NTIA-Report-81-65

Analysis of Interference from the Solar Power Satellite to General Electronics Systems

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for Communications and Information

February 1981

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ANALYSIS OF INTERFERENCE FROM THE SOLAR POWER SATELLITE TO GENERAL ELECTRONICS SYSTEMS

by

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The concept of collecting solar energy in an orbiting, geostationary, solar power satellite (SPS) and then beaming this power to earth via a focused microwave beam at 2.45 GHz has received considerable attention in recent years. This report examines some of the potential interference problems that might exist between SPS and general electronics equipment. The report specifically considers the possibility of interference to conventional consumer electronic devices such as TV receivers, AM/FM stereo receivers, electronic calculators, and FM mobile receivers. Also included are estimates of the field intensities that would be required to produce interference in three different types of integrated circuits. The report also examines the potential for interference to medical electronics devices, with specific emphasis on pacemakers and site security devices such as proximity detectors and security TV cameras.

Key words: electromagnetic compatibility; interference; satellites; solar power

1. INTRODUCTION

The concept of collecting solar power in an orbiting, geostationary, solar power satellite (SPS) and beaming this power to earth via a focused microwave beam has received considerable attention in recent years. Solar power, collected by an array of orbiting solar cells, would be converted to microwave energy, and then beamed to earth on a 2.45 GHz focused microwave beam. The obvious advantages of such a system would be that solar energy could be collected 24 hours a day and not be substantially affected by the earth's rotation or cloud cover. It has been estimated that such a system could potentially generate 5 to 10 gigawatts of usable power at a single, earth-based, receiving site (U.S. Department of Energy and National Aeronautics and Space Administration, 1978).

The electromagnetic compatibility of these systems with other electronic equipment is recognized as a potential problem. Electronic equipment well removed from the SPS receiving site can be affected by microwave fields that are generated by SPS antenna sidelobes and grating lobes. Significant amounts of energy can also be expected at frequencies other than the fundamental of 2.45 GHz. Noise radiated outside of the 2400-2500 MHz industrial, scientific, and medical band and at

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harmonics can be particularly harmful if it particularly falls in frequency bands occupied by other rf sensitive electronic systems.

This report will consider some of the electromagnetic compatibility problems associated with SPS. The study described here is limited to consumer oriented devices such as TV, AM radio, FM/FM stereo, and FM land mobile radio. The report also considers potential electromagnetic interference problems to medical electronics devices such as pacemakers.

2. DESCRIPTION OF SPS

The following material briefly describes some of the proposed characteristics of SPS. These characteristics, as shown in Table 1, are the results of studies by Boeing Aerospace Company and Rockwell International (U.S. Department of Energy and National Aeronautics and Space Administration, 1978). Basically, the orbiting portion of SPS is a 10.4 x 5.2 km array of solar cells that converts solar energy to dc. The dc is then converted to cw microwave energy and beamed to earth by a 1 km diameter phased antenna array. Proper phasing of the microwave beam at the earth's surface is maintained by a special retrodirective pilot signal that is transmitted from the earth antenna to the satellite. Rectification of microwave energy at the earth antenna (rectenna) is accomplished by illuminating panels of multiple half-wave dipoles that are connected to diodes for direct conversion of

Table 1. Characteristics of SPS

Orbiting Transmitter	
Frequency	2.45 GHz
Solar Array Size	10.4 x 5.2 km
Solar Conversion Efficiency	7%
Microwave Antenna Size	1 km Diameter
Microwave Transmission Efficiency	63%
Power Density Center of Transmit Antenna	2.2×10^3 mw/cm^2
Power Density Edge of Transmit Antenna	2.4×10^2 mw/cm^2
Estimated Number of 50 kw Microwave Power Sources	140,000
Radiating Elements	Slotted Waveguide
Antenna Subarrays (10 m x 10 m)	7220
Rectenna	
Size	10 x 13 km
Rectenna Energy Collection Efficiency	88%
RF-DC Conversion Efficiency	89%
Elements Construction	1/2 Wave Dipole-Diode Rectifier

rf energy to dc. Estimates of the power densities at the surface of the earth from a single SPS are shown in Table 2.

Table 2. Approximate Power Density of the 2.45 GHz Fields at the Surface of the Earth

	POWER DENSITY	FIELD STRENGTH
Center of Rectenna	23 mw/cm^2	294 v/m
Edge of Rectenna (5 km from center)	1.0	61.4
Exclusion Fence (5.7 km from center)	0.1	19.4
First Side Lobe (9.0 km from center)	0.08	17.3
Second Side Lobe (13.0 km from center)	0.03	10.6
Third Side Lobe (17.0 km from center)	0.01	6.1
50 km from Center	.001	1.9
200 km from Center	.0002	.87
400 km from Center	.00005	.43
First Grating Lobe 450 km from Center	.01	6.1

It should be noted that these estimates apply only to the 2.45 GHz fundamental signal. Signal levels at the surface of the earth due to out-of-band noise and harmonic radiation are significantly different. In the event multiple satellites are placed in orbit, the exposure levels outside of the main beam can be significantly altered due to overlapping of sidelobes from adjacent beams. For 60 orbiting SPS satellites, a typical average exposure level for locations well removed from an SPS rectenna site would be of the order of 10^{-4} mw/cm^2.

