subsystem by some convenient metering technique. In electrical, mechanical, hydraulics, and other areas, the conception and development of meters has grown with the discipline itself, and with minor changes in use and interpretation of existing meters it is possible to provide metering techniques that are compatible with the MNT methodologies in the analysis of subsystems from each of these areas. In the analysis of human subsystems, this is not at all the case. Of course, there are really no Q meters or M meters in existence. The problem is not so much a lack of meters as such, but really one of metering the appropriate variables in a manner consistent with the requirements.

If an analysis of a man-machine system is to be made and compared with an actual system, it is mandatory that at least one of the two variables of the Q, M pair be measurable in some sense. (If a subsystem element has been defined and one of the variables measured, the other variable can, in general, be derived by calculation.) In an attempt at determining the value of the standard physiological variables as a measure of the desired variables, a search of the literature was undertaken.

A most clear result of this search was that there are large amounts of data that indicate that performance of muscular work results in measurable changes in such physiological parameters as respiratory rate, heartbeat rate and volumetric rate, oxygen consumption rate, carbon dioxide expiration, and others. Of these, heart rate is by far the most easily measured and interpreted. Another advantage of heart rate is that the literature indicates the existence of a rather simple functional relation between this parameter and total body work. Total body work is measured by gas analysis techniques that measure oxygen consumption and carbon dioxide production. The gas analysis technique produces a measurement that would seem to be a good metering basis for the Q variable. However, the complexity of the analysis and the effect of the apparatus on human subjects makes the technique appear most undesirable, especially for preliminary work.

A further argument for the heart rate measurement is that, although gas analysis may provide a more accurate measure of total internal work, the parameter of interest is actually work done on the environment, or "external work." Measurements reported in reference 9, for example, would indicate that either oxygen consumption rate or heart rate would be suitable for making preliminary measurements on the correlations that might exist between either parameter and the external work (or Q) for a subject.

A series of measurements of heart rate as a function of physical task performance were made on a small sample of subjects over a rather extended period of time. The equipment utilized for these measurements consisted of an electrocardiac monitor, a

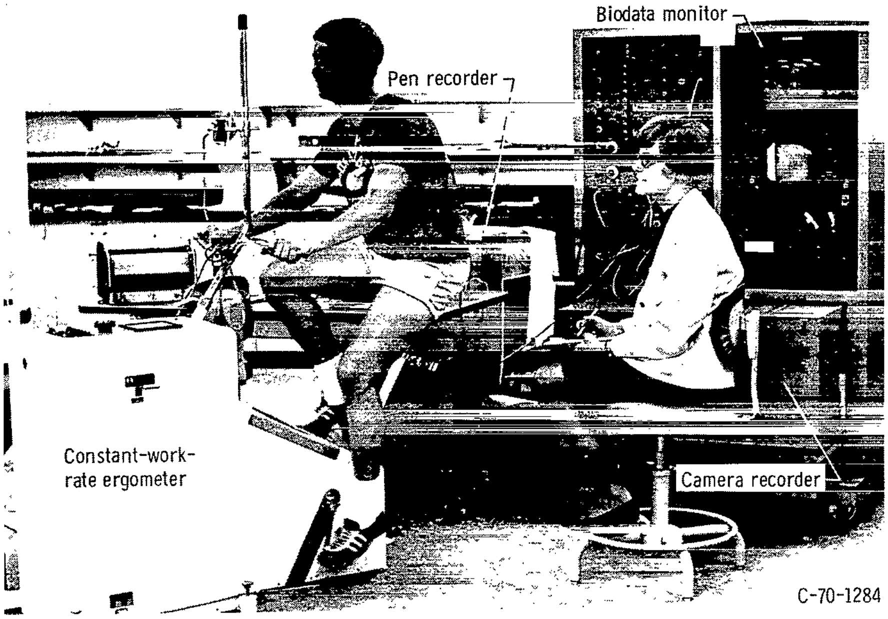


Figure 6. - View of exercise physiology laboratory showing some of the equipment used in this study.

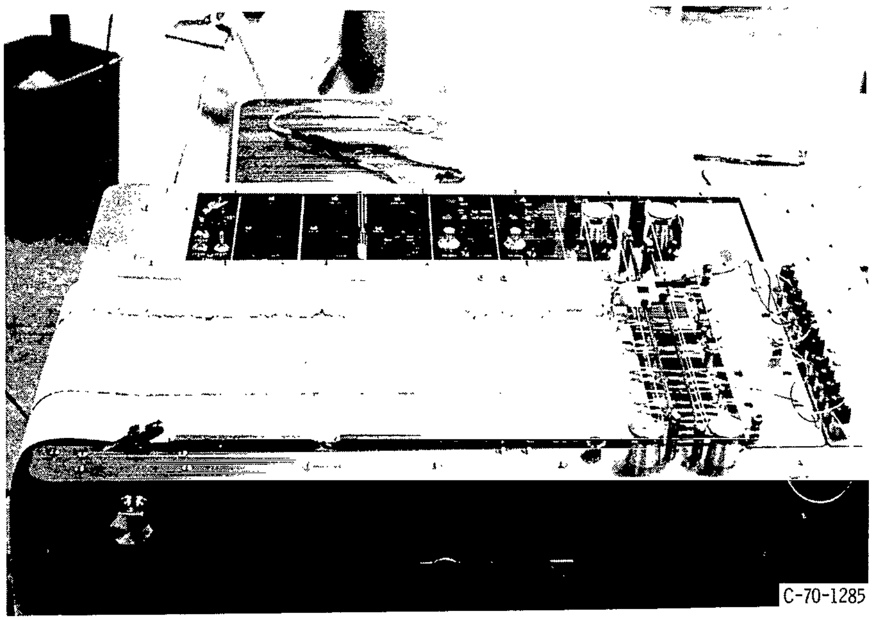


Figure 7. - Pen-type physiological data recorder.

cardiotachometer, two recording oscillographs (one pen-motor type and the other a cathode ray tube - camera type), and a constant-work-load bicycle ergometer. This equipment is shown in figures 6 and 7.

The subjects were male college student volunteers and were chosen with the idea of approximating the stamina and physical build of astronauts. For example, while none of the subjects were athletes, all were in what the author would term "good shape." Two of the subjects were involved in an abnormal amount of outside bicycle riding for pleasure, and one had been involved in competitive cycling on at least one occasion in the year preceding the experiments.

The experiments were done in two phases. Initially, each subject was subjected to a work load of 130 watts (~800 kg-m/min) for 19 minutes, followed by a 1-minute rest period. This was repeated six times for a total run time of 2 hours. The subjects were, in general, told to pedal the ergometer at any rate that seemed comfortable to them. Almost invariably all subjects preferred a rate of about 65 rpm, as indicated on a tachometer that was mounted in the visual field of the subject. At higher work rates used in the second phase of the experiment, all subjects increased pedalling speed to over 90 rpm (the limit of the tachometer). During the entire run, the subject's electrocardiac output was monitored and recorded.

One problem encountered was the large noise levels from the ECG leads which resulted in many artifacts in the recorded data and which tended to obscure the desired signals. This problem was satisfactorily solved through modifications of the electrode application technique. It was determined that the majority of the noise signals were caused by the large amounts of perspiration resulting from the relatively high work load. (The intent was to have the subjects work at a level that would be nominally high, but not so high as to cause fatigue of the musculature used by the subject in performing the ergometer task.) The perspiration caused problems by at least two different mechanisms. The primary action was to cause loosening of the adhesive patch that held the silver electrode terminals to the abdominal epidermis (see fig. 8). The loosened electrode would then move in and out of contact with the subject causing large noise pulses and periodic loss of the ECG signal. Secondly, droplets of perspiration that ran down from above the electrodes would cause noise pulses as they crossed the electrode area.

The first part of the problem was adequately solved by topical application of a standard aerosol-borne antiperspirant prior to the installation of the ECG electrodes. This one application was usually sufficient to prevent electrode detachment over the 2-hour run period.

