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SUMMARY REPORT ON A REVIEW OF BIOLOGICAL MECHANISMS FOR APPLICATION TO INSTRUMENT DESIGN

VOLUME V

August 1967

SUMMARY REPORT ON A REVIEW OF BIOLOGICAL
MECHANISMS FOR APPLICATION TO INSTRUMENT DESIGN

VOLUME V

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FOREWARD

The study presented in this report was performed for the Office of Advanced Research and Technology, and the Advanced Concepts Section, National Aeronautics and Space Administration under Contract No. NASw-1515. This work was performed under the jurisdiction of Mr. Robert Trapp and Mr. James Shiner, RBA.

The program presents the extension of an interdisciplinary study of biological mechanisms, particularly biosensors, for application to instrumentation design and engineering performed by Allied Research Associates under Contract No. NASr-16, NASw-535, and NASw-1228.

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1. Introduction

This report, together with the four preceding Summary Reports*, summarizes the results to date of a review of biological mechanisms for application to instrument design and engineering performed for the National Aeronautics and Space Administration, Office of Advanced Research and Technology, under Contracts NASr-16, NASw-535, NASw-1228 and NASw-1515. This report is the fifth volume of the series and is published, as were its predecessors, in two parts:

ARA 346-2 Part 1	Summary Report on a Review of Biological Mechanisms for Application to Instrument Design - Volume V
ARA 346-2 Part 2	Bibliography on Biosensors - A Sampling of the World Literature, 1960 - 1966, Volume V

This study is concerned with investigating biological receptor mechanisms and, to some extent, their associated systems, from an engineering viewpoint. Structural, functional, and operational principles of various classes and types of biosensors as they occur throughout the animal phyla are sought and analyzed. These principles are then evaluated from a bionic standpoint against the background of current and anticipated instrumentation requirements and techniques. Thus, ingredients are extracted for use in a variety of engineering applications.

The exploration of interplanetary space and hydrospace made possible by our rapidly advancing technology is continually creating new and unprecedented instrumentation requirements. Design concepts resulting from such as this study can have application in these areas, as illustrated in this report and its predecessors. Additionally, as man pursues the exploration of new frontiers, he will continue to place himself in a variety of unnatural environments. Relatively little is known about the biological implications of such environments. The function of man's sensory systems is vital to his performance. Furthermore, it is these systems which enable him to perceive and monitor his environment, and which mediate his adaptability to the elements of these environments. Knowledge is still inadequate of the effect (transitory or long term, immediate or cumulative) of severely altered environmental parameters on the sensory systems and their components. In this sense, more

fundamental understanding of individual sensor mechanisms may enable us to predict response, to enhance the detection capability, to protect against adverse effects, and perhaps, in some cases, to utilize the response of the biosensor itself as part of a physical sensing or warning system.

Among the various sensed parameters and sensory phenomena included in this study, a particularly interesting area is the little understood interaction of electric and magnetic fields with living organisms. While the existence of these interactions is generally accepted, very little is known about their effects and even less about the body mechanisms involved in the perception of these fields. In only one case -- that of certain electric fish -- have specialized bioreceptors been identified with the reception of electric fields. Even less is known about magnetic field sensitivity. However, there is evidence to indicate that man, like certain lower life forms, is affected by magnetic fields. (Volume IV of this report series reviews research in this area.) Space conditions and other unusual environments may expose man to electric and magnetic fields significantly different from those to which he is accustomed. Knowledge about the potential effects of these fields can therefore be critical in maintaining man under these conditions and may also provide the basis for developing new methods of interacting with the nervous system.

Selected aspects of the aforementioned area and a variety of others are reported in this document. For additional information and for areas not included in this volume, the reader is referred to the previous volumes in this series.

* Vol. I	(1) Summary Report on a Review of Biological Mechanisms for Application to Instrument Design, 1962	ARA-1025 (NASA N62-10369)
	(2) Bibliography on Biosensors, A Sampling of the World Literature, 1900-1961	ARA 1026 (NASA N62-10370)

Vol. II	(1) Second Summary Report on a Review of Biological Mechanisms for Application to Instrument Design, 1964	ARA-T-9211-5 (1) (NASA CR-76) (N64-26609)
	(2) Bibliography on Biosensors, A Sampling of World Literature, 1900-1963	ARA-T-9211-5 (1) (NASA CR-76) (N64-24116)
Vol. III	(1) Summary Report on a Review of Biological Mechanisms for Application to Instrument Design, Volume III, 1965	ARA-211-F-4 (1) (NASA CR-415) (N66-21094)
	(2) Bibliography on Biosensors, A Sampling of World Literature, 1960-1964, Volume III	ARA-211-F-4 (2) NASA CR-63145 (N65-25270)
Vol. IV	(1) Summary Report on a Review of Biological Mechanisms for Application to Instrument Design, Volume IV, 1966	ARA 298-F-4 (1)
	(2) Bibliography on Biosensors, A Sampling of the World Literature, 1960-1965, Volume IV	ARA 298-F-4 (2)

SECTION 2. PHOTORECEPTION

- 2.1 Introduction
- 2.2 Review of Research
 - 2.2.1 Optics
 - 2.2.2 The Chemical/Electrical Transducer Mechanism
 - 2.2.3 Information Processing in the Retina and Brain
 - 2.2.4 Color Vision
- 2.3 Applications
 - 2.3.1 Focusing Mechanism
 - 2.3.2 New Concepts in False-Color Imagery
 - 2.3.2.1 False-Color Presentation of Data from
Mid-Infrared Remote Sensing
 - 2.3.2.2 Real-Time Display Techniques

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2.1 Introduction

Vision is at once the most and the least understood of all the senses, both by laymen and experts. Most non-specialists have at least a nodding acquaintance with some of the quite impressive list of facts which have been accumulated over the past 150-odd years concerning the optics of vertebrate eyes, the mechanisms for focusing and light/dark adaptation, and the basic principles of color vision. But many details of the visual mechanism remain mysterious. Modern research in the physiology, psychology, and bio-chemistry of vision has discovered a rather bewildering mass of facts concerning those details -- glimpses which often raise more questions than they answer.

In the following paragraphs, we will review briefly some of the recent research and discuss three possible fields of applications in bionics.

2.2 Review of Research

2.2.1 Optics

In the field of basic research into visual mechanisms, relatively little attention has been devoted to the optics of vertebrate eyes during the past few years. One of the few papers on this subject (Ref. 2 -1) presents evidence that the human fundus oculi (interior of the eyeball) behaves in part as a specular reflector rather than only as a diffuse reflector, as had been believed.

More work has been done on invertebrate eyes. One study (Ref. 2 -2) indicates that the scallop eye behaves optically as a combination refracting and reflecting instrument with the refracting lens shaped to correct some of the aberrations of the spherical reflector, and with the photoreceptor cells located between the two elements. The image-forming properties of compound arthropod eyes have been receiving increased attention, and it has been found, contrary to classical theory, that the visual fields of adjacent ommatidia are broadly overlapping and that, in some species at least, an image is formed by each lens in the region of the photoreceptor cells.

2. 2. 2 The Chemical/Electrical Transducer Mechanism

It is now generally agreed that the first stage of the visual response is a photochemical reaction in the photoreceptor cell pigments. The chemistry of these pigments, and the series of transformations they undergo during and after exposure to light, are now becoming fairly well understood. However, the mechanisms by which the chemical changes are converted to changes in electrical potential are hardly understood at all. The first detectable electrical result following the exposure of a retina to light is a small voltage transient, called a "fast photoelectric effect", whose waveform depends on the chemical state of the visual pigments before the exposure. There appears also to be a slower thermoelectric voltage due to the heating effect of the exciting radiation (Ref. 2 -3). It has been suggested that the fast photoelectric effect is due to changes in the molecular charge distribution of the pigments (Refs. 2 -3, 2-4).

The attempt to understand how the photoreceptor cells work has been handicapped by the obvious difficulties in the way of recording the electrical activity of single cells in the living retina, but much progress has been made in the design of experiments. In a study of the horseshoe crab, electrodes were implanted in the receptor cells of excised eyes. The cells were identified by injecting dye through the electrodes after the light-induced activity had been recorded (Ref. 2-5).

Paralleling the research in chemical and electrical effects at the cellular level is a continued study of the histology of the photoreceptor cells. There appears to be no widely accepted theory accounting for the functions of the rather complex structures of these cells as they appear in electron micrography. One study (Ref. 2-6) has revealed considerable variations in the structure of rhesus monkey rod cells, so it may be that in addition to the division into rods and cones (and of cones specialized for different spectral sensitivities) there is further specialization among the retinal photoreceptors.

2. 2. 3 Information Processing in the Retina and Brain

Between the absorption of photons in the photoreceptor cell pigments and the presentation of a picture to the conscious and subconscious mind,

there must occur an enormously complicated chain of electrical events. Some of these events are beginning to be partly understood.

It has been clear for some time that a good deal of information processing must take place in the retina. This is suggested by the histology of the retina, with its three layers of nerve cells (receptor, bipolar, and ganglion), and the system of interconnections between them. The ganglion cells, whose axons comprise the optic nerve, each synapse with several bipolar cells, which in turn each synapse with several receptor cells. (This is not true of the central part of the fovea, where visual acuity is highest and where each ganglion cell is connected to only one receptor.) Most of the optic nerve axons transmit information from overlapping fields of the retina.

Some ganglion cells receive signals from both rods and cones and the response of such cells in the monkey have been recorded; the ganglion cell responses arising from excitation of the two types of receptor cells were quite distinct and their relative timing depended on the intensity and wavelength of the stimulus flash.

Some of the most interesting recent experiments have been on the optic nerve and retina of the frog. There are five morphological types of ganglion cells in the frog retina, and the optic nerve axons give five types of response; these are sustained edge detectors, curved edge detectors, changing contrast detectors, dimming detectors, and dark detectors (Ref. 2-7).

Another interesting field of research, this time in human vision, is the study of eye movements during fixation of a point stimulus, and of the interaction between these movements and visual perception. There are three classes of ocular movement (Ref. 2-8): a high frequency tremor of about 35 cycles per second and amplitude of about 18 seconds of arc; a slow irregular drift with duration about 0.2 seconds and amplitude about five minutes of arc; and a rapid flick of saccade of about the same amplitude as the drift but a duration of only about 0.03 seconds. The net result of the motions is to maintain the fixated image within a small area of the fovea. If the image is stabilized instrumentally, image detail perception tends to fade. It has also been shown that the visual threshold is raised during a saccade, and that this depression in the subject's ability to perceive a

stimulus actually is initiated several tens of milliseconds before the saccade begins (Ref. 2-9). Thus, it appears that eye motions are a necessary condition for acute perception and that these motions are under the brain's control.

The interrelationships between receptor dimensions and eye movement rates and amplitudes have been pointed out by Leibovic (Ref. 2 -8), who also discusses the critical flicker fusion frequency and the time needed for a "good look", which are comparable to the tremor frequency and the slow drift durations respectively.

A related area of research, and one that should be closely watched for future developments of interest to bionics, is the study of the effect on vision of applied electric currents. Small alternating currents, applied through skin electrodes on the eyelids with the same frequency as a simultaneous flickering light stimulus, affect a human subject's perception of the light, altering the critical flicker fusion threshold. The phase difference between the electrical and the light stimuli is an important parameter of this effect (Ref. 2 -17).

2. 2. 4 Color Vision

The spectral absorptivities of the photoreceptor pigments determine the spectral response of the visual process, and if the retina contains two or more pigments with different spectral absorptivities, then frequency discrimination, or color vision, becomes possible. There is as yet no complete theory of color vision, and this is an active area of research.

Many animals besides man (and including even the lowly scallop) (Ref. 2 -10) appear to have color vision; for the lower animals this phenomenon can be detected and studied by several means, including behavioral studies, the electroretinogram (ERG), direct recording of electrical potentials in the retina, and measurement of the absorption spectra of retinal pigments. Many animals have also been shown to have a duplex visual system like man's, in which one class of receptors, the rods, contains one type of pigment and is sensitive to dim light; while another class, the cones, contains different pigments and is sensitive to bright light and to color. The goldfish ERG, for instance, shows different bright light (photopic) and dim light (scotopic) spectral sensitivities, while the sensitivity

to bright long-wavelength light agrees reasonably well with the measured absorption curve for a red pigment in the fish's retina (Ref. 2 -11).

Recent studies have disclosed new color vision puzzles. One series of experiments using intense narrow-band adapting fields seems to show evidence for a fourth, yellow, visual pigment in man in addition to the three pigments of classical theory (Ref. 2-12). (One technique in color vision research is to saturate one or more of the color-sensing mechanisms with a large adapting field; a smaller light patch of another color will then presumably stimulate only one mechanism.) Another study (Ref. 2 -13) showed that for a given energy content, the adapting field is more efficient in raising the test stimulus threshold when it has a broad rather than a narrow spectral distribution. This may, of course, be the result of interaction between two or more different pigments involved in the adaptive mechanism.

There are other distinctions between the color-sensing mechanisms beyond their obvious spectral response differences. For instance, the blue-sensitive mechanism has been shown to have a markedly lower maximum flicker fusion frequency than do the red- or green-sensitive mechanisms (Ref. 2 -14).

Practically all theories of color vision invoke the action of sets of pigments as the basis of color sensation; the major differences among the theories lie in their explanations of the neural mechanisms which process the receptor cell signals. One theory which has recently received strong experimental support is that of opponent colors. Experiments with tench (*Cyprinidae*) retinas (Refs. 2 -15 and 2-16) have revealed the presence of two types of cells (not positively identified, but probably located in the bipolar layer) whose response to light consists of a d. c. potential change. The sign of the potential change depends on the wavelength of the stimulus and the amplitude depends on the intensity. One of the cell types shows negative potential change with blue light and positive with green; the other type goes negative with green and positive with red. (A third type of cell gives a similar response, but with negative polarity for all wavelengths.) Each cell is affected by light falling anywhere within a retinal field of appreciable size. The action spectra of the cells agrees reasonably well with the measured absorption spectra of visual pigments from the closely-related goldfish.

2.3 Applications

Our study of these phenomena from a bionics viewpoint has resulted in two ideas of possible utility to engineering systems. One of these has been developed to some extent. The other is presented in embryonic form since, as a concept, it contains application value.

2.3.1 Focusing Mechanism

Adjustment of focus in optical instruments is universally accomplished by adjustment of the axial distances between the elements of the instrument. There may well be some applications where adjustment of lens curvature, similar to the mechanism of vertebrate eye accommodation, would be a more desirable technique. A possible approach is shown in Fig. 2-1. The lens is a lenticular pod of plastic containing a clear liquid or gel of relatively high refractive index, supported in a transparent container filled with a liquid or gel of lower refractive index but similar density. Lens curvature would be changed by changing the relative pressure in the two liquids.

2.3.2 New Concepts in False-Color Imagery

The Bionic applications derived from studies of visual processes presented in this section involve the use of false-color imagery for infra-red remote sensing and the real-time display of false-color data.

False-color imagery in itself is not a new concept; but the applications we propose represent a drastic extension of the technique in terms of wavelength and of the method of data presentation.

In effect, the false-color technique extends or shifts the range of wavelengths to which the human visual system is sensitive, and thus takes advantage of the remarkable ability of that visual system for information processing. The following brief discussion of normal color photography and of a currently available false-color process will illustrate this.

In its simplest form, color photography works this way: three photographs are taken of the same scene, using a red, a green, and a blue filter respectively. The resulting negatives are printed to provide three black and white positive transparencies, and these are projected simultaneously on a screen using the appropriate filters. That is, the "red" transparency is projected

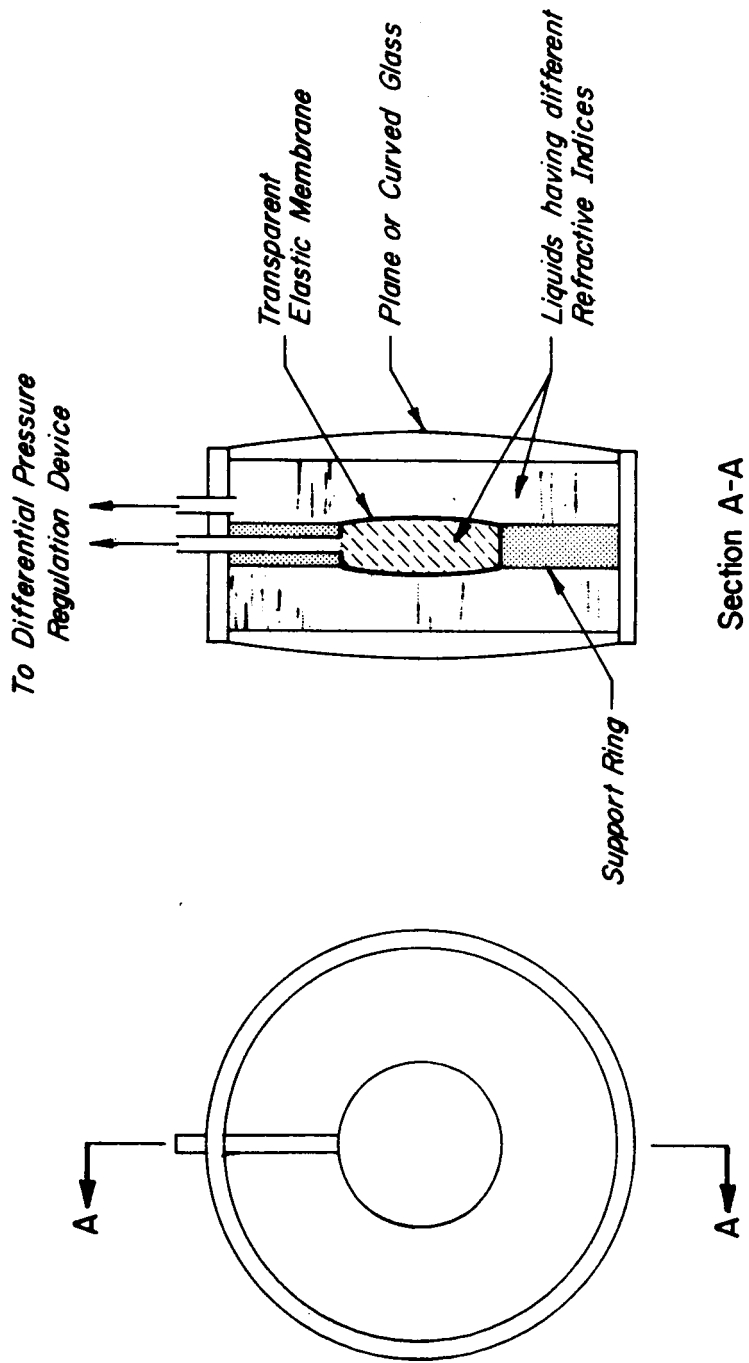


Figure 2-1. Variable Focal Length Lens.

through a red filter, etc. There are, however, some surprising facts. While for the truest possible reproduction of natural color, it is apparently necessary to use a three-color process, it is not necessary to use the same color filters for projection that were used for recording. Furthermore, it is possible to achieve reasonably faithful color reproduction using only two colors (despite the accepted tri-stimulus theory of color vision). In a two color system, two transparencies made respectively with red and green filters may be illuminated with quasi-monochromatic orange and blue-green light to reproduce a full range of approximately true color. This is made possible because of the sophisticated processing ability of the visual mechanism which is capable of synthesizing a highly complex and discriminative color experience from a relatively simple set of inputs.