The characteristics of the interference fields at a frequency other than 2.45 GHz are largely unknown. Estimates of the fields due to SPS harmonic and noise emissions are described in a separate report. (The report "Analysis of interference between the solar power satellite and conventional satellite systems," by J. R. Juroshek, is being prepared for publication as an NTIA Technical Report.) This report estimates that noise in frequency bands ± 50 MHz from SPS could be as high as 10^{-15} mw/cm^2. Estimates of signal levels at 2nd, 3rd, and 4th harmonics at the earth surface range from 10^{-6} to 10^{-16} mw/cm^2. The variability in these estimates is due to an uncertainty in the gain of the SPS transmit antenna at harmonic frequencies (the gain is assumed to be between 87 dBi and 27 dBi), as well as an uncertainty in the amount of harmonics present in the SPS waveform (the power in the harmonics is assumed to be between -70 dBc and -120 dBc where dBc denotes dB relative to the power in the carrier). The estimates of harmonic level of 10^{-6} mw/cm^2 are indicative of a highly focused SPS transmitting antenna at harmonics with antenna gain at the harmonics comparable to the gain at the fundamental. The likelihood of having a highly focused SPS transmitting antenna at harmonics is not known at the present time. If the gain of the SPS transmitting antenna at harmonics is comparable to the gain at the fundamental, then the beamwidths at harmonics and fundamental can also be expected to be comparable. Thus the areas on the surface of the earth illuminated with 10^{-6} mw/cm^2 harmonic levels can also be expected to be highly localized. However, there is no guarantee that these locations could be predicted a priori or that they would remain stationary. Estimates of 10^{-16} mw/cm^2, on the other hand, are indicative of a defocused transmitting antenna at SPS harmonics, and if such conditions exist, these signal levels could be expected over a significantly large portion of the earth surface.

3. INTERFERENCE TO GENERAL ELECTRONIC EQUIPMENT

The behavior of general electronic equipment such as TV, FM radio, and electronic computers in high-level microwave fields is not entirely understood at the present time. While it is known that these systems can be affected by microwave fields of the magnitude projected for SPS, the ability to predict these interactions has not been developed. Experimental data is primarily limited to laboratory tests conducted by a few experimenters. The purpose of the following discussion is not to precisely predict the SPS interference thresholds, but rather to gain some coarse estimates of the levels of microwave fields that can cause interference. This section of the report will also describe some of the interference mechanisms that are active in these instances.

The mechanisms that are involved when a microwave signal interferes with electronic devices are varied and complex. With TV, for example, a 2.45 GHz interfering signal would be many megahertz higher in frequency than the normal TV operating frequencies. Laboratory tests of TV's in gigahertz microwave fields have shown that the primary interference mechanism is due to the leakage of signals directly into the chassis. Interference coupled through the antenna system is secondary. Leakage signals, once they are within the chassis, produce interference by coupling into rf sensitive circuits such as mixers, IF amplifiers, and detectors. A priori prediction of interference of this nature is all but impossible given the current state of electromagnetic compatibility analysis.

One of the more comprehensive studies of consumer and industrial electronic equipment in high level microwave fields is the result of a series of measurements by the Engineering Experiment Station of the Georgia Institute of Technology in Atlanta, Georgia (individual references are supplied later in the report). This series of tests provides a valuable insight into what might be expected with SPS even though the tests were conducted at frequencies other than 2.45 GHz, and in a pulsed interference environment. The following material will summarize some of these results.

The tests at Georgia Institute of Technology were designed to investigate the electromagnetic compatibility of the SAFEGUARD Ballistic Missile Defense System and consumer/industrial electronic equipments and systems operating within the site environment. Interference thresholds of a variety of devices were measured at interfering frequencies of 420 to 450 MHz and 3.1 to 3.5 GHz. Although it is primarily the 3.1 to 3.5 GHz tests that are of interest in this report, the lower frequency tests will also occasionally be discussed to give the reader a feeling for the effects of frequency. The test results described in the remainder of this section of the report were measured with an interference pulse width of 120 μsec and a repetition rate of 400 pps. Although it is difficult to project results from a pulsed interference environment to the continuous case, the interference thresholds for continuous interference are not expected to be vastly different in view of the active interference mechanisms. Threshold values quoted in the following are all peak signal levels and denote the signal level where adverse reaction was first observed.

It is important, throughout the following discussion, to realize that two distinctive interference mechanisms were observed during the tests. The first mechanism is called high-power interference, since it typically occurs at interference levels above 10^{-3} mw/cm^2 and is due to leakage of signals into the device being interfered with. High-power interference is usually frequency insensitive in that a change in frequency of the order of 100 MHz in either the interferer or victim does not produce any significant difference in interference characteristics. This phenomena is due, at least in part, to the fact that the amount of power coupled through apertures, cables, and wires is not significantly different over a frequency range such as the one from 3.1 to 3.5 GHz.

In contrast, the second mechanism, which is designated low-power interference, typically occurs at interference levels below 10^{-3} mw/cm^2 and is due to spurious or harmonic interactions between interferer and victim. A typical example of this case is a conventional TV receiver, which has a spurious relationship between certain UHF channels and the SPS frequency assignment. This type of interference is highly frequency dependent in that a frequency difference of a few megahertz can significantly affect the interference. With television, a change in frequency of only 6 MHz in either the victim or interferer can produce large changes in interference characteristics. Examples of both of these interference mechanisms can be seen in the following discussion.