To control the other part of the problem, the upper two ECG electrodes were located high on the chest wall and all adhesive patches were then covered with a large square (~16 sq in.) of an adhesive-backed felt-like material available from the Johnson and Johnson Company under the trade name "Mole Skin." This material is highly ab-

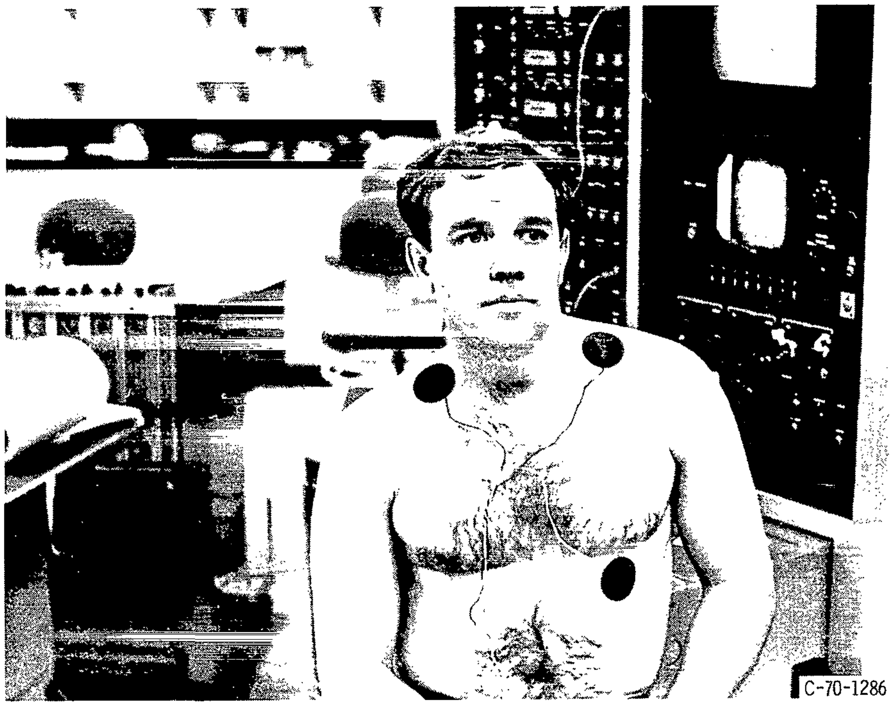


Figure 8. - Electrode placement on test subject.

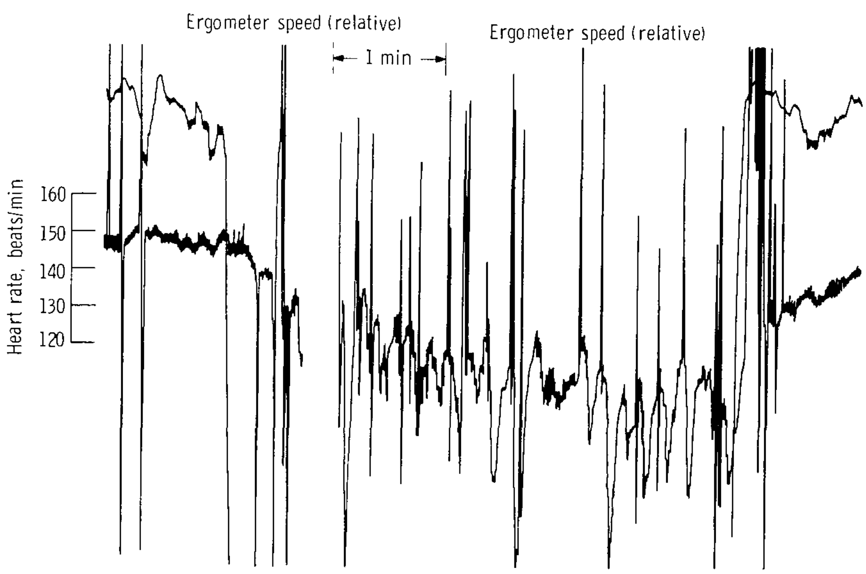


Figure 9. - Typical data record prior to modification of ECG electrode mounting procedure.

sorbent and adequately prevented problems of the second type.

As the electrode in the region of the subject's waist was subjected to a large amount of motion in the performance of the ergometer task, a further precaution was taken to ensure the stability of this electrode. This was done by loosely wrapping a nonadhesive elastic bandage (called an "Ace" bandage) around the subject's waist so as to cover and hold this electrode.

The resulting signals were then exceptionally free of artifacts and were completely analyzable. Figures 9 and 10 are "before and after" samples of the improvement, as represented by the pen recorder output of heart rate as measured on a beat-to-beat basis by the cardiotachometer.

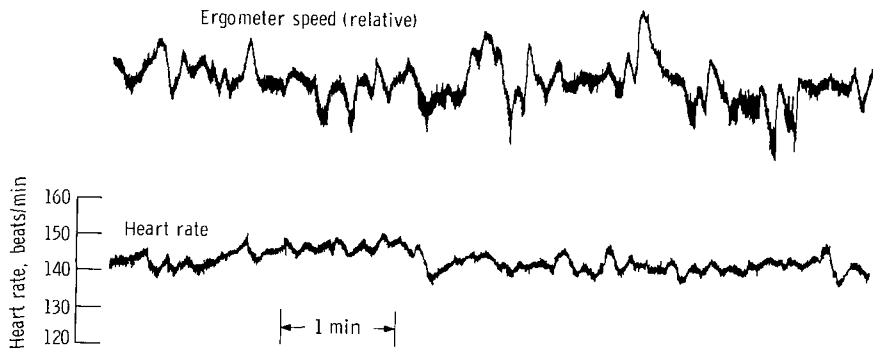


Figure 10. - Artifact-free data record made possible by modified ECG electrode mounting procedure.

Tests on four different subjects were then run almost daily over a period of approximately 3 months. Samples of the heart rate data obtained showed that an individual subject's rate would climb to some value while under the physical stress of the ergometer task within the first minute or sooner and would not significantly vary from this value until the task was stopped for the 1-minute rest period. The repeatability for each subject over the entire time of the first phase of the experiment was very high and only one of the subjects showed signs of "training" over the first 10 runs, as indicated by a faster cardiovascular response to the onset and termination of the task. (Training refers to an increase in efficiency with experience.)

A typical example of the rapid cardiovascular response observed in some of the test subjects is displayed in figure 11.

An unexplained phenomenon observed in these experiments was a notch or dip, in the heart rate data, that occurs shortly after the beginning of the task and while the increase in the rate is still rather high. The appearance of this dip is reminiscent of the response of regulated systems that are controlled by two regulators, one which is fast

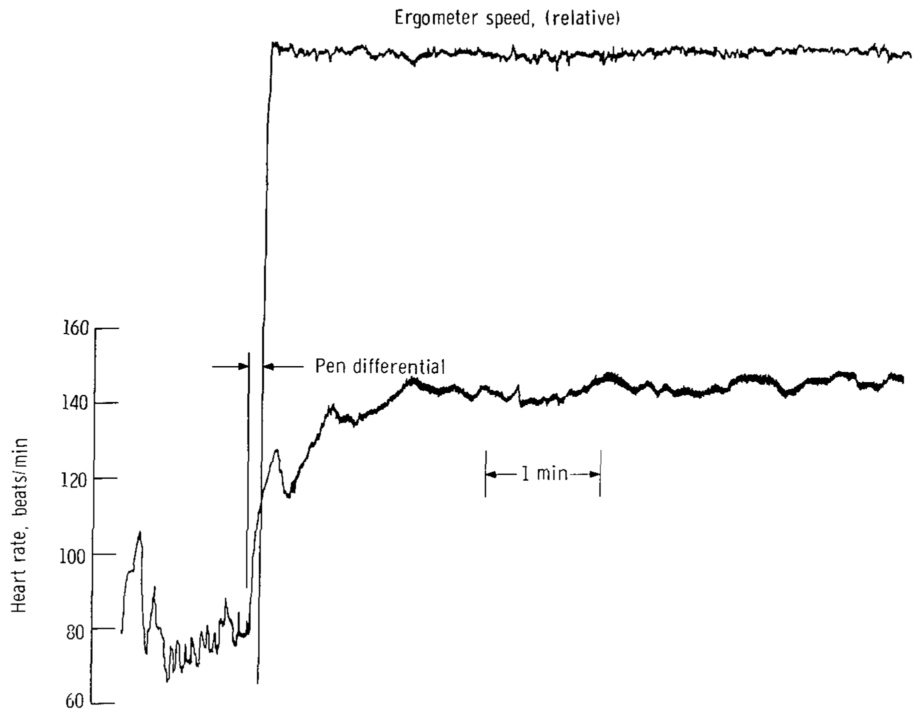


Figure 11. - Heart rate as a function of time for work rate change from 0 to 130 watts.

but coarse and another which takes over when the desired value is approached and then exerts the fine control of the regulated parameter. A search of the literature did not reveal any explanation or corroboration of this effect, but this may be expected since the heart rate is rarely measured on a beat-to-beat basis and the anomaly clearly would not show up in measurements made in the usual manner (i. e., averaging over some fraction of a minute).

