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COMPARISON OF POTENTIAL DEVICE INTERFERENCE AND BIOLOGICAL EXPOSURE HAZARDS IN MICROWAVE LEAKAGE FIELDS

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Abstract

The potential for interference in devices including medical devices and instrumentation exposed to leakage or stray fields of microwave sources is explored. A study of semiconductor devices in arbitrary circuitry suggests a maximum potential interference in microwave fields. Experimental data on interference of demand pacemakers in microwave fields is reviewed in the context of electromagnetic compatibility. Potential interference levels are far below biological exposure hazard levels. Effective methods of reducing susceptibility of devices to microwave radiation are shown to include shielding and filtering techniques.

Introduction

There has been considerable discussion of potential biological hazards from exposure to microwave radiation emanating from radar transmitters and the smaller incidental leakage from microwave ovens which is now controlled by Public Law 90-602.[1] Somewhat overlooked has been the potential interference which microwave radiation can cause in consumer electronic devices as well as medical and scientific instruments. This interference can cause annoyance or even hazards to users of such equipment at radiation levels far below biologically hazardous levels, particularly if the equipment is poorly designed to reduce susceptibility to microwave interference. A study of such interference shows that it must be approached from a different perspective than in the case of biological exposure, with emphasis on reduction of susceptibility of devices to "out of band" radiation which is legally permitted by HEW and FCC regulations.

Review of Microwave Exposure Standards

The characteristics of some principal safety standards[2-7] on microwave radiation exposure are depicted in Fig. 1 in the form of maximum exposure (power density) as functions of exposure duration.

The specified frequency ranges for different standards are somewhat loosely defined between 10 MHz and 300 GHz. The power density referred to in the standards is that average density measured in accessible regions (USASI or military) or at actual exposure sites (USSR and Czech) in the absence of the subject. The averaging times are not thoroughly defined but can range from three seconds (Navy) to eight hours (Czech). Generally far field probes are intended with response times implied to be much greater than pulse durations and much smaller than duration of exposure - i.e., generally the order of seconds. Some use of true dosimetry - i.e., integrated absorbed energy - is made in the USSR and Czechoslovakia.

The standards suffer from absence of restrictions on peak power, modification for partial body exposure, considerations of modulation effects (except in Czech standards) and allowance for environment. A proposal on the latter has been made by Mumford[7] and general improvement is being sought by the American National Standards Institute (ANSI).

The principal performance standards[8,9] limiting leakage from microwave ovens are depicted in Fig. 2 in the form of maximum exposure density as functions of distance from leakage source.

The frequency range of the standards varies from 890 to 6000 MHz but are principally directed to the two microwave oven ISM bands at 915 and 2450 MHz. The standards specify maximum "effective" power density at any point 2.0 inches from the external surface of an oven. The instrumentation is specified to include an averaging time of 3 seconds and small effective aperture of less than 25 cm^2 for probes.

It is important to realize the distinction of these oven performance standards from exposure standards. These standards specify leakage levels at 2.0 inches and do not specify exposure levels. The latter can be estimated, however, from the known spatial distribution of leakage fields from ovens. These leakage fields generally exhibit a $1/r$ dependence of power density close to the oven (< 6.0") and a $1/r^2$ dependence further away (> 1 foot). Actual distributions such as the one shown in Fig. 3 show minor fluctuations (e.g., up to 3 dB) around smooth $1/r^2$ extrapolations.

Estimated upper limits shown in Fig. 2 approximate the maximum far field radiation assuming in-phase radiation along entire door perimeter at the maximum permitted level into a hemisphere.

The estimated lower limit approximates the distribution resulting from one localized source. Typical measured distributions fall between these estimated limits, when measured along a line normal to the point of maximum leakage. Thus a reasonable general estimate is a simple $1/r^2$ extrapolation from the measured power density at 2.0 inches.