Television: The sample of home television receivers that was tested by Georgia Institute of Technology contained 45 tube and solid state, home type, television sets (Donaldson and Jenkins, 1974a). These sets were subjected to the 420 to 450 MHz and 3.1 to 3.5 GHz interference field for a variety of test conditions such as different channel tuning, control setting, and desired signal level. Orientation of the TV set relative to the interference field was a particularly important parameter since rf leakage is dependent on alignment of chassis openings and wires within the interference field. Values reported in the following are the worst case interference thresholds that were measured during the most susceptible combinations of control settings and set orientation. The range of values denotes the variability over the different sets. Threshold values observed are:

3.1 to 3.5 GHz	mw/cm^2
tests where the interference frequency is not a spurious response of the television frequency	max 2 avg 3×10^{-1} min 3×10^{-3},
tests where the interference frequency is a spurious response of the television frequency	max 2 avg 8×10^{-5} min 9×10^{-9},
420 to 450 MHz	
tests where the interference frequency is not a spurious response of the television frequency	max 6×10^{-1} avg 6×10^{-2} min 5×10^{-6},
tests where the interference frequency is a spurious response of the television frequency	max 6×10^{-2} avg 3×10^{-5} min 1×10^{-7}.

A spurious response in a single conversion receiver, such as a TV receiver, is due to the nonlinear mixing of the interferer and local oscillator signals and occurs at a frequency of

$$f_s = \frac{p\, f_{lo} \pm f_{IF}}{q} \tag{1}$$

where

f_{lo} = receiver local oscillator frequency,
f_{IF} = receiver intermediate frequency,
p = integer,
q = integer.

A computer program was written for this equation in order to find out which TV channels would be spuriously related to SPS. Values of

f_s = 2450 MHz,
$p = 1,2,\ldots 50$,
$q = 1,2,\ldots 50$,
f_{IF} = 41 to 47 MHz,

were searched in order to find out which TV channels satisfied the spurious response equation. The local oscillator frequency of a TV is dictated by set design and is 41 MHz above the upper TV band edge. For example, a television tuned to channel 4 (66 to 72 MHz) would have a local oscillator at 72 + 41 = 113 MHz. Results of the spurious response search are given in Table 3.

Table 3. Summary of TV Channels that have Spurious Responses at 2.45 GHz

TV CHANNEL	FREQUENCY	p	q	SIGN in (1)
4	66-72 MHz	43	2	+
8	180-186	11	1	-
14	470-476	38	8	-
19	500-506	18	4	-
28	554-560	4	1	+
29	560-566	8	2	+
38	614-620	37	10	+
44	650-656	14	4	+
54	710-716	13	4	-
55	716-722	16	5	+
58	734-740	47	15	+
67	788-794	47	16	-
76	842-848	22	8	+
77	848-854	11	4	-
80	866-872	8	3	+

Fortunately, many of the cases listed in Table 3 can be eliminated from consideration since the susceptibility of receivers to spurious interference decreases with increasing p and q. Spurious responses are generally not significant when p or q values are much greater than 11. Thus, the most likely TV channel to experience

AM/FM/FM-Stereo: Interference susceptibility measurements were made on 20 combination AM and FM stereo receivers (Donaldson et al., 1974b). These receivers were typical consumer units including both portable and console models. The test conditions were the same as described previously for TV. Interference thresholds that were measured at 3.1 to 3.5 GHz are:

	mw/cm^2
AM radio	max 4×10^{-1} avg 3×10^{-2} min 2×10^{-3},
FM/FM-stereo	max 6×10^{-2} avg 5×10^{-3} min 1×10^{-4}.

All of these interference thresholds are due to high power effects since the AM and FM receivers do not have any significant spurious responses at 3.1 to 3.5 GHz. The values of p and q required to produce spurious responses at these frequencies would be too large to be a significant factor in this situation. Also no significant spurious responses are anticipated at 2.45 GHz since values of $p > 20$ are required in order to satisfy the spurious response equation.

Some improvements in the susceptibility of the these receivers were obtained by improving the shielding effectiveness of the receiver cabinets, increasing the power line filtering, and by filtering and shielding the antenna input leads. These improvements were typically of the order of 2 to 17 dB.

VHF FM mobile transceiver: In these tests, a single FM mobile transceiver unit and two handheld portables were subjected to the interfering microwave fields (Jenkins et al., 1973a). These sets are solid state and are typical of the 164 MHz communication equipment used in commercial, VHF land mobile radio. Interference thresholds observed during the tests are:

	mw/cm^2
Transceiver in receive mode	6×10^{-1}
Handheld units in receive mode	1×10^{-2}

These thresholds are also all high power thresholds. The receivers do not have significant spurious response characteristics at 3.1 to 3.5 GHz.

Electronic calculator: The susceptibility of a single programmable calculator was also tested at Georgia Institute of Technology (Jenkins et al., 1973b). The unit tested was a self-contained calculator that could be programmed from a keyboard or cassette magnetic tape. Alpha numeric output from the calculator was through an external electronic printer which was also included in the tests. The minimum interference threshold for this device was:

Electronic calculator	1×10^{-1} mw/cm^2.

CATV distribution system: Community antenna television (CATV) systems were also tested (Jenkins et al., 1973b). For these tests, equipment typical of such an installation was tested in the 3.1 to 3.5 GHz microwave interference described previously (ibid). Although it is probably not beneficial to describe the equipment tested in any detail, a brief listing of the equipment will be given in order to give the reader a feel for the scope of the problem. The "head-end" equipment tested consisted of a rack of equipment normally used in community cable installation. This rack of equipment contained:

Channel 4 preamplifier
Channel 8 preamplifier
Channel 12 preamplifier
Preamplifier power supply
Signal processor channel 4 to 4
Signal processor channel 8 to 6
Signal processor channel 12 to 10
Band pass filters channels 4, 6, and 10
Combining networks channels 6 and 8
AGC pilot tone generator.

Also included in the tests were six different types of line amplifiers that are also normally found along a typical cable network. The range of interference thresholds that were measured during these tests is:

	mw/cm^2
CATV system	max 20 min 6.

Analysis of the tests showed that the head-end system was the part of the system most susceptible to interference.