If the red, green, and blue filters used in the recording of an ordinary color photograph are replaced by three filters with transmission peaks respectively in the near-infrared, red, and green; and the resulting three transparencies are projected in registration using red, green, and blue light, a full-color picture will be seen even though the colors are obviously false. If the photograph is of a landscape scene, the most surprising result will be the red color of healthy deciduous foliage which is due to the strong reflectivity of chlorophyll in the near infrared. Diseased foliage appears blue-green; evergreens, a dark purple. There is a commercially-available film, Kodak Infrared Ektachrome Aero Type 8443, which works this way, and the same basic concept is used in a camera on one of NASA's ATS satellites.

What we propose is an extension of the concept in two directions. First, to record three wavelength bands in the mid-infrared, and second, to develop a real-time system which would give a color television presentation.

2.3.2.1 False-Color Presentation of Data from Mid-Infrared Remote Sensing

In the spectral region between 8 and 25 microns wavelength (in the infrared) the curves of spectral reflectivity and emissivity for common rock-forming minerals show several maxima and minima whose positions are functions of the mineral composition. It is thus possible that false color pictures

could be used as an aid in the identification of minerals, particularly for remote-sensing applications.

This spectral region is outside the range of sensitivity for the photographic process. Therefore, some type of scanning infrared detector would need to be used, but this would of course be a question of adapting state-of-the-art instrumentation. The principle development task would be in the output end of the system, and the most straightforward approach would probably be a photofacsimile process with subsequent reproduction using standard color-printing techniques.

We have recently made some preliminary tests of this method of output presentation, and were fortunate to have available a most interesting source of photo-facsimile multi-spectral imagery to use in false-color processing. This was the film data from the Nimbus II Weather Satellite Medium Resolution Infrared Radiometer (MRIR) experiment. The MRIR instrument consists essentially of five radiometers which scan across the orbital track; one of the output formats is 4 X 5-inch film transparency containing five photofacsimile strips. Four of the strips are of records made in different infrared wavelength bands while the fifth is a visible wavelength record. All five strips represent the same coverage on the earth (approximately 360 degrees of the sub-satellite track), and thus any three of them comprise a set of transparencies for false color processing. We have made a few test exposures on Kodak color printing paper using only three colors and three of the five facsimile strips from one orbit's data, but even these rudimentary attempts have aroused the interest of the meteorological research group at Allied Research who are using the MRIR data, since differences between the three records show up so clearly in the false-color presentation. Such differences provide a key to the understanding of the weather systems which they are studying. Fig. 2-2 provides an example of our preliminary results.

2. 3. 2. 2 Real-Time Display Techniques

The Kodak film mentioned above, which has emulsion sensitivities in the near-infrared, red, and green, finds applications in forestry, plant pathology, crop and ecological surveys, physiology, and medicine. In many of these applications, a real-time system would be advantageous, and should

FIGURE 2-2 LEGEND

False-Color Imagery Technique Applied to Nimbus II MRIR Data

Processing Technique - MRIR Channel 1 (6.4-6.9 micron band) printed with blue filter to give yellow color on the Kodak Ektacolor Professional paper. Channel 2 (10-11 micron band) printed with green filter to give magenta color. Channel 5 (visible, 0.2-4.0 micron band) printed with red filter to give cyan (blue-green) color. The negative used for printing was made directly from the MRIR standard format 4 x 5-inch transparency which contains photofacsimile strips of the five radiometer channels as shown in the black and white print. In this format, Channels 1 through 4 are actually "negatives" while Channel 5 is positive; this accounts for the blue-green color of outer space, along the margins of the horizon-to-horizon strip, since this appears as black on Channel 5 and white on Channels 1 through 4 of the standard format. The Channel 1 wavelength band is centered on the strong water vapor absorption line at 6.7 microns, and the information contained in this record is derived principally from the water vapor in the upper troposphere with radiation intensity varying inversely with humidity at these levels. Channel 2 is centered on the atmospheric window; radiation intensity depends mainly on the temperature of the emitting surface and hence provides information on cloud height or ground/water temperature. Channel 5 senses reflected solar radiation, with heavy continuous cloud areas recorded as white and ocean surfaces as black; land areas and thin or scattered clouds give intermediate shades of gray, but very thin high clouds are generally indistinguishable from underlying clouds or land. (The black and white print of the standard MRIR format shown here has Channel 1 on the right.)

Area Covered - The strip extends from horizon to horizon, centered on the sub-satellite track of Nimbus II. Orbital altitude was approximately 1100 Km. The time was approximately local noon on 26 June 1966, Orbit Number 564. The white crosses are at 60°N, 80°W; 30°N, 70°W; 0°, 60°W; and 30°S, 50°W respectively from top to bottom. Eastern North America appears in the upper portion of the strip, with the Gulf and Atlantic coast lines and the Great Lakes faintly discernable; South America is toward the bottom.

Geophysical Interpretation - Cloud-free land appears reddish purple and ocean areas are bluish purple. Areas of thick high clouds are yellowish white and thick low cloud is red to orange-red. Thin high cloud is blue-white. The yellow-orange area at top right is probably middle clouds overlain by very dry air. A cold front extends from SW to NE across the Great Lakes, with a jet stream just to the north. The orange area here is probably due to a region of very dry upper troposphere air associated with the jet stream. This preliminary attempt at false color MRIR imagery contains, in a compact and striking presentation, most of the information in the individual strips. Our experiments have already suggested that different assignments of color among the recorded bands, and manipulation of color balance, will give even more information than is shown here.

be entirely within the state-of-the-art. We suggest the development of a closed-circuit color television system with a conventional high-quality receiver, but with a camera tube sensitive to the near-infrared, red, and green.

The same principle could also, of course, be applied to the mid-infrared system discussed in the previous section. However, since sensor scanning would be mechanical rather than electronic, additional problems would be involved and the presentation could probably be only quasi-real-time.

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SECTION 3 - MECHANORECEPTION

- 3.1 Review and Analysis of Current Experiments and Theory
- 3.2 Cutaneous Stimuli in Man-Machine Systems
- 3.3 A Fixed-Sequence Transducer Design

REFERENCES

3. Mechanoreception

3.1 Review and Analysis of Current Experiments and Theory

Biosensor research over the course of years has identified and associated various receptors with the specific types of mechanical inputs to which they have been found to respond. Experimental investigations were designed to find what mode of stimulation produced a maximum response from a particular sensor. That is, what amplitude, frequency, power level or force or combination of these variables must be applied to the mechanoreceptor to evoke the maximum response sensitivity. When the combination of input signal characteristics that evoke maximum response sensitivity was isolated, the receptor was "typed". Vibratory receptors, acceleration receptors, tactile receptors and pressure receptors are some of the ensuing subclasses of mechanoreceptors. A close examination of the precise operation of each of these classes of mechanoreceptors reveals, however, that the fundamental mode of operation is that of a displacement sensor. It comes as no surprise, in fact, that a similar situation exists in the field of instrumentation. Here a displacement transducer measures the deflection of some suitable "motor" and thereby generates an analog of the motor input. Pressure may be measured by monitoring the deflection of a diaphragm of a Bourdon Tube; vibration may be measured by monitoring the deflection of a small mirror placed on the vibrating surface. Similarly, acceleration may be measured by monitoring the relative deflection between a spring-supported seismic mass at its case.

The performance characteristics and functional elements of various types of mechanoreceptors have been analyzed and examined for their engineering principles and implications. In nearly every case, the common fundamental operating principle is that of deflection. Between the site of the input stimulation and the deflection sensing element is the receptor structure which modifies as well as transmits the input stimulation. The extent and the type of modification heavily influences the overall characteristic of the mechanoreceptor.

The lateral line has been studied by many workers because: (1) it is readily available and naturally exposed and (2) it is a fundamental sensor from an evolutionary point of view. The evolutionary aspect of the lateral line is indicated

in the fact that the sensing elements for hearing are hairs similar to the hairs in the lateral line (Ref. 3-1). The inner ear develops by the in-sinking of an originally superficial organ near the head, leaving the remainder of the lateral line intact. Further evolutionary developments apparently still retain the hair sensor system -- for example, the organ of Corti and hair sensors in the semi-circular canals. In all three of these cases (the lateral line, the organ of Corti and the fluid accuated hair sensors in the semi-circular canals), the deflection of a hair produces a generator potential.

The precise means whereby the deflection sensing element ultimately produces a generator potential (neural impulse) is not yet fully explained. In fact, according to Inman (Ref. 3-2), the greatest gap in understanding of mechano-receptor function is the lack of knowledge of the mechanism that creates (or triggers) the generator potential. It is known that the generator potential arises as a result of the flow of sodium and potassium ions across a membrane surface within the sensor. The exact mechanism that causes the sudden change in membrane permeability as the result of a deformation of a sensor element is unknown. Experimental evidence exists which indicates that in some cases the deflection gives rise to the generator potential directly by mechanically altering the membrane structure and not through the release of an intermediate chemical moderator. By contrast, in certain bio-transducers an intermediate chemical trigger is involved in producing the generator potential. Jande (Ref. 3-3) suggests that chemical transmitter substances are responsible for a transfer occuring at neuromuscular junctions, but that these are not a factor in the transducer action within a Pacinian corpuscle. In the latter case, mechanical deflection appears to produce the generator potential directly without a chemical mediator. Recent work by Goldman (Ref. 3-4) provides an analytical approach to understanding the generator potential mechanism which is worthy of specific attention.

The analysis that Goldman presents might be applicable to Pacinian receptors, touch receptors of the skin, vertebrate muscle spindles, crustacean stretch receptors, statocysts of several species, vestibular organs, lateral line systems, auditory receptors and various other sensory hairs. The

concepts involved are not new but their combination, set down in an orderly sequence, helps to elucidate the electromechanical sequences of receptor operation. Fig. 3-1 shows a block diagram of the elements that seem to perform the necessary steps in the production of a nerve impulse. Taken in the directional order of signal flow, the first circuit element encountered is the signal transformer. This element is most important since it serves the same function in the neural circuit as does a signal conditioning network in an electronic circuit. It is at this point that the input signal will be operated on to create the type of reception desired. That is, a differentiating element may be inserted here to make the circuit a rate (\dot{x}) responsive circuit or a double differentiating element will produce an acceleration (\ddot{x}) sensitive system. Seldom is a simple one-for-one differentiation (or integration) performed; more often a hybrid transformation is performed whereby the signal is a combination of both displacement and rate and even possibly some second derivative of displacement. These signal modifiers in the biological world are such devices as the lamellae of the Pacinian corpuscle (a differentiating device) or the sensory hair found in the crustacean statoreceptor which converts a bending movement into stretching of the neural element. A change of the force systems is evident in the mechanoreceptor hair of a honeybee where a bending of the exposed hair is transformed into a compression of the sensitive portion of the mechanoreceptor bulb. In essence, the transformer transfers, and in many cases alters, the input information delivered to the deflection sensitive portion of the mechanoreceptor. The signal now enters the transducer section of the sensor where the generator potential is created. Goldman discusses some of the proposed methods whereby the generator potential may be created. Taken in order, they include:

- (1) A piezoelectric effect where a charge is generated directly by a mechanical motion.
- (2) A direct action of pressure on the structure of the membrane.
- (3) The force could drive water through the cell membrane thereby creating a streaming potential.
- (4) The potential could be formed by the production of a secondary chemical moderator that itself triggers the generator potential.
- (5) The sudden exchange of ions across the membrane could be caused directly by a mechanical strain.

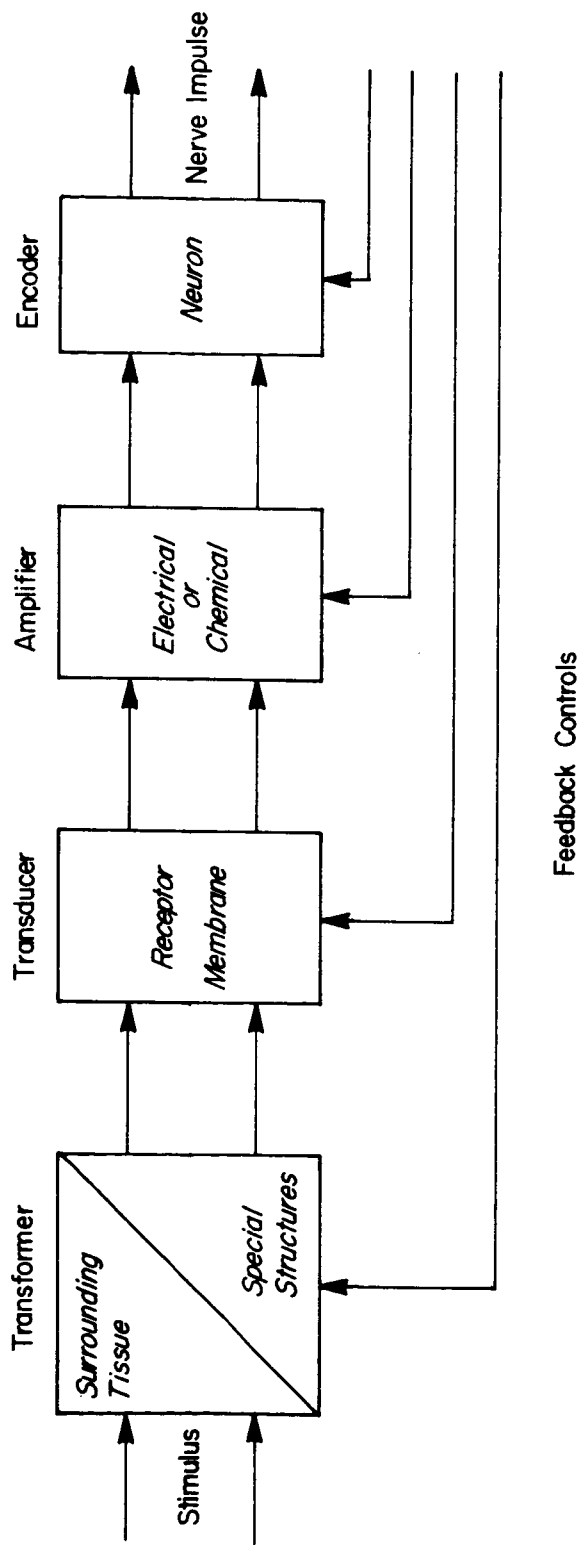


Figure 3-1. Block Diagram of Mechanoreceptor.

Goldman feels that item number 5 of the above suggestions is the most likely mechanism. He supports this theory with a model which provides a simplified picture of the membrane's molecular structure (a close square array of spherical molecules). He speculated that the sodium permeability increased about 20% if the free area between molecules increased by 1%. While the values may not be precise, they do suggest the exquisite sensitivity of the membrane material to stretching. While the stretching hypothesis is not new or completely supported, this presentation by Goldman does make the theory much more attractive and real.

Basically, two techniques have been used for the mechanical stimulation of the sensors in the lateral line organ, and also the Pacinian corpuscle. One method is direct stimulation by a tool of some kind; the other is indirect stimulation by imposing an alternating pressure field on the sensor through the fluid medium surrounding the sensor. Using the first technique, a common arrangement is to use a piezoelectric crystal with a probe attached to one of the moving surfaces of the crystal. The probe is placed in contact with the sensor and displacements are transmitted from the oscillating crystal to the sensor via the probe. The fundamental weakness in this type of arrangement is that the amplitudes imposed on the sensor are not known precisely because of the mechanical loading effects of the sensor mass on the crystal stimulator. This was the principle objection raised by Agalides (Ref. 3-5) prompting his use of an experimental arrangement where a loudspeaker established an alternating pressure field in a fluid tank that contained a Pacinian corpuscle under study. As the intensity of the sound pressure imparted to the fluid medium was increased, the neural response of the corpuscle was monitored on an oscilloscope. The difficulty in this experiment was in establishing the pressure level imparted to the fluid medium, and therefore, also to the surface of the corpuscle. This made it difficult to correlate accurately pressure with the threshold of corpuscle response. A similar experiment was performed by Suckling (Ref. 3-6) where the fluid medium was again vibrated by a loudspeaker. In this case, a fish was placed in the tank and portions of the lateral line of the fish were connected to an oscilloscope. Bursts of tone from the speaker were used and sound pressures of approximately 1 dyne/cm^2 were measured with a calibrated hydrophone in the vicinity of the fish. The minimum pressures that produced a response from the fish were associated with fluid motions of less than $1/2\mu$ at the lateral line sensors. These deflections also were measured with a calibrated hydrophone. The lateral line apparently

responds to water motions produced by various types of water surface influences. This work helps to resolve the controversy surrounding the lateral line sensors by demonstrating the extreme deflection sensitivity of these receptors. Van Bergeijk (Ref. 3-7) summarizes the situation particularly well by saying that "the lateral line is a sensory system that responds to water motions. It is not sensitive to pressure or pressure waves, and thus not to sound in the conventional sense. However, a real sound source in water produces water motions as well as pressure waves in its near field. The old controversy of whether the lateral line does or does not respond to sound is thus laid to rest by the simple expedient of defining 'sound' more accurately".

In instrumentation systems, the input information is processed through what might be called a signal modifier in a mathematical sense. In an instrumentation sense, these devices would be called motors. Bellows, for example, will convert a pressure in a liquid to a deflection by expanding. However, the signal will be modified by the dynamic characteristics of the bellows. So, one could say that the dynamic performance of the transducer system is determined by the bellows characteristics. The introduction of this term into a control loop or a regulation circuit is called a transfer function. A simple but striking demonstration that shows the biological counterpart of the effect of a transfer function is provided by Catton (Ref. 3-8). In this case, the speed of response of a frog's touch receptor stimulated mechanically was recorded. The same touch receptor was stimulated electrically and the response time was observed to be nearly half that of the response time obtained mechanically.

Recent work in the Pacinian corpuscle has revealed rather classic behavior of the exterior lamellae of the receptor by the way this covering operates as a signal conditioner. Loewenstein and Mendelson (Ref. 3-9) were able by dissection and stimulation to isolate and identify operating phenomena associated with the Pacinian corpuscle and its component parts. They essentially established the following principles in regard to the operation of the Pacinian corpuscle as a sensing unit.

(1) Experiments on the nerve ending after removal of the lamellated capsule revealed nerve response very similar to slowly adapting sensory endings. In fact, it is shown that the decapsulated nerve ending produces generator

potentials continuously with stimulus duration. The response of the nerve ending to a sustained mechanical stimulus may last as long as 70 msec as compared to a 6 msec burst associated with the stimulation of an encapsulated nerve fiber.

(2) The unencapsulated nerve fiber will not respond to a decompression (off) stimulus. By contrast, the encapsulated nerve ending does not discriminate direction and responds with the same polarity and duration of signal when the loading and unloading rate is kept the same.

(3) The lamellae covering the nerve ending (encapsulation structure) may be simulated by a multilayer elastic covering with fluid in the inter-spaces between layers of material. This substitute structure closely resembles the natural corpuscle in material density and dimensions.

(4) The number of nerve impulses emanating from the sensory axon is independent of the duration of the generator potential. When the generator mechanisms are bypassed and a source of electric current is connected directly to the terminal region of the sensory axon, the resulting impulses are also independent of the current duration.

(5) There appear to be two components to the adaption phenomena in the receptor. One is the purely mechanical filtering of the layered covering to inhibit the passage of mechanical impulses below a certain strain rate. A second adapting feature is an electromechanical one whereby the production of nerve impulses is limited, preventing a train of pulses, even though the generator potential still remains on.

Along these same lines, the transducer action of the Pacinian corpuscles is quite clearly shown in the analysis performed by Loewenstein and Skalak (Ref. 3-10). (This work is summarized rather thoroughly in Ref. 4 along with supporting data.) From data gathered on the physical properties of the lamella, Loewenstein and Skalak were able to construct both a mechanical analog and an electrical analog of the receptor. A picture of the mechanical and electrical analog is shown in Fig. 3-2. From the analog circuit and from the fact that the actual lamella is composed of 30 layers, 30 simultaneous differential equations were solved by the method of finite differences to yield static and dynamic pressure -- displacement data as a function of lamella radius. Fortunately, excellent displacement data was available (Hubbard, 1958) against which the displacement theory could be checked. The theoretical displacements fit the experimental ones very well. Using these

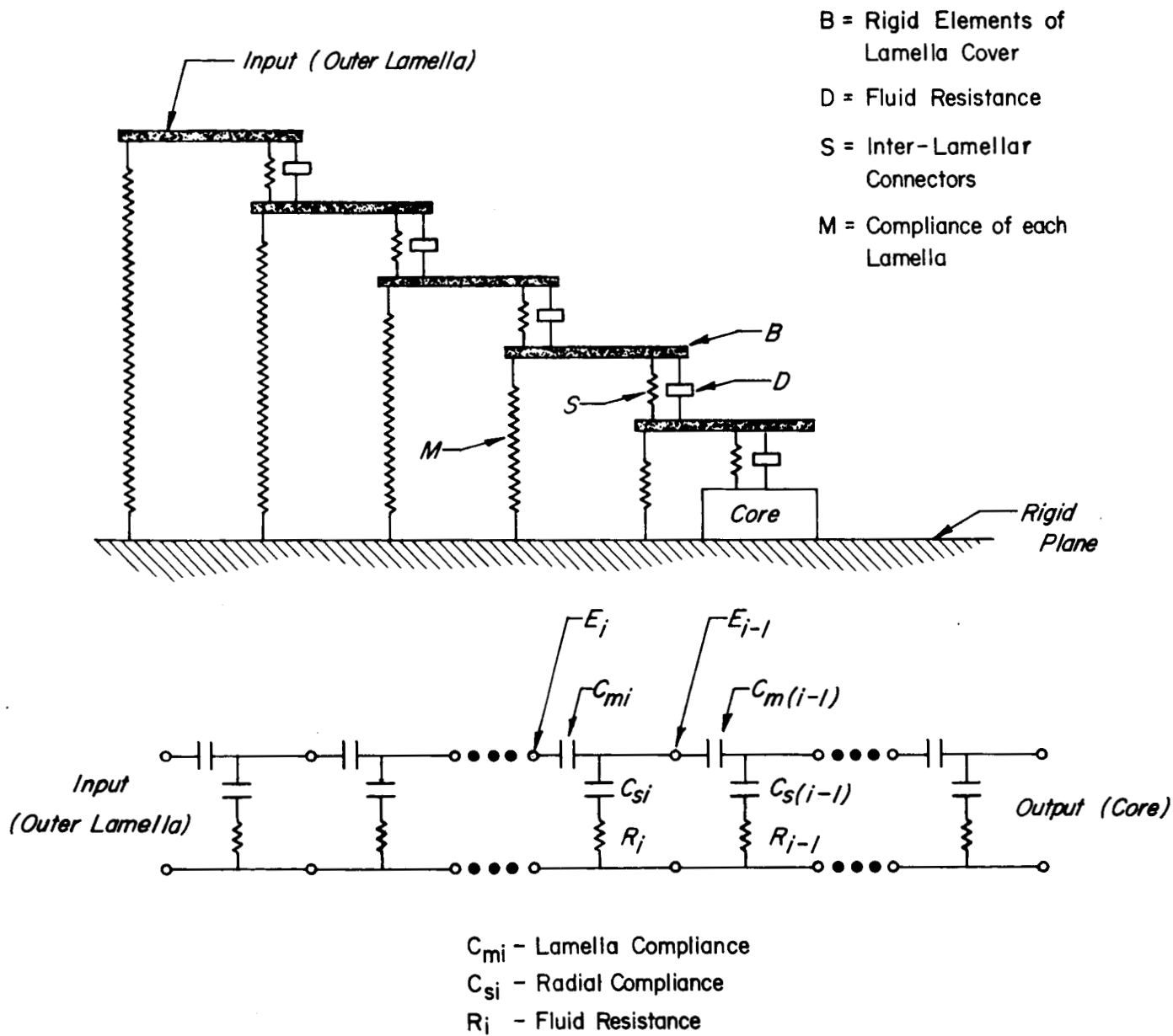


Figure 3-2. Mechanical and Electrical Analog of a Pacinian Corpuscle (Ref. 3-10).

equations, the actual pressures brought to bear on the core of the receptor for a typical input deflection were computed. With some surprise, these pressures were found to be only about 3% of the value of the input pressure. Now, in addition to providing the pressure profile information, the dynamic equations for the electrical analog can easily be divided into two components; the static pressure component and the dynamic component. Inspection of the planes of symmetry of the lamellae show that in one plane (x, y in Fig. 3-3a) the dynamic pressure component will be non-linear. This implies that the core of the corpuscle will only be activated by a non-linear pressure distribution which will, of course, produce strain -- i. e. , deflection. Earlier work by Loewenstein (1960) bears this out. At that time, the unencapsulated core of the receptor was shown to be sensitive to differential pressures but not sensitive to hydrostatic pressures. The ratio of sensitivity between hydrostatic and differential pressure fields was exceptionally high; as much as 26:1. With this in mind, a final summary of the status of knowledge of the Pacinian receptor may be made.

(1) A mathematical model is now available to describe the pressure field (static and dynamic) in the Pacinian corpuscle.

(2) The actual production of a generator potential is the result of a deflection and not a stress field. This is an excellent contribution to the proposal of membrane deformation made earlier by Goldman.

(3) The actual pressure felt at the core level in the receptor is only a few percent of the surface pressure.

(4) The strain theory of generator potential production explains the oddity of the receptor in producing the same polarity of pulse for an "on" deflection pulse and an "off" deflection pulse. This is because an "on" pulse looks like an "off" pulse at 90° around the x axis (Fig. 3-3b).

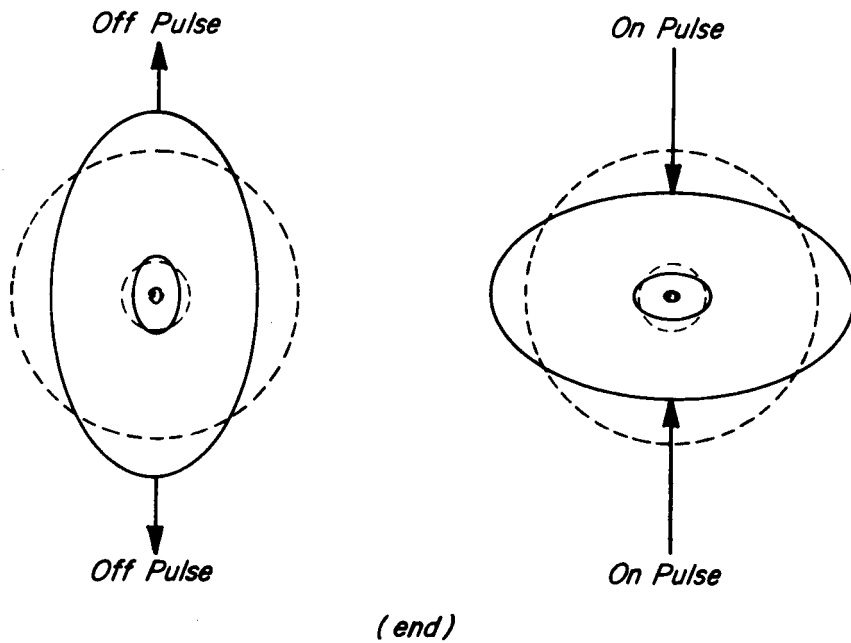
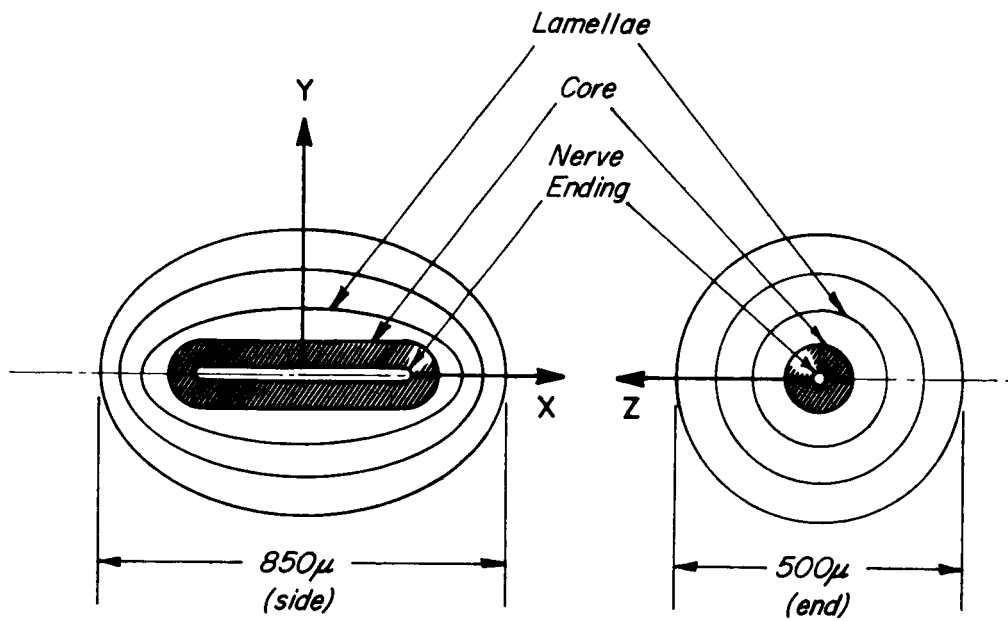


Figure 3-3. Schematic Drawing of a Pacinian Corpuscle.

3.2 Cutaneous Stimuli in Man-Machine Systems

Some aspects of the use of the cutaneous sensory system for control applications are considered here. In previous work (Ref. 3-11), the application of oculometry was suggested for human-operator-controlled missile guidance systems to overcome sluggishness and inaccuracies caused by conscious neuromuscular control. Subsequent developments in the air-to-surface missile guidance field have made it possible to eliminate the human operator to a large degree. However, there are still a number of critical man-machine interface areas where the dynamic characteristics of the human controller is of vital interest, especially in the control of flight vehicles of all types. Precision control of machines having six degrees of freedom places maximum demands on the skill of the pilot, especially where there are several lags between the application of an actuation force and an appropriate change in the primary variable to be controlled.

A number of studies have dealt with describing the human operator as an element of a feedback control system in order to permit quantitative analysis of system stability and performance. An example of publications in this field is Reference 3-12, which discusses the characteristics of the human transfer function. In terms of the Laplace complex variable, $s = \sigma + j\omega$, the simplified model of this transfer function for compensatory situations is,

$$G_p(s) = K_p \left[\frac{T_L s + 1}{T_I s + 1} \right] \frac{e^{-\tau s}}{T_N s + 1}$$

For the case of a visual pilot input from either a display or the real world and a manual output to a manual control manipulator, τ represents reaction time delay due to excitation and actuation of the eyes, nerve conduction, and computational or decision-making lags. T_N represents the response time constant of the neuromuscular actuation system represented as a simple first-order system, which appears to be adequate for the frequency ranges of interest. T_N has been found to be of the order of 0.1 seconds and τ ranges from about 0.1 to 0.3 seconds. K_p , T_L , and T_I are the parameters which the pilot adjusts, through both training and adaptation to changing situations. K_p is the sensitivity or gain factor, T_L is the lead equalization time constant when the pilot must develop anticipation, i. e., react to the rates as

well as to the magnitudes of observed errors, and T_I is a lag equalization time constant when the pilot must modulate the rate of control input to the system to slow down its response. Since the human pilot cannot easily derive rate information visually, his ability to provide lead equalization is limited, that is, T_L must be one second or less. For this reason, some systems display an error signal which includes rate as well as displacement information in order to assist the pilot in increasing his value of T_L . This is referred to as "quickenning" by the engineering psychologists. On the other hand, the human pilot can control input rate more readily and values of T_I as large as ten seconds are obtainable, according to Reference 3-13.

A fundamental question for improving man-machine system performance is whether or not there are techniques for reducing τ , the reaction time, and T_N , the neuromuscular time constant. Some reduction in T_N appears possible through the use of fingertip versus full limb manipulators (such as steering wheel or airplane control stick), but a more significant gain would be realized through a reduction in reaction time. As suggested in Reference 3-11, one approach is through oculometry, to take advantage of the tracking capability of the eye-brain closed-loop system. Even here, however, the phase-angle data (Fig. 3-18 of Ref. 3-11) indicates an increased reaction time of greater than 0.1 seconds between predictable and unpredictable target motions. These data apply to the case where the eye is used continuously for a single tracking task; in real situations, many visual displays may have to be monitored, resulting in another lag dependent on scanning rate.

Considering the overloading of the visual sense for communication of information, the possibilities of a tactile communication scheme for selected information has some attraction. In certain situations, cutaneous transmission of information may also provide an approach for the reduction of reaction time for control. Considerable research has been performed on the application of mechanical and electrical energy directly to the skin for communication. "Cutaneous communication" generally implies the transmission of the full range of information contained in normal speech, but may also be applied to the transmission of a very restricted range of information for special purposes. The use of information supplied by cutaneous stimuli to cause operation of a control manipulator would be in the latter category. References 3-13 and 3-14 are of particular interest for both categories, although emphasis is on the

broad-range communication problem. An indication of response times in this situation is the objective of reaching a reception capability up to 300 words per minute, or five per second (Ref. 3-13). Assuming that the individual words, with appropriate abbreviations, contained an average of four letters each, this implies that cutaneous inputs were detected and discriminated at intervals of 0.05 seconds or less. (On the other hand, recognition of intelligible language involves much anticipation of normal combinations. Recognition of purely random letter groups would be slower.) The possibility of achieving manipulative control based on cutaneous cues, alone or in combination with visual cues, is certainly indicated by these data. Indeed, certain experiments along this line have been performed, as reported in Reference 3-14 Project 17, 17A and 17B of the Virginia Cutaneous Project dealt with the illusion of movement that could be generated by successively energizing stimulators located on a continuous line on some portion of the body. Bice, and later Sumbly, utilized this effect to perform tracking studies, utilizing six vibrators positioned around the thorax. Various experiments showed that tracking could be done as well to vibratory signals as to analogous flashing lights.

Sumbly's studies of vibrotactile motion showed that the best illusion of apparent motion was experienced with 0.1-second delays between onsets of successive stimulators. The cutaneous inputs were applied to the skin of the back and tracking accomplished by hand (steering wheel). The nature of this method for obtaining control response is thus analogous in concept and also in performance to the visual-input, hand-manipulator-output transfer function. However, Bice also showed that trained subjects could discriminate two inputs separated by only 0.02 seconds (Project 17C). Thus, there remains the very interesting possibility that reduction of reaction time might be accomplished more effectively by providing cutaneous inputs to the body area which delivers control actuation in order to minimize the time to interpret the input signal and convert it into a command to the neuromuscular (motor) system. . Man-machine performance using hybrid visual-tactile displays would be a very pertinent topic for further study. For simple situations, this could be accomplished by a special stick controller with vibrators or electrical energizers on the front and back to signify the direction of desired action. This approach would also be consistent with many control situations where the pilot uses proprioceptive cues to provide anticipation for subsequent visual observations.

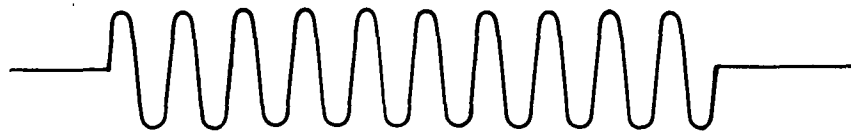
3.3 A Fixed-Sequence Transducer Design

Pulse and gate generators have been used in computer and logic circuits for a number of years. In addition, testing and programming equipment are in constant need of pulse information of various widths and repetition rates. Equipment of this type is available in various configurations for many uses. An example of this class of instrument is embodied in the General Radio Corp. type 1396A Tone Burst Generator. Typically, instruments of this type can supply the wave-forms shown in Fig. 3-4. The number of pulses, pulse widths, frequency of pulses and mode of release (continuous or triggered) are under the operator's control. Another instrument (the Browning Sweep calibrator) produces the typical pulse sequence shown in Fig. 3-5. This is nothing more than a variation on the tone burst generator. Another interesting illustration of programmed pulse information is the General Radio type 1395A Pulse Generator. Staircase functions, time marks and single pulses are available on a continuous basis or a single group upon a command. One thing is shared in common with these pulse generators; the time space between pulses (or gates) is fixed from one pulse to another within a group of pulses. The frequency of the pulses is, of course, adjustable from one fixed frequency to another, but the space between recurrent phenomena is fixed within a group.

There exists a very different pulse relationship in mechanoreceptors and in the nerve pulses resulting from various mechanical inputs to mechanoreceptors. Nerve and receptor information are coded by frequency and change in frequency rather than by amplitude or grouping. For example, Tapper (Ref.3-15) recorded the output of isolated tactile receptors in the skin of cats and observed the outputs sketched in Fig. 3-6. In this case, the output was elicited by the displacement signal shown below the nerve signal in the figure. In addition, the change in frequency (or frequency rate) is also plotted. This type of tone burst is not offered in calibration equipment currently available. Another example of this type of frequency modulated signal is seen in the records obtained by Flock (Ref.3-16.) from hair sensors located in the lateral line. These small hairs have the option of being bent in such a way as to produce neural excitation in one direction and inhibition in the reverse direction. A diagram showing the input and output functions is shown in Fig.3-7. Once again, the output of the sensor is repeatable and predictable for known input deflections,



Three Cycles of 1000cps in Three Millisecond Bursts
(Repetative)

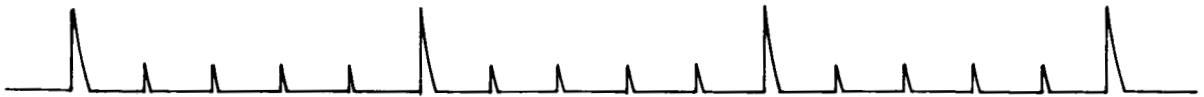


Ten Cycles of 10,000 cps, Single Gate on Demand

Figure 3-4. Some Typical Waveforms Obtainable from a Tone Burst Generator.



5 Pulses Each 1 μ Sec Long Spaced.
10 μ Sec in Groups of 5.
Gate Space, 5 μ Sec.
Single Sweeps on Demand.



Continuous Pulses Spaced 1 μ Sec, Reenforced at 5.

Figure 3-5. Some Typical Waveforms Obtainable from a Sweep Calibrator.

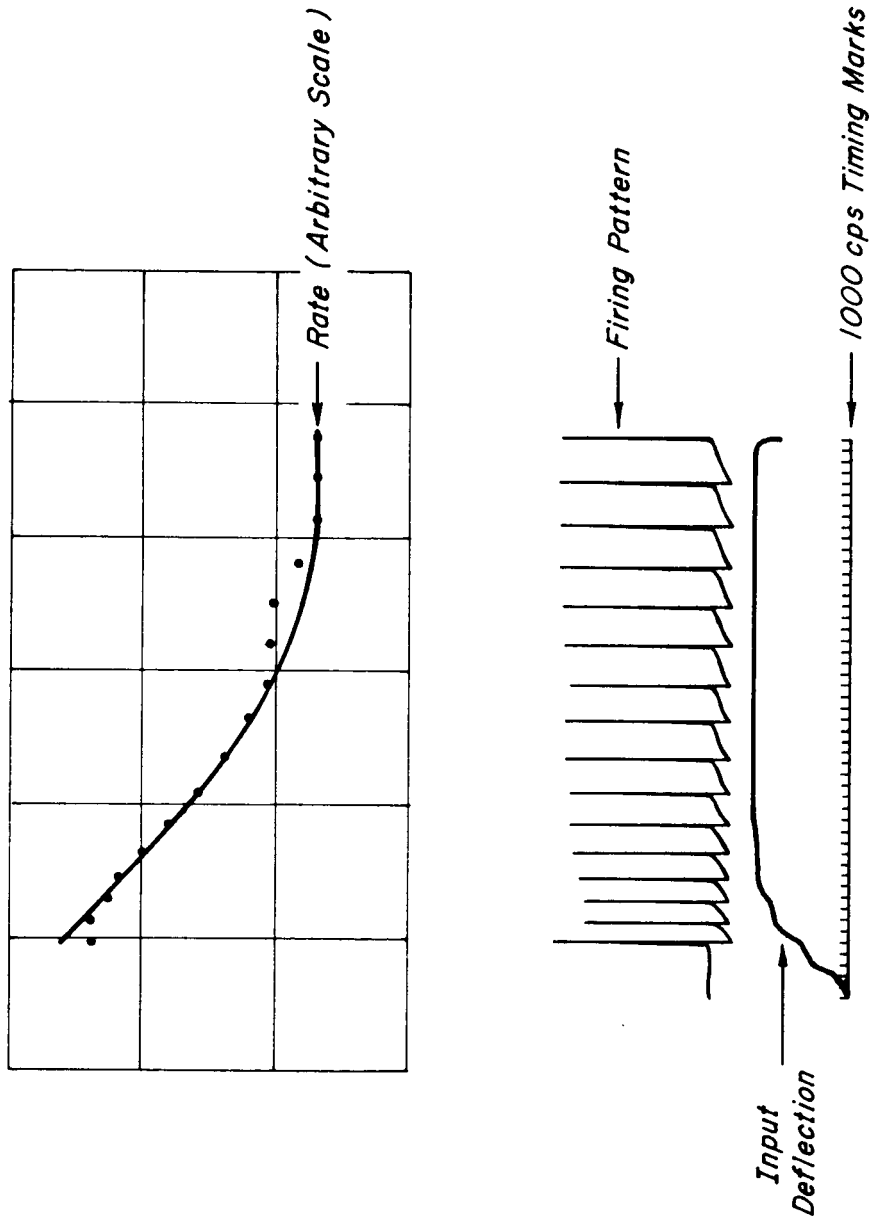


Figure 3-6. Nerve Firing Pattern for a Mechanoreceptor in Cats Skin (Ref. 3-15).

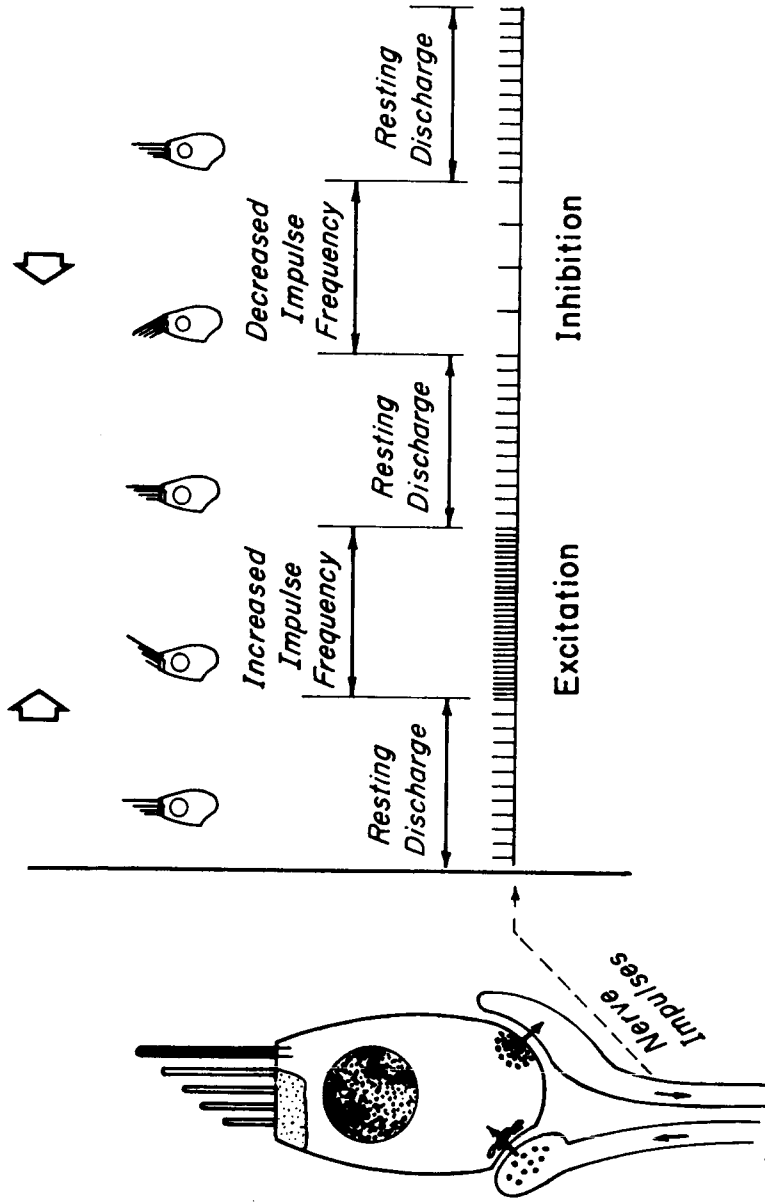


Figure 3-7. Input and Output Information Associated with Hair Sensors of the Lateral Line.

but the spacing between pulses is continuously variable depending upon the degree of input deflection. Many variations in input can present an equal number of pulse width variations, each combination of pulses corresponding to a particular pattern of input information.

Consider a time variable input of time duration that always yield the same output pattern of pulses, each pulse separated from the others by a group of different time spacings, t_1, t_2, t_3, \dots etc. Such an output might be represented by the group of pulses shown in Fig. 3-8. Each time the same mechanical input is provided, the same order of pulses results. In very much the same way that the spacing of pulses sent up the auditory nerve from the organ of Corti are interpreted as a "tone" by the CNS, groups of pulses originating in a mechanoreceptor with various time spacings are interpreted as an individual experience by the CNS. Each time a particular series of pulses is received by the CNS, the series is identified with a particular input to the mechanoreceptors. Another way of looking at this type of signal is that the time sequence variations can produce sufficient combinations of pulse patterns that a single group of N number of pulses could constitute a "word". Thus, groups of time coded signals could constitute various pieces of information much like memory functions might operate. In fact, Dyson (Ref.3-17) proposes something along these lines to explain a type of information storage that may be interrogated repeatedly without any risk of erasing the original information. Dyson proposes that a small mechanical disturbance could be transmitted along an element of "memory-record" nucleo-protein and that a pattern of pulses could be generated that are related to the previously laid-down physical structure of the protein involved. An analog of this scheme for time coded storage could be the device proposed in Fig.3-9. This is a small metal rod that has a number of circumferentially placed strain gages along the length of the rod. The gages are not spaced equally. With the gages placed in the circuit shown in Fig. 3-10, any expansion of the rod will be detected on the output lead, L. If the rod is struck on one end, an elastic pulse will travel down the rod at a velocity equal to the sound velocity in the rod material. As the pulse passes each gage, the local expansion will be detected by the strain gage and a pulse will appear at the output. The placement of the gages will constitute the pattern of the time coded pulse output as shown in Fig.3-10. Every time this rod is

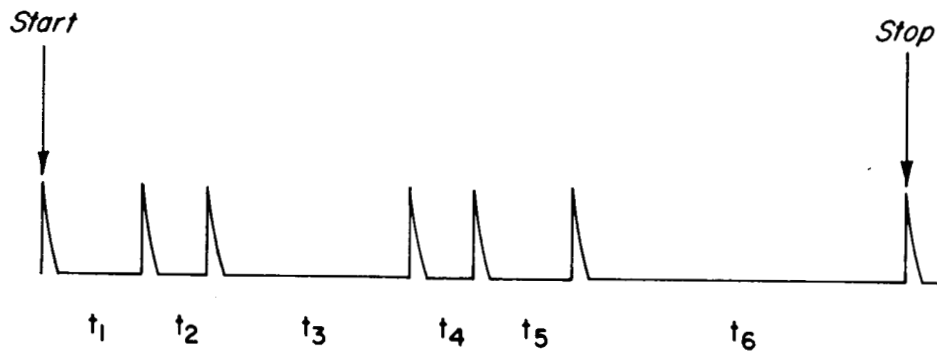
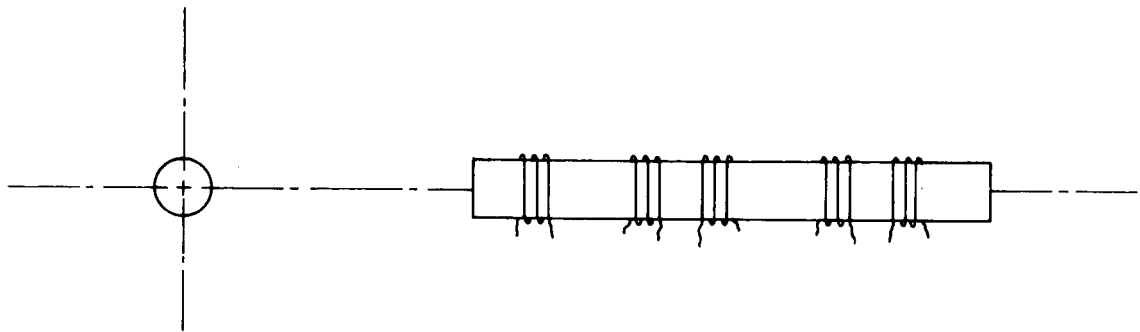
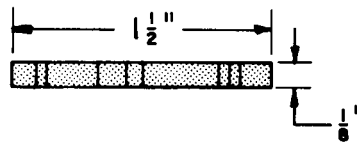


Figure 3-8. Time-Spaced Variable Pulse Group.

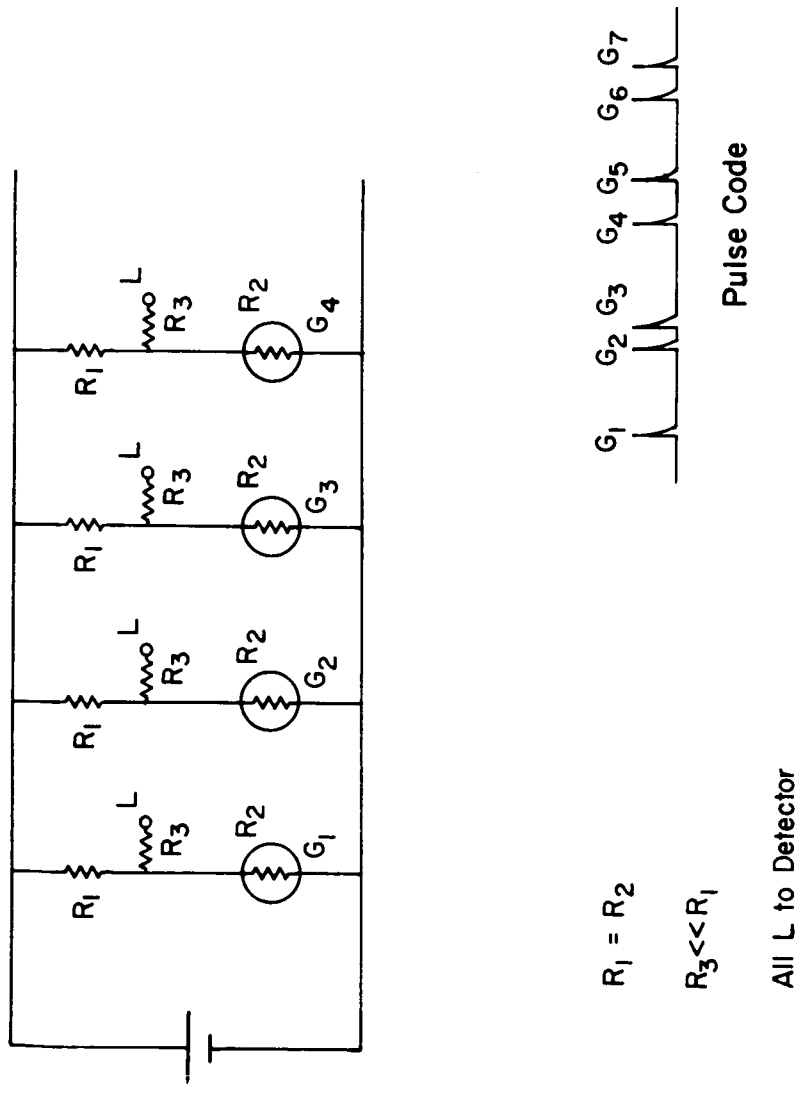


Rod and Gages (Schematic)



Actual Rod with 8 Gages

Figure 3-9. Schematic and Sketch of Pulse-Code Rod.



$$R_1 = R_2$$

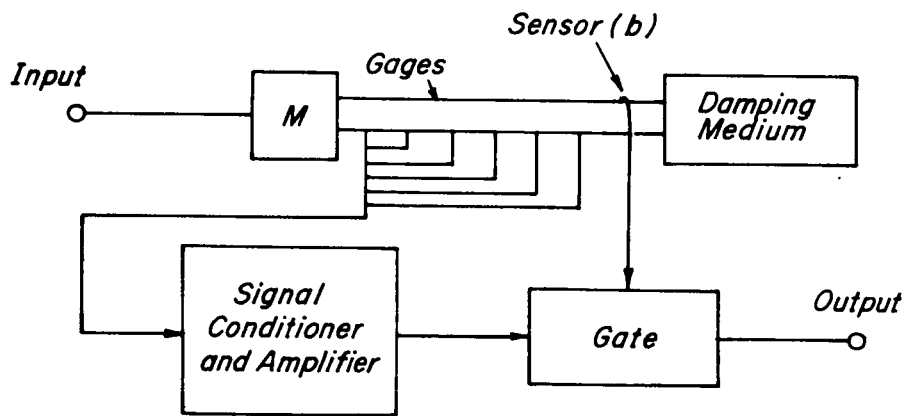
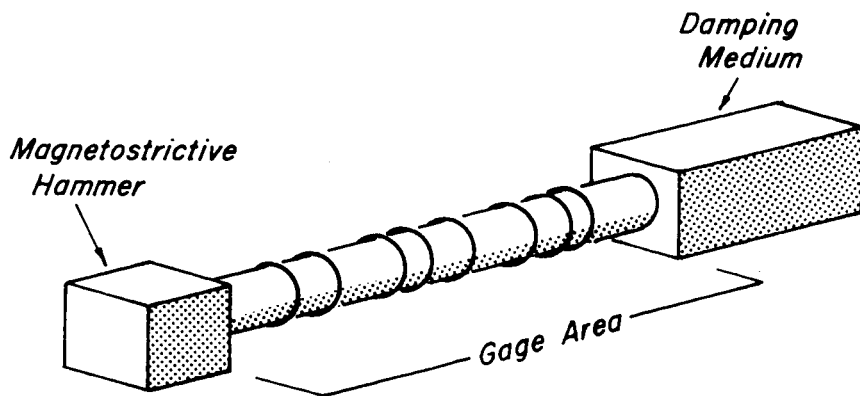
$$R_3 \ll R_1$$

All L to Detector

Figure 3-10. Circuit Schematic for Pulse Code Rod.

struck on one end, the same time coded information appears at the output of the element, so that each rod with its various gage spacings constitutes a "word" in storage.

In practice, the rod will reverberate as the elastic pulse reflects from the far end of the bar. Also, there are disadvantages to mechanically strike the end of the rod. In practice, the memory element would have the components outlined in Fig.3-11. Here a magnetostrictive hammer would supply the pulse to the end of the rod. After the pulse has traversed the region mounting the sensors, a sensor (L) triggers the gate circuit and isolates the output of the element from the rest of the circuit by means of a gate. The end of the rod is pressed into a damping medium which assists in reducing the reverberation time of the rod. By this scheme, any number of "words" could be set up on rod cores to store time coded information in pulse form.



M = Magnetstrictive Hammer

Figure 3-11. Outline Drawing and Operating Schematic of Pulse-Coded Transducer.

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SECTION 4. CHEMORECEPTION

- 4.1 Introduction
- 4.2 Chemoreception in Fish
- 4.3 Radiation and Olfaction
 - 4.3.1 X-ray
 - 4.3.2 Infrared Radiation
- 4.4 Isolation of a Receptor Protein in Taste Buds
- 4.5 Combination Olfactory Theory

REFERENCES

4. Chemoreception

4.1 Introduction

In previous reports in this series the theories and processes of olfaction and gustation were examined and reported at some length. Special emphasis was placed on insect and certain vertebrate exo-chemoreceptors and particular mammalian internal chemoreceptors. In this report chemical receptors in fish will be discussed with an emphasis on the findings of some of the more recent experiments in this area. Effects and detectability of particular long and short wave radiation on olfaction and the olfactory system itself will also be discussed. Two interesting new developments in olfaction and gustation are mentioned--one concerns a further step toward discovering actual receptor molecules involved in gustation and the other is a proposed new theory on olfaction combining the stereochemical and vibrational theories.

4.2 Chemoreception in Fish

In previous reports, chemoreception in air breathing vertebrates has been discussed. Less attention has been devoted to examining the processes and mechanics of chemoreception in fish and other water dependent animals. Since it has been found that some fish are capable of recognizing chemicals in as low concentrations as 1×10^{-11} ppm of water (Ref. 4-1), elucidation of the responsible sensory structures and mechanisms could be very useful in bionic applications such as trace chemical detection devices, pollution monitors, etc.

Although fish contain anatomically and physiologically distinct olfactory and gustatory receptors, the two sensory parameters overlap to some extent and some substances elicit responses from both. Since the conducting media for both processes is the same, which is not true for the other vertebrates, we are provided a unique chance to study similarities and differences between the sensing principles involved which can lead to further clarification of the transduction processes. Great varieties of olfactory and gustatory mechanisms exist in fish. This is probably the result of specific adaptation to their surroundings over the many years that aquatic life has existed.

Studies of fish reveal in general a high specific sensitivity to their chemical surroundings. Some fish exhibit a very high sensitivity to a particular chemical or chemicals in their environment, probably an evolutionary adaptation for survival. For instance, the eel has been shown to be able to detect certain aromatic substances in concentrations so low as to permit only a few molecules to enter the nasal area and it has been demonstrated that blind cavefish can respond to chemicals of 0.00001 M concentration (Ref. 4-2).

The anatomy of the nose as developed through evolution has been related to the ecological habits of the fish. Teichman (Ref. 4-3) established three categories:

- a) Schooling or nonpredatory fish have well-developed eyes and noses.
- b) Microsomatic daylight predators have more highly developed eyes than noses.
- c) Macrosomatic solitary predators have highly developed noses but not eyes.

In general fish have two olfactory pits, usually with two openings, consisting of an anterior inlet and a posterior outlet. Pipping (Ref. 4-4) has classified the mechanics of the olfactory process into three general types:

- a) Water is drawn in and out of an olfactory pouch opening when breathing compresses the pouch.
- b) Water passes through one opening and out another as a result of breathing or movement of cilia.
- c) Water is deflected through a capsule as the fish moves through the water.

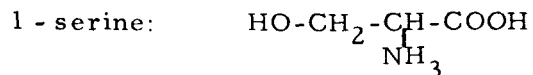
Van den Berghe (Ref. 4-5) found a unique olfactory system in Zeus fabre. Movements caused by breathing compressed the lymphatic sinuses in such a way that the olfactory rosette is pushed against the back of the nose and released, opening and shutting it like a valve.

Though the gustatory receptors of most vertebrates are located in the mouth, in some species of fish these receptors cover the whole body and are especially concentrated on the barbels and/or fins. Additionally, the pharynx, lips, and gills have been shown to be important in gustation. The taste buds of fish have fine nerve fibers surrounding them which end just below the surface of the skin. Here these surrounding fibers join with the bundle of nerves coming from the individual taste cells within the buds. Thus, in using a single nerve to study gustation it is sometimes difficult to be sure whether the nerve comes from the taste cells or the surrounding epithelial network. In electrophysiological investigations this distinction is important since these surrounding fibers are sensitive to other than chemical stimuli (Ref. 4-6).

Wrede (Ref. 4-7) and Göz (Ref. 4-8) have shown that some fish have the ability to recognize differences between closely related species of fish and individual fish in a school. A specific body odor was recognized even when mixed with many other odors.

Injured fish skin from a minnow was found to cause a fright reaction in other minnows. When the olfactory areas of the minnows were destroyed, no alarm

response was noticed (Ref. 4-9). One chemical found to cause an alarm response in very low concentrations in salmon was identified as being



This is given off in quantities sufficient for detection by a bear paw or human hand dipped in water, and is thus called the "mammalian skin factor" (Ref. 4-10). Such high sensitivity and specific chemoreception probably developed to insure the survival of the fish during the salmon runs. Thus, the old fisherman's tale that handling the fish bait repels the fish has its basis in fact.

Fish are also able to discriminate between the odors of different aquatic plants. Destruction of the olfactory epithelium destroys this ability. Furthermore, they are able to distinguish individual odors superimposed on each other. Walker and Hasler (Ref. 4-11) suggest that this ability may play an important role in helping fish to find feeding grounds when visibility is poor and also in keeping immature fish from straying too far from protected areas.

The homing ability of certain fish for spawning purposes has a demonstrated olfactory basis once the fish has reached the mouth of the river (Ref. 4-10). Series of experiments have been performed to determine the basis of this migratory ability. These fish have been found to be capable of returning to the area where they were hatched if their olfactory organs are intact. Blindness was found not to be a deterrent. The chemical composition of the guiding scent is unknown, but it is known to be heat labile and neither acid nor alkaline. The odor is also constant irrespective of seasonal changes, changes in landscapes, or even water pollution.

Bardach et al (Ref. 4-6) studied the external (gustatory) chemoreceptors on fins and/or barbels of fresh and saltwater fish. Acid was found to elicit a response in fresh water fish in one-tenth the concentrations necessary for a response from marine fish. However, ten fold more acid was necessary to lower the pH of sea water proportionally to that of fresh water. Salt concentration higher than that of the natural environments of the fish produces increased neural discharge. However, salt concentrations lower than the natural concentrations for marine animals produced an inhibitory reaction, with fresh water resulting in almost complete inhibition.

An interesting phenomenon has been noted in the chemoreception of certain fresh water fish. Konishi (Ref. 4-12) found that they are highly sensitive to very dilute salt solutions, but that higher concentrations cause an inhibition. Again at a very high concentrations,

a response was noticed. At concentrations where salt solutions depressed the receptor activity, distilled water was found to elicit a strong response named the distilled water effect (DWE). Results obtained by Konishi indicate that two chemoreceptor systems are involved, one responding to dilute salt solutions and demonstrating the DWE, and one responding to concentrated salt solutions. A dual receptor mechanism has previously been suggested to exist in the cat (Ref. 4-13).

The receptor system stimulated by dilute electrolytes was found to be stimulated best by inorganic salts with polyvalent anions. Salts with polyvalent cations and organic electrolytes did not stimulate this system at all. The magnitude of the response was different from salt to salt and increased as the valency of the anion increased. The concentration at which the magnitude of the response reached a maximum seemed dependent upon the salt normality.

Polyvalent cation salts at high concentrations (where monovalent cations depressed the response) produced a good response though at lower concentrations no appreciable response was noticed.

When the distilled water effect came in to play, an increase in concentration produced a similar increase in the DWE. This effect was only noticed with monovalent cation electrolytes. This provides further evidence that the same receptor system which responds to low concentrations of electrolytes is also responsible for the DWE. The higher the valency of the cation, the higher the depression of the distilled water effect.

The response-concentration curves which Konishi obtained for dilute electrolytes are quite similar to those of Loeb for the effects of dilute electrolytes on the electrophoretic charges of protein particles. Also, Konishi noticed that the data from his experiments was in line with electrokinetic phenomena. Based on his experiments, he proposed a hypothesis on the stimulation mechanisms of chemoreceptors that respond to dilute inorganic electrolytes in freshwater fish. He states that the active receptor surfaces are positively charged ampholytes and that they absorb anions on to the surface in increasing amounts as the salt concentration of the solution increases. Thus, the electrokinetic potential at the receptor surfaces becomes increasingly negative. The higher the valency of the anion, the greater the electrokinetic potential becomes. He suggests that this potential may cause some ionic changes at the receptor membrane which will cause the receptors to become excited. As the salt concentration increases further, however, the cation may cause a screening effect, decreasing the potential and thus depressing the response. Konishi suggests that "ionic movements" brought about by certain electrokinetic driving forces may be involved in the stimulation of the chemoreceptors by extremely dilute electrolyte solutions.

4.3 Radiation and Olfaction

4.3.1 X-Rays

The ability of rats to detect the presence of X-rays has been recognized for some time. It was generally thought that an X-ray receptor system was diffusely present throughout the whole body of the animal. More recently, however, Hull et al (Ref. 4-14) have shown that detection was greatest when the radiation was directed at the olfactory region of the head. When X-rays were directed at sleeping animals, they awoke within two seconds. Removal of the olfactory bulbs, however, caused an almost complete loss of sensitivity to these rays. Similarly, Brust-Carmona, et al (Ref. 4-15) found the olfactory bulb to be important to rats in X-ray detection. Both normal and bulbectomized rats were taught to press a lever in order to receive a saccharine solution as a reward. The rats were conditioned to pressing the lever irrespective of whether they were being irradiated or not until they developed a uniform rate. Tests were then conducted which consisted of giving the rats an electric shock when they pushed the lever during irradiation. The control rats quickly learned to press the lever only in the absences of the rays. However, the bulbectomized rats never learned, and as a result rarely pressed the lever at all. Throughout these tests the whole body was irradiated but, as the results show, only those animals with olfactory bulbs intact were able to detect X-rays.

4.3.2 Infrared Radiation

Infrared radiation was found to have some connection with the olfactory system of certain animal species. The olfactory system of the large American cockroach is sensitive to this radiation (Ref. 4-16). In darkness, these cockroaches showed a preference for situating their heads and antennae (where the olfactory receptors are located) in a black (heat-absorbing) rather than a bright (heat-reflecting) area. When an odor, known to be pleasant to the cockroaches was released into the air, the roaches had an even greater preference for the black areas than before. This seems to indicate that black body radiation (infrared radiation) somehow has a stimulating effect on the sense of smell as mediated by the insect's antennae.

4.4 Isolation of a Receptor Protein in Taste Buds

A protein has been isolated from bovine taste buds which has been shown to complex sugars and saccharine (Ref. 4-17). The strength of the complexes (assayed by refractometry and ultraviolet-difference spectroscopy) was found to be proportional to the degree of sweetness of the compounds.

Refractions of the different ammonium sulfate fractions of the protein preparations from the taste buds and many different sugars and synthetic sweeteners were determined separately and in combination (one-protein fraction to one sugar). The differences of the refractive indices of the combinations and the separate compounds were determined and represented as R in Beidler's fundamental equation which relates the magnitude of the taste response to the concentration of the stimulatory chemical:

$$C/R = C/R_m + 1/KR_m$$

where

C	=	concentration of chemical stimulus
R	=	magnitude of response
R _m	=	maximum response
K	=	equilibrium constant

When C/R is plotted against C, straight line curves were obtained. A typical example is that of fructose shown in Fig. 4-1. Although Beidler originally derived this equation to explain interaction of salts with the taste buds the results of Dastoli et al show that it also describes the interaction between sugar and a protein derived from the taste buds.

The strengths of the complexes formed between the 20 to 40 percent ammonium sulfate protein fraction and a particular sugar seemed to be proportional to the actual sweetness (by taste) of the sugars used. The free energy, ΔF , of the complex is rather low, about 2 kcal/mole, which suggests that the two are held together by hydrogen bonding. Interestingly enough, the pH dependency of the sugar-protein complexes parallels that of the effects of pH on the sweet taste of the sugar. All these results suggest very strongly that this protein isolated from the taste buds is a receptor molecular responsible for the detection of sweetness in gustation.

4.5 Combination Olfactory Theory

Perhaps a couple dozen theories of olfaction have been proposed. Of those a small number have come to be of particular interest. Wright (Ref. 4-18) has taken

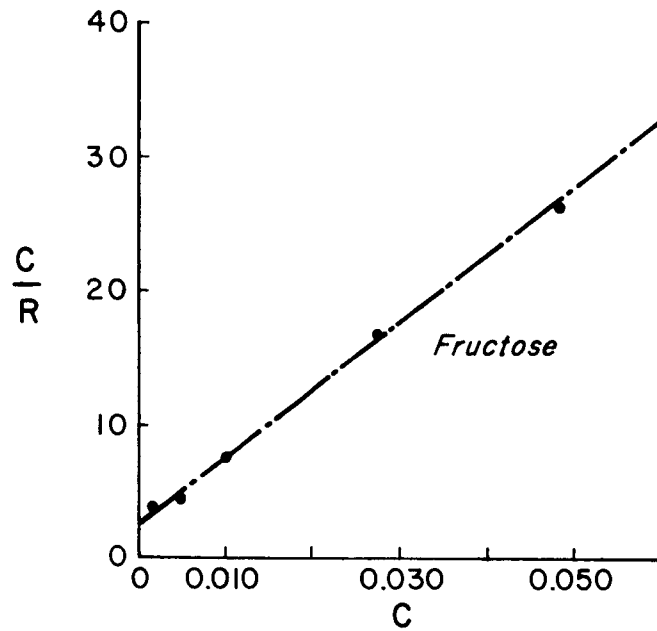


Figure 4-1. Typical plot of data observed for fructose, according to theoretical treatment. C, molar concentration of fructose; R, change in refractive index upon interaction of active protein fraction with fructose (Ref. 4-18).

two of these that seem to be conflicting (the vibration and the stereochemical theories), has shown how they were developed, and has developed a scheme in which they are complimentary. Wright's combination theory helps to eliminate some of the objections surrounding each of the other two individually.

The stereochemical theory proposes that the physical shape of the molecule determines its smell by determining what receptor site it can fit into. The vibrational theory proposes that it is the intermolecular vibrations of the odorant molecules that causes smell through resonance or interference with the receptor system.

Davis developed a theory that gave quantitative data on the concentrations of odorants necessary to cause specific odors. His olfactory threshold theory was calculated by taking into consideration two things. The first, is the partition coefficient of the odor in the air: water-oil interface which determines the number of molecules that would come in contact with the receptor surface. The second is the cross-sectional area of the odorant molecule, because the molecular contact area with the membrane determines its ability to puncture the nerve cell which is necessary to initiate an action potential.

In order to understand what properties in odorant molecules are important in the olfactory system (osmic properties) several theories have been put forth. One such important property suggested by Beet (Ref. 4-19) concerned by the shape of the molecule (profile) and the functional group that determines its attachment to the membrane surface. This Profile-Functional Group Theory is a continuation of that suggested by Davies because it determines which is the important cross-sectional area of the molecule. The stereochemical theory of Amoore is a further continuation of these two (Davies and Beet). Amoore made models of the odorous molecules and superimposed the silhouettes of those with similar odors.

The vibrational theory suggested in turn by Faraday, Tyndall, and Dyson says that it is the vibrating frequencies of the molecules that determines the odor of the molecule. Wright suggests that the frequencies must be low in order to acquire the necessary quanta of energy from the collisions of the molecules. He resolved the motion of a vibrating molecule into three axis, two being parallel to the surface of the receptor membrane and one being perpendicular. It is this perpendicular axis of vibration that is osmically important or active. This suggestion by Wright would include Beet's functional group hypothesis because it would be the functional group that would determine the osmically active oscillations (those which are perpendicular to the membrane surfaces.)

Because of the oscillation amplitude is usually of the order of $1/4$ to $1/3$ of the molecular diameter, Amoore's silhouettes become rather diffuse. However, Amoore's stereochemical theory takes on additional strength if the out-of-plane vibrations of the molecule conform with the out-of-plane vibrations of the receptor surface. Thus, larger areas of contacts would be made between stimulus and receptor, resulting in lower threshold response values. This is consistent with Davies' theory. The interaction between odorant and receptor would then be quite strong.

The combination of vibrational and stereochemical theories eliminates some of the controversy surrounding each theory taken alone. One objection to the vibration theory was that the supposed dipole-dipole coupling of receptor and odorant molecule wasn't consistent with spectroscopic data and quantum mechanics. However, Wright's new theory replaces the dipole-dipole coupling with strong van der Waals forces and eliminates this problem. Also, it eliminates the objection to the vibration theory that the energy would be of too low a frequency to affect stimulation, because it is not the vibration of the odorous molecule alone that affects olfactory activity.

In previous studies of "osmic frequencies" the resultant difference frequencies caused by two normal modes becoming excited in a molecule simultaneously have not been taken in consideration. If this is considered, Wright suggests that some of the "holes" in the correlation are eliminated (Ref. 4-20).

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SECTION 5. ELECTROSENSING PHENOMENA

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- 5.2 External Stimulation Mechanisms
 - 5.2.1 Current Excitation
 - 5.2.2 Voltage Excitation
- 5.3 Description of Observed Sensory Phenomena
 - 5.3.1 Skin Response to Audio-Frequency Currents
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 - 5.3.3.2 Microwave Excitation
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REFERENCES

5. Electrosensing Phenomena

5.1 Introduction

Living organisms perceive and respond to electric fields in a variety of ways. If electric currents or fields of increasing intensity are applied to various parts of the body, there is at first no conscious sensation, then a variety of possible sensory effects (taste, tingle, pressure, etc.), and, for large intensities, harmful electric shock effects. The intensity range above the threshold of sensation and below the shock threshold is often finite and offers a variety of means of conveying information via electric stimulation to the human body. It is the purpose of this section to review available information relative to this subject and to indicate applications where electrically produced sensations may offer a valuable means of information transfer.

This section begins with a relatively simplified description of two mechanisms whereby electrical fields or externally applied currents may be used to produce sensory effects. This description is followed by a brief review of the most significant experimental studies concerning excitation of primarily tactile and auditory sensations in man by audio-frequency and radio frequency electrical signals. Also the naturally occurring ability of electric fish to communicate and navigate with self generated electric fields is discussed. Finally, potential applications for electric communication systems, safety requirements, and the design of an "artificial" microwave sensor are discussed.

5.2 External Stimulation Mechanisms

Before proceeding to a discussion of specific observed stimulation phenomena, it may be useful to consider in a general manner some of the body's electrical characteristics and some elementary mechanisms of bioelectric stimulation by direct current or by low audio-frequency alternating currents.

Ordinarily, external electrical stimulation of the body is produced by one or the other of two relatively distinct means, which will be designated here as current excitation and voltage excitation. Current excitation corresponds to the case where relatively low voltages with associated high currents are applied to the body through electrodes placed directly in contact with the skin; voltage excitation corresponds to the case where high voltages with associated low currents are applied to the body through electrodes placed near to but not touching any conductive areas of the body.

5.2.1 Current Excitation

Considering first the case of current excitation, Fig. 5-1 illustrates the essential parameters involved. A voltage \underline{V} is applied across two separate electrodes of area \underline{A}_1 in contact with the skin. This voltage produces a current flow passing between the electrodes whose intensity \underline{I} depends essentially only on the electrical resistance of the epidermis or outer layer of the skin directly below the two electrodes. (The resistance of the body beneath the epidermis is negligible at low audio-frequencies compared to that of the epidermis.) The magnitude of the current passing through the body is given by Ohm's law as

$$I = \frac{1}{2}VA_1/R \quad (5-1)$$

where

I is the total current
R is the skin resistance per unit surface area.

The magnitude of the skin resistance is highly variable, depending on such parameters as skin and electrode condition and frequency and duration of electrical excitation (e. g. , Refs. 5-1 and 5-27). However, for the sake of illustration herein, it will be assumed to have the nominal constant value of

$$R = 20,000 \text{ ohm-cm}^2 \quad (5-2)$$

which is a representative low value for long duration electrical stimulation. (At the onset of electrical stimulation, the resistance may be about 10 times greater.)

The electric field \underline{E} inside the body is also of interest, and is given by Ohm's law as

$$E = Jr \quad (5-3)$$

where

$$J = I/A_2 \quad (5-4)$$

J is the current density
 A_2 is an effective area within which the current I is assumed to be confined
r is body resistance per unit volume

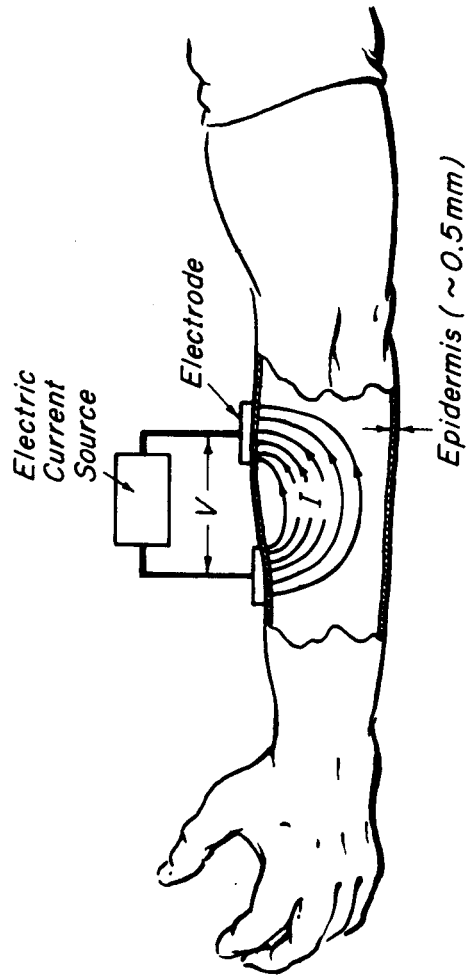


Fig. 5-1 Current Excitation of the Arm

The value of body resistance r appropriate to low-frequency electrical currents in body fluids in and surrounding nervous tissue is approximately

$$r \approx 1 \text{ ohm-meter} \quad (5-5)$$

The effective area needed to estimate local current densities varies greatly with the location in the body and with the electrode configuration, but for the sake of calculations herein the arbitrary value of

$$A_2 = 5 \text{ sq. cm} \quad (5-6)$$

will be assumed to apply.

It is next desirable to estimate the values of the above electrical parameters which are associated with sensory phenomena. For example, consider the direct current excitation of a body neuron of one millimeter in length. It is known that such a neuron can be electrically excited by a voltage across its surrounding membrane on the order of 10 millivolts; hence, it can be expected that a voltage charge of the same order of magnitude along the length of the neuron, or, in other words, an electric field of

$$E \approx 10 \text{ millivolts/mm} = 10 \text{ volts/meter} \quad (5-7)$$

will excite the neuron.

Assuming that the electric field required to excite a nerve is given by Eq. (5-7), and with the assumption of an electrode area of 1 cm², the various electrical parameters associated with nerve excitation may be estimated from the preceding equations as

$$\begin{aligned} J &= 10 \text{ amp/meter}^2 = 1 \text{ milliamp/cm}^2 \\ I &= 5 \text{ milliamps} \\ V &= 200 \text{ volts} \end{aligned} \quad (5-8)$$

With due regard to the relatively crude assumptions involved in the above estimates, it may be noted that the above current estimate of several milliamperes concurs reasonably well with the experimentally observed range of currents required to produce low-frequency electrical sensations such as tingling and shock (e. g., see Table 5-1); the voltage estimate of 200 volts may also be intuitively recognized as being of an order of magnitude appropriate to the creation of an electric shock.

TABLE 5-1

Quantitative Effects of Electric Current on Man*

Effect	Milliamperes (thousandths of an ampere)					
	Alternating Current					
	RMS Values					
	Direct Current		60 Cycle		10,000 Cycles	
Men	Women	Men	Women	Men	Women	
No sensation on hand	1	0.6	0.4	0.3	7	5
Slight tingling. Perception threshold	5.2	3.5	1.1	0.7	12	8
Shock -- not painful and muscular control not lost	9	6	1.8	1.2	17	11
Painful shock -- painful but muscular control not lost	62	41	9	6	55	37
Painful shock -- let-go threshold	76	51	16.0	10.5	75	50
Painful and severe shock -- muscular contractions, breathing difficult	90	60	23	15	94	63
Possible ventricular fibrillation from short shocks:						
Shock duration 0.03 sec.	1300	1300	1000	1000	1100	1100
Shock duration 3.0 sec.	500	500	100	100	500	500
Ventricular fibrillation -- certain death						

Multiply values immediately above by 2 3/4.
To be lethal, short shocks must occur during susceptible phase of heart cycle.

*This table was taken from Reference 5-5.

5. 2. 2 Voltage Excitation

Voltage excitation of the body may be conveniently produced by placing one electrode directly against the skin and applying a voltage between this electrode and another electrode held some finite distance from the skin. In this case, the active electrode and the skin form the two plates of an electric condenser. A similar situation also exists when the active electrode is immersed in a conducting fluid placed inside the outer ear; in this case, the eardrum and opposite wall of the middle ear form the condenser plates.

In both cases, an electrostatic pressure (or tension) acts on the skin or eardrum. This pressure may be calculated from the expression

$$p = \frac{1}{2}\epsilon (V/d)^2 \quad (5-9)$$

where

p	is pressure
ϵ	is the dielectric constant
V	is voltage
d	is the mean distance between the plates of the condenser.

This electrostatic pressure may, in turn, excite body sensations via activation of any of the body's sensory receptors which react either directly to mechanical pressures or indirectly to deflections produced by the electrostatic pressures.

5. 3 Description of Observed Sensory Phenomena

In this section, a brief description is given of the types of observed sensory phenomena which have been produced by electrical stimulation of the human body by audio-frequency signals. Topics considered include audio-frequency stimulation of tactile and auditory sensations and auditory stimulation of the head by amplitude-modulated radio frequency signals. The electrosensory capabilities of certain fish are also discussed.

5. 3. 1 Skin Response to Audio-Frequency Currents

If electrical currents are passed between two electrodes placed at two different places on the surface of the body, there may be produced such sensations as pain, pressure, touch, throbbing, tingle, sting, feeling of being stroked by a comb, and shock. The threshold currents required to produce these various sensations depend on many variables such as electrode size and

spacing, type of electrode, skin condition, current frequency, pulse duration, number of pulses, etc. For practical applications in information transfer, these various sensations are of interest, of course, only if sensations tolerable to the subject have lower threshold currents than those which produce unpleasant or painful sensations. This is fortunately often the case. For example, Anderson and Munson (Ref. 5-1) determined the threshold currents which produced a sensation similar to a comb stroking feeling in the arm and also those required to produce pain. They found that in the frequency range from 100 to 10,000 cps there exists a moderate range of current values where skin sensations can be produced without inducing pain. For frequencies below 100 cps or over several thousand cps, however, pain was often found to be the first sensation to be elicited.

In view of the above circumstances, various investigators have been, or are developing equipment for utilizing electrical skin reception of signals, which employ short (fractional-second) bursts of high audio frequency signals (at one to several thousand cps) of a few milliamperes intensity, where information is transmitted in the form of morse code or a similar system (e. g. , Refs. 5-6 and 5-16).

With respect to more complex processes of sensory reception in the skin, some investigators have found that the skin has some limited ability to discriminate between different frequencies of excitation; also, if the skin is excited alternately or simultaneously at several not-too-close locations, it is possible for the subject to recognize the excitation locations. Through recognition of these two perception capabilities, Anderson and Munson have suggested that the skin can be used to electrically perceive some limited characteristic of human speech, by either making use of the limited frequency discrimination of the skin or by electrically channeling incoming frequency signals in different frequency ranges to different electrodes on the skin (Ref. 5-1).

5.3.2 Auditory Response to Audio-Frequency Currents

Early studies of hearing of electrical audio-frequency signals were conducted by Stevens et al (Refs. 5-17, 5-24 and 5-25), who also discussed previous work by others. They used human subjects, to whose ears electric currents were applied through a pair of electrodes. An inert electrode was usually attached to the arm or wrist and an active one was usually inserted into the external meatus of the ear. Good conductance between the meatus wall and electrode were insured by filling the ear with a salt solution.

Conducting only the reactions of subjects with normal

hearing, the following results were obtained upon direct stimulation by audio-frequency signals:

(1) For frequencies between about 200 cps and 10,000 cps, most subjects experienced an auditory sensation at current intensities lower than those required to produce an electric shock effect.

(2) For lower or higher frequencies, most subjects experienced shock effects at lower intensities than those required to produce hearing sensations.

(3) Two subjects were able to hear frequencies as low as 125 cps without experiencing shock effects. The sensations experienced here were of a complex nature, combining auditory, tactile and pressure sensations.

(4) With respect to the fidelity of perception of pure tones, music, and speech induced by this electrophonic experiment, Stevens' initial studies (Ref. 5-24) indicated that too high a degree of distortion was present to encourage development of this electric hearing effect as an alternate means of hearing for special purposes. (This particular problem was subsequently overcome, as described below.) More specifically, it was found that, in this experiment, the sensory mechanisms involved tended to obey a square-law variation, so that the perceived sound appeared to have twice the frequency of the applied electrical signals. The mechanism involved in this process was explained in a fairly convincing manner by Stevens and Jones (Ref. 5-25; see also Sec. 5.2.2). An electric field exists inside the middle ear between the eardrum and the opposite wall of the middle ear of intensity E equal to V/d where V is the applied voltage and d is a mean distance between the eardrum and the opposite wall. This electric field produces an electrostatic pressure p on the eardrum which is given by the standard equation for the electrostatic force on the plates of a plane-parallel condenser as $p = 1/2\epsilon E^2$, where ϵ is the dielectric constant for air.

(5) After discovery of this square-law perception effect ($p \sim E^2$) described above and following some observations by Craik et al, Stevens and Jones calculated and experimentally proved that application of a direct current bias voltage to the ear in addition to the alternating current audio input could produce a linear good fidelity ear response to the audio signal (Ref. 5-25).

In addition to the particular test configuration used by Stevens et al, other investigators have evoked similar square-law auditory sensations by placing an electrode in the ear without the presence of a saline solution directly connecting the electrode to the eardrum (e. g., Refs. 5-7 and 5-23), or even by simply holding an electrode a short distance from various parts of the head near the

ear. In each case, the investigators claimed that the effect can be explained by the action of electrostatic pressures acting directly on the eardrum, or acting less directly on the skull to produce hearing by the bone conduction mechanism, or acting through other less well defined electrostatic processes (Refs. 5-7 and 5-23). It might also be noted that some subjects without eardrums can experience the square-law auditory excitation (Ref. 5-7).

A number of tests were made by Jones et al (Ref. 5-17) to determine the practicality of producing sound sensations electrically in subjects suffering from severe hearing defects such as removal of eardrums and middle ear structures. For subjects of this type an electrode covered with a salt-dipped cotton tuft was usually placed inside the middle ear against the oval or round window. In these cases, no square-law electrostatic effect was experienced, but some subjects experienced linear response to applied tones of a given frequency, others experienced only buzzing noises roughly independent of frequency; and others experienced no auditory sensations at all.

Some very recent electrical stimulation studies were made by Simmons et al (Refs. 5-31 and 5-32) with small electrodes permanently implanted in the auditory nerve of a severely deaf subject. They found that the subject was capable of a very limited discrimination of intensity and pitch via this method of electrical stimulation. The sensations produced depended primarily on electrode selection, stimulus repetition rate, and current density, and secondarily on stimulus waveform, duration, and order of presentation. While the investigators saw little probability of conveying complete speech information to the subject, they did succeed in conveying the sensations of a few simple musical tunes.

5.3.3 Response to Radio Frequency Excitation

In addition to direct audio-frequency electrical excitation of the human body, it is possible to produce auditory sensations by similarly applying radio-frequency signals containing an audio-frequency amplitude modulation. Results of experimental studies in this area are described below, both for experiments utilizing frequencies in the conventional AM radio communication bands (up to several megacycles) and for microwave frequencies (over 200 megacycles).

5.3.3.1 Excitation at Radio Communication Frequencies

The reception of radio-frequency stimulæ by the human body has been studied by Puharich and Lawrence (Refs. 5-20 and 5-21), Bredon (Ref. 5-4) and Harvey and Hamilton (Ref. 5-15). While these investigators used superficially different techniques, each subjected the heads of human subjects to an amplitude-modulated radio-frequency electric field, where the amplitude modulation consisted of an audio-frequency signal--either speech, a pure tone, or music.

Puharich and Lawrence have performed some tests which showed that amplitude-modulated radio-frequency currents passed through some regions of the human head can produce high-fidelity auditory sensations. No details of Puharich and Lawrence's studies were available to us during the course of this project, but information from several secondary sources (e. g. Ref. 5-28) indicates that the effect does exist, that a very strong electric field is required (Ref. 5-23 indicates that over 10^4 volts/cm were used by Puharich and Lawrence), and that the effect is most likely produced by the electromechanical pressure of this field exciting the normal auditory bone conduction mechanism of hearing.

Bredon (Ref. 5-4) conducted no detailed studies, but made some informal experiments where subjects compared perception of modulated radio-frequency excitation with direct sound excitation for the same signal inputs--tones, speech and music. He found that the electrically perceived sound was relatively undistorted.

Harvey and Hamilton (Ref. 5-15) performed an electric hearing test to determine the threshold voltage at which a subject can detect an audio-frequency modulation of 3.5 megacycle radio-frequency current applied across his head, for audio frequencies between 200 and 5000 cycles. They did not report the actual voltages and modulations used in their experiments (probably on the order of thousands of volts/cm) but restricted their data presentation to calculated values of the corresponding electrostatic pressures, from which they concluded that the electrostatic-pressure threshold for perception of the electric signal was comparable to the mechanical pressure required to excite hearing via the conventional bone conduction mechanism.

In addition to these hearing sensation tests, Harvey and Hamilton also produced tactile sensations by applying amplitude-modulated radio-frequency voltages to the fingers of several subjects and determined the associated threshold electrostatic pressures. These threshold pressures were found to be several orders of magnitude larger than those required to produce auditory sensations by application of radio-frequency voltages to the head.

5.3.3.2 Microwave Excitation

The possibility of conveying audibly sensed information to the human body by electromagnetic waves in the microwave range has been recently experimentally demonstrated by Frey (Refs. 5-8 through 5-11) and has been confirmed by several other investigators (Refs. 5-12 and 5-30).

Frey utilized a series of pulsed microwave beams covering the frequency range from about 200-3000 megacycles. These pulsed beams were directed at the heads of subjects with normal and impaired hearing and effects of the following variations were examined: location of the beam on the head, pulse shape, frequency and duty cycle, shielding of parts of the head from the beam, and subject hearing ability. As a result of these studies, Frey made the following observations:

(1) For sufficiently high electromagnetic field intensities, most, but not all, subjects experienced sounds described as a buzz, tickling, hiss or knocking, depending on the transmitter characteristics.

(2) Initial experiments indicated that ability to perceive the radio-frequency sound depended on good subject hearing ability by either air or bone conduction up to frequencies of at least 5000 cps (Ref. 5-8). Later experiments, however, revealed subjects with ability to hear 5000 cps sound normally, but who could not perceive radio-frequency sounds.

(3) Throughout the investigated range of microwave frequencies covering frequencies from 216 to 2982 megacycles, the radiosound effect was experienced, with sensitivity being greatest in the middle part of the range near 1000 megacycles. Frey noted that this minimum at about 1000 megacycles corresponds to the frequency at which microwaves of a given intensity have been calculated to penetrate most deeply into the forehead (Ref. 5-11).

(4) Regardless of the orientation of the incident microwave beam, the subject feels the perceived sound to come from the same apparent source located a short distance behind the head.

(5) The minimum signal required to produce an auditory sensation was found to depend on the peak power density of the pulsed wave and not on the average power. The corresponding threshold peak electric field intensities were about 14 volts/cm for frequencies between about 400 and 1300 megacycles.

The mechanism by which the body perceives this microwave signal is not known with any degree of certainty. However, Frey has located the area most sensitive to this phenomena as a region over the temporal lobe of the brain, which suggests the possibility that the applied radiation may be directly stimulating the auditory nerve or the auditory region of the brain, rather than creating auditory sensations conventionally via stimulation of the peripheral auditory receptors. Sommer and von Gierke have suggested that the phenomena involved is simply produced by the mechanism of radiation pressure acting on the head (Ref. 5-22), where the resulting mechanical deformations of the head excite the

normal process of hearing by the bone conduction process. It is recognized, however, that this explanation is not entirely satisfactory since it implies a greater sensitivity of the ear than is normally believed to exist.

Frey reported no specific tests directly indicating the possibility of conveying complex auditory information such as speech to the body by audio-modulated microwaves, but did indicate that variations in the produced sensations could be produced by varying transmitter characteristics such as frequency, pulse width, and pulse repetition rate. More recent tests of a similar nature by Constant (Ref. 5-30) showed more specifically that some subjects can hear and distinguish individual microwave pulses at frequencies of 3,000 and 6,500 megacycles, for pulse durations as short as one microsecond and for pulse repetition rates below 100 pulses per second. For more rapid repetition rates, the subjects experienced a continuous "buzz". Constant also found that some subjects, who could not initially hear the microwave signal, could, through repeated exposure, learn to hear the signal.

5. 3. 4 Electric Communication and Object Location by Fish

In a previous volume in this report series (Vol. III) the then available information was reviewed on the characteristics of electric fish with respect to their ability to detect distant objects by the action of self-generated electric fields reflected by these objects. This section briefly summarizes some of this information and results of more recent studies, with particular emphasis directed toward the understanding and potential applications of the information processing systems utilized by electric fish.

5. 3. 4. 1 Observed Electrosensory Phenomena

The most significant early studies of the electrosensory capabilities of electric fish were performed by Lissman and Machin (Ref. 5-38), who demonstrated that some fish possessing weakly electric organs (generating single volts) can detect potential gradients and, more important, can detect changes in the conductivity of the medium around them. Through the action of an electric organ located in the posterior of the fish, a self-produced dipole field is set up around the animal, and variations of the field strength are detected by specialized electroreceptors. These receptors, mormyromasts in Mormyrids and similar structures that occur in Gymnotids and other groups, are usually distributed along the lateral line of the fish. The receptors generate potentials in response to applied electric stimuli, and these potentials, in turn, activate responses in the innervating nerve fibers. The brain centers into which these nerves run are remarkably large and complex in Gymnarchus niloticus.

Lissman and Machin (Ref. 5-38) calculated that the most sensitive known electric fish, *Gymnarchus*, could detect changes of the electric field of the order of $0.03 \mu\text{V}/\text{cm}$ produced by direct currents. They postulated that the most probable mechanism used by *Gymnarchus* to locate objects is a receptor system operating in the second derivative mode and they calculated the threshold of the electric field to be about $0.05 \mu\text{V}/\text{cm}$. The corresponding change in current in the electroreceptors was calculated to be approximately $0.003 \mu\mu\text{A}$ for 1 millisecond pulses at a frequency of 300 cps. This is a remarkable sensitivity.

Subsequent to the above-described studies of Lissman and Machin, a number of investigators have studied in much greater detail the electroreceptor characteristics of many other electric fish and have obtained a better appreciation of the receptor mechanisms and of the complex information processing systems which are involved in the electrosensory activities of these sensitive fish (Refs. 5-33 through 5-41). Agalides et al (Refs. 5-33 and 5-34) obtained information on about 140 fresh and marine water electric fishes, both strong and weak types. Pulses emitted by the electric fishes were found to vary in duration, repetition rate, and amplitude from species to species.

In a series of behavioral experiments Agalides et al (Ref. 5-33) demonstrated the ability of *Sternarchus albifrons* understand its own signals or those of another fish of the same species. Signals from *Sternarchus* were recorded while it was undisturbed, while it was feeding and when it was undergoing stress. When played back from a pair of electrodes in the water, these signals evoked responses which were the same as those of the fish during the recording.

Bennett (Ref. 5-35) has defined three types of electroreceptors in Morymids, termed large medium, and small pores. The responses vary with the type and he has postulated on an electrical model of the large pore. The threshold current of the large pore is calculated to approximate 10^{-10} amperes. In comparing the sensitivity of a large pore to the Johnson noise of his receptor model, excitation by noise would be extremely infrequent.

Murray (Ref. 5-40) has studied the receptor mechanisms in the Ampullae of Lorenzini of Elasmobranch fish and Hagiwara et al (Ref. 5-37) have described properties of electroreceptors in the eel.

Results of these recent investigations, however, have not explained the great sensitivity of *Gymnarchus niloticus* observed by Lissman and Machin, which remains unsurpassed by other fish.

5.3.4.2 Information Processing

With respect to the nature and capabilities of the information processing systems of electric fish, recent studies have indicated the following.

Temporal integration of the electric organ pulses of *Gymnarchus* has been observed by Machin and Lissman (Ref. 5-39). These pulses occur at a 300 cps rate and an integration time constant of approximately 25 milliseconds was determined experimentally. The threshold current of 0.003 $\mu\mu\text{A}$, calculated by Lissman for *Gymnarchus*, flowing for 25 milliseconds corresponds to a movement of 1000 univalent ions. This signal will be very 'noisy'; in terms of impulse transmission in the sensory nerve, it may represent an indiscernibly small change in the firing due to standing current and noise. Since the pulsing of the electric organ is controlled by the fish's brain, the mechanism of synchronous detection is presumed to be available to the fish. However this still does not account for the sensitivity of *Gymnarchus*. Machin and Lissman (Ref. 5-39) claim that only the correlation of the outputs of 50,000 receptor channels could produce a clear signal, free from noise. They presume that *Gymnarchus* utilizes pattern recognition mechanisms in detecting threshold conductivity changes.

Stagge and Schief (Ref 5-41), in studying *Gnathonemus petersii*, suggest the existence of a threshold detector which suppresses nearly all noise that occurs between fish pulses. Their experiments where noise signals were superimposed on information signals indicate that the fish's threshold is controlled by the noise level.

Agalides et al (Ref. 5-33) have observed that the South-American electric fish *Sternarchus albifrons* utilizes a phase-permuted coding system for transmitting and receiving electric signals, which system corresponds in an astonishing manner with a recently developed complex man-made low-error-rate coding system developed by General Dynamics/Electronics (DEFT system).

In view of the above observations, it is evident that continued study of electric fish and their electrosensory systems offers a guide for development of improved man-made coding and communication systems, patterned on those of the electric fish, which will permit the transmission of more information without an increase in bandwidth or power. Also, a man-made analog to the electric fish could serve the useful military purpose of providing a not-now-realizable sensitive means of detection of foreign objects in or below the seas.

Moreover, since the design of such analog systems is beyond the state-of-the-art of current technology, it can be seen that the continued bionic investigation of these fish systems is of considerable import.

5.4 Applications

This section briefly describes some current and potential applications of the above described electrical sensory processes to problems of human information reception.

(1) In communications between workers in unnatural atmospheres, there may arise situations where normal speech and hearing processes are too distorted to convey reliable information. In particular, both divers below the oceans (Ref. 5-20 and 5-25) and astronauts in space (Ref. 5-16) or other extraterrestrial environments may live in atmospheres different in composition, pressure, and density from normal sea level conditions and may experience such communication problems. For such situations, the introduction of systems for direct electrical stimulation of the body, whether to convey simple warning signals, morse code, or complete speech, could well provide a valuable supplement to normal communication systems.

(2) In situations where operators of complex control-panel systems (e. g., aircraft or spacecraft pilots) are forced to divide their attention between monitoring a host of visual and auditory displays, it would be valuable to augment such displays by electrical stimulae devices. For example, an operator may well overlook one of a multitude of visual indicators or, in a crowded or noisy area, conventional conversational or earphone reception might be masked by the noise of the environment. On the other hand, a localized electric signal applied to one or more distinct areas of the skin might well be designed to offer a group of hard-to-overlook simple warning signals or more complex information. With respect to speech communications in this situation, replacement of conventional earphone receptors by electric hearing devices might appreciably reduce the noise level of the environment.

(3) In situations where a group of workers are subjected in crowded quarters to continuous irregular alterations of work and sleep for days at a time, it might be valuable to utilize electrical stimulae devices as "silent alarm clocks" to selectively awake workers, either according to preset time schedules or on demand from situation monitoring instruments upon their realization of any critical conditions.

(4) Other applications of electrical sensory devices might arise in situations where a human operator functions as a critical integral part of a complex feedback control system, such as in the piloting or control of flight vehicles of all types. In such cases, the ability of the operator to control the system is considerably limited by the cumulative human time lags involved in perception of the need to perform a control operation via visual, auditory or other sensory means, in neural travel and decision time for transfer of the information from receptors to the brain and back to the appropriate muscular control output, and in time delays involved in manually handling input and output parts of the control system. Here, the use of electrical stimulae devices offers a means of decreasing the accumulative operator reaction time by introducing control information to the operator at a more optimum location which bypasses or minimizes (slower) mechanical elements and shortens neural travel distances.

(5) For front line military communications, situations will exist where use of conventional vocal-radio communications presents too much of a threat of detection by the enemy to be desirable, or where use of quiet enough earphones might distract the users from auditory indications of enemy approach. For such situations, electrical sensory devices for functions now performed by voice offers a possibility of safer more secure military operations.

(6) One final obvious area where it would be desirable to make use of electric sensing is in the field of aids to the deaf. As was noted in Section 5.3.1, it has been shown to be possible to convey some limited degree of speech information to a subject via tactile stimulation and that direct auditory information can be conveyed to subjects experiencing some moderate degree of hearing deficiencies such as ear drum or middle ear losses, but without loss of the capability to hear by bone conduction. The practical value of electrical hearing techniques over conventional techniques would have to be established but they may offer advantages in certain types of deafness and therefore this approach appears worth some further investigation.

5.5 Related Consideration

5.5.1 Safety Considerations

One important and possibly overriding consideration in the above-described potential applications of electric sensation phenomena to practical information sensing problems is the question of subject safety. For example, some subjects may well experience an electric shock sensation at lower intensities of electric current or voltage than those required to produce an auditory or tactile sensation. The harmful effects of direct current and audio-frequency

have been studied sufficiently well to permit a reasonable assessment of the hazards of any particular current applied to the body (e. g. , Ref. 5-5); but for radio-frequency and microwave-frequency applications, the situation is less clear, and is particularly least clear for pulsed wave applications. For example, U. S. standards for long duration exposure to electromagnetic radiation give a maximum allowed power exposure of 10 milliwatts/cm² (Ref. 5-29), which corresponds to rms voltage of about 400 volts/meters. However, Soviet standards for biological hazards (e. g. , Refs. 5-18 and 5-19) indicate that radio-frequency power densities a thousand times smaller may be harmful.

5. 5. 2 Design of a Microwave Dosimeter

5. 5. 2. 1 Background

Considerable research effort has been directed toward investigating the perception and response of a variety of living organisms to electric and magnetic field phenomena. While the only case in which a sensory system of distinct receptors, specifically responsive to electric fields, has been experimentally isolated and identified in the case of certain electric fish, there does appear to be general agreement that other life forms are definitely affected by electric and magnetic fields. The exact manner in which these interactions occur and the responsible bio-mechanisms are yet to be uncovered and explained. Despite some limited experimental evidence and a good deal of theoretical hypothesizing, there is as yet no clear picture as to the nature of these effects.

Additionally, in the field of health physics, there has been continuous interest and activity directed toward microwave radiation. A wealth of information has been gathered and analyzed by Allied Research on the biological implications of such non-ionizing radiations. It is interesting to note that the microwave power available at 3000 Gigahertz has gone up by 5 orders of magnitude since 1940 (Ref. 5-42). The use of high energy nuclear power sources presents a similar situation. In both these areas, the natural human senses are useless for detection, measurement, and control. Man can only monitor these radiations with the aid of instruments and alarm systems. Personal detection systems are at present highly developed for nuclear radiations but are almost non-existent for microwave radiations.

With the above in mind and in the light of the foregoing discussion of potential safety hazards, it appeared desirable to consider providing people with an "artificial" sensor or sensors responsive to these electro-

magnetic radiations, thereby extending the range of their natural environmental monitoring ability. In this section the design of such a "sensor" is presented.

5.5.2.2 The Device

The measurement of microwave energy for the purpose of health monitoring involves more than a survey of the area in the vicinity of radiating equipment. Unlike nuclear radiation, microwave energy may be reflected in such a manner as to create hot spots where the energy density of the radiation may easily exceed the average radiation density in the immediate area of the equipment. In addition, microwave systems have moving elements that can change radiation patterns in both a cyclic mode (search antenna patterns) and other unpredictable modes, such as electronic countermeasures devices. For either nuclear or microwave radiation measurements, the man-carried dosimeter has distinct advantages over semi-permanent energy density monitoring equipment in matters of personnel protection.

Therefore, a microwave dosimeter is proposed that would be similar in performance to the pocket carried nuclear ionization gage which measures the total ionizing radiation to which the wearer has been exposed. This instrument is intended to measure the time-intensity product of the radio-frequency energy to which it is exposed. It is proposed that the wearer would carry the device on such a part of the body that the exposure measurement would represent an average of the whole body dose. The instrument is divided into three component parts as depicted in Fig. 5-2. These components may be described as follows.

A. The Antenna Unit

The function of the antenna is to capture sufficient energy to operate the electronic signal conditioner. Since the polarization and direction of incidence of the microwave radiation may be random, the radiation pattern of the receiving antenna should be isotropic. A short dipole antenna (short relative to the radiation wave-length) has a toroidal shaped power pattern, where the dipole axis is normal to the equatorial plane of the toroid. Four dipoles arranged as shown in Fig. 5-3 provide an omnidirectional pattern for circularly polarized radiation. The maximum effective aperture of a short dipole antenna is $3\lambda^2 / 8\pi$ (Ref. 5-43), where λ is the wavelength of the incident radiation and is independent of the length of the dipole, provided only that it is small (dipole length $\ll \lambda$). However, this assumption neglects the effects of any losses, which are considerable for a short dipole antenna. If it is assumed that the terminating

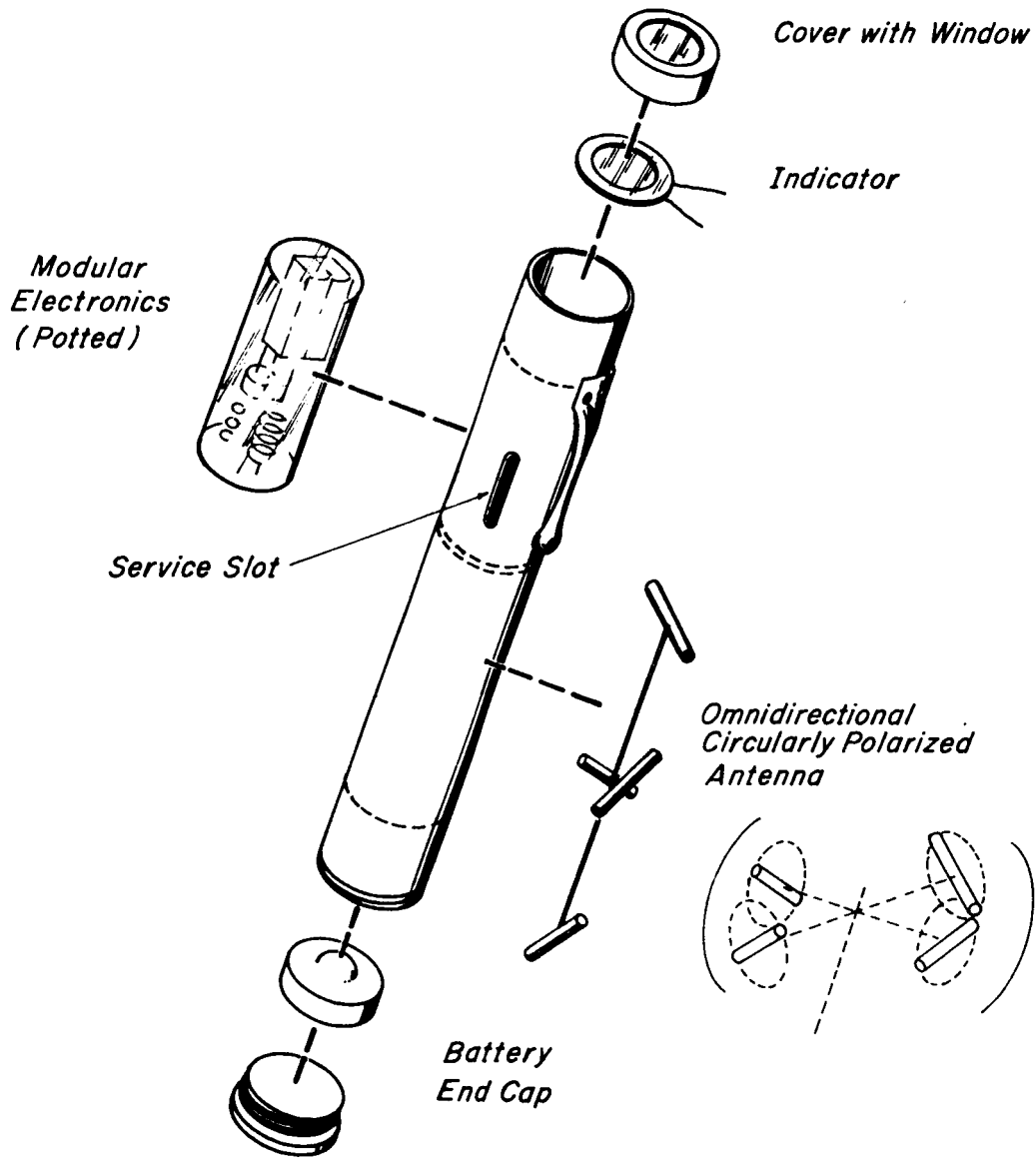
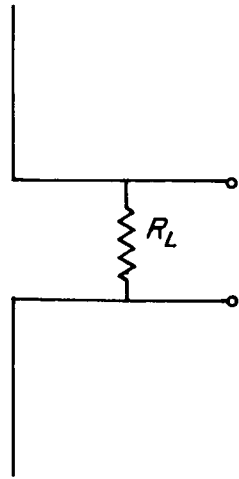


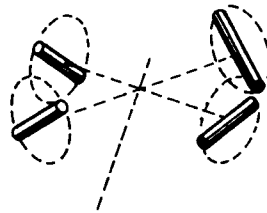
Fig. 5-2 A Microwave Dosimeter

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Dipole Schematic



Dipole Arrangement

Fig. 5-3 Dipole Schematic and Arrangement

impedance (R_L in Fig. 5-3) is matched to the antenna impedance and that the antenna has a loss resistance equal to its radiation resistance, the effective aperture is half of the maximum effective aperture or approximately $0.05 \lambda^2$. The power available from a short dipole is equal to the product of its effective aperture and the power density of a wave maximally incident in the antenna pattern. Thus, an incident radiation density of 10 mw/cm^2 with a one cm wavelength would result in a useful power of $.05 (1)^2 \times 10 = .5$ milliwatts. This is many orders of magnitude above the thermal noise power which would appear across the load terminals. Consequently, simple antennas such as short dipoles seem feasible as receptors at the required power levels. If the radiation wavelengths to be detected are in the range of 1-10 centimeters, dipole antennas which are short compared to these wavelengths will be physically unobtrusive and reasonably easy to package.

B. Rectification and Signal Conditioning

The power captured by the antenna system can be delivered through a deplexer to a full wave rectifier. Rectification of microwave radiation has been demonstrated by several experimenters. George and Sabbagh (Ref. 5-44) describe the use of a bridge rectifier mounted in a waveguide for conversion of S-band radiation to DC power. In these tests, high-burnout, point-contact silicon diodes and certain of the ultra-fast switching silicon diodes have shown special promise for energy conversion. However, somewhat different requirements exist for the efficient rectification of low power level microwave signals. The most significant of these is the low power input to the bridge rectifier from the antenna system. At these signal levels, the forward resistance of the diodes will be high due to the very low signal currents. To accommodate the dosage indicating unit, a signal conditioning section will be incorporated to amplify the rectified microwave signal into a strong enough DC signal to operate the dosage indicator. As outlined in the following section, the range of current for the indicator will be 0-10 ma. A symbolic representation of the signal conditioner is shown in Fig. 5-4.

C. The Integrator Detector

Radiation dose, be it from nuclear energy or microwave energy, must be arrived at by considering the duration of exposure as well as the radiation power density. For example, the U. S. A. standard for the maximum safe dose of electromagnetic radiation from 10 MHz to 100 GHz is 1 milliwatt hour/cm² or 3.6 joules/cm^2 during any 0.1 hour period and is 10 milliwatts/cm² for periods of 0.1 hour or more (Ref. 5-29). In nuclear radiation health monitoring the

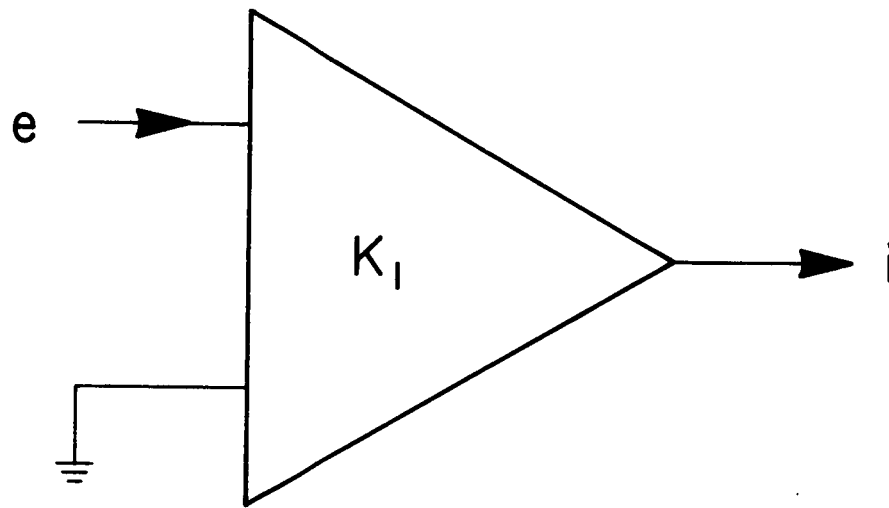


Fig. 5-4 Signal Amplifier and Conditioner

required integration of the directly measured dose rate is rather easily accomplished by the use of the film badge or the pocket ionization chamber. The type of integration proposed in the microwave health monitor would be chemical integration.

Fig. 5-5 shows a schematic of the dye marker chemical integrator which will give a visual indication of dosage by a change in color of the indicator pad. The principle of operation of this dose indicator is that the passage of a DC electric current produces a shift in the pH of an acid solution. The shift in pH causes a color change in an indicator which is dissolved in the acid solution. This change of color is proportional to the product of current and time within controllable limits.

A great number of common chemical reactions involving electric power are sensitive to the product of time and current. Electroplating is typical of this class of reaction. In this case, the measure of the current-time product is the total weight of metal deposited during the reaction. It is desirable in the present application to employ a reaction that produces a visible change of some kind. There are some broad categories of electrochemical reactions (Refs. 5-45, 5-46 and 5-47) from which one could choose a reaction suitable for this application. However, the limiting parameters should be listed to establish the bounds for a reasonable choice. These proposed limits are indicated in the tabulation shown below.

1. Indicator Current. The value of the current flowing in the visual detector would vary in a truncated linear manner according to the following schedule:

<u>Power Density (mw/cm²)</u>	<u>Current (ma)</u>
0-10	0
10-20	1-10
over 20	10 (continuously)

2. Indicator Color Change. The color indicator would be chosen to permit a current intensity discrimination of $\pm 5\%$ over the operating range of the instrument. This match would be obtained in a special optical comparitor. A coarse match to $\pm 20\%$ would be obtainable by using color matching cards. These two schemes are outlined in a subsequent section.

The chemical reaction employed in the indicator cell would be essentially a coulometric titration similar to experiment No. 19-1 described by Willard (Ref. 5-47). In this reaction, the pH

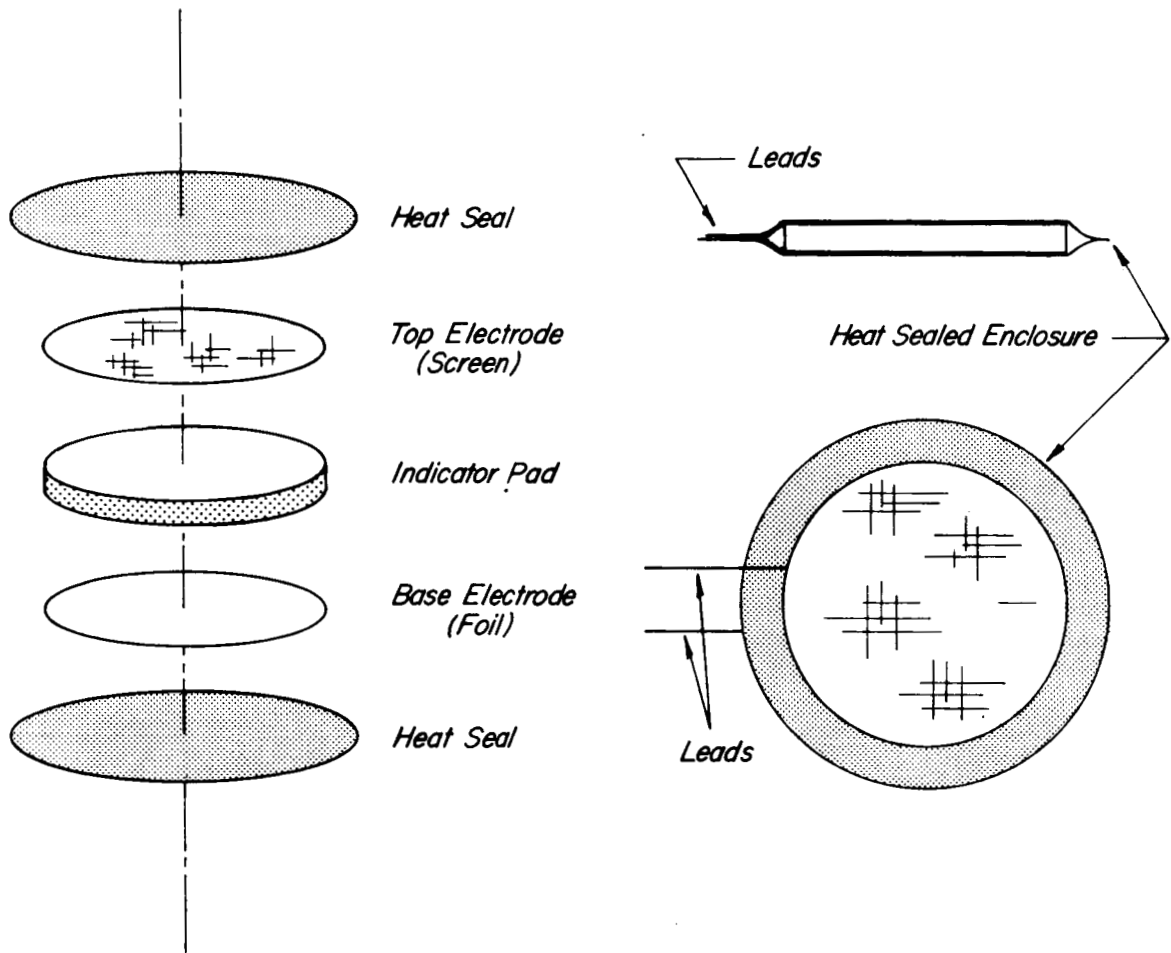
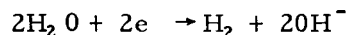


Fig. 5-5 Chemical Current Detector-Integrator

of the solution is adjusted by the addition of acid until the chosen indicator does not register any color. If current is then passed through the solution, the following reaction takes place:



The formation of the hydroxal radicals drives the pH of the solution toward the basic and the color of the indicator begins to appear. The structural elements of the indicator are shown in Fig. 5-5. One of the electrodes is a screen so that the solution-soaked patch may be viewed during exposure. The whole assembly is heat sealed in a transparent plastic film with pigtailed left exposed for circuit connections.

Fig. 5-2 shows the assembly of the microwave dosimeter. The battery is placed under a screw cap in the end of the instrument. The replaceable dye marker cells are screwed in under the viewing port. After the instrument is serviced with a battery and a marker cell, the instrument is turned on and checked for operation in the dosimeter check console shown in Fig. 5-6. The console has a service plug that mates with the service slot on the dosimeter to perform an internal check on the battery condition and the current flow to the dye marker. The two checks are made with a dummy input signal to the antenna equivalent to 10 milliwatts/cm² of microwave radiation. This signal is provided by a microwave power source built into the console. The dosimeters are now ready for distribution to the wearers.

At the end of the designated work period, all dosimeters are returned to a health control center. The dye indicators are examined for color change and may be checked by two available systems. A coarse check ($\pm 20\%$) could be made using a color chart such as is indicated in Fig. 5-7. Alternately, a $\pm 5\%$ reading may be made in the optical comparator built into the checking console. At this time the instruments are turned off and returned to storage. This type of routine service might be carried on at a health service center for each microwave installation, for example, in a similar manner to the processing of ionization gages and film badges used at nuclear reactor installations.

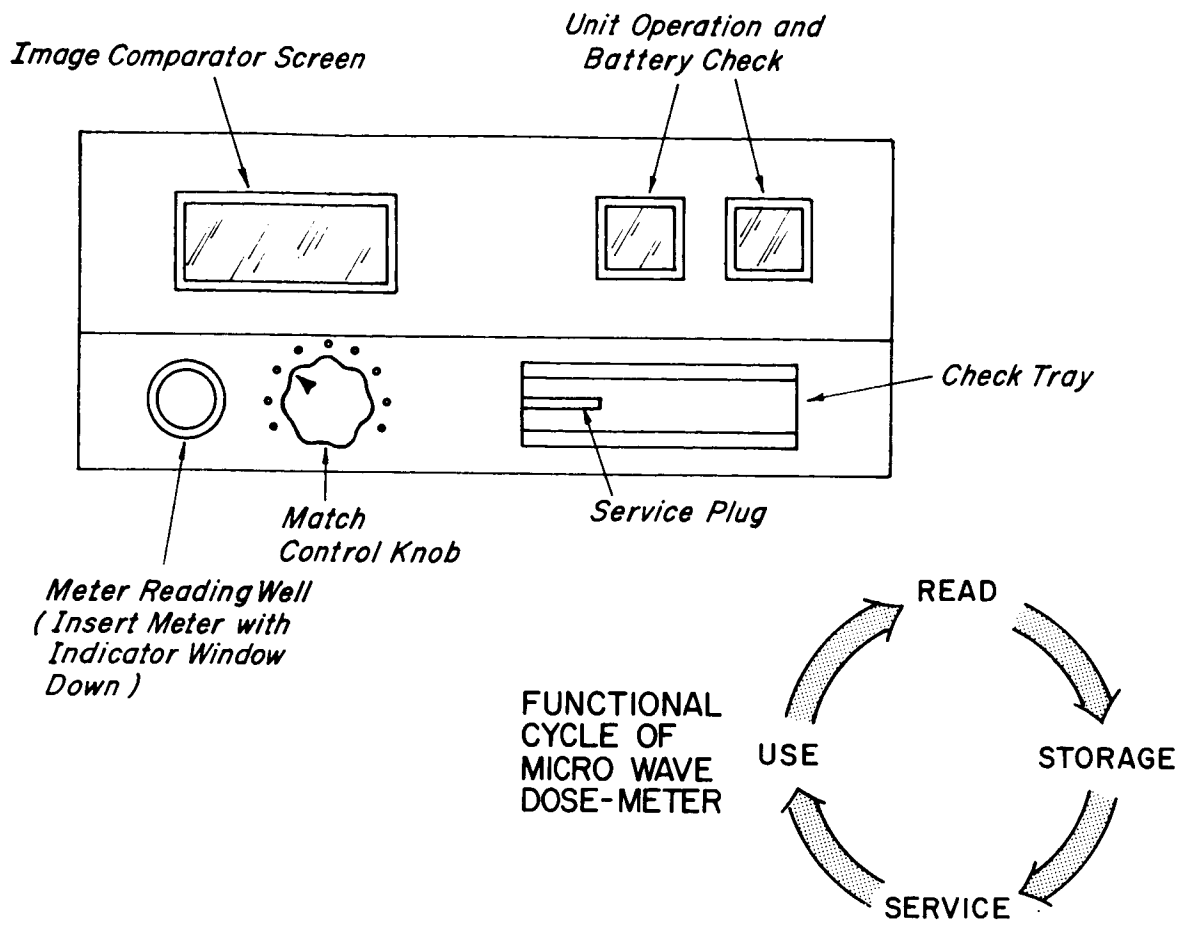
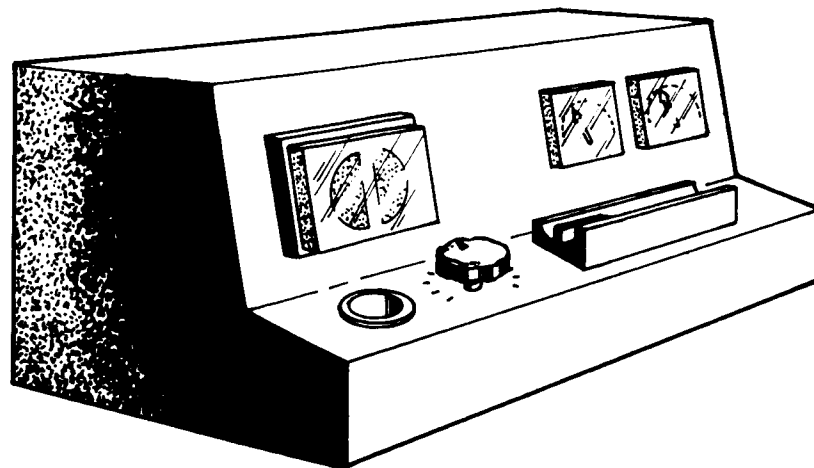
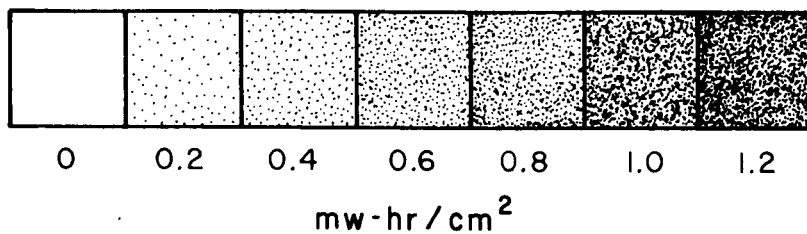
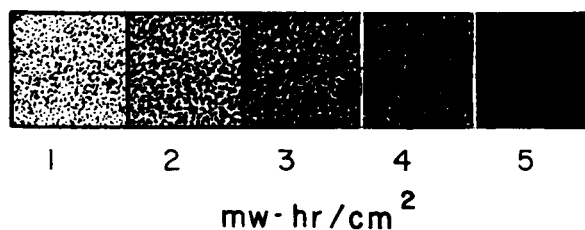
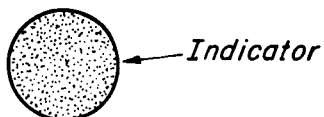


Fig. 5-6 Microwave Dosimeter Servicing and Reading Console





Comparison Strip, Serial No. 1



Comparison Strip, Serial No. 2

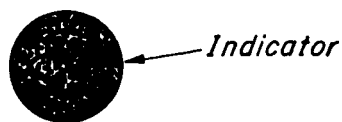


Fig. 5-7 Color Comparitor Indicator for Preliminary Dose Measurement

In conclusion, a survey of available information regarding information reception by the human body and electric fish has indicated that there exist a number of potential applications where electrical sensing may be valuable, and that some such applications have been actively considered by various groups. However, the available experimental information on electric sensing is still too limited to permit a realistic appraisal of the practicality of such applications; in particular, study of the potentially valuable area of human reception of audio-frequency-modulated ultra-high-frequency and microwave frequency electromagnetic fields has scarcely opened.

As a final point of interest for interested readers, it might be noted that the references to this chapter contain a great deal of additional information on the subject of electrical information transfer which could not be covered in this brief review.

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