In the second phase of the experiment, the subjects were stressed at various work loads from zero to near maximal (as determined from ref. 9) and the heart rate was again recorded (e. g., fig. 12). Observations were also made on the standard Lead II ECG pattern in an attempt at determining if any other effects of the stress would show up and perhaps be useful in the analysis of the individuals working capacity. It was observed that the time of cardiac diastole (the time during which the ventricles fill) is drastically shortened at high heart rates, which probably places at least one limit on the maximum work rate for an individual subject.

Also, during this series of runs, the subjects were asked to pedal at a number of different speeds over a range from 20 to 90 rpm with the work load maintained constant at some value. Without exception, there was no detectable change in heart rate noted as a function of ergometer speed. (A later series of runs during which the subject wore an actual Gemini space suit pressurized to a value just greater than half the 3.6 psi nor-

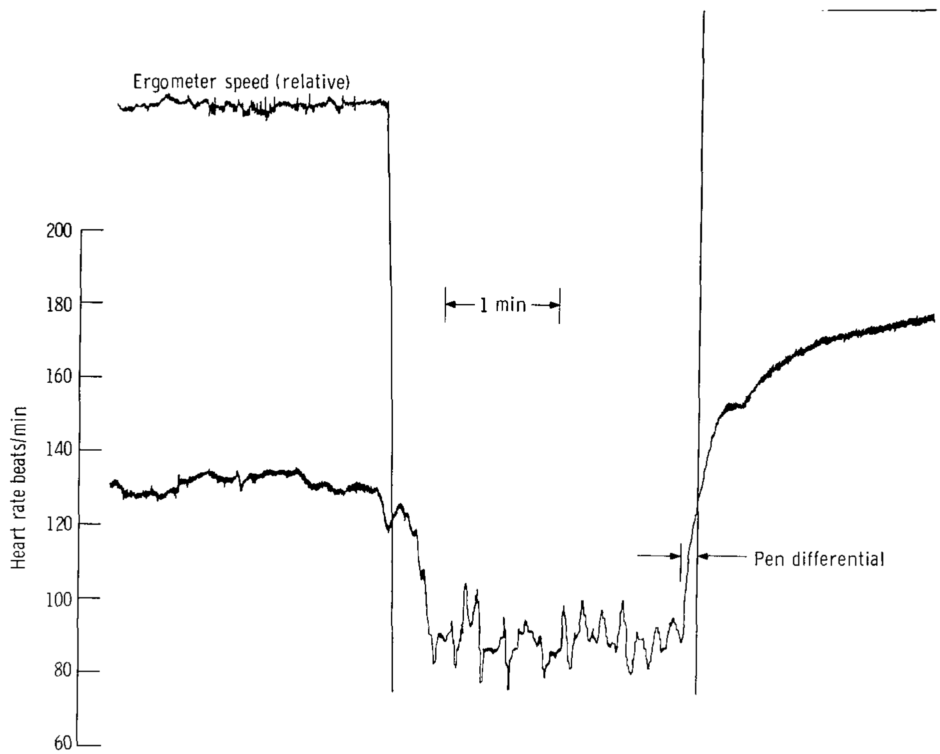


Figure 12. - Heart rate as function of time for work change from 100 to 0 to 300 watts.

mally encountered during Gemini flights showed a marked effect of pedalling speed on heart rate. This was due, of course, to the large amount of resistance encountered in merely bending the legs of the suit against the pressure differential across the suit fabric.)

A computer program was written to perform a statistical analysis of the data obtained. A small sample of typical results is shown in figure 13.

From the results obtained in this series of experimental runs, it can be seen that an extremely high degree of correlation exists between an individual subject's heart rate and the amount of ergometer work being performed. It is also rather interesting and useful that the data show a strong linear relation, which is always desirable in any metering technique.

The heart rate for no work (i. e., resting) for each subject was observed to be substantially higher during the half-hour period following the work session as compared to the prework rate as measured after attachment of the electrodes but preceding any ergometer activity. This effect was as expected, but the resting rates observed throughout the experiment were found to be remarkably constant. It appears as if the human cardiovascular subsystem has two values of resting heart rate; one value not related

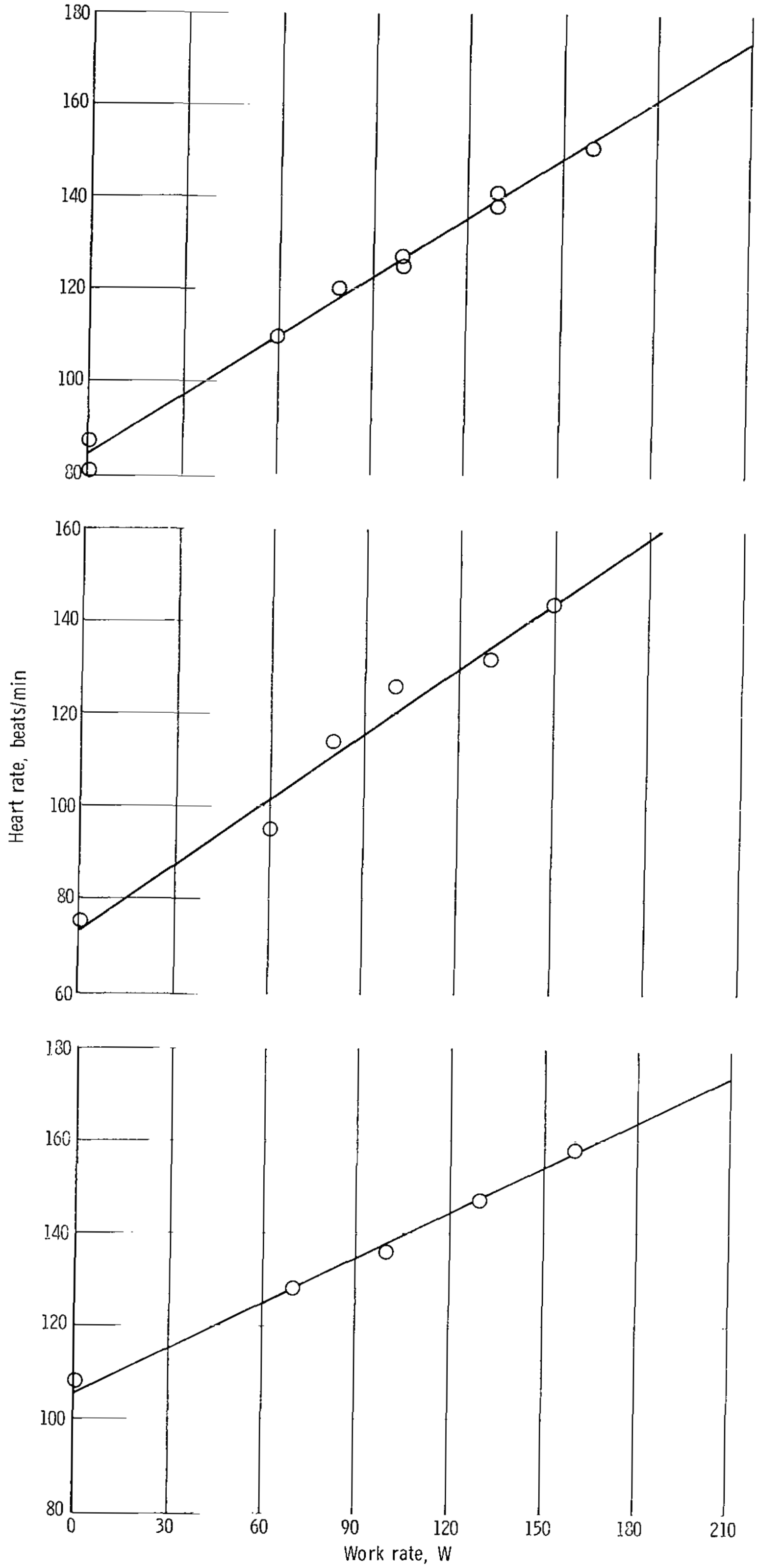


Figure 13. - Heart rate as function of work rate data with computer-calculated regression line.