Television camera and video tape recorder: Susceptibility tests were also conducted on a black and white television camera and a video tape recorder (ibid). The two units were conventional 525 line, consumer type of TV components. Security cameras with environmental housings are discussed later in this report. Interference thresholds at 3.1 to 3.5 GHz are:

	mw/cm^2
Television camera	max 9×10^{-1} min 4×10^{-2},
Video tape recorder	2×10^{-1}.

Site security devices: Six different types of site security devices were examined during the series of tests (Jenkins et al., 1973b; Donaldson and Jenkins, 1972). These devices were (1) radar intrusion detectors, (2) microwave motion detectors, (3) proximity detectors, (4) infrared detectors, (5) security television cameras, and (6) seismic/magnetic detectors. Two devices from different manufacturers were tested in each category. The security television cameras received additional testing to determine if there were any significant differences in interference susceptibility with either VIDICON, PLUMBICON, TIVICON, or EPICON tubes in the cameras. No significant differences were noted. Interference thresholds for these devices are:

	mw/cm^2
Radar intrusion detector	24 8,
Microwave motion detector	4×10^{-1} 1×10^{-1},
Proximity detector	4×10^{-1}
Security television cameras	17 10,
Infrared detector	24,
Seismic line sensor	13.

Interference thresholds reported for security TV cameras were measured with the environmental housing that normally surround these cameras.

These measurement results are summarized in Figures 1 through 3. Also shown in the figures are typical power densities that can be expected at various distances from an SPS rectenna. It should be noted that the SPS power densities are approximate as the exact values are site dependent and can be affected by other SPS rectennas in the vicinity. The power density estimate labeled multiple satellite is typical of what might be expected at relatively large distances (1000 km or greater) in a multiple satellite configuration of 60 or more SPS rectennas spread throughout the United States.

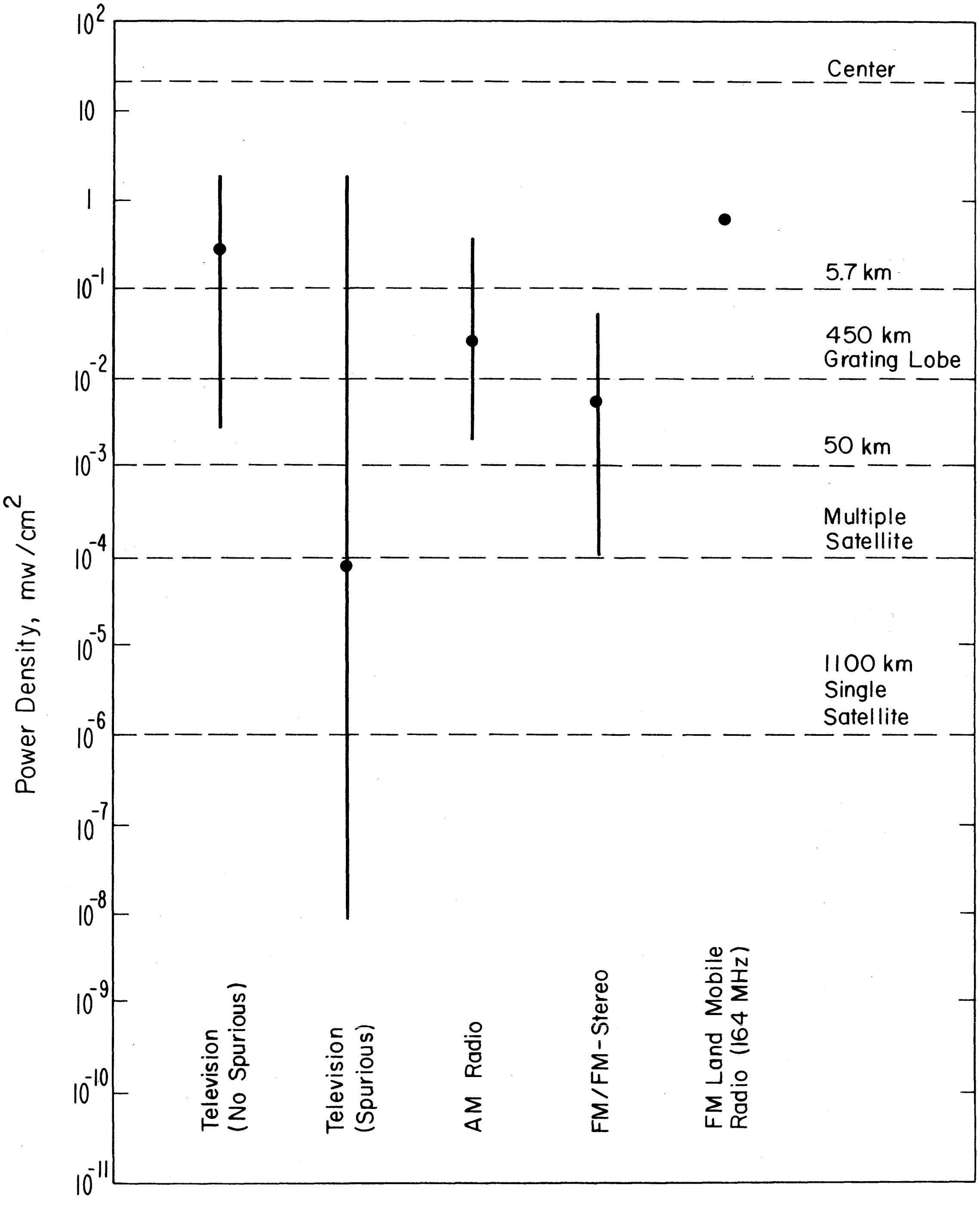

Figure 1. Summary of microwave interference thresholds as measured by Georgia Institute of Technology at 3.1 to 3.5 GHz. Signal levels expected at various distances from an SPS rectenna are shown with dashed lines.