These estimated distributions apply to in band radiation for ovens leaking at maximum permitted levels. It should be noted that out of band radiation is restricted to much lower levels by the FCC. An extrapolation of these levels, usually measured much further from the oven is shown in Fig. 2 to be about six orders of magnitude below HEW limits on in band radiation.

It also can be seen that likely exposure levels at several feet from an oven compare favorably with exposure standards in the USSR and Czechoslovakis. This reflects a large safety factor relating likely exposure levels to the specified performance level measured at 2.0 inches.

Microwave Interference with Cardiac Pacemakers

In recent years it has been found that the "demand" type of cardiac pacemakers can suffer serious interference in microwave fields near microwave ovens[10] and at substantial distances from radar transmitters.[11] These incidents of interference can result in temporary malfunction of the pacemaker and serious hazard to the health of the user.

In order to gain an understanding of the degree and nature of the interference, several demand type pacemakers were tested under exposure to microwave fields close to a radiating source. Pacemakers with catheter leads attached and using a small indicator meter were positioned at distances between 6 to 10 inches in front of radiating waveguides at 950 MHz (approximating 915 MHz) and 2450 MHz. The pacemakers were exposed to CW, amplitude modulated, and pulse modulated radiation and the average power density of the microwave leakage at the location of the pacemaker was measured with a Narda 8100 probe. Changes in geometrical arrangement of the pacemaker and catheter lead result in significant changes in interference but the results do show how low critical power densities can be as well as a clear indication of the dependence of the interference on modulation frequency.

The results of one measurement are shown in Fig. 4. Shown are the critical power densities at which the demand function is inhibited resulting in no output pulse from the pacemaker. It is seen that interference is much more serious with low frequency AM than under CW conditions. The exact dependence on modulation frequency reflects the characteristics of the circuitry in the pacemaker. In this case at least interference is possible at power density levels below 1 $\mu w/cm^2$. Also shown in this figure is the approximate threshold for appearance of the modulation as a significant artifact in the output of the pacemaker.

Similar curves for six different makes of pacemakers are shown in Fig. 5. These data were obtained at 2450 MHz only with the pacemakers placed in the same location in succession. It is seen that a wide variety of characteristics are obtained, reflecting mostly the different circuit characteristics of different models of pacemakers. With the exception of the model denoted F, all the pacemakers are more sensitive to amplitude modulated microwaves than CW microwaves, with the most critical modulation frequencies in the range of 10-1000 Hertz.

The measured thresholds for microwave inhibition of these pacemakers denoted A-F as well as two others denoted G and H are summarized in Table I. The thresholds under CW conditions are generally of the order of maximum exposure or performance standard levels specified for biological exposure. The thresholds under conditions of 100 percent amplitude modulation can be as much as three orders of magnitude below exposure safety limits although some models are relatively insensitive - e.g., model F. The latter model, however, proves to be sensitive to peak values of power density rather than average density as shown under the column of "Short Pulse Threshold". In the case of model H, we have inserted a note on "switching to fixed rate" in the absence of any finding on complete inhibition of the demand function. It is possible that this different (and less serious) response exists for the other models as well but it was not sought. (Other effects such as change of pacemaker rate below threshold have been observed.)

These data are consistent with the reports[10,11] on the microwave interference of pacemakers. Since most microwave ovens have mode stirrer rates of a few cycles per second it is reasonable to expect significant modulation of microwave oven leakage in the critical frequency range for pacemakers. From Fig. 2 we can estimate that an oven leaking at the maximum specified limits may conceivably have sufficient leakage levels at several feet to stop a pacemaker. Ovens leaking well below the standard limits could be expected to interfere only at a distance of inches. These types of observations have been confirmed qualitatively with actual ovens. In most cases, even with leakage of 1 mw/cm^2 at 2.0 inches, pacemaker interference has been observed only within a foot of an oven. It is conceivable that a badly leaking oven (>> 5 mw/cm^2 at 2.0 inches) with accidental matching of modulation content to the critical range of a pacemaker, could inhibit the pacemaker at distances of 10 to 100 feet. From our measurements of thresholds for a variety of pacemakers, it would appear that this case is exceptional considering the variety of ovens.