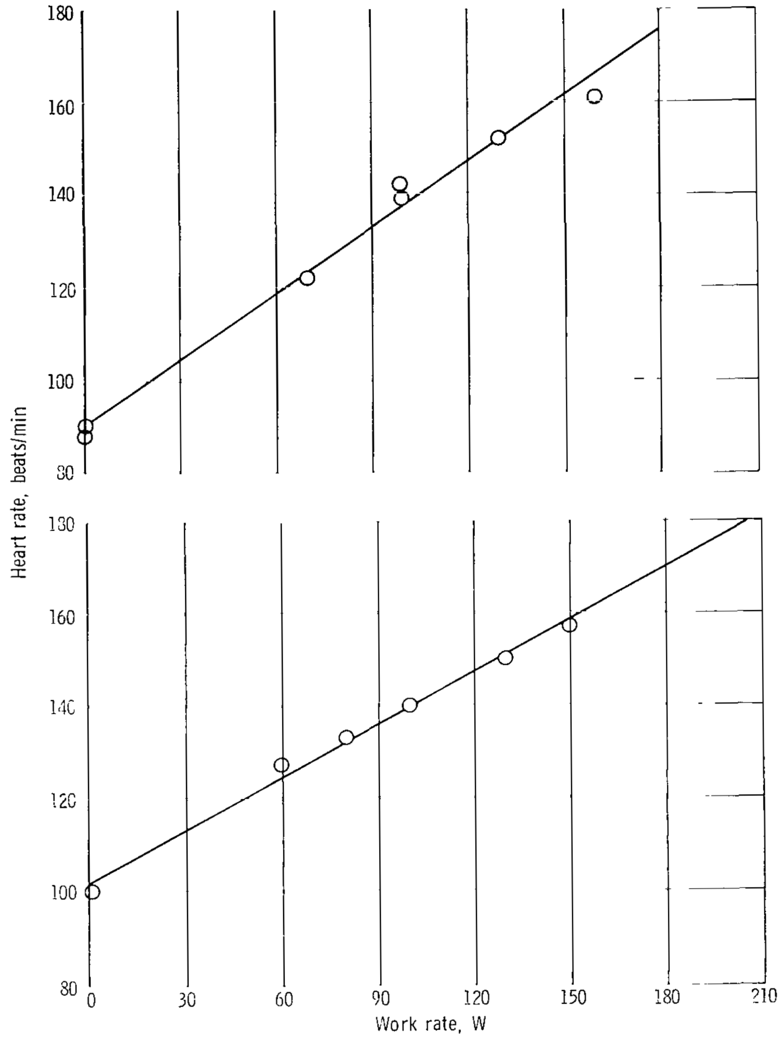


Figure 13. - Concluded.

to the performance of work, and a higher rate maintained while the body is making up the so-called "oxygen debt" incurred when the muscles use metabolic materials faster than they are supplied.

The zero-work heart rate values, measured after the task performance were the values used in the analysis of the data, since these values showed an extremely high correlation with the work data. Figure 14 displays the data obtained with one of the subjects along with the prework heart rate.

The differences in response displayed by different individuals is certainly not unexpected and clearly indicates the need for analytical techniques that allow for the inclusion of individuality. It was also noted that small differences could be found in the re-

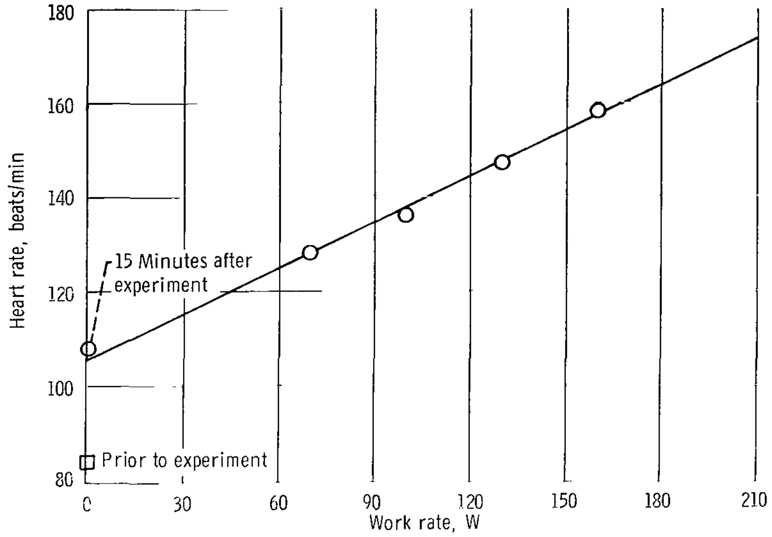


Figure 14. - Data from one subject with prework resting heart rate also displayed.

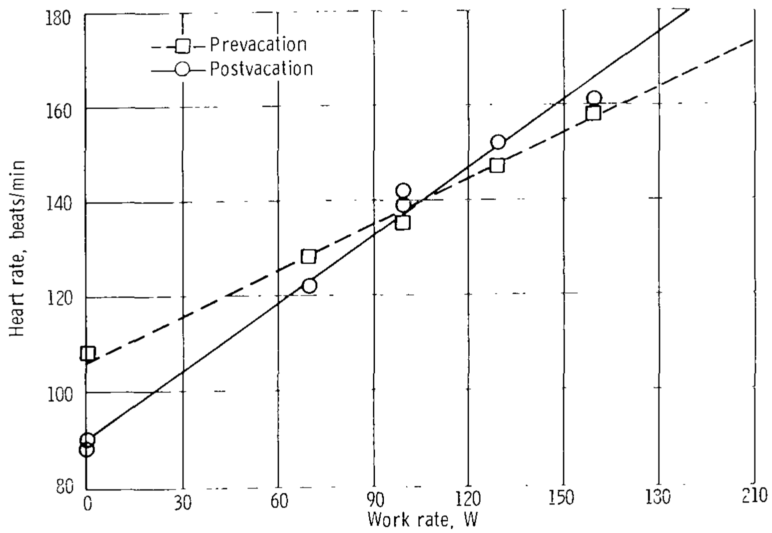


Figure 15. - Change in response in one subject due to approximately 3 months of relative inactivity.

sponse of any one individual subject, as for instance, after the end of the summer vacation session during which no tests were run on the regular subjects, there were evident differences in the response of each subject as compared with his presummer response. No attempt was made at correlating the changes with the type of summer activity pursued by each subject. After a short period (about 2 weeks) each subject returned to a response which was similar to his presummer response. Figure 15 shows the amount of change displayed by one of the subjects who attended classes during the summer session and reduced his physical activity somewhat over this period.

Because of the location of the laboratory used for these experiments (altitude about 5000 ft) and because of the limited scope of this phase of the overall program, there are, of necessity, certain limitations to the value of the particular data. The bicycle ergometer was the only device available that could provide a known work input or task-performance rate for a human subject. Because of the nature of this task (i.e., involvement of the large muscles of the body and the pneumo-cardiovascular system), it is hoped that the results are indicative of general situations involving nonmaximal physical task performance.

ANALYSIS OF A MAN-MACHINE SYSTEM

The preceding sections have described a methodology for the analysis of manned systems in general, and have demonstrated that the human subsystem is also "meterable" in the engineering sense, at least for one important human function. It would appear that nonhuman subsystems are, for all practical purposes, at a state where analysis by MNT techniques is both possible and feasible at this time. It would appear that human subsystems are not nearly as amenable to this same methodology, due to a lack of information and perhaps to oversimplification, as are the other subsystems to be found in any typical man-machine system.

In an attempt at evaluating the usefulness of man-machine systems analyses that include man as a nontrivial subsystem but depend upon simplified human subsystem parameters, a sample system was conceived and set up for analysis on a digital computer. The intent was to require the performance of more than one task by the human subsystem according to some prearranged schedule and to then observe the response of the overall system with the passage of time.

Description

In considering various existing man-machine systems that would fit the scope and intent of this research, the author learned of a feat undertaken by two men which seemed to meet the requirements. Reference 10 describes this project in which two men rowed a boat across the Atlantic Ocean from Cape Cod to England in a period of 92 days. The activities of these two men over the course of a typical day are quite well defined as clearly each was either sleeping, rowing, or engaged in a period of relative inactivity.

An estimate of the average amount of work done by each man was possible since the total distance traveled was known, as was the time for the completion of the journey. Certain assumptions were made which greatly simplify the analytical procedures and indeed made the analysis possible. The first of these assumptions was that the two men were identical with respect to the task performance parameters that were used in the analysis. Secondly, it was assumed that, given sufficient dietary intake, the ability to perform tasks (i. e., the amount of Q contained by the human subsystem) is a function only of the sleep-rest-work history of the subsystem. Thus, Q is regained through sleep and rest, and is dissipated in the performance of one simplified muscular task.

In the initial analysis program, the following constraints were imposed on the system:

(1) Ordinary 24-hour days are to be considered.

(2) Both men sleep at "night" for 8 hours.

(3) During the 16-hour "day" either one or the other of the men is rowing while the other rests.

(4) All pertinent parameters are independent of time.

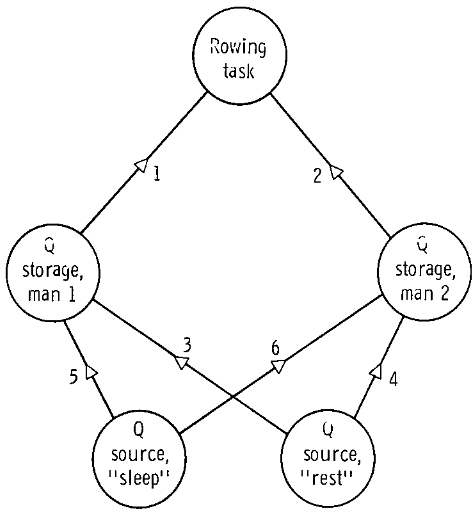
Although the boat rowing venture was used as the "model" for this sample man-machine system, an almost complete lack of actual data from reference 10 precluded any analysis of the actual mission. The intent was merely to analyze the idealized situation of two identical men rowing an idealized boat within the limits imposed by the assumptions and the constraints, and to then determine through consideration of the results if the approach would have any merit in analyzing and predicting the performance of similar real systems.

System Equations

The ideas developed in the section MAN AS A SUBSYSTEM and those in reference 4 were utilized in forming the system equations for this man-machine system. Figure 16 is a schematic of the system model used. (Fig. 16 is not a "graph" in the MNT sense since the apparent vertices have properties and would actually be elements of the system graph. A graph of the system appears in fig. 17.) Time period A1 means that man number 1 is working (denoted by the A) and that this is the first work shift of the day (denoted by the 1). Thus B1 means that man number 2 is working, and again this is the first shift (or work period). Condition C puts both men to "sleep." The elemental equations used were adapted from those derived in the section MAN AS A SUBSYSTEM, namely,

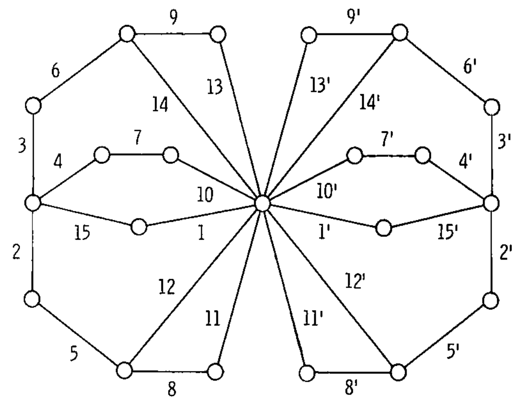
(1) Sleep and rest: equation (4) with appropriate values for the parameters to differentiate between sleep and rest

(2) Work: equations (5) and (6)



Time period	Conducting paths					
	1	2	3	4	5	6
A1	1	0	0	1	0	0
B1	0	1	1	0		
A2	1	0	0	1		
B2	0	1	1	0		
.						
.						
.						
An	1	0	0	1	↓	↓
Bn	0	1	1	0		
C	0	0	0	0	1	1

Figure 16. - Simplified schematic of man-machine system.



Elements	Function
1, 15	Q storage
2, 3, 4	Task selection
5, 8, 11, 12	Q source (sleep)
6, 9, 13, 14	Q source (rest)
7, 10	Work task

Figure 17. - Graph used for establishing system equation for two-man boat-rowing man-machine system. (Unprimed numbers refer to man 1, primed numbers refer to man 2.

These equations were not employed directly, either in their differential or integral forms. For digital computer solutions, the simplest approach is one which specifies the increase in Q to be expected in a fixed time interval as a function of the prevailing values of all the parameters at the start of the time interval. One could justify as a crude approximation

$$\Delta Q(t_1, t_2) \approx (t_2 - t_1)\left(\frac{dQ}{dt}\right)_{t=t_1}$$

where dQ/dt is obtained from the differential form of equations (3) to (6). However, the use of equations of the preceding form can also be justified by another argument. Remembering that the electrical analogs used to derive the initial set of equations were intended only as analogs, it can be hypothesized that the man-system equations are such that equations of the form

$$\Delta Q(t_1, t_2) = \alpha + \beta Q(t_1)$$

exactly represent the behavior for a particular value of the time interval.

In the analysis, the values of t spaced by 6-minute intervals (1/10 hr) were chosen.

The sleep/rest equation was taken as

$$\Delta Q(t_1, t_2) = \frac{A - Q(t_1)}{B} \tag{7}$$

where $\Delta Q(t_1, t_2)$ is the change in Q(t) over the interval t_1 to t_2, A and B are constants, and $Q(t_1)$ is the value of Q at the time t_1 (the beginning of the interval).

For the work task, the following equation form was used:

$$\Delta Q(t_1, t_2) = \begin{cases} -C & \text{for } Q(t_1) > F \\ \dfrac{Q(t_1) - D}{E} - C & \text{for } J < Q(t_1) < F \\ \dfrac{G - Q(t_1)}{H} - C & \text{for } Q(t_1) \leq J \end{cases} \tag{8}$$

where C, D, E, F, G, H, and J are constants, and again $\Delta Q(t_1, t_2)$ and $Q(t_1)$ are as previously described. Note that in this equation $Q(t_1)$ affects not only the ΔQ but the form of the equation as well.

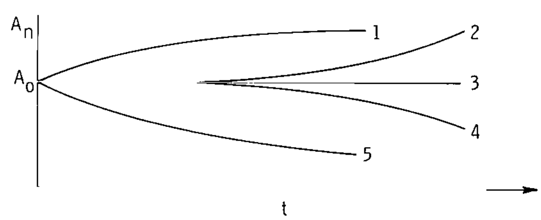
Equation (8) is actually a bit more elaborate than equations (5) and (6) because it also includes a transition region (as discussed earlier) to smooth the change from one function to the other. When J is chosen to be equal to F, equation (8) is fully equivalent to equations (5) and (6).

Initial runs of the computer program showed that, indeed, the response of such an idealized system could be determined by the methodology described herein and, despite the simplifications invoked, the results were definitely nontrivial.

Because of the availability of a considerably larger and faster digital computer than the one used for the first set of analyses, it was decided to elaborate on the system equations to allow for the inclusion of other pertinent parameters as they become available. For instance, it was felt that "learning" or improvement in the performance of a task with practice was a significant phenomenon and should be allowed for in the system equations. Also, that characteristic of man to become inefficient over a longer period of time (due to what might be called "boredom," or for some other reason) should certainly be included. Therefore, the systems equations were modified and equation (7) became

$$\Delta Q(t_1, t_2) = \frac{A_n - Q(t_1)}{B_n} \tag{9}$$

where the difference is that the "constants" are no longer constant, in the sense that they can now vary with the passage of time in any of five different ways. These five ways are shown for A_n in the following sketch:



where A_o is the initial value of A. Values of A_n are determined by the following relation:

$$A_n = A_o + \alpha_A \exp(\beta_A t)$$

where α and β are parameters that are chosen to produce the desired shape in the time response curve (curves 1 to 5) in the preceding sketch.

The work-performance equation (eq. (8)) becomes

$$\Delta Q(t_1, t_2) = \begin{cases} -C_n & \text{for } Q(t_1) > F_n \\ \dfrac{Q(t_1) - D_n}{E_n} - C_n & \text{for } G_n < Q(t_1) < D_n \\ -\dfrac{Q(t_1)}{H_n} & \text{for } Q(t_1) \leq G_n \end{cases} \tag{10}$$

where other modifications from equation (8) are due to boundary conditions such as

$$Q(t) \geq 0 \qquad \text{for all } t$$

which results in

$$\frac{G_n}{H_n} = C_n \qquad \text{for all } t$$

$$G_n > 0 \qquad \text{for all } t$$

The values for the "constants" are determined by the following relation:

$$P_n = P_o + \alpha_P \exp(\beta_P t) \tag{11}$$

where P is any of the parameters A to H and α and β are provided as required to shape each of the parameters as required. (Note that t is a "counter" rather than a continuous variable.)

A new digital computer program was then written which utilized the more flexible equations and which also included the following advantages over the previous program:

(1) Up to eight men may be included.

(2) Up to 10 tasks may be included.

(3) Each man is an "individual."

(4) No restrictions are put on the scheduling of tasks (including rest-sleep tasks).

Advantages 1 and 2 are not really limited as indicated and can be easily increased to any reasonable value, consistent with the capacity of the particular computer being used, by a simple modification of the program.

This computer program, along with a description of the various parameter definitions, is given in the appendix.

Results

A set of test cases for various sets of data input with α, β was run to test the program and to demonstrate the inherent response of the two-man rowing system described earlier. Figure 18 shows a plot of the computer output data for inputs corresponding to the expected "steady-state" system performance with 4-hour work shifts and

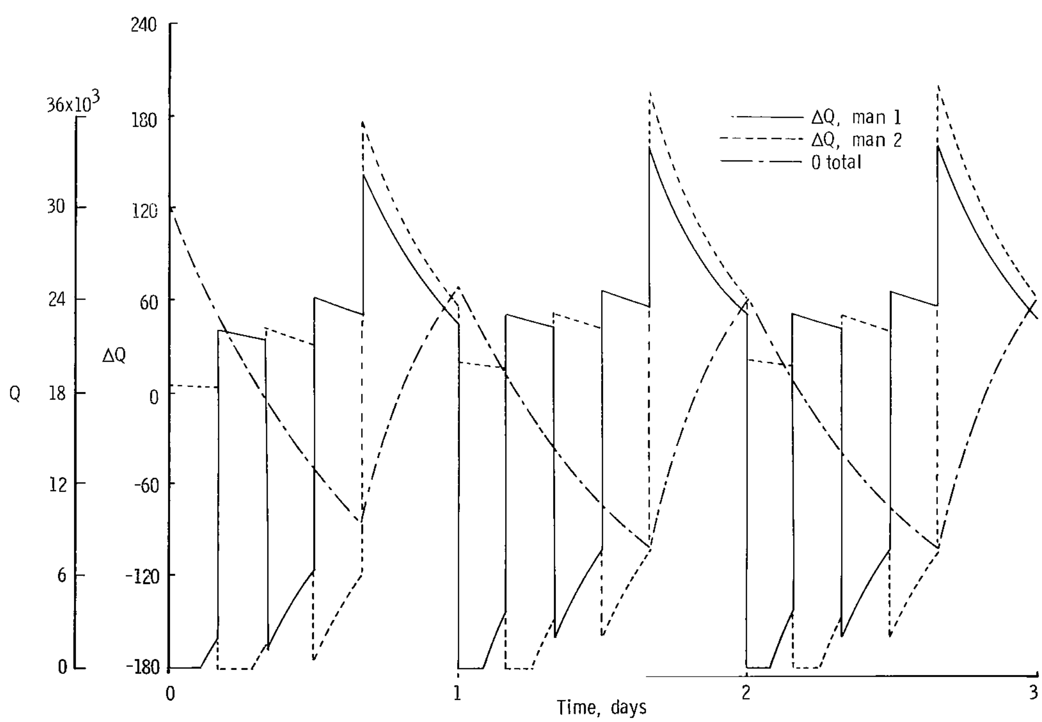


Figure 18. - Typical system response with 4-hour work shifts.

over a period of 3 days. For the sake of clarity, the individual $Q(t)$ values have been omitted from the plot, but these values do appear in the computer output.

The responses are as would be expected. For example, when each man begins rowing for the first time on any day, he displays a constant ΔQ value for the first 2 hours or so. This implies that for the prescribed value of M (i.e., he is rowing only because it is his turn and there is no requirement for maintaining any particular rate of speed) the man has more than sufficient Q for the task. He then displays a dropoff in output that is consistent with becoming tired. Note further that upon retiring, the man who has just previously been rowing gets more "good" from his sleep. The total amount of work done by the men in any day is the integral of the ΔQ curves (i.e., the areas) in the negative ΔQ region.

It was noticed during the many computer runs that the choice of $Q(t_0)$ (i.e., the initial value of Q for a man) could be made quite arbitrarily and after a few "days" the value of $Q(t)$ upon "waking" would have approached a stable value (provided, of course, that all α and β were zero). This led to the idea that some kind of "basic system response" could be determined by, for instance, initializing $Q(t)$ at zero and then observing the manner in which $Q(t)$ each morning approached its asymptote.

Such a run was made, and a plot of this data over a 3-day period is shown in figure 19. This plot shows that the response of this system on a day-to-day basis is rather fast. Although no attempt was made to do so, it might be useful to define a pa-

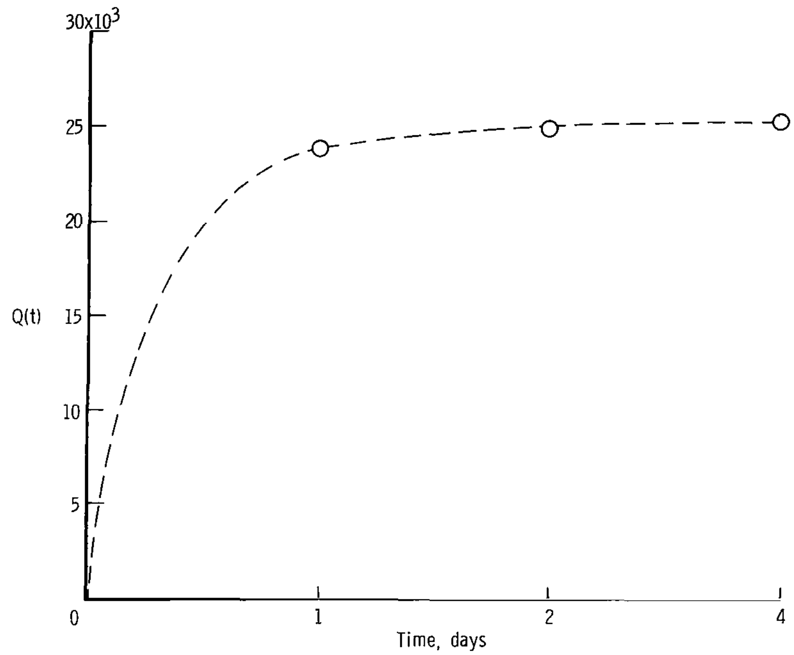


Figure 19. - Q(t) total at the start of each day, showing basic recovery response of man-machine system.

rameter that relates this particular response as a basic system response characteristic.

When it became clear, through acceptable system behavior, that reasonable values for the various input parameters had been selected, it was decided to further test the system recovery response from a perturbation caused by some type of unscheduled phenomenon. This took the form of a "storm" which was conjured up at the beginning of the 8-hour night and which lasted for the entire 8-hour sleep session. The effect on the crew was to be that neither man could recover Q by either sleep or rest because of some supposed small tasks which were continuously performed, such as tying down gear and keeping from falling out of the tossing boat. At the end of the storm (and of the sleep period), the two men returned to their usual schedule.

The recovery of the system can be gleaned from the computer output, a plot of which appears in figure 20. Again the Q(t) values for the individual men have not been shown because of the complexity of the plot. It is seen that the total output for the two men in the day following the sleepless night is substantially less than for a normal day. Also, it is interesting to note that with no extra sleep during the next night the recovery as indicated by the Q(t) values is within 7 percent of being complete. One additional hour of sleep would have been sufficient to make up for the lost 8 hours. The difference, of course, shows up in the decreased output during the time when both men were working while at low Q levels.

These results are not at all inconsistent with the author's own experience.