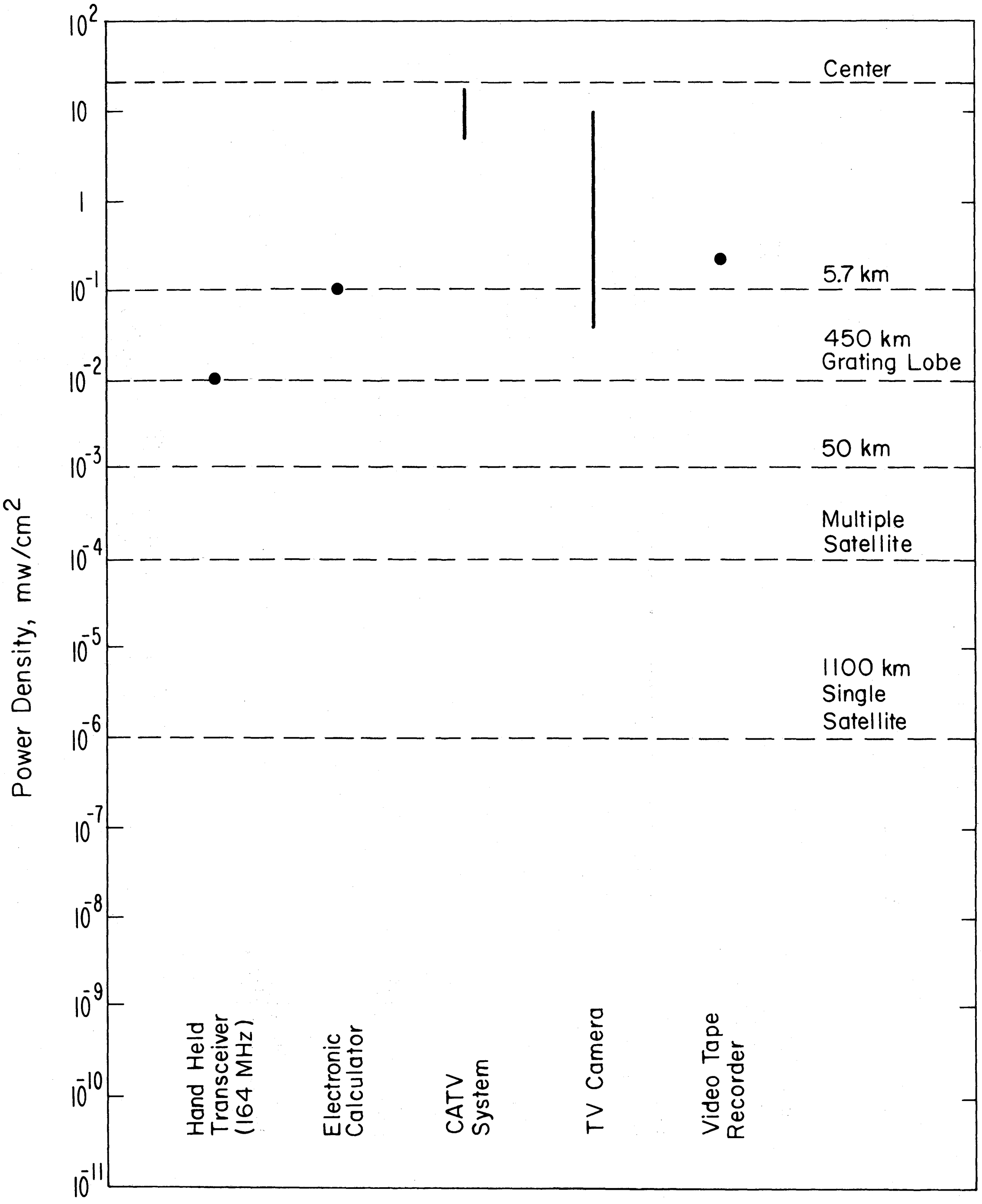

Figure 2. Summary of microwave interference thresholds as measured by Georgia Institute of Technology at 3.1 to 3.5 GHz. Signal levels expected at various distances from an SPS rectenna are shown with dashed lines.