Informal tests with pacemakers at airports have shown that several pacemakers can be inhibited at distances of several hundred yards from airport radar scanning antennas. These tests and the report in the literature[11] are consistent with estimates of radars yielding peak power densities of the order of 1 mw/cm^2 and average power densities of the order of 1 $\mu w/cm^2$ at these distances during the short period of scan in which the radar beam is pointed toward a subject at these distances.

In the above no consideration has been given to the shielding effect of the human body in which a pacemaker may be implanted. Although at lower frequencies a considerable shielding is predicted by a spherical shell model of Bridges and Brueschke[12] this same model predicts possibly "only nominal shielding effectiveness" at VHF frequencies or higher. Calculations of transmission using planar tissue models and plane waves using the data of Schwan[13] show that one can expect only a few dB attenuation at 915 or 2450 MHz for a one inch body tissue thickness shielding the pacemaker. Certainly the body shielding is high at high microwave frequencies and predicted high at low frequencies[12] but in the range of frequencies (915 - 2450 MHz) it is low and no basis for protection. (The correspondence with basis for best cooking frequencies is not entirely unrelated.)

Unique Features of Microwave Interference

The discussion of body shielding suggests that interference of pacemakers may be particularly possible at low microwave frequencies. Actually there are other reasons why such interference is particularly prone at low microwave frequencies. These reasons relate to the dependence on frequency of various solid-state devices (diodes, transistors) in their detection sensitivity and the efficiency of incidental wiring (inches of wire etc.) as antennas.

Consider a short dipole antenna with an untuned load. Then if the incident radiation has a power density p_o then the power P_L delivered to the dipole load can be written as

$$P_L = A_e p_o \qquad (1)$$

where A_e is an "effective aperture" given by

$$A_e = \frac{h_e^2 \zeta_o R_L}{|Z_a + Z_L|^2} \qquad (2)$$

where h_e is the effective height ($\sim$ physical height ℓ for short antennas), ζ_o = 377 ohms (impedance of free space), R_L is the load resistance, and Z_a, Z_L are the complex antenna input and load impedance, respectively.

For short antennas[14] where the radiation resistance

$$(\sim 200\ (\frac{\ell}{\lambda})^2 \text{ ohms})$$

is small compared to the antenna reactance, the effective aperture can be written approximately as

$$A_e \approx \frac{h_e^2 \zeta_o R_L}{Z_o^2} \ (\beta\ell)^2 \qquad (3)$$

where

$Z_o = 120\ [\ell n \frac{2\ell}{a} - 1]$; β is the free space propagation constant and a is the antenna diameter.

Thus for a given untuned dipole one would expect the received signal power to increase with the square of frequency. Note that the signal from a tuned dipole, assuming ideal lossless tuning were possible, would have an entirely different dependence on frequency in which the effective aperture varies inversely with the square of frequency. For the incidental interference under discussion, it is more reasonable to assume that something like an untuned dipole is characteristic of the "receiver".

The equipment under interference can thus be expected to deliver more signal power to arbitrary load elements, the higher the frequency, for a given radiation level p_o. The arbitrary load elements could include a variety of solid state devices which though not designed for all frequencies including microwaves could act as demodulators in the form of simple video diode detectors. Thus the p-n junctions in transistors as well as diodes could perform this detection.

Since devices like pacemakers are not designed for microwave frequencies, it is expected that most solid state elements would show detection sensitivity which falls off rapidly with frequency, beginning somewhere in the microwave or VHF range. The high frequency drop in sensitivity can be as fast as 12 dB/ octave corresponding to a circuit R-C type response for most diode-equivalent circuits, or faster corresponding to operation beyond transit time limits of a p-n junction diode.

Qualitatively at least these expectations are confirmed by the results of measurement, on a variety of semiconductor diodes and transistors used in pacemakers and consumer electronics. These components were operated as untuned diode detectors as a load on a 50 ohm coaxial line and compared in sensitivity to a Hewlett Packard 423 diode detector. The results shown in Fig. 6 show that most of these components show rapidly decreasing sensitivity beginning in the UHF range but little change in sensitivity at lower frequencies.

In general then, if one considers the rising antenna sensitivity predicted by Eqs. (1) to (3) and the flat detection sensitivity of typical diodes out to VHF frequencies, one can expect a maximum potential interference somewhere in the UHF or lower microwave range. Only under exceptional conditions of components and tuning can one expect the higher microwave range to contribute comparable interference.

It is reasonable from our considerations of the incidental antennas and diode detectors present in a pacemaker device that without shielding or filtering that there is significant interference at microwave frequencies. The modulation of any microwave carrier would be incidentally presented through diode detection into the circuitry of the pacemaker and inhibit the demand pacemaker if the detected signal resembled in spectrum the

QRS complex of the heart. Evidently this inhibition can occur at interference levels considerably below that producing a considerable artifact in the pacemaker output.

Similar but less critical interference from microwave radiation can be expected to occur in other medical, scientific and consumer devices, which are not designed for microwave performance, because of the residual high frequency detection capability of most arbitrary semiconductor components. Some examples include artifacts induced in EKG recording apparatus at levels of 10 $\mu w/cm^2$ at 915 MHz, and detection of audible "mode-stirrer action" by pocket transistor radios held within several feet of a microwave oven. Similar interference from microwave diathermy, radar etc. can be expected when devices are not shielded or filtered against microwave interference.

Assessment and Solutions to Microwave Interference

The discovery of microwave interference of pacemakers has led to the realization of a more general susceptibility of all kinds of devices and equipment to microwave interferference. Because of the frequency-dependent properties of incidental antennas and diodes found in such equipment, it is likely that significant interference can occur in the increasing amount of microwave radiation fields associated with radars, ovens, diathermy etc. Because this radiation, obeying both HEW and FCC regulations, can be expected to become more prevalent, it is appropriate to assess this problem as one of susceptibility of equipment to interference rather than as a radiation hazard.

In the case of the pacemaker the microwave interference is only one of a rather wide class of potential interference sources including auto and lawn motor ignition noise, Tesla coils, light dimmers, some television receivers, and electric shavers.

In its review[15] of the problem, the Bureau of Radiological Health (HEW) has called for wide-scale distribution of warnings about potential microwave interference from many sources through professional channels to those capable of informing the pacemaker wearer of the overall interference problem. It has also urged pacemaker manufacturers to reduce the susceptibility of future pacemaker models to all forms of electromagnetic interference.

For microwave interference, at least, this appears to be quite feasible. In laboratory experiments aluminum foil was used for shielding and two miniature microwave feedthrough capacitors were inserted at the catheter connections to the bipolar type of pacemaker. Subsequent tests, under all types of amplitude and pulse modulation described above, showed no evidence of interference through change of rate, inhibition, or artifacts up to exposure power densities of 10 mw/cm^2 at 915 and 2450 MHz. This test showed that techniques of shielding and filtering should be feasible in reducing susceptibility to microwave interference without altering the normal electrical operation of the pacemaker.

It seems appropriate to assess the pacemaker interference problem and other analogous problems in a general framework of a philosophy of electromagnetic compatibility. In the evolving modern civilization the prevalence of electromagnetic fields will increase - whether intended or unintended radiation or localized near field or leakage type fields. The levels of these fields are regulated by HEW and FCC limits at least and are particularly stringent for radiated out-of-band signals. The latter restrictions are usually sufficient to prevent interference with users of other bands of the spectrum. It is generally incumbent on the designers of receivers to reject out-of-band signals. It is reasonable that designers of medical, scientific, and even consumer electronic equipment should give some thought to protection against incidental microwave interference. Suppression of susceptibility to out-of-band radiation - particularly microwaves can be sought through shielding, feed-thru and other type of filtering, and even reduction of the sensitivity of active elements to microwave frequencies. Concurrently it is desirable to continue reducing unnecessary radiation as technology yields new techniques of economical leakage suppression from devices such as microwave ovens.

In special cases where reduction of susceptibility is difficult it may become necessary to prepare guides on minimum safe distances from various microwave transmitters similar to guides[16] prepared by standards organizations for safe use of electro-explosive devices.

Conclusions

With the increasing use of sources of microwave radiation and the concurrent increase of all solid-state equipment for medical, scientific, and consumer applications it is likely that the type of microwave interference discussed above will reoccur. It is important to realize that the interference, whether causing only annoyance or more serious disruption, can occur at microwave radiation levels far below levels of biological hazards. It is likely that the greatest potential interference of an incidental nature will occur in the low microwave or VHF range of the spectrum. The most effective solutions to this interference appears to be introduction of shielding and filtering techniques to reduce susceptibility of electronic equipment to microwave interference. Continuing advances in suppression of unnecessary microwave leakage is also desirable.

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Table I

Thresholds for Microwave Inhibition of Typical Demand Pacemakers

Pacemaker	CW Threshold (mw/cm^2 average)		100 percent AM Threshold (mw/cm^2 average)		Short Pulse* Threshold (mw/cm^2 peak)
Frequency (MHz)	915	2450	915	2450	2450
A	4.25	.38	.04	.0022	----**
B	> 4.8	> 1.35	.53	.095	----**
C	> 4.25	> 1.35	.048	.0052	0.44*
D	> 4.8	> 1.35	.106	.044	(0.028)***
E	11.7	6.0	0.021	.0095	----**
F	8.5	1.64	8.5	0.6	2.8*
G	> 5.0	> 5.0	0.15	1.9	----**
H	> 5.0	> 5.0	.015	.15	(0.005)****

* Duty Cycle = 0.01 - 0.001, 1-10 μsec pulses.

** Can't be stopped at peak levels < 6 mw/cm^2.

*** Average power independent of duty cycle or pulse width.

**** Switches to fixed rate at 0.005 mw/cm^2 average power density.

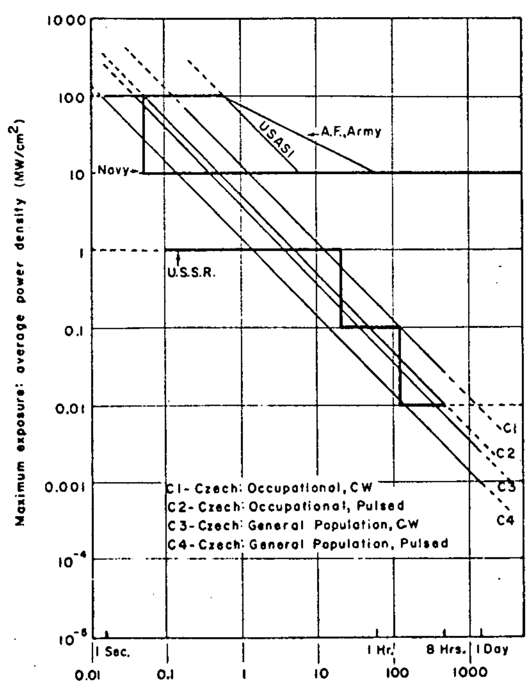

Fig. 1 Maximum Permitted Exposure (Average Power Density) as a Function of Exposure Duration for Several Microwave Radiation Safety Standards on Exposure.

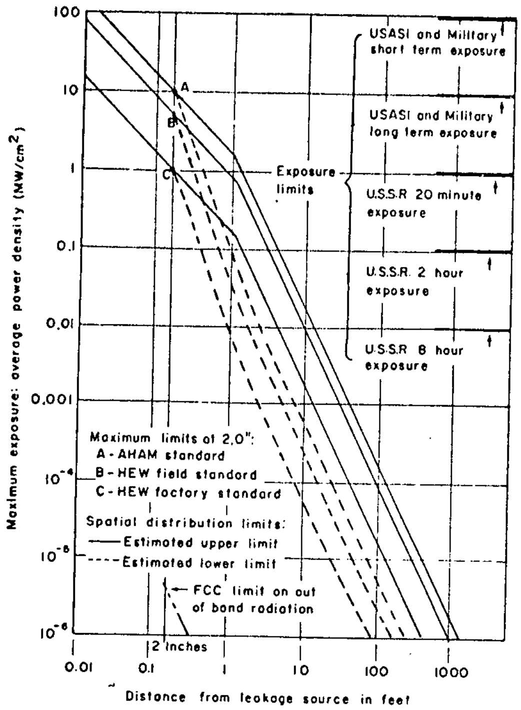

Fig. 2 Estimated Spatial Distributions of Exposure (Average Power Density) Associated with the Principal Microwave Oven Leakage Performance Standards.

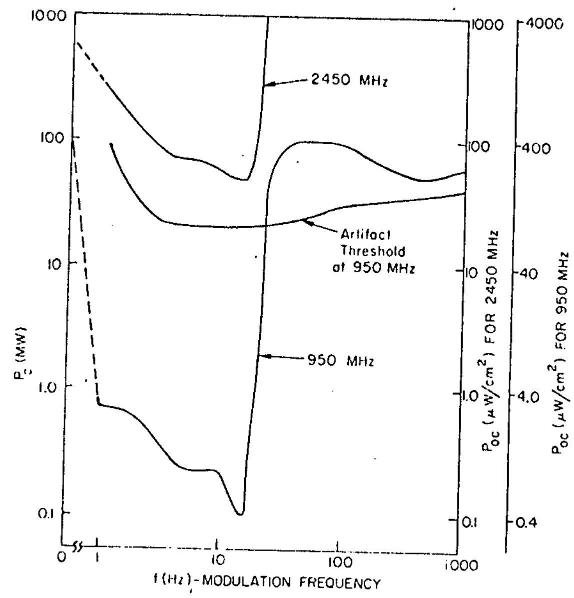

Fig. 4 Critical Power Density Required for Inhibition of a Demand Pacemaker at 915 and 2450 MHz as a Function of Modulation Frequency.

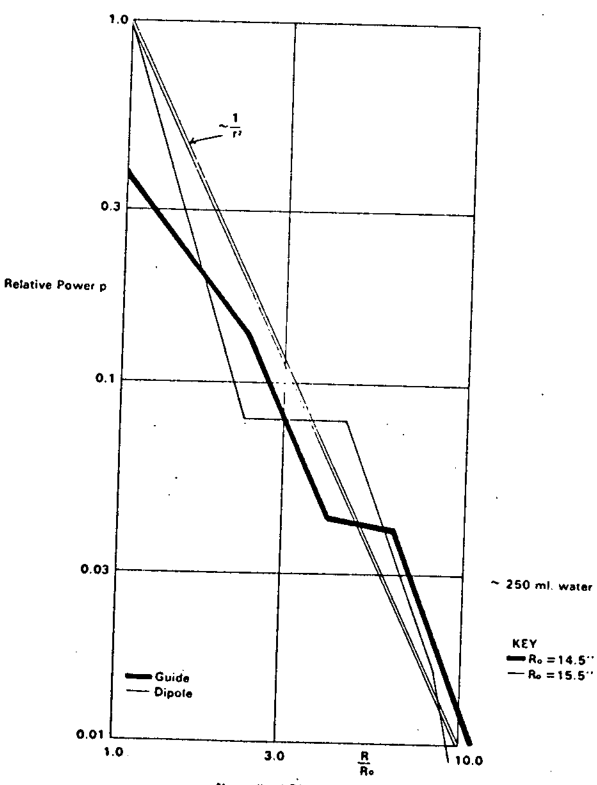

Fig. 3 Relative Level of Microwave Oven Leakage as a Function of Distance from Oven.

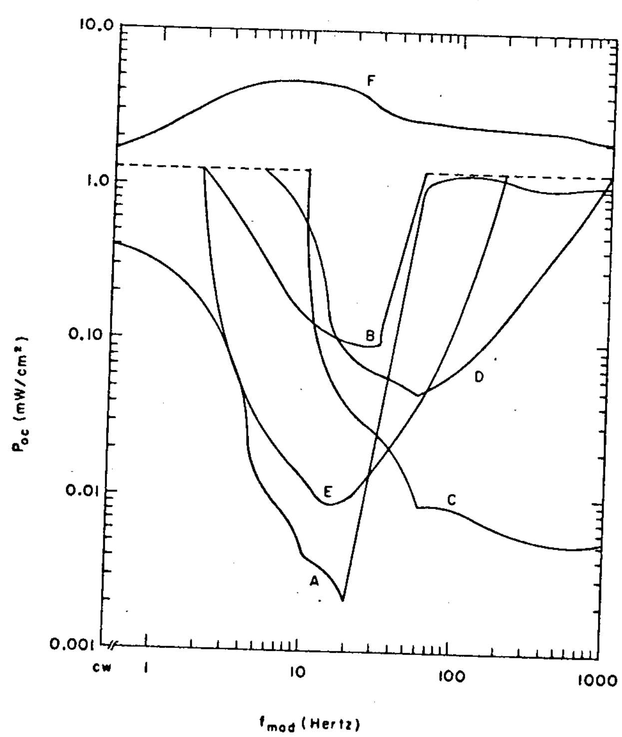

Fig. 5 Critical Power Density Required for Inhibition of Several Models of Demand Pacemakers at 2450 MHz as a Function of Modulation Frequency.

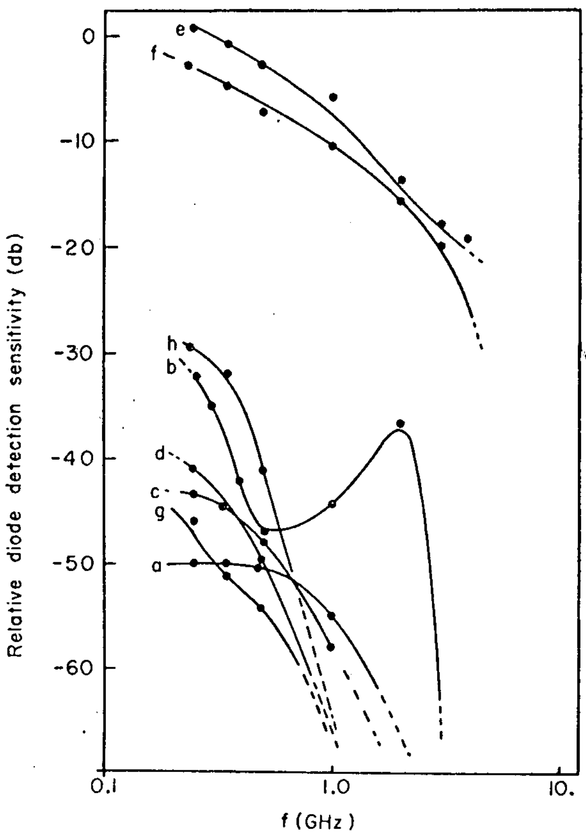

Fig. 6 Relative Diode Detection Sensitivity of Several Semiconductor Components used in Pacemakers, Consumer Products, and Laboratory Instruments as a Function of Frequency: (a) NPD400 diode, (b) IN914 diode, (c) NPD200 diode, (d) 2N4413 transistor, emitter-base, (e) IN295 diode, (f) IN60 diode, (g) 2N3855A transistor, emitter-base, (h) 2N3855A transistor, base-collector.