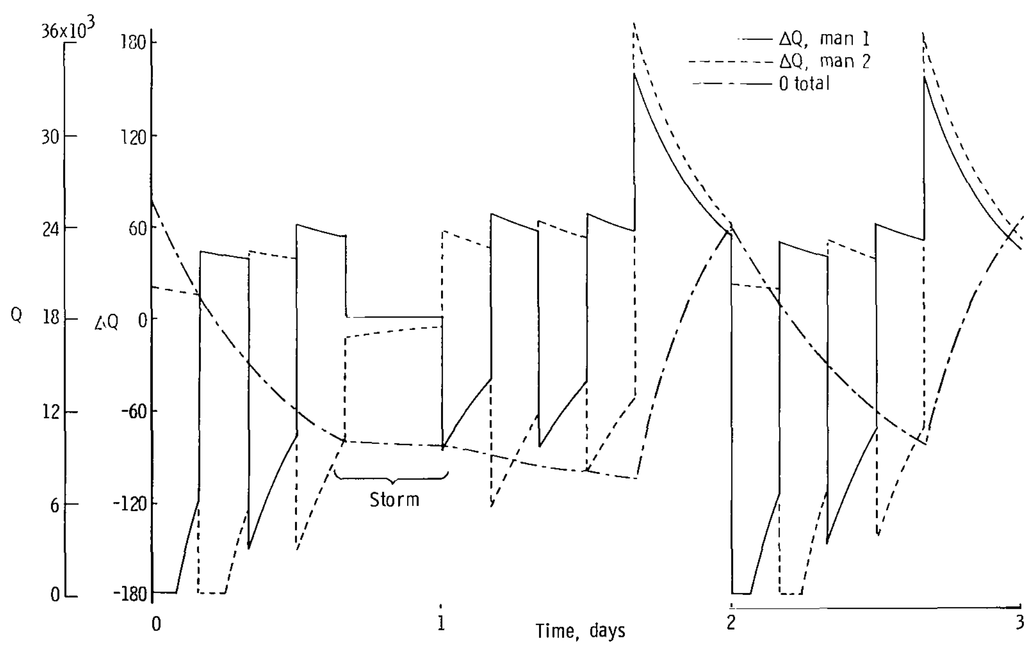


Figure 20. - System response with no sleep during first night.

FUTURE POSSIBILITIES

The results of the preceding analysis immediately bring to mind many other interesting possibilities as regards extensions to the particular man-machine system which was hypothesized for the purpose of demonstrating the methodology. For instance, it would also be possible with the improved computer program to study the effect of "naps" during the daytime period. Another extension might be enlarging the size of the crew and the number of tasks to be performed and then perhaps studying the effects of the particular choice of crew talents as a function of the scheduling of the tasks. Or the effects on the system of partial or total loss of one or more crew members due to sickness, injury, or other cause might be studied.

It would also be quite possible with a slightly modified program to optimize the task performance schedule for any given crew composition. One criterion for optimization would be to maximize the area under the negative portion of the ΔQ curves and thus maximize the total work done by the given crew. There are, of course, other ways of defining the optimal performance of even this simple system.

An extension of the ideas of the analysis presented in the last section to a manned planetary expedition system provides a rich source of new ideas for study by these techniques. As was suggested in the INTRODUCTION, man will visit at least the Earth's nearest planetary neighbors in the foreseeable future, and some methodology for the analysis of the man-machine systems proposed to perform these visits must be formulated before these missions can really be seriously considered.

The Apollo Program was carried out only after a tremendous amount of costly and most necessary preliminary study which included both the Mercury and the Gemini programs. Nonetheless, there presently exists no analytical procedure for the analysis of complete man-machine systems of this kind. Rather, the development of these systems has had to depend upon a combination of experience, intuition, and whole-hearted cooperation on the part of the specialists in the many disciplines that are, of necessity, involved in these studies. The author believes that mission analyses patterned after that described in this report can be expected to provide a significant increase in the efficiency with which information from every source is utilized. Also to be expected is an increased ability for evaluating the effects of various possible perturbations on the planned performance of a system, which would thus allow the determination of a meaningful "reliability factor" for such systems.

Another advantage inherent in any analytical methodology that utilizes digital computers is the tremendous time compression available because of the microsecond-per-operation speeds of these devices. The programs that might represent typical man-machine space-flight systems could well be expected to result in time compression factors of about 1000, which would allow, for example, the study of a 2-year Mars mission in less than a day.

Because of the absence of any requirement for the tangible existence of the ideas represented by the MNT variables, many other possibilities exist for the use of MNT techniques as, for example, analyzing problems in such areas as urban renewal, finance, social behavior, and others which heretofore have been well outside the domain of the system analyst. When properly defined and scaled, such an idea as "desire" becomes a perfectly valid MNT system variable. Also, considering the ideas of a "chain of command," an organizational chart bears a striking resemblance to a special MNT subgraph known as a "tree," thus making it an easily studied structure. And the idea of "command" might surely be made a valid through variable.

A long list of possible uses for the ideas presented in these pages could be prepared, and it is certainly outside the abilities of the author to provide such a list. However, in the light of the ideas and proposals that have been included, many other, and perhaps more significant, ideas should present themselves to the reader.

CONCLUSIONS

In view of the results obtained in the analyses by Modern Network Theory of the assortment of examples presented in this report, and after consideration of the techniques used to obtain these results, certain significant conclusions can be stated:

1. Man in the role of a physical-task-performing subsystem is amenable to the Modern Network Theory analysis techniques, and there is no apparent reason that would preclude the analysis of Man in toto by these same techniques, provided only that sufficient defining information and metering technology becomes available.

2. Human heart rate, when measured and interpreted in certain ways, constitutes a reasonable and useful metering parameter for defining physical-task-performance output. Measurements made as a part of this investigation show a sufficiently high correlation to allow detection of differences, not only between different human subjects but in individual performance variations as well.

3. Man-machine systems, of themselves, present no inherent characteristics that preclude their analysis by these techniques, provided that sufficient information, consistent with the desired level of system-to-equation fidelity, is available.

4. The analysis of even highly simplified man-machine systems by these techniques yields results that can be both useful and significant.

5. Because of the broad implications of the ideas presented, it can be concluded that the suggested applications of these techniques is by no means exhaustive.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 1, 1970,
129-02.

APPENDIX - PROGRAM FOR ANALYSIS OF MAN-MACHINE SYSTEMS

The final digital computer program used to study the man-machine system discussed in the last section is listed in this appendix.

The system equations that are solved by this program have been derived from the graph displayed in figure 17. This graph is the result of appropriate modifications to the network of figure 16 to include two men involved with three tasks (i. e., sleep, rest, and work).

The program, when provided with input data that defines appropriate performance characteristics for each man, a definition of each of the tasks to be included, and a schedule that assigns every man to the appropriate task for each time interval, will analyze and compute the performance parameters Q(t) and ΔQ(t) for each man and also Q(t) total for the system. These computed values will be listed in tabular form under appropriate identifying headings by the computer.

Following the listing is a sample data set for the same conditions that were analyzed by an earlier and more restrictive computer program. This data set was used to check the performance of the final version of the program by comparison of the results with those previously obtained.

The general nature of the program allows for broad application to a variety of manned systems. If the program is to be used to study and to modify a given system in earnest, it is recommended that some type of computer-driven plot routine be used to aid in appreciating the character of the output.

Plots of some of the output appear in figures 18 to 20.

```
FINAL PROGRAM FOR THE ANALYSIS OF MAN/MACHINE SYSTEMS INVOLVING INDIVIDUAL
MEN AND ALLOWING FOR BOTH LEARNING AND LOSS OF "MOTIVATION" WITH TIME.

PROGRAM LANGUAGE IS FORTRAN IV WITH CONTROL STATEMENTS SUITABLE FOR USE ON
AN IBM MODEL 360/67 DIGITAL COMPUTER.


//STEP EXEC FORTRANH
//COMPILE.SOURCE DD *
C     A = THE SLEEP/REST ASYMPTOTE.
C     B = THE SLEEP/REST INVERSE RATE.
C     C = THE "BASE LOAD" DQ/DT FOR A TASK.
C     D = Q(T) FOR ONSET OF INEFFICIENCY.
C     E = INVERSE RATE OF INCREASE ABOVE BASE RATE TO COMPENSATE FOR
C        INEFFICIENCY.
C     G = Q(T) FOR ONSET OF "FATIGUE".
C     H = INVERSE RATE OF DECREASE DUE TO FATIGUE.
      DIMENSION A0(10,8),B0(10,8),D0(10,8),E0(10,8),G0(10,8),H0(10,8),
     1BETA(10,6),ALPHA(10,6),QT(250),Q(10,250),DELQ(10,250) ,NJ(10)
C     NMEN = NUMBER OF MEN IN SYSTEM.
C     NREST = NUMBER OF  Q  RECOVERY MODES AVAILABLE.
C     NWORK = NUMBER OF WORKING TASKS TO BE PERFORMED.
```

```
C     NTIME = NUMBER OF 1/10 HOUR TIME UNITS PROGRAM IS TO ANALYZE.
      READ(5,100)  NMEN,NREST,NWORK,NTIME
      NTASK=NREST+NWORK
C     I  SUBSCRIPT REFERS TO THE MEN.
C     J  SUBSCRIPT REFERS TO THE TASKS.
      DO 2 I=1,NMEN
      DO 1 J=1,NTASK
C     READ INITIAL VALUES OF PARAMETERS.
    1 READ (5,101)    AO(I,J),BO(I,J),DO(I,J),EO(I,J),GO(I,J),HO(I,J)
      READ (5,101) (ALPHA(I,K),K=1,6)
    2 READ (5,101) (BETA(I,K),K=1,6)
      READ (5,101) (Q(I,1),I=1,NMEN)
      QTO=0.
      DO 3 I=1,NMEN
    3 QTO=QTO+Q(I,1)
      NT=0
    5 NTO=NT+1
      KT=0
    6 READ (5,100) NP,(NJ(I),I=1,NMEN)
      DO 20 NTP=1,NP
      KT=KT+1
      NT=NT+1
      QT(KT+1)=0.
      DO 20 I=1,NMEN
C     NJ(I) = CURRENT TASK ASSIGNMENT FOR MAN I
      J=NJ(I)
      XNT = NT
      IF(J-NREST)8,8,9
C     COMPUTE CURRENT VALUES OF SLEEP/REST PARAMETERS
    8 A=AO(I,J)+ALPHA(I,1)*EXP(BETA(I,1)*XNT)
      B=BO(I,J)+ALPHA(I,2)*EXP(BETA(I,2)*XNT)
      DELQ(I,KT+1)=(A-Q(I,KT))/B
      GO TO 15
C     COMPUTE CURRENT VALUES OF WORK PARAMETERS
    9 D=DO(I,J)+ALPHA(I,3)*EXP(BETA(I,3)*XNT)
      G=GO(I,J)+ALPHA(I,5)*EXP(BETA(I,5)*XNT)
      H=HO(I,J)+ALPHA(I,6)*EXP(BETA(I,6)*XNT)
      C=G/H
C     TEST Q(T) TO DETERMINE CONDITION OF MAN NOW WORKING AT TASK
      IF(Q(I,KT)-D) 10,10,14
   10 IF(Q(I,KT)-G) 12,12,11
   11 E=EO(I,J) + ALPHA (I,4)*EXP(BETA(I,4)*XNT)
C     IF G   Q(T)   D
      DELQ(I,KT+1)=(Q(I,KT)-D)/E-C
      GO TO 15
C     IF Q(T)   G
   12 DELQ(I,KT+1)=-Q(I,KT)/H
      GO TO 15
C     IF IF Q(T)   D
   14 DELQ(I,KT+1)=-C
   15 Q(I,KT+1)=Q(I,KT)+DELQ(I,KT+1)
      QT(KT+1)=QT(KT+1)+Q(I,KT+1)
C     REPEAT FOR  NP  TIME PERIODS
   20 CONTINUE
      IF(NTIME-NT)22,22,21
   21 IF(KT-240)6,22,22
C     WRITE OUT INITIAL AND FINAL VALUES OF TIME AND INITIAL VALUE OF  Q  TOTAL
   22 WRITE(6,102)NTO,NT,QTO
      DO 42 I=1,NMEN
C     WRITE OUT NUMBER OF MAN  AND HIS INITIAL VALUE OF  Q
      WRITE(6,103)I,Q(I,1)
```

```
      WRITE(6,104)
      KT=1
   24 MT=KT+NTO-1
      MT1=MT+1
      MT2=MT+2
      MT3=MT+3
      MT4=MT+4
      L=NT-MT
      IF(L-4)26,30,30
   26 K=5-L
      DO 28 LM=2,K
      KTM=KT+LM+L
   28 DELQ(I,KTM)=0.
C     WRITE ONE LINE OF OUTPUT CONSISTING OF FIVE COMPUTED VALUES IN ARRAY
   30 WRITE(6,106) MT,DELQ(I,KT+1),MT1,DELQ(I,KT+2),MT2,DELQ(I,KT+3),
     1MT3,DELQ(I,KT+4),MT4,DELQ(I,KT+5)
      MT=MT4
      KT=KT+5
      IF(NT-MT)32,32,24
   32 WRITE(6,107)
      KT=1
   34 MT=KT+NTO-1
      MT1=MT+1
      MT2=MT+2
      MT3=MT+3
      MT4=MT+4
      L=NT-MT
      IF(L-4)36,40,40
   36 K=5-L
      DO 38 LM=2,K
      KTM=KT+LM+L
   38 Q(I,KTM)=0.
   40 WRITE(6,106)MT,Q(I,KT+1),MT1,Q(I,KT+2),MT2,Q(I,KT+3),MT3,Q(I,KT+4)
     1,MT4,Q(I,KT+5)
      MT=MT4
      KT=KT+5
      IF(NT-MT)42,42,34
   42 CONTINUE
C     SUPPLY HEADING FOR OUTPUT
      WRITE(6,108)
      KT=1
   44 MT=KT+NTO-1
      MT1=MT+1
      MT2=MT+2
      MT3=MT+3
      MT4=MT+4
      L=NT-MT
      KNT=KT+L+1
      IF(L-4)46,50,50
   46 K=5-L
      DO 48 LM=2,K
      KTM=KT+LM+L
   48 QT(KTM)=0.
   50 WRITE(6,106)MT,QT(KT+1),MT1,QT(KT+2),MT2,QT(KT+3),MT3,QT(KT+4),
     1MT4,QT(KT+5)
      MT=MT4
      KT=KT+5
      IF(NT-MT)52,52,44
   52 IF(NTIME-NT)58,58,54
   54 DO 56 I=1,NMEN
```

```
   56 Q(I,1)=Q(I,KNT)
      QTO=QT(KNT)
      GO TO 5
   58 CALL EXIT
  100 FORMAT(20I4)
  101 FORMAT(8F10.0)
  102 FORMAT(30H1COMPUTATIONS FOR TIME PERIODS,I4,3H TO,I4,3X,24HINITIAL
     1 VALUE OF TOTAL Q,F10.3/)
  103 FORMAT(4H1MAN,I4,3X,19HINITIAL VALUE OF Q=,F10.3)
  104 FORMAT(54H0  DELTA Q FOR EACH TIME PERIOD - FIVE VALUES PER LINE/)
  106 FORMAT(1H ,5(4X,I4,F12.3))
  107 FORMAT(1H1,//46H Q FOR EACH TIME PERIOD - FIVE VALUES PER LINE,/)
  108 FORMAT(1H1,//53H TOTAL Q FOR EACH TIME PERIOD -- FIVE VALUES PER L
     1INE,/)
      STOP
      END
/*
```

```
C       INPUT DATA FOR TYPICAL RUN

//EXECUTE.DATA DD *
   2   2   1 720
 16000.    200.0       0.0       0.0       0.0       0.0
 16000.     70.0       0.0       0.0       0.0       0.0
    0.0      0.0    10000.      55.0    10000.      55.0
    0.0      0.0       0.0       0.0       0.0       0.0
    0.0      0.0       0.0       0.0       0.0       0.0
 16000.    200.0       0.0       0.0       0.0       0.0
 16000.     70.0       0.0       0.0       0.0       0.0
    0.0      0.0    10000.      55.0    10000.      55.0
    0.0      0.0       0.0       0.0       0.0       0.0
    0.0      0.0       0.0       0.0       0.0       0.0
  12500.   12500.
  40   3   1
  40   1   3
  40   3   1
  40   1   3
  80   2   2
  40   3   1
  40   1   3
  40   3   1
  40   1   3
  80   2   2
  40   3   1
  40   1   3
  40   3   1
  40   1   3
  80   2   2
/*
```

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