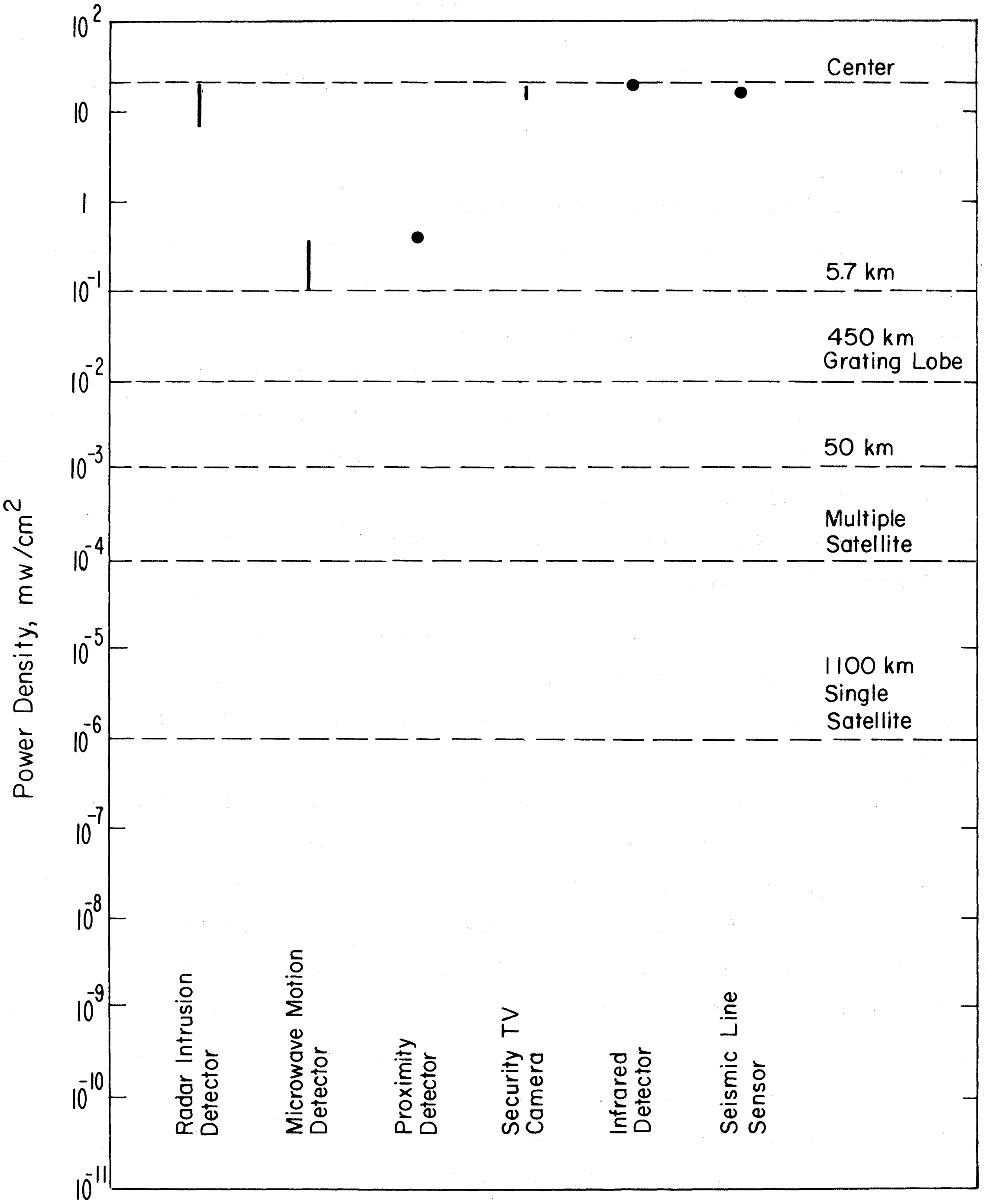

Figure 3. Summary of microwave interference thresholds as measured by Georgia Institute of Technology at 3.1 to 3.5 GHz. Signal levels expected at various distances from an SPS rectenna are shown with dashed lines.

4. MEDICAL ELECTRONICS EQUIPMENT

This section of the report briefly discusses some published work on the effects of electromagnetic interference on medical electronic devices and examines the possibility that solar power satellites could interfere adversely with the devices. The term "Medical Electronic Device" as used here implies individual cardiac pacemakers and those primarily health-oriented electrical devices (diagnostic and therapeutic) found in hospitals, clinics, physicians' offices, and in emergency vehicles.

Taken as a group, there are in excess of 5000 medical electronic devices available today (Jenkins and Woody, 1978). Because of this great number, it is impractical to study them individually. It is best to broadly group them, establish priorities for study, and identify some relevant trends.

To assess the possibility of adverse SPS electromagnetic interference with medical electronic devices, an exhaustive literature search was conducted and many people were contacted for information and assistance. Those contacted were engineers or others involved in the maintenance, manufacture, or sale of medical electronic devices; researchers who test them; or government officials directly concerned with establishing EMC standards.

4.1 Cardiac Pacemakers and EMI

It is apparent, after discussions with workers in the medical electronics industry and a survey of pertinent literature, that cardiac pacemakers are prime subjects for a study of compatibility with the SPS power beam. This stems from their immediate importance to cardiac patients, the large numbers now in use, and the fact that many interference related failures have been observed.

Four basic types of pacemakers are in use today. Probably the simplest and least likely to be affected by interference is the asynchronous or fixed rate pacemaker, as shown in Figure 4(a). This unit stimulates the heart at a fixed rate that is usually around 70 beats per minute. The second type is the p-wave synchronous as shown in Figure 4(b). These units sense the electrical activity in the atrium and provide a stimulation pulse to the ventricle after a delay of approximately 120 milliseconds. The third type is the R-wave synchronous as shown in Figure 4(c). A unit of this type is essentially the same as a p-wave synchronous except it senses and stimulates the ventricle without any time delay between sense and stimulation. The fourth type which is also described by Figure 4(c) is the demand or R-wave inhibited pacemaker. This unit also senses the ventricle activity, but unlike the others remains inactive until the rate falls below a predetermined

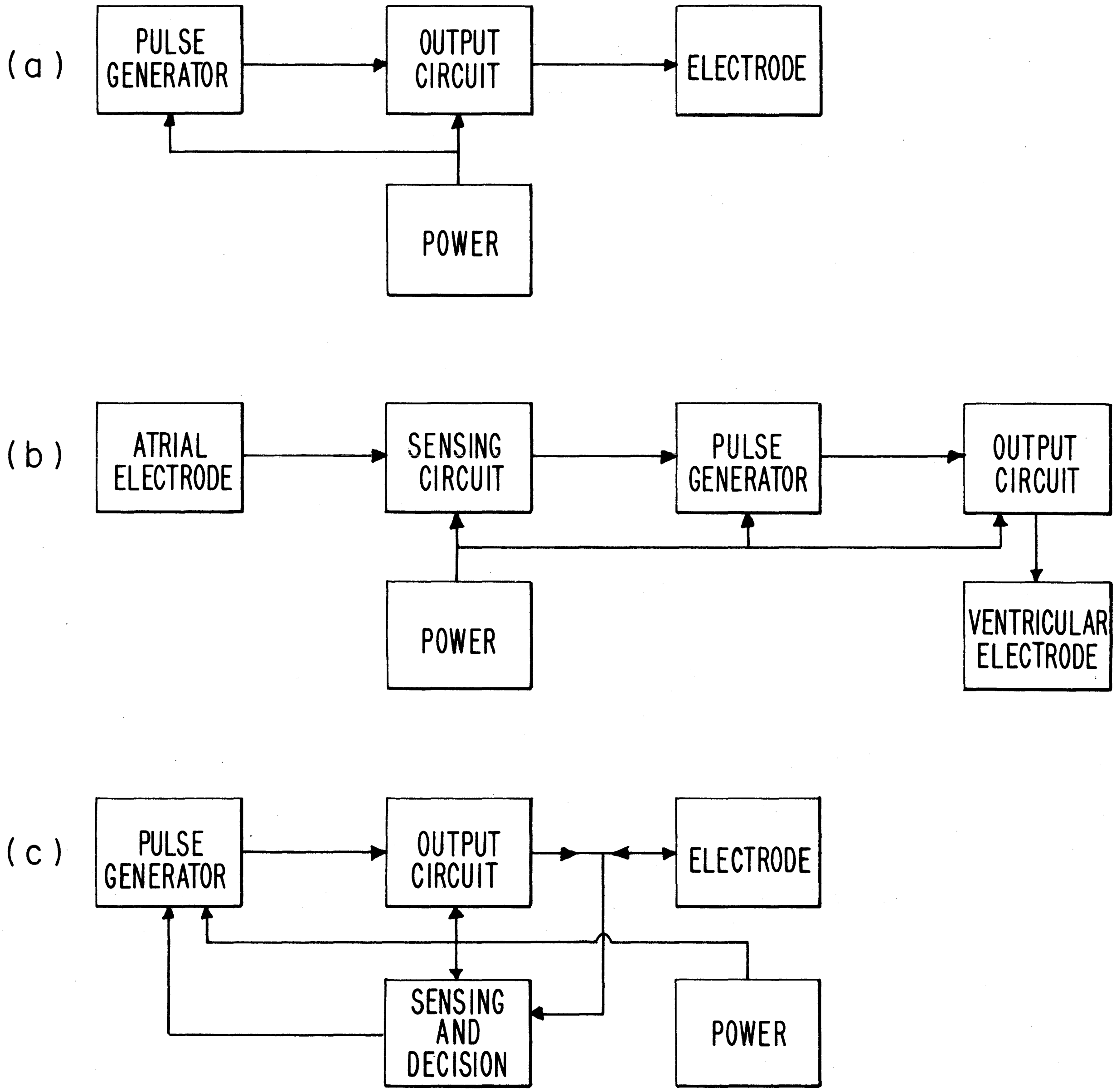

Figure 4. General types of cardiac pacemakers.

value. It has been estimated that 80 percent of the implanted pacemakers are of this type. The units that sense electrical activity are generally more susceptible to interference.

Interference related failures (failure to pulse within design specifications) in demand pacemakers have been attributed to such diverse sources as radar, small electrical appliances, lightning strokes, microwave ovens, and motor vehicles. To identify potential hazards for pacemaker users, rf sources which cause failures should be quantified as to frequency, field intensity, and modulation. Fortunately, many pacemakers have been laboratory tested, and it is now possible to identify some important trends in the thresholds of failure of pacemakers in terms of frequency, field intensity, and modulation. These trends will aid in evaluating the SPS power beam as a potential pacemaker hazard.

Table 4 indicates the electrical test conditions employed by various workers in establishing levels of potential hazards for pacemakers. Very early work on highly specific testing has been omitted here in favor of later work which tends to identify important current trends.

4.2 The Effects of Frequency

The field intensities or thresholds at which demand pacemakers malfunction increases dramatically with frequency. For example (Figure 5), Mitchell and Hurt (1975) found that the average threshold increased from less than 50 volts/meter at 450 MHz to nearly 600 volts/meter at 3200 MHz even when the pulse rate and width of the test source were maintained constant. This observation is qualitatively supported by some earlier work (Figure 5) of Bonney et al., (1973), which shows that the potentially hazardous field intensity level increases from about 75 volts/meter at 915 MHz to 250 volts/meter at 2810 MHz. One of the conclusions of the study by Bonney is that "a field of 75 volts/meter appears to be acceptable as a nominally safe figure for all units tested at each of the four frequencies and for all modes." This conclusion is particularly applicable to SPS since one of the four frequencies tested was 2.45 GHz. The tests at 2.45 GHz, however, were conducted with a 120 Hz half-wave rectified modulated waveform.

The only evidence that was found indicating a potential for pacemaker failures in microwave fields below 75 volts/meter is in a study by Georgia Institute of Technology which identifies failures in fields as low as 40 volts/meter (Jenkins and Denny, 1976). These tests were conducted in a 3.0 GHz, pulsed interference field using 110 pulses per second and 120 microsecond pulse width. Even then, only 10 percent of the sample was affected at the 75 volt/meter level, with 50 percent of

Table 4. Pacemaker EMC Test Summary

Frequency (MHz)	Reference
450	1,2
950	2
1600	1
2450	1
2810	2
3000	3
3050	2
Pulse Repetition Frequency (PPS)	
2	3
10	3
20	3
120	2
300	2
Pulse Width (m sec)	
0.01	1
0.02	1
0.05	2
0.50	1
1.0	1
1.5	2
2.0	1
5.0	1,2
7.0	2
10.0	1
20.0	1
Modulation	
CW	2
120 Hz Sine Wave	2,1
120 Hz Square Wave	2
Test Environment	
Air	3
Implanted	2,3
Simulated	1,3
Simulated Implant	1,3

References

(1) Mitchell and Hurt (1975)
(2) Bonney, et al. (1973)
(3) Denny, et al. (1977)

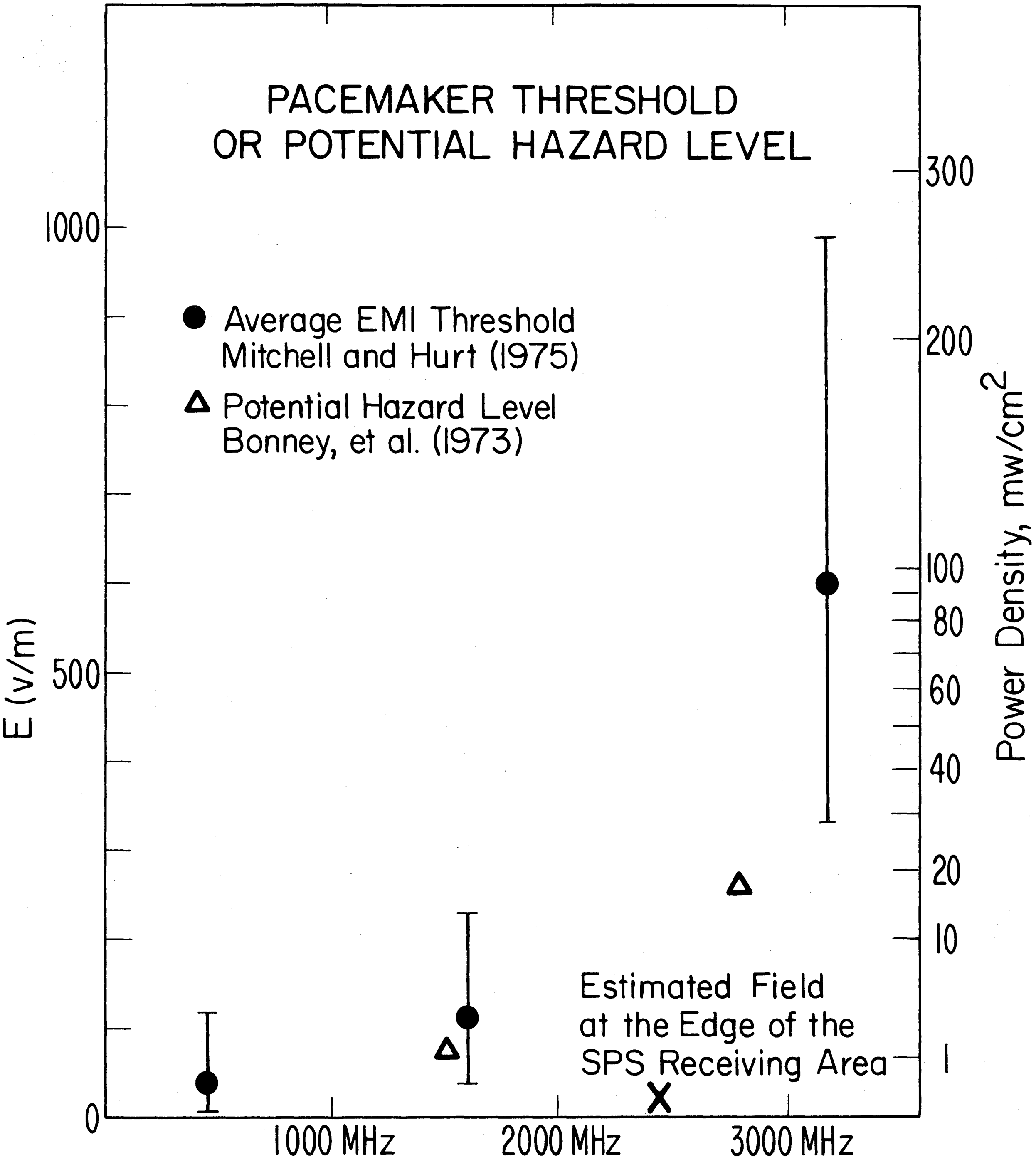

Figure 5. Pacemaker threshold of potential hazard level as a function of frequency.

the sample being able to withstand fields greater than 200 volts/meter. Since the SPS power beam outside of the receiving area is projected to be 19 volts/meter or less (0.1 mw/cm^2), pacemakers are not likely to fail based on the results of these particular tests.

4.3 The Effects of Pulse Width and Repetition Rate

Pacemakers are more likely to fail in low intensity pulsed rf fields if the pulses are wide (at least to a point) and at lower pulse repetition frequencies (PRF). Data taken by Mitchell and Hurt (1975) indicate that the average failure threshold decreases from 117 v/m at a pulse width at 10 μsec, to 33.8 v/m (1 m sec) and to 18.6 v/m (20 m sec) when the PRF and frequency were constant. Denny et al., (1977) found that failures are more likely to occur if the rf source is pulsed at a rate of 10 pps or less. Some demand pacemakers, by design, revert to an asynchronous mode of pulsing if they are subjected to an intense rf source pulsed at a high rate.

These observations regarding the effects of pulse width and pulse repetition frequency, though not directly applicable to the problem of possible interference from the cw SPS power beam, could be important when considering the effects of communication signals used in control of the SPS beam.

4.4 Effects of Modulation

It is a prevalent opinion among workers in the pacemaker industