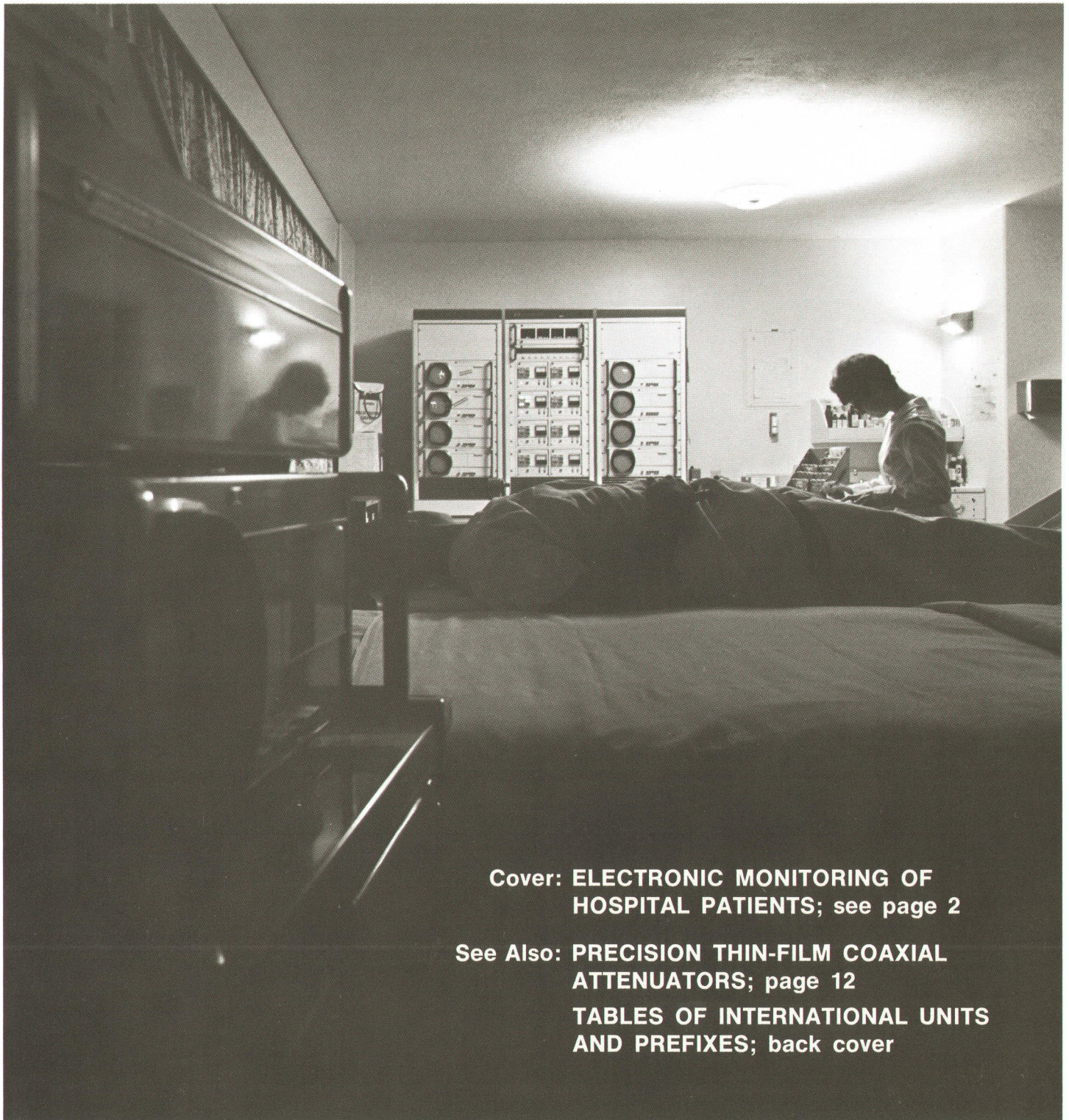


HEWLETT-PACKARD JOURNAL



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HOSPITAL PATIENTS; see page 2

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JUNE 1967

The Role of Electronic Medical Instrumentation in Patient Monitoring

By H. Ronald Riggert

THE ANCIENT GREEKS BELIEVED that an individual's good health depended upon an internal equilibrium among the four elements: earth, air, fire and water; the four qualities: dry, moist, hot and cold; and the four humors: phlegm, blood, black bile and yellow bile. In their time and for many centuries thereafter, disease was believed to result from lack of proper equilibrium among these elements, qualities, and humors. Medical therapy, accordingly, was directed toward returning these elements and humors to a healthy state.

Modern medicine is based upon the tenet that life processes, both normal and pathological, are essentially complex physical phenomena, which follow the physical laws elucidated by modern physical science. Electronics is important to the modern physician and medical scientist in many ways. Two are discussed here. First, many life processes are ionic in nature and produce concomitant electrical signals. These include propagation of nerve impulses along nerve fibers, and the electrical depolarization and repolarization of muscle cell membranes during muscular contraction and relaxation. Secondly, by transducing non-electrical phenomena into electrical signals, electronic instruments are useful for detection and measurement of non-electric events which play important roles in life processes. These include pressures, flows, chemical concentrations, etc.

Ever-expanding electronic knowledge has been generously applied both to the understanding of biological phenomena and toward creation of instruments for the medical research laboratory. In the past several years, however, electronics has come to play an increasingly

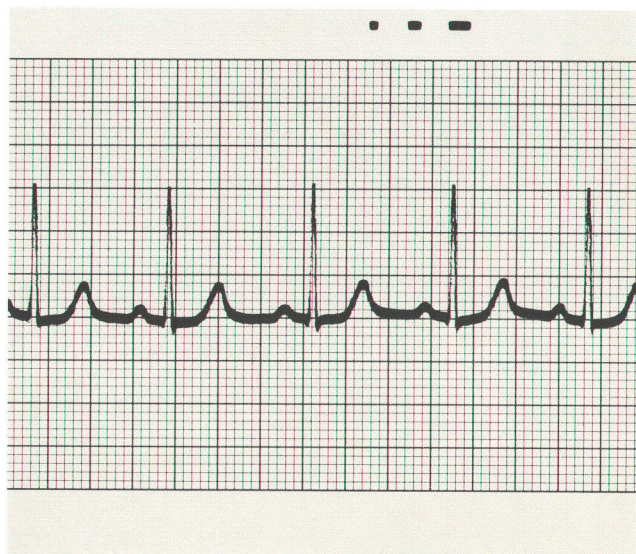


Fig. 1. Typical heart waveforms (electrocardiograms) as measured at body surface. Large peak, known as "R" wave, is about $1\frac{1}{2}$ millivolts; time scale is $\frac{1}{5}$ second per major division.



Fig. 2. Typical central station patient-monitoring equipment. Heart-waveforms are displayed on large-screen Sanborn scope. Alarm equipment is also provided to signal low or high heart rates, etc. Patient rooms are often arranged so that nurse always has patients in view.

important role in the clinical management of patients, especially those critically ill. For example, through continuous electronic monitoring of individuals admitted to hospitals after acute coronary occlusions, hospital mortality from this most common cause of death has been reduced from its former value of 40% to 20%. The impact of this single example is striking when one considers that some 600,000 Americans will die this year from occlusive coronary disease.

An important consequence of establishing intensive care areas, above and beyond the availability of the hardware for patients, is the concentration of experience which results. High skills naturally develop among members of the intensive care team.

Design and development of electronic medical instrumentation has been carried out for many years at the Sanborn Division of HP, formerly the Sanborn Co., in Waltham, Massachusetts. One engineering group here is responsible for developing instrumentation for monitoring critically-ill patients. This article describes some engineering and interface aspects of such monitoring equipment.

The Body as a Source

From an instrumentation point of view, the body can be considered by the engineer as the site of physical,

chemical and electrical phenomena that relate to the functions of various tissues, organs, and organ systems of the body. In the case of electrical phenomena, some form of data transmission impediment exists between the electrical signal source and the 'outside world'. The engineer must devise means that somehow avoid or adequately overcome the barrier in order that the signals may reach signal conditioners and be put into meaningful forms for presentation. To present non-electrical phenomena, it is necessary to convert or transduce to an electrical signal before signal conditioning and presentation. The aim of such presentation is to aid in detection and diagnosis of abnormal conditions and to follow the results of treatment.

Heart Measurements

Much of the presently-available patient monitoring instrumentation is used to assess heart function. The reasons for this are twofold. First, heart disease is a leading killer. Second, the electrical depolarization and repolarization potentials that accompany the rhythmic contraction and relaxation of the heart muscle are readily-available and highly meaningful signals.

The time-varying electrical field surrounding the heart is dependent upon the pathways and velocities of propagation of electrical activity in the heart walls. The

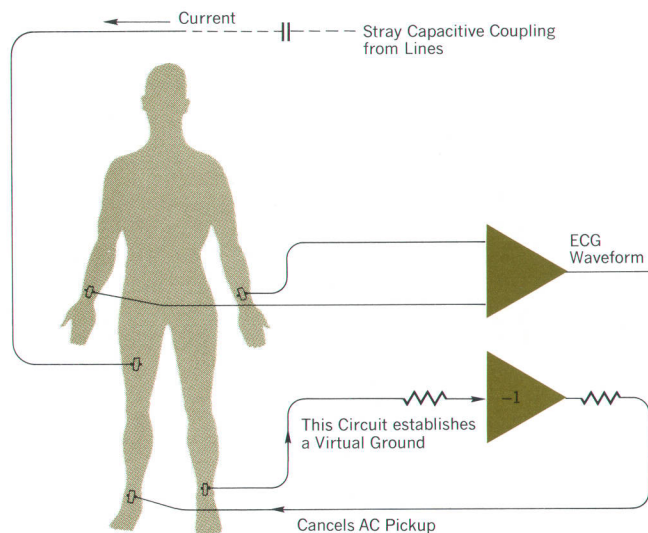


Fig. 3. Preventing shock hazard is important in designing monitoring equipment. Currents in the <100 microampere range are suspected of being potentially lethal in some circumstances. An arrangement such as that shown here for the HP Electrocardiograph limits patient-to-ground currents to negligible levels. It also minimizes hum signals into the ECG.

electrical field generated by the heart is an aggregate of the electrochemical activities of each of the muscle cells, going through the contraction-relaxation cycle. The muscle cells forming the walls of the heart's pumping chambers contract during each pumping cycle, decreasing the chamber volume and forcing blood out. In the normal heart, the electrical activity propagates along well-defined paths with propagation velocities that vary along the path. This pattern of electrical activity results in synchronization and appropriate time relationship in the contraction of the upper receiving chambers (atria) and lower pumping chambers (ventricles).

The resultant current flow in the electrically-conductive organs and tissue that surround the heart transmits the electrical activity to the surface of the body where electrodes can be placed to furnish a connection to an ECG amplifier. A form of data transmission impediment, mentioned earlier, exists between the heart and the ECG amplifier and may be considered in two parts. One is due to electrical noise generated by muscles other than the heart that are near the electrodes. This noise appears on the electrocardiogram as bursts or spikes, often of

considerably greater amplitude than the ECG waveform. Muscle noise picked up by the limb electrodes commonly used in taking clinical ECG's can usually be adequately reduced if the patient will relax. Critically ill patients frequently are unable to cooperate and relax. It is then necessary to place the electrodes on the chest wall.

The second impediment to extracting ECG signals is that of the relatively nonconductive outer layer of skin (epidermis) through which the signal must pass. Electrodes on dry skin establish contact impedances of typically 100 kilohms, often higher. Peak ECG signal levels are usually about 1 millivolt. Under these conditions there can be enough capacitive coupling (as high as 1 microamp rms) from power-line-operated de-interference into the ECG. This problem is overcome by reducing the electrode contact impedances and minimizing the ac potential on the body.

Electrode impedance can typically be reduced to the 10-kilohm level by permeating the epidermis with a salt-solution electrolyte. Needle electrodes also establish a lower contact impedance but are not commonly used.

With the use of electrolyte on the two signal electrodes and on the patient-grounding electrode, ac interference is adequately reduced in most situations. However, the direct connection to ground exposes the patient to a potential shock hazard should he contact faulty or improperly connected equipment. Improper grounding of the monitoring instrument itself also presents the possibility of shock. The danger is most serious in those situations where currents may pass directly through the heart since the lethal current level in the human heart is thought to be as low as 10 to 100 microamperes rms. This situation is possible wherever equipment may be connected to the heart, as through a conductive catheter passed via a blood vessel from the body surface into the heart for diagnostic or treatment purposes.

The shock hazard is significantly reduced in a series of ECG monitors recently devised at the Sanborn laboratories of HP. The technique avoids a direct wire connection from the patient grounding electrode to ground. Instead, the patient is actively driven to ground potential by an amplifier with current-limited output (Fig. 3). Assuming negligible current flow in the patient signal electrodes, the patient's floating potential appears across the amplifier input. This results in a current output (with negative-feedback phasing) being returned to the patient; this, in turn, lowers the patient's floating potential. When operating within the current output limits of the amplifier, this technique can, as a result of gain in the grounding amplifier, produce an effective patient grounding

impedance lower than the actual electrode contact impedance. Thus the patient will become effectively disconnected from ground, should he contact a voltage source.

ECG Diagnosis

ECG waveforms with specified characteristics should be found at certain electrode locations if electrical activity of the heart is normal. Unusual origins of electrical activity, and variations in conduction paths or propagation velocities may alter these characteristics.

Detection of abnormal ECG waveshapes or rhythms are critical aspects of patient monitoring in coronary care units and other intensive care areas. This can hardly be overemphasized, since it is through vigilant surveillance of the heart's electrical activity as manifest on the electrocardiogram, with appropriate early therapy of abnormalities, that the hospital mortality from coronary occlusions has been cut in half.

Heart Rate

Heart rate is implicit in the cardiograph signal. It can be derived from the ECG by triggering a cardi tachometer from the relatively narrow and large-amplitude 'R' component of the ECG that accompanies each contraction of the heart. A direct reading of heart-rate alone is provided on a separate meter which has built-in threshold-limit settings. The attending physician sets limits within which he believes there is no cause for alarm. If the patient's heart rate should slow below the lower limit set, or exceed the selected upper limit, the instrument triggers alarms. The physician may decide that momentary excursions are tolerable, so an alarm time delay is provided with adjustments to permit exclusion of momentary out-of-limits readings.

Pacing

The rhythmic beat of the heart is intrinsic to heart muscle and needs no external trigger. Animal hearts excised from the body and maintained in an appropriate nutritional medium have been experimentally kept beating for years. While all heart tissue has intrinsic rhythmicity, the rate of intrinsic contraction varies from place to place within the heart. That area with the fastest intrinsic rate normally sets the pace, and is known as the pacemaker. This area is usually at a particular site in the right atrium of the heart.

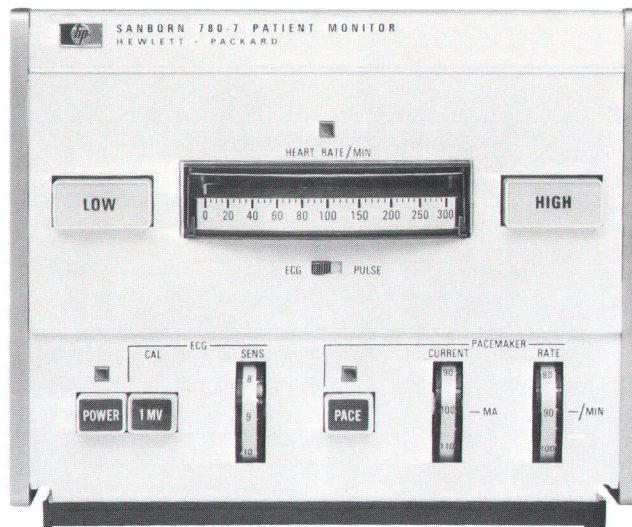


Fig. 4. Cardi tachometer is designed with low and high rate alarms.

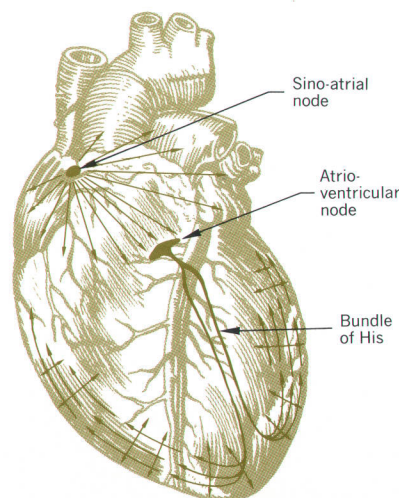


Fig. 5. Natural heart impulse is initiated in 'pacemaker' located at heart's upper right. Impulse spreads through muscle as shown.

The normal pacing impulse spreads through the heart, as indicated in the diagram, in about 0.3 second at the usual rate of 60-100 per minute and produces a cardiac cycle waveform at the surface of the body, Fig. 1.

In some abnormal situations, the natural site of pace origin may be displaced, and in many such cases the normal synchronism of successive heart actions will be disturbed. The effect is serious; it is to reduce the heart output, which we cannot monitor simply. It is likely to be accompanied, however, by changes in heart rate and ECG waveform. If these are monitored, an alarm will occur in these cases and the attending medical personnel can determine the exact nature of the problem and act appropriately.

It is often possible to stimulate the heart muscle artificially with an electrical impulse train from an electronic pacemaker. There are several varieties of pacemakers, each with special usefulness. The pacing impulse may be applied through electrodes placed on the body surface. In other circumstances the signal may be applied by passing a pacing catheter through a vein into the heart. Electrodes may also be surgically attached to an exposed heart. Self-powered artificial pacemakers may even be surgically implanted, as prosthetic devices.

The pacing impulse has a duration of about 2 milliseconds. HP pacemakers deliver a constant-current pulse whose amplitude can be adjusted from several milliamperes for internal electrodes to over 100 milliamperes

for external electrodes. The impulse rate is adjustable from 50 to 150 pulses per minute, 70 ppm being a typical selected value. For patient safety, the pacing impulse is delivered from a floating output having low capacitance to the equipment cabinet. In some Sanborn monitoring equipment, a pacemaker is integrated into the same package with the monitoring equipment as well as being designed as a separate unit.

Defibrillation

A more serious disturbance in the synchronous sequence of heart action is known as ventricular fibrillation. It may result from coronary occlusion, from electric shock, and from abnormalities of body chemistry. Ventricular fibrillation is a gross defect in synchrony of contraction amongst the muscle fibers of the lower chambers of the heart. The heart is in a state in which the muscle fibers contract so asynchronously as to 'twitch' ineffectively. The situation requires immediate countermeasures, since a fibrillating heart cannot effectively pump blood. It is hardly possible to distinguish between this condition and a cessation or arrest of electrical activity, without an electrocardiogram. It is important to make the distinction, since treatment, which must be immediate, is different. With an electrocardiogram, however, the distinction can quickly be made from the waveform.

In fibrillation, the fundamental problem is that the heart muscle fibers are continually stimulated by adjacent

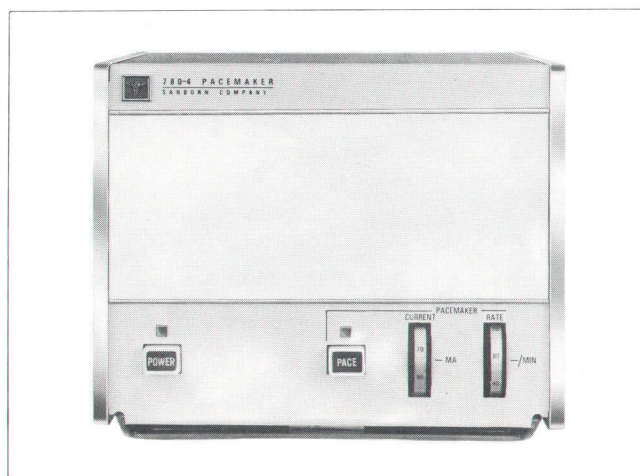


Fig. 6. Sanborn pacemaker is designed with two current ranges for use with chest electrodes or electrodes placed directly on heart.

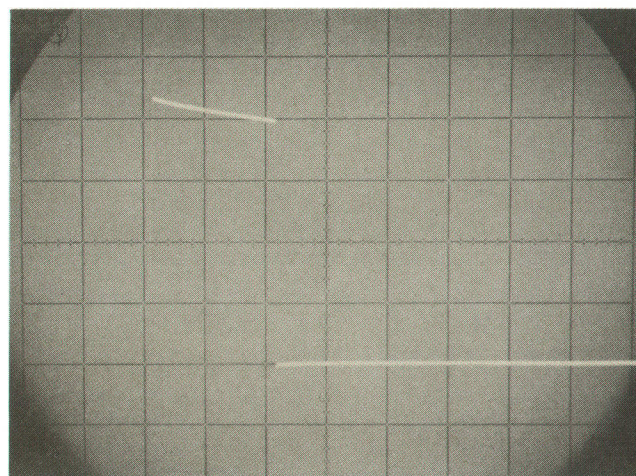


Fig. 7. Typical output current waveform from pacemaker (chest electrodes). Current and rate are adjustable. Vertical scale here is 2 ma/cm, horizontal about 1 ms/cm.

cells so that there is no synchronized succession of rest (or repolarized) and active (depolarized) states among the cells. Consequently, control over the normal sequence of cell action cannot be captured by ordinary stimuli, internal or external.

To overcome the random electrical activity that characterizes fibrillation, a high-amplitude external electrical pulse (countershock) has been found effective. The countershock depolarizes all cells simultaneously, allowing the muscle cells then to recover (repolarize) to the rest condition simultaneously. Now there is a good chance some portion of the heart's naturally rhythmic tissue will initiate synchronous functioning, hopefully the natural pacemaker center.

Less severe heart irregularities, such as 'atrial fibrillation' (which involves the receiving chambers rather than the pumping chambers) and 'ventricular tachycardia' (dangerously fast but not entirely ineffective pumping) are two other arrhythmias which may respond to judicious use of the defibrillator.

In these cases, where heart efficiency is only partially impaired but where the heart still has a definite cycle, timing of the countershock is required. Countershock must not be applied during certain vulnerable portions of the cardiac cycle when the cells are repolarizing and when an applied electrical impulse could initiate new arrhythmias. Suitable circuitry is included to enable the operator to determine in advance at what point in the

cardiac cycle the equipment will automatically trigger the countershock.

The defibrillator provides up to 400 joules in a single dc pulse. The dc energy is stored in a 16-microfarad capacitor at voltages up to 7.1 kV. A high-voltage relay switches the capacitor from the charging circuit to the patient electrode. A 0.1 henry inductor in series with the patient circuit controls the peak amplitude and duration of the discharge current waveform. The result is a slightly-underdamped waveform with a duration of about 5 milliseconds.

The patient electrodes are large discs about 3" in diameter. They are designed as either flat or concave surfaces for external chest or internal direct application to the heart. On the chest the electrodes are placed in such a way that the defibrillating pulse traverses the heart. Electrolyte is used between the discs and the body tissue to provide uniform current density.

Blood Pressure

Blood pressure measurement on patients under intensive care is important since adequate pressure is necessary to perfuse or force a supply of blood through the body's vital organs. Without adequate perfusion, the organs function improperly and consequent deterioration in the body systems can eventually lead to death. The heart is the pump in the circulatory system, forcing blood into arteries at typical mean pressures of 100 mm Hg.



Fig. 8. Sanborn monitoring array includes electrocardiograph and pacemaker with other monitoring equipment. Equipment is normally located at bedside.



Fig. 9. Defibrillator produces up to 400 joules in a dc pulse typically applied to heart through chest wall.

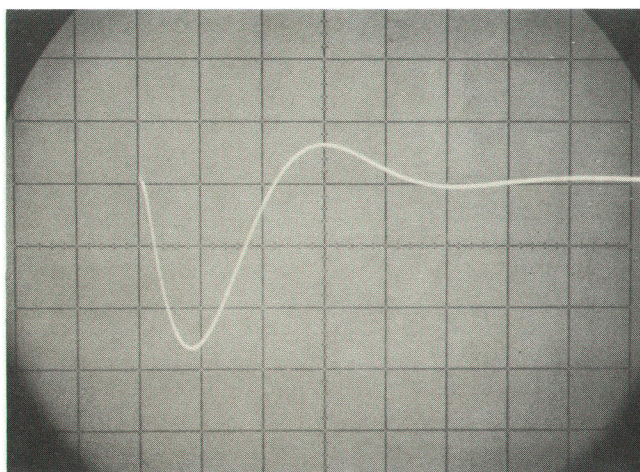


Fig. 10. Typical countershock waveform provided by Sanborn defibrillator. Amplitude is adjustable up to 7 kv. Time scale is 2 milliseconds/cm.

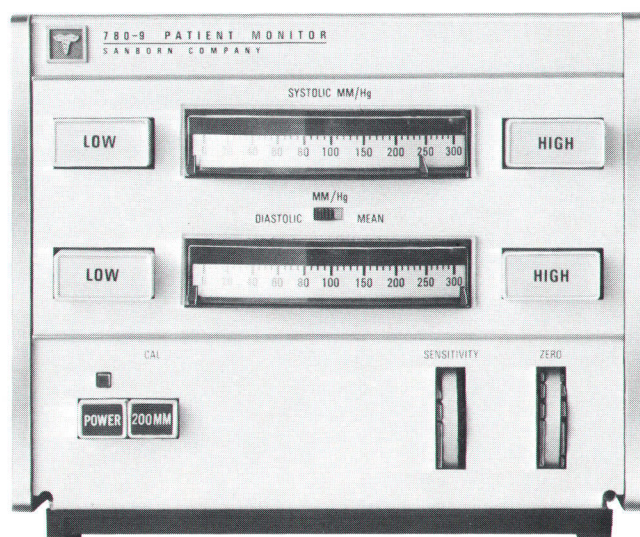


Fig. 11. Blood pressure monitor arranged with high and low limit alarms.

Arterial pressure rises sharply with each contraction of the heart then drops off more slowly. The maximum is called 'systolic,' the minimum 'diastolic' pressure. Typical values might be 120 and 80 mmHg. This pressure drop is mainly the result of flow resistance in the small muscular arterioles of the circulatory system. These arterioles precede and selectively regulate flow through the capillary system consisting of very small thin-walled vessels where nutrients, gases, etc., are exchanged between the blood stream and body cells.

Blood pressure is most commonly measured with the sphygmomanometer, a pneumatic cuff encircling the up-

per arm with an inflatable section in continuity with a pressure indicator. This may be a mercury column or a mechanical gauge. The cuff is inflated to a pressure exceeding that of the blood in the large brachial artery of the arm. The applied pressure is transmitted through the tissues of the arm, collapsing the contained vessel's pliable walls. Pressure is then gradually released from the cuff while the examiner listens to a stethoscope bell placed over the brachial artery beyond the cuff. When pressures within the cuff have dropped to levels just below the peak (systolic) pressure in the artery, a brief jet of blood squirts through the compressed segment. Since this spurt is at high velocity, and is turbulent, it can be heard at the stethoscope. As long as the vessel is compressed, jets will only intermittently squirt through, each associated with a pumping cycle, and the turbulence will continue to be heard as pressure decreases. When the vessel is no longer significantly restricted turbulence ends and the sounds disappear. The cuff pressure at this time is taken to be the diastolic pressure. The sphygmomanometer technique is only accurate to about 15%. Further, the measurement is an intermittent one, and there are discontinuities in the blood pressures obtained. Lastly, and most severely, the technique is often inapplicable at the low blood pressures that occur in shock, when readings are most needed. There is, then, an important requirement for a blood pressure measurement technique without these disadvantages.

For continuous and accurate blood pressure measurement, a small sterile hollow fluid-filled tube is inserted directly into a suitable artery or vein. These tubes (catheters) are led to a pressure-gauge from which direct intravascular blood-pressures can be measured (Fig. 12).

The fluid pressure transducer in the HP Series monitoring systems is a magnetically-coupled device working into carrier amplifier circuitry to obtain a calibrated pressure-voltage output. This voltage contains pressure waveform information and can be displayed on an oscilloscope or recorder. The waveform is processed by peak detection circuitry to detect and hold the systolic and diastolic levels for meter presentation. As on the heart rate meter, threshold limits can be set to provide alarms should either systolic or diastolic pressures exceed the limits selected by the physician.

Venous pressure instrumentation is carried out in a similar way, but the equipment must be an order of magnitude more sensitive, to work at the lower pressure levels. Venous pressure-measuring equipment does not use peak detection circuitry, since an average pressure reading is normally desired.

When using the direct pressure technique, several precautions must be taken. Accidental rupture of the fluid system which would result in a loss of blood from the system must be avoided; one must avoid clotting at the catheter tip, and the introduction of infection. Clotting is prevented by keeping the transducer and catheter free of blood and filled with a saline solution containing an anti-coagulant agent. Occasional flushing of small amounts of saline into the bloodstream prevents clotting of blood at the catheter tip. Infection is minimized by using sterilized materials and by topical antiseptic application around the puncture site.

An indirect method of detecting loss of circulation uses a photoelectric plethysmograph (volume change sensor) to sense blood pressure pulsation in surface tissue. This device incorporates a small light source and photoresis-

ances (within 0.1°C) which makes calibration of instruments to individual probes unnecessary. They are also available in a variety of configurations for use at different body locations. Rectal, esophageal (throat), and axillary (underarm) locations are commonly used. Since body temperature changes occur relatively slowly, instrumentation of temperature measurement has its greatest value in cases where temperature management is critical or where frequent readings by manual means is too time-consuming.

Respiration

Oxygen supply to the vital organs is a continuous requirement the body meets by maintaining proper gas levels in the blood stream through respiration and by delivering an adequate supply of the oxygenated blood

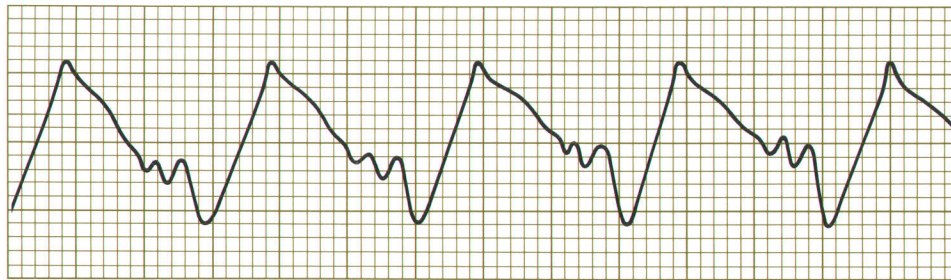


Fig. 12. Typical blood pressure waveform.

tive detector which senses modulation of light transmission through the ear. This modulation occurs in the red portion of the spectrum, resulting from a change in tissue blood volume as arterial pressure pulsates following each heartbeat. Although a pressure waveform can be observed on an oscilloscope or recorder, the technique does not lend itself to providing calibrated pressure information due to the several uncontrolled variables that are also involved. The waveform can be fed to a cardiometer to obtain pulse rate, as an alternate to deriving rate from the ECG.

Body Temperature

Body temperature can be measured using a thermistor probe as the sensor. Thermistors are of suitable sensitivity, with resistances varying on the order of 3% per degree Centigrade. They are available with close toler-

ances to the vital organs through the circulatory system. Since continuous measurement of blood oxygen has so far been impractical, physical chest expansion is detected to indicate respiration. Respiration rate is derived, and presented as an indicator; at least it shows that the respiration part of the respiration/circulation cycle is going on. A sensitive displacement transducer is used as the sensor, driving tachometer circuitry which indicates respiration rate on a meter.

Signal Delay

In the management of critically-ill patients, it is frequently not enough just to be aware that an abnormal event has occurred. It may also be of much importance to be able to go back and review information leading up to the time when the abnormality was detected, i.e., to re-examine in detail a record of the abnormal event. It

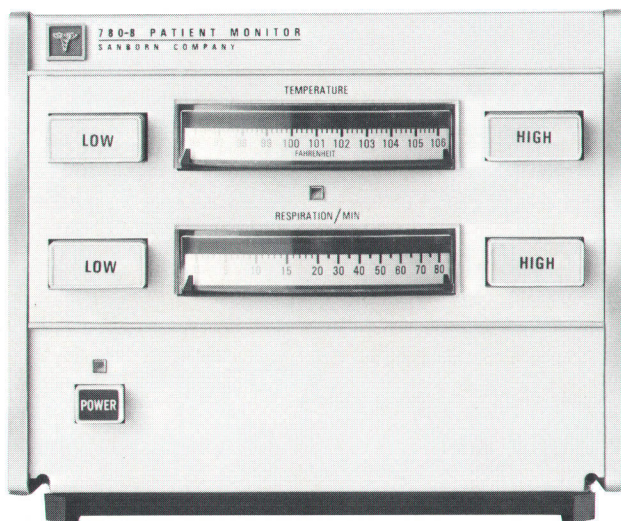


Fig. 13. Body temperature and respiration rate monitor.

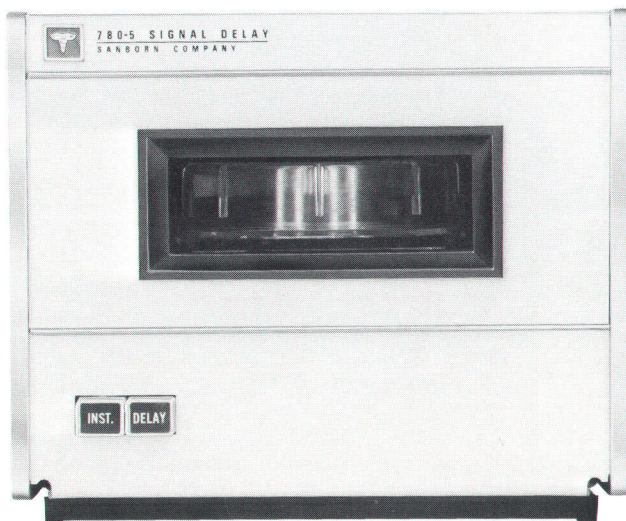


Fig. 14. Tape-loop recorder for recording ECG signals on magnetic tape. Tape loop records for 40 seconds including 10 seconds after a distress signal which also initiates a chart recorder.

is possible to accomplish this with continuous recording, either on written record or magnetic tape, but at the expense of accumulating excessive data. However, a continuous-loop tape recorder can store information for a given period and then erase and reuse the tape on a continuing basis. The HP 780 Series tape delay can be pre-programmed to respond to an alarm situation in one of two modes. One model automatically starts a direct-writing recorder (heated stylus recorders are normally used) upon detection of the alarm, thereby recording information coming off the tape just prior to erasure. These data are delayed in time by the length of the loop, typically 40 seconds. After the tape has completed one full loop, the data recorder on the loop at the time of the alarm will just begin to be recorded on the paper recorder. This recorder continues writing for a fixed period, typically 10 seconds, and then automatically shuts off. Thus, the written record is 50 seconds in length, containing 40 seconds of before-alarm information and 10 seconds after. The tape loop, meanwhile, has not stopped but continues to write, store, read out and erase.

The second mode of loop operation is to automatically stop the tape loop shortly (typically 10 s) after occurrence of an alarm. After stopping, assuming again a 40 second tape length, the tape contains 30 seconds of data prior to alarm and 10 seconds after. This tape can now be played back at will on a paper recorder or oscilloscope without erasing the data. In this mode, the data are retained on tape for further use, but manual intervention by an operator is needed to obtain a written record and to restart the tape loop. Since the tape loop is packaged in the form of a plug-in cartridge, a loop that is stopped and holds alarm information can be replaced with a fresh cartridge and reviewed at a later time.

The instrument has a capacity of two data channels. These might be used for ECG and blood pressure on a single patient or an ECG from each of two patients. Depending on the type of installation, the device can be located either at the patient's bedside or at the central station.

General

Patient-monitoring equipment is unquestionably destined more and more to play a large and important role in the hospital care of the seriously ill. Even though the use of such equipment is in the growth stages, some notable results have already been obtained. Medical directors are sure that tens of thousands of lives each year will be saved through wider use of intensive care programs employing patient-monitoring equipment.

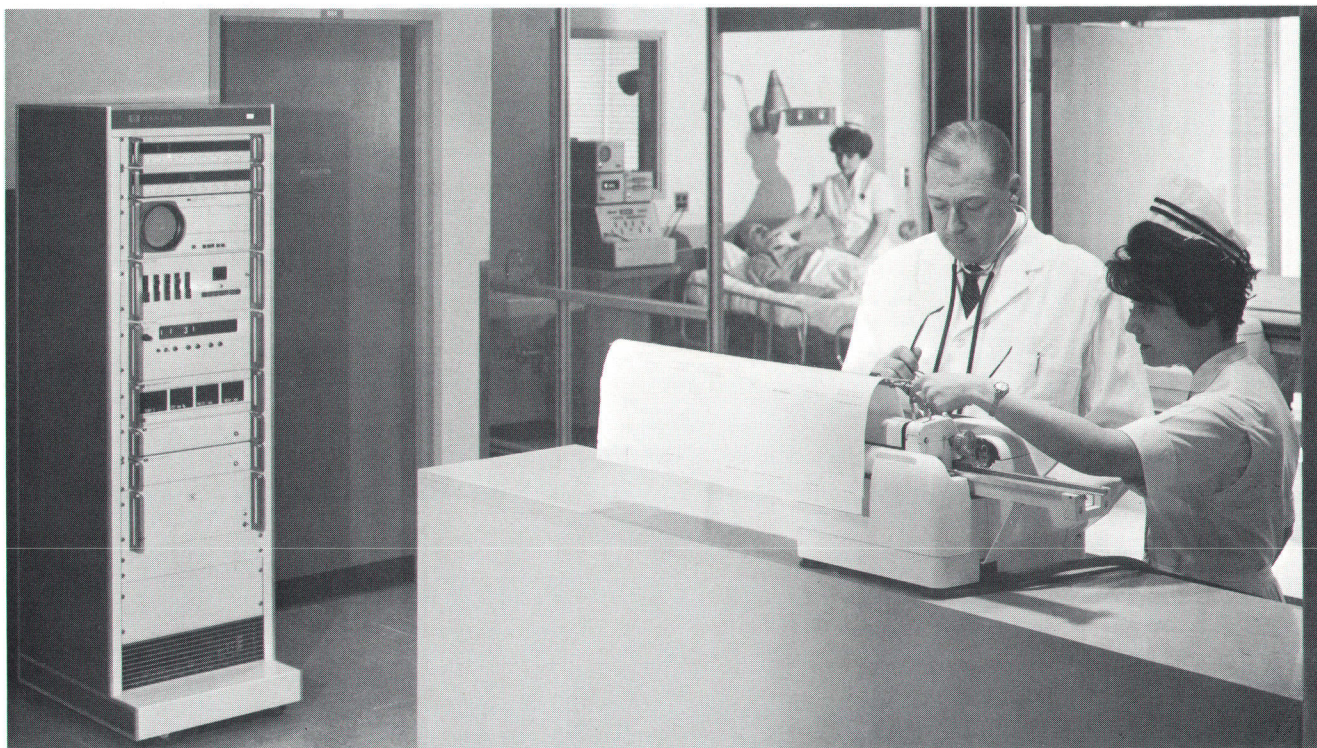


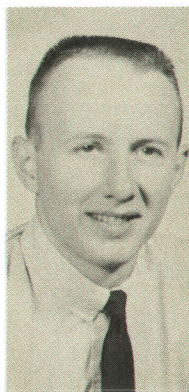
Fig. 15. Central station in intensive care medical unit supplements bedside monitoring instrumentation (background) with Sanborn/Dymec data acquisition system (left) and typewriter printout system (center). Data are sometimes digitally recorded for computer processing. Installation shown is at Lenox Hill Hospital, New York City.

The speed with which monitoring equipment is being put to use in hospitals is limited by the need for specialized personnel. The usefulness of the equipment has been demonstrated but the interpretation and profitable use of the information it provides requires suitable training and retraining on the part of the medical unit staff. The necessity for training programs is being accepted and reemphasized by hospital personnel and it is not unrealistic to expect that virtually every major hospital will employ patient monitoring in special-care units in the foreseeable future.

Acknowledgments

The author is glad to acknowledge contributions by colleagues and others to this article, and to the life-saving equipment described here.

Edwin Merrick has had project responsibility for the defibrillator and much of the intensive care nurses' station equipment. Randall Clark played the same role in connection with the bedside patient monitors and pacemakers. Walter R. McGrath, Jr., has been responsible for most of the mechanical and package design in the Sanborn Division's intensive care equipment program. ■



H. Ronald Riggert

At Hewlett-Packard's Sanborn Division in Waltham, Mass., Ron Riggert is a laboratory group leader for the design and development of patient monitoring and display instrumentation. Ron was educated at the University of Nebraska, obtaining a MSEE in a program that included training in medical instrumentation. As a part of this training, he studied in courses oriented toward medical

instrumentation and worked in the electronics laboratory of the College of Medicine of the University of Nebraska.

Ron joined Sanborn in 1960, where he has participated in the design of several monitoring instruments, including the 780 Series instruments referred to in his article.

Precision Thin-Film Coaxial Attenuators

Semi-automated thin-film techniques yield attenuators that are exceptionally precise and wideband (dc to 18 GHz), yet so economical that they can logically be used even in non-critical applications.

By Stephen F. Adam

MODERN METHODS OF DESIGN AND PRODUCTION have brought about development of a family of coaxial attenuators precise enough for insertion loss and return loss measurements and for extending power ranges of measuring instruments without sacrificing accuracy. On the other hand, their cost is low enough to make them useful for non-critical padding and isolation, such as reducing VSWR or lowering power levels to avoid over-driving sensitive instruments.

Bandwidths of the attenuators are compatible with

today's coaxial systems. They give constant attenuation from dc to 18 GHz, or in less costly versions from dc to 12.4 GHz. They have linear phase shift and low VSWR. All of them are checked by swept-frequency methods which have certified accuracies traceable to the National Bureau of Standards.

High precision and wide bandwidth in these attenuators are achieved by use of a new kind of lossy element, a two-dimensional attenuating 'card' which provides both series and shunt losses of a distributed nature. It consists

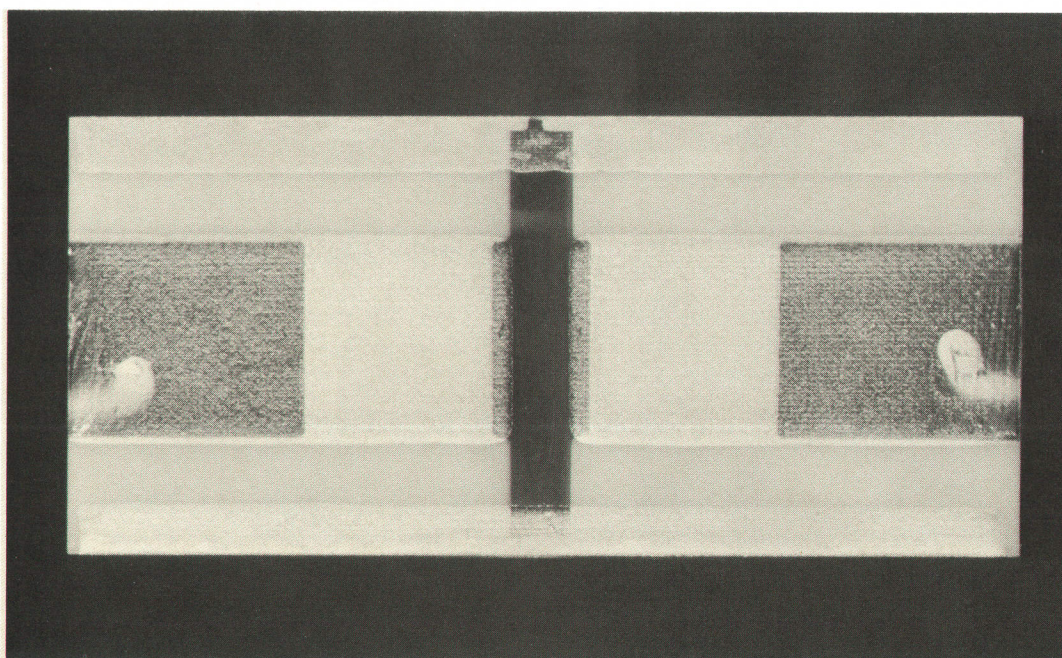
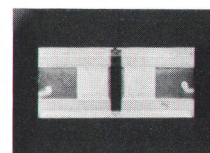


Fig. 1. Thin film of resistive material (dark area in center) on dielectric substrate is a low-cost wideband attenuating element used in several HP coaxial attenuators. Silver areas on card are electrodes.



Actual Size

of a thin rectangular sheet of resistive material on a dielectric substrate, Fig. 1. The resistive film is applied by vacuum deposition. Also on the card are ground electrodes along two opposite sides of the resistive film and input and output electrodes along portions of the two remaining sides of the film.

For coaxial service, the cards are loaded into cylindrical cartridges and stripline transitions to the input and output are added. The transitions accommodate either type N connectors or Amphenol precision 7mm connectors.

These attenuators are used in the input step attenuator of the HP Spectrum Analyzer and in some 50Ω loads. For general coaxial-attenuator use, the designs include three types of fixed 3, 6, 10, and 20 dB coaxial attenuators and a variable 0 to 60 dB step attenuator. Fixed 30, 40, 50, and 60 dB coaxial attenuators were also designed, to be made available on special order.

Theory

A complete treatment of how the card attenuator works would include field equations; however, a basic understanding of the device can be gained from transmission-line theory. In the arrangement showing dimensions of the film and electrodes on the substrate, Fig. 2, the resistive film is almost a pure resistance. Neglecting its small reactance and susceptance, its characteristic impedance is found from well-known transmission-line equations to be

$$Z_0 = \sqrt{\frac{R}{G}} \text{ ohms}$$

where R is the series resistance per unit length and G is the shunt conductance per unit length.

The attenuation factor, the real part of the propagation constant, is

$$\alpha = \sqrt{RG} \text{ nepers per unit length.}$$

If the resistivity of the film is ρ ohms per square, then

$$R = \frac{\rho}{a} \text{ ohms per unit length,}$$

$$G = \frac{4}{\rho(D-a)} \text{ mhos per unit length,}$$

$$Z_0 = \rho \sqrt{\frac{D-a}{4a}} \text{ ohms,}$$

$$\text{and } \alpha = \sqrt{\frac{4}{a(D-a)}} \text{ nepers per unit length.}$$

The last equation shows that the attenuation is independent of the resistivity of the film provided, of course,

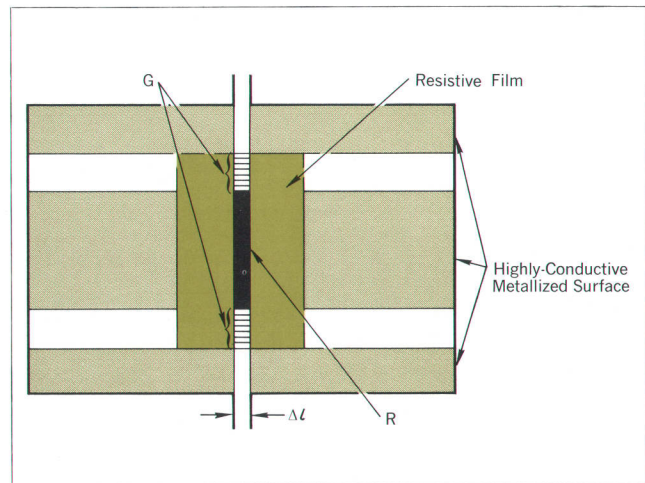


Fig. 2. Due to the structure of the attenuating card, there is, at any increment of length Δl , a series resistance part R and a parallel conductance part G .

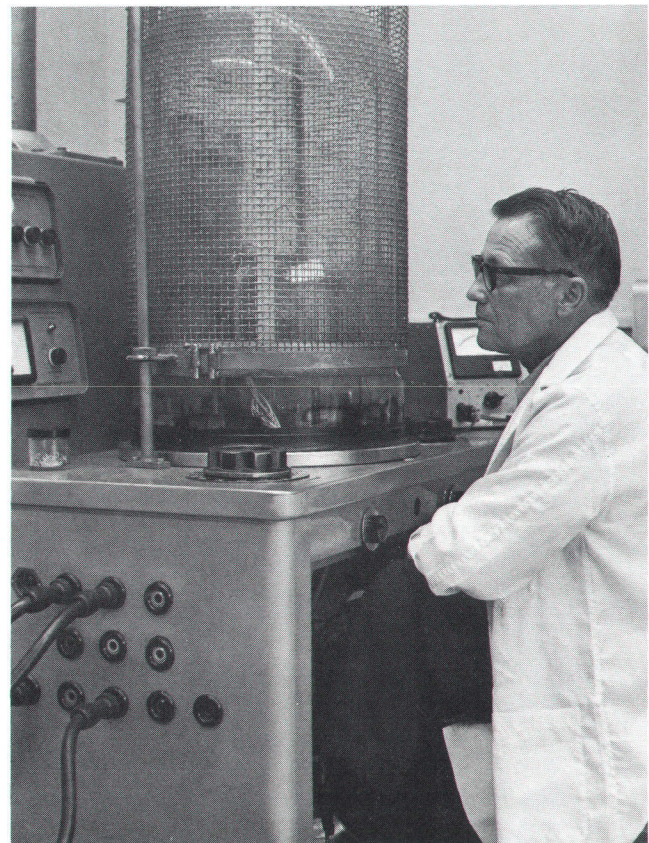


Fig. 3. One of the vacuum deposition units which deposit the resistive film on the attenuator cards. Many cards can be processed at once, thereby keeping costs low.

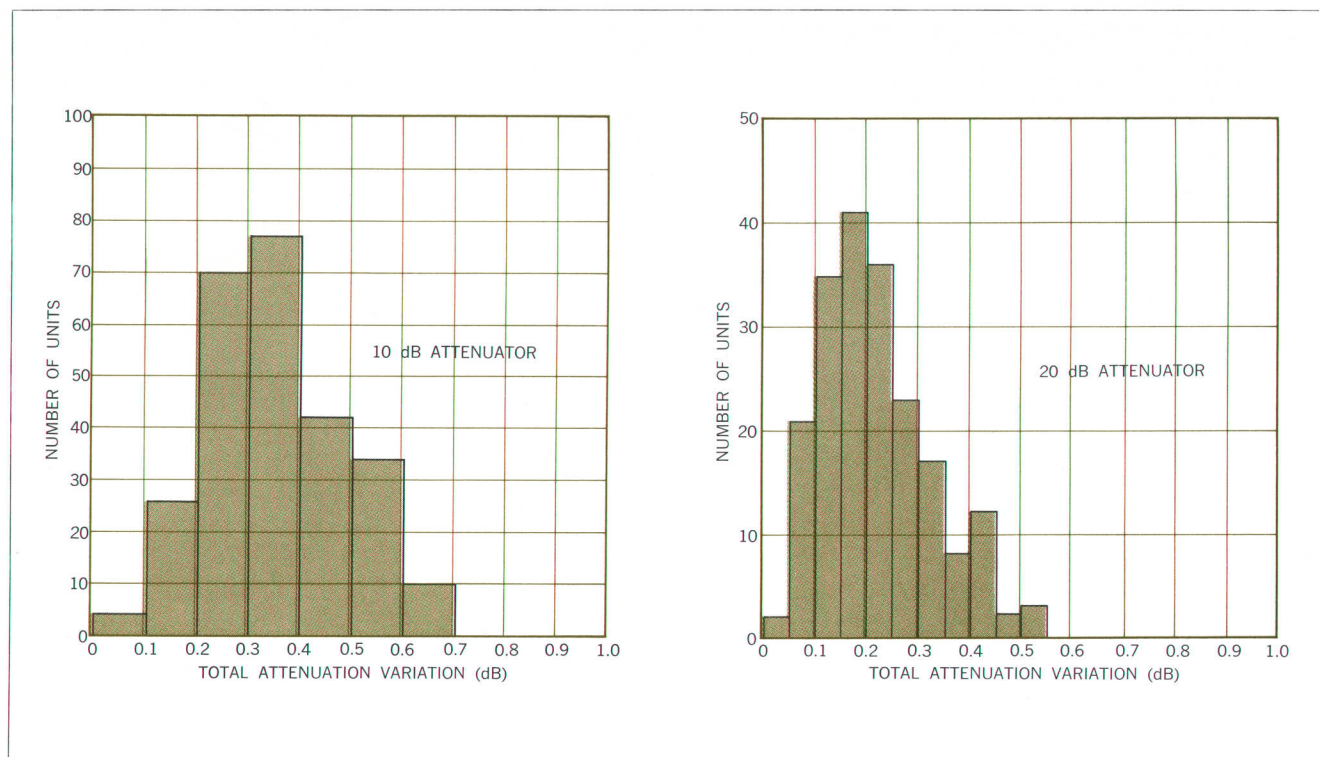


Fig. 4. Repeatability of thin-film deposition process is shown by distribution of attenuation variations of over 200 of each of HP Model 8491A 10 dB and 20 dB attenuators. Total variations are within the design specifications without any hand touchup.

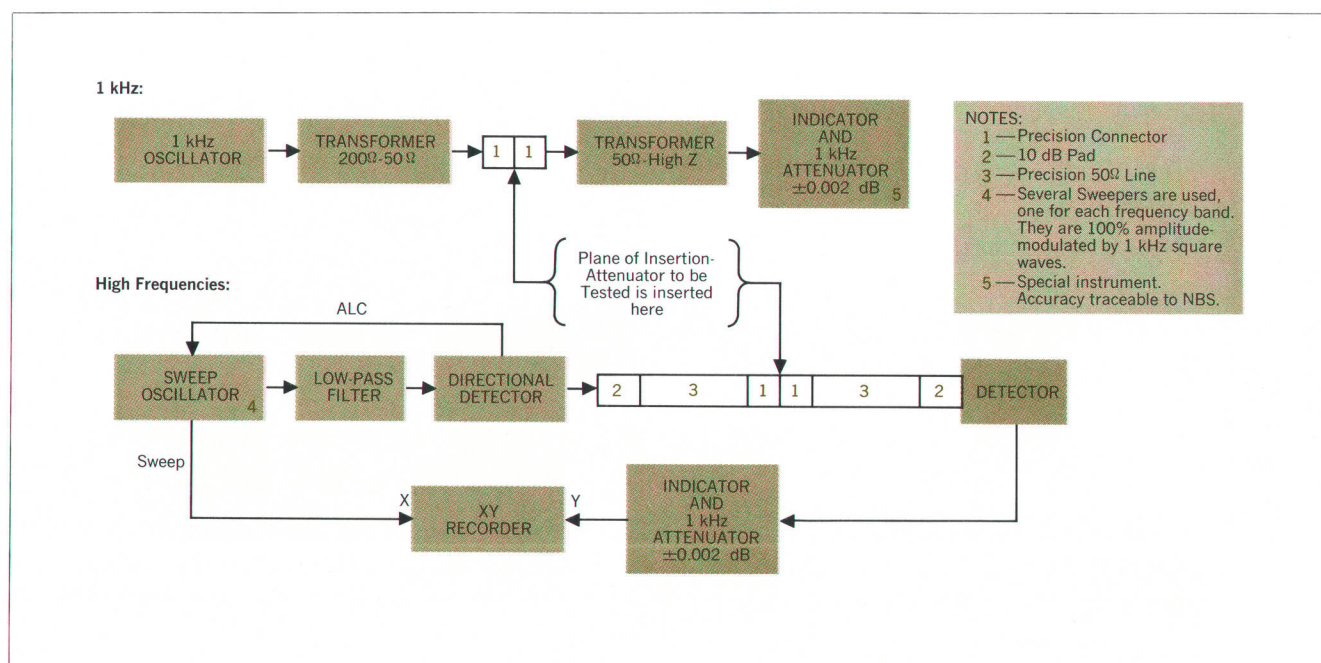


Fig. 5. Block diagrams of test setups used in final calibration of thin-film coaxial attenuators. Attenuators are compared with special 1 kHz attenuator calibrated to ± 0.002 dB, traceable to NBS. Low-frequency calibration is at 1 kHz, top; high-frequency tests use swept-frequency technique, bottom.

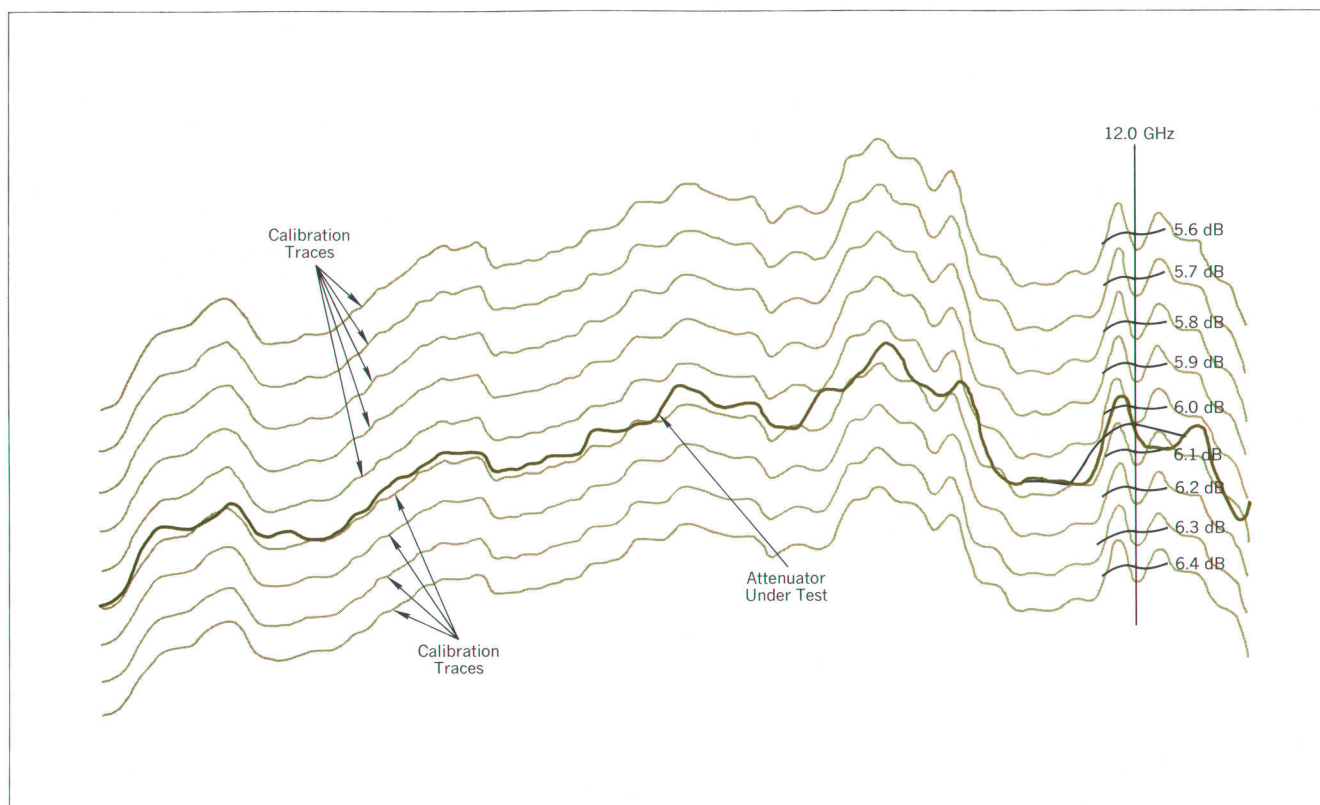


Fig. 6. Recorder traces for attenuation calibration of typical HP Model 8492A 6 dB Attenuator from 8.0 to 12.5 GHz. Setup was as shown in Fig. 5. Ripples in traces are caused by changing phases of multiple reflections. True curves are found by averaging out the ripples as shown by the black lines in the vicinity of 12 GHz in the above record. This attenuator's true value at 12 GHz is 6.05 dB.

that the film is homogeneous. The attenuation in dB depends only upon the geometry of the resistive film. Moreover, because the attenuation is independent of resistivity and the dielectric substrate's dimensions show only negligible changes with temperature, the attenuation is virtually insensitive to temperature changes.

In the foregoing paragraphs the resistive film was assumed to have no reactance or susceptance. Actually, the current paths in the film produce small inductive effects which cause the attenuation at high frequencies to deviate from the desired value. The effects are different for different values of attenuation. To compensate for these effects, capacitive elements of various types are added to the finished attenuators. Total variation in attenuation among finished attenuators, Fig. 4, proved to be well within the design tolerance.

TDR and Mechanical Scaling

To eliminate any discontinuities that might degrade the frequency response, VSWR, or phase response of the

attenuators, the designs were checked by time domain reflectometry. But since no TDR system available at that time would test up to 18 GHz, mechanical scaling was used.* Everything was constructed to 5 times scale and checked by TDR up to 3.8 GHz. When all of the objectionable discontinuities had been removed from the large model, its dimensions were divided by five to get the actual attenuator dimensions. The actual attenuators work as well at 19 GHz as the models did at 3.8 GHz.

Production Methods

Precision silkscreening and semi-automated thin-film deposition are employed in the manufacture of the coaxial attenuators. Silver input, output, and ground electrodes are silkscreened onto the dielectric substrates. Then the cards are loaded into special fixtures and aligned under a microscope to make certain that the resistive film will be deposited in the right places.

* H. Poulter, 'Mechanical Scaling Enhances Time Domain Reflectometry Use,' presented at Western Electronic Show and Convention, 1965. Reprinted in Hewlett-Packard Application Note 75.

Table I
Accuracy of Swept Attenuation Tests

Attenuator Model No.	8491B		8492A	
Connectors	Type N		Amphenol precision 7mm	
Frequency (GHz)	12	18	12	18
Connector mismatch uncertainty (dB) Calibration Test	± 0.0035 ± 0.046	± 0.0076 ± 0.088	± 0.002 ± 0.03	± 0.0035 ± 0.05
Connector repeatability (dB)	± 0.03	± 0.03	± 0.03	± 0.03
Detector error (dB)	± 0.02	± 0.02	± 0.02	± 0.02
Drift and readability (dB)	± 0.02	± 0.02	± 0.02	± 0.02
Standard attenuator uncertainty (dB)	± 0.002	± 0.002	± 0.002	± 0.002
Maximum possible errors (dB)	± 0.1215	± 0.1676	± 0.104	± 0.1255
rms errors (dB)	± 0.062	± 0.097	± 0.051	± 0.065

Next, the fixtures containing the cards are placed in a vacuum chamber, Fig. 3, and a thin film of resistive material is evaporated onto them. The process is precisely controlled. Each card is tested repeatedly as the film is being deposited. The finished cards do not require any hand touch-up, which would be quite expensive.

Before the cards are removed from the vacuum chamber, a microscopic coating of silicon monoxide is evaporated onto them to increase their stability and protect them from hostile environments. The cards are then removed, tested, and loaded into their cartridges.

Variations in attenuation over the frequency range of the 10 and 20 dB attenuators was from ± 0.30 to ± 0.35 dB, thus indicating good uniformity and repeatability of the thin-film processes. The design target was a maximum variation of ± 0.5 dB.

Sweep Testing for Attenuation and VSWR

After the cards are placed into their cylindrical cartridges, each device is pretested in a special test fixture over the entire frequency range. Then, when the connectors have been added, the completed attenuators are again tested.

Audio-frequency-substitution techniques are used in final testing and calibration of the thin-film attenuators. Each attenuator is compared to a special 1-kHz atten-

uator which is calibrated to an accuracy of ± 0.002 dB, traceable to NBS.

Low-frequency calibration of the attenuators is performed at a single frequency of 1 kHz, using the setup shown at the top of Fig. 5.

At higher frequencies, calibration is by swept-frequency methods so that no spot-frequency resonances are overlooked. In the test setup at the bottom of Fig. 5, only one sweep oscillator is shown, but several are used in the tests to cover all frequencies up to 18 GHz.

The sweepers are 100% square-wave modulated at 1 kHz. A wideband detector recovers the 1 kHz signal at the output of the test section.

Attenuators to be tested are inserted between two attenuators which have been especially selected for low reflections over the frequency range of interest. Lengths of precision 50Ω line between the attenuators and the plane of insertion, Fig. 5, are part of a scheme to eliminate multiple mismatch errors, which would otherwise be so large that precise calibrations would be impossible.

Multiple mismatch errors are caused by the reflections from the attenuators at the source and detector ends of the test section, and by reflections from the attenuator being tested. If Γ_s is the source reflection coefficient, Γ_D the detector reflection coefficient, Γ_1 the reflection coefficient at the source end of the test device, and Γ_2 the reflection coefficient at the detector end of the test device,

then multiple mismatch uncertainty in dB equals

$$10 \log |1 \pm \Gamma_s \Gamma_D|^2 + 10 \log |1 \pm \Gamma_s \Gamma_1|^2 + 10 \log |1 \pm \Gamma_2 \Gamma_D|^2$$

Γ_1 and Γ_2 include the reflection coefficient of the precision connectors at the plane of insertion.

The 50 Ω line separates Γ_s and Γ_D by several wavelengths at the lowest frequency of interest. As the sweeper sweeps across the band, the phases of these reflections make many complete revolutions because of the changing phase shift of the 50 Ω line. The result is a recorder plot which has a great number of ripples, Fig. 6.

Averaging out the ripples eliminates the multiple mismatch errors. The only errors that remain are small errors contributed by the reflection coefficients of the connectors at the plane of insertion.

If Γ_s and Γ_D were not separated by several wavelengths by the 50 Ω line, their phases would make less than one complete revolution and it would be impossible to average out the multiple mismatch errors.

Before and after the test devices are inserted into the test section, the calibration of the system is checked. A series of calibration traces is drawn on the recorder plot. These correspond to 0.1 dB increments above and below the nominal attenuation of the test devices. These traces also have ripples, but the true calibration lines can be found by simply averaging the ripples. Averaging, interpolation, and drift during the test contribute an uncertainty of about ± 0.02 dB to the measurements.

Table 1 summarizes the uncertainties in the swept tests for two types of attenuators at 12 GHz and 18 GHz.

In addition to the attenuation tests, each attenuator is tested for VSWR, using a swept-frequency technique.* Typical test results are shown in the oscillogram, Fig. 7. VSWR's of the thin-film attenuators range from less than 1.15 to about 1.5, depending upon the type of connectors, the frequency, and the attenuation.

Linear Phase Response

Thin-film attenuators are not only flat in frequency response; their phase responses are quite linear. The oscillogram, Fig. 8, shows the deviations from linearity of a typical 6-dB attenuator from 1.0 to 2.0 GHz, measured by the HP Network Analyzer (Hewlett-Packard Journal, February 1967). Deviations are a small fraction of a degree.

Linear phase response makes the attenuators suitable for precision pulse work, which requires not only constant attenuation over a wide bandwidth, but also constant group delay.

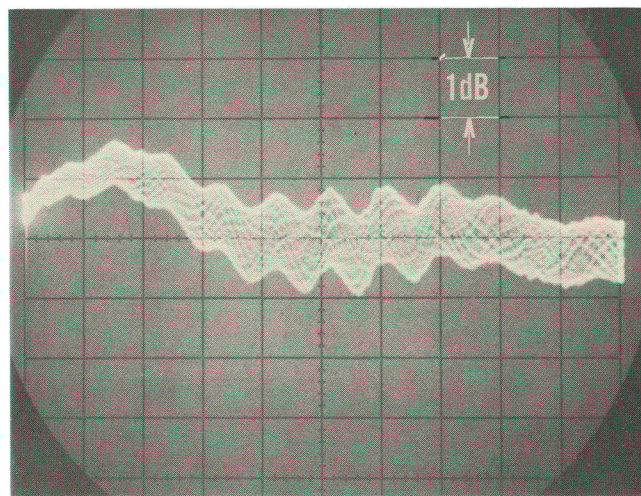


Fig. 7. Each thin-film attenuator is swept-frequency tested for VSWR. This is a typical test result for a Model 8491A 20 dB Attenuator. Vertical scale is 1 dB/cm. $VSWR = \log^{-1}$ (width of pattern in dB/20). Maximum VSWR shown here is 1.16.

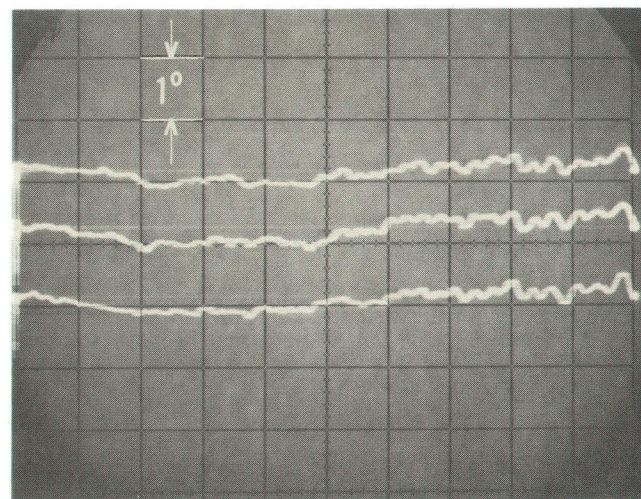


Fig. 8. Center trace is the nonlinear phase shift of a HP Model 8491A 6 dB Attenuator, measured by HP Model 8410A Network Analyzer. Top and bottom traces are $\pm 1^\circ$ calibration. Because nonlinear phase variations are small fractions of one degree, the thin-film attenuators are suitable for pulse work.

* S. F. Adam, 'Swept-Frequency SWR Measurements in Coaxial Systems,' *Hewlett-Packard Journal*, Vol. 18, No. 4, Dec., 1966.



Fig. 9. Fixed attenuators were designed to be used singly or in sets of four — one each of 3, 6, 10, and 20 dB values. Sets contain calibration reports for all four attenuators.



Fig. 10. HP Model 354A 0-to-60 dB Coaxial Step Attenuator uses thin-film attenuating cards. Frequency range is dc to 12.4 GHz.

Fixed Attenuators

Three types of fixed thin-film attenuators are produced. One has type N connectors and an upper frequency limit of 12.4 GHz. The other two are accurate up to 18 GHz, one having type N connectors and the other having Amphenol precision 7mm connectors. All three types are made in 3, 6, 10, and 20 dB values. They can also be supplied in 30, 40, 50, and 60 dB values.

Each fixed coaxial attenuator has a plate showing its measured attenuation at 0, 4, 8, 12, and 18 GHz (plates on 12.4 GHz attenuators show nothing at 18 GHz).

One each of the 3, 6, 10, and 20 dB attenuators are also packaged in sets, Fig. 9. A calibration report accompanies each attenuator, showing its measured attenuation and reflection coefficients at 0, 4, 8, 12, and 18 GHz.

Variable Attenuator

Thin-film attenuators are also used in a turret-type coaxial step attenuator, Fig. 10, which provides attenuation of 0 to 60 dB in 10 dB steps. This attenuator has type N connectors (Amphenol precision 7mm connectors can also be supplied). Its frequency response is flat from dc to 12.4 GHz.

The attenuator is operated with a simple knob rotation; no push-turn-pull sequence is required. Each unit



Stephen F. Adam

Before he joined Hewlett-Packard in 1957, Steve Adam was a research and development engineer in Budapest, Hungary. At HP he has worked on waveguide wavemeters and rotary-vane attenuators, and has been project supervisor for the development of two coaxial wavemeters and the thin-film coaxial attenuators. He has several patents pending, some of them related to thin-film attenuators. Steve is now an

engineering group leader in the HP Microwave Laboratory and is responsible for the development of several types of passive components.

Steve studied mechanical and electrical engineering at the Technical Institute of Budapest. He holds the equivalent of an MS degree in electrical engineering. He is a member of IEEE, an instructor of microwave electronics at Foothill College, and a member of the board of directors of the Bay Area Council for Electronics Education.

was designed with a base for bench use, but the base is removable so the attenuator can be panel-mounted.

Acknowledgments

The author wishes to express his appreciation to David R. Veteran for his many valuable contributions to the

development of the attenuators. Douglas Christensen, George R. Kirkpatrick and Karl-Heinz Johannsmeier contributed to the early stages of development, and Richard W. Anderson provided many helpful suggestions. William R. Hewlett and William B. Wholey are the inventors of the card attenuators. ■

SPECIFICATIONS

HP

Models 8491A, 8491B, 8492A Coaxial Attenuators

	8491A dc to 12.4 GHz		8491B dc to 18.0 GHz			8492A dc to 18.0 GHz		
ATTENUATION ACCURACY	dc-7	7-12.4	dc-12	12-18		dc-12	12-18	
3 dB	±0.3 dB		±0.3 dB			±0.3 dB		
6 dB	±0.3 dB	±0.4 dB	±0.3 dB	±0.4 dB		±0.3 dB	±0.4 dB	
10 dB	±0.5 dB		±0.5 dB			±0.5 dB		
20 dB	±0.5 dB	±1 dB	±0.5 dB	±1 dB		±0.5 dB	±1 dB	
SWR	dc-7	7-12.4	dc-7	7-12	12-18	dc-8	8-12	12-18
3 dB	1.25	1.35	1.25	1.35	1.5	1.2	1.3	1.5
6 dB	1.2	1.3	1.2	1.3	1.5	1.2	1.3	1.35
10 dB								
20 dB								
						1.15	1.25	1.3
CALIBRATION FREQUENCIES	dc, 4, 8, 12.4 GHz		dc, 4, 8, 12, 18 GHz			dc, 4, 8, 12, 18 GHz		
MAXIMUM INPUT POWER	2 watts average		2 watts average			2 watts average		
CONNECTORS (50Ω)	Type N*		Type N*			APC-7**		
DIMENSIONS	2 $\frac{1}{16}$ " long, 1 $\frac{3}{16}$ " dia. 62 x 21 mm		2 $\frac{1}{16}$ " long, 1 $\frac{3}{16}$ " dia. 62 x 21 mm			2 $\frac{3}{4}$ " long, 1 $\frac{3}{16}$ " dia. 70 x 21 mm		
WEIGHT	Net, 3 $\frac{1}{2}$ oz. (100 g) Shipping, 8 oz. (220 g)		Net, 3 $\frac{1}{2}$ oz. (100 g) Shipping, 8 oz. (220 g)			Net, 3 $\frac{1}{4}$ oz. (90 g) Shipping, 8 oz. (220 g)		
PRICE (specify option)								
Option 03—3 dB nom. attenuation								
06—6 dB nom. attenuation	\$50.00 ea.		\$65.00 ea.			\$125.00 ea.		
10—10 dB nom. attenuation								
20—20 dB nom. attenuation								

ATTENUATOR SETS

Model 11581A (for 8491A) Includes 3, 6, 10, 20 dB values.....\$225
Model 11582A (for 8491B) Includes 3, 6, 10, 20 dB values..... 285
Model 11583A (for 8492A) Includes 3, 6, 10, 20 dB values.....525

HP

Model 354A Coaxial Attenuator

FREQUENCY RANGE: dc to 12.4 GHz.

INCREMENTAL ATTENUATION: 0 to 60 dB in 10-dB steps.

ACCURACY (including frequency response): ±2 dB.

RESIDUAL ATTENUATION: Less than 1.5 dB.

IMPEDANCE: 50Ω.

REFLECTION COEFFICIENT:

0 to 8 GHz: Less than 0.2 (1.5 SWR, 14 dB return loss).
8 to 12.4 GHz: Less than 0.273 (1.75 SWR, 11.3 dB return loss).

30, 40, 50, and 60 dB attenuator values available on request.

* Mate with Mil-C-71 and Mil-C-39012 connector dimensions.

** Amphenol RF Division, Danbury, Connecticut.

MAXIMUM POWER: 2 W average.

CONNECTORS: Type N female, stainless steel.

DIMENSIONS (maximum envelope): 4 in. wide, 3 $\frac{1}{8}$ in. high, 4 $\frac{1}{2}$ in. deep (102 x 79 x 114 mm); panel mount, 3 $\frac{1}{16}$ in. wide, 2 $\frac{1}{16}$ in. high, 3 $\frac{3}{4}$ in. deep behind panel (78 x 59 x 95 mm).

WEIGHT (with base): Net, 2 $\frac{3}{4}$ lbs. (1.2 kg). Shipping, 4 lbs. (1.8 kg).

PRICE: Model 354A, \$350.00.

MANUFACTURING DIVISION:

HP Microwave Division
1501 Page Mill Road
Palo Alto, California 94304

International Units, Multiple and Submultiple Prefixes

The units for physical quantities which are used in the Hewlett-Packard Journal follow the SI System (Système Internationale d'Unités). Defined and given official status in a resolution of the 11th General Conference on Weights and Measures at a 1960 Paris meeting, the SI system has also been adopted by the U.S. National Bureau of Standards for use in its publications, except where use of the units would complicate the communication of information.

One unit is specified for each quantity, multiples and submultiples designated with approved prefixes, shown separately here. Four of the basic units are independent (length, mass, time, and temperature). All others, including the ampere and the candela, involve other units in their definition.

The Table of Units appeared originally in the HP Journal, Vol. 15, No. 7, March 1964. The Table of Prefixes appeared originally in Vol. 14, No. 7-8, March-April, 1963.

Submultiple Prefixes

Multiple/ Submultiple	Prefix	Symbol	Pronunciation	Multiple/ Submultiple	Prefix	Symbol	Pronunciation
10^{12}	tera	T	tě'r' à	10^{-2}	centi	c	sě'n' tš
10^9	giga	G	jš' gà	10^{-3}	milli	m	mš'l' š
10^6	mega	M	mě'g' à	10^{-6}	micro	μ	mš' krō
10^3	kilo	k	kš'l' ō	10^{-9}	nano	n	nān' ō
10^2	hecto	h	hě'k' tō	10^{-12}	pico	p	pě' cō
10	deka	da	dě'k' à	10^{-15}	femto	f	fě'm' tō
10^{-1}	deci	d	dě's' š	10^{-18}	atto	a	āt' tō

International System Of Units

Basic Units			Quantity	Unit	Symbol
Quantity	Unit	Symbol	Force	newton	N (kg·m/s ²)
Length	meter	m	Pressure	newton per sq. meter	N/m ²
Mass	kilogram	kg	Kinematic viscosity	sq. meter per second	m ² /s
Time	second	s	Dynamic viscosity	newton-second per sq. meter	N·s/m ²
Temperature	degree Kelvin	° K	Work, energy, quantity of heat	joule	J (N·m)
Electric current	ampere	A	Power	watt	W (J/s)
Luminous intensity	candela	cd	Electric charge	coulomb	C (A·s)
Supplementary Units			Voltage, potential difference, electromotive force	volt	V (W/A)
Plane angle	radian	rad	Electric field strength	volt per meter	V/m
Solid angle	steradian	sr	Electric resistance	ohm	Ω (V/A)
Derived Units			Electric capacitance	farad	F (A·s/V)
Area	square meter	m ²	Magnetic flux	weber	Wb (V·s)
Volume	cubic meter	m ³	Inductance	henry	H (V·s/A)
Frequency	hertz	Hz (s ⁻¹)	Magnetic flux density	tesla	T (Wb/m ²)
Density	kilogram per cubic meter	kg/m ³	Magnetic field strength	ampere per meter	A/m
Velocity	meter per second	m/s	Magnetomotive force	ampere	A
Angular velocity	radian per second	rad/s	Flux of light	lumen	lm (cd·sr)
Acceleration	meter per sec. squared	m/s ²	Luminance	candela per sq. meter	cd/m ²
Angular acceleration	radian per sec. squared	rad/s ²	Illumination	lux	lx (lm/m ²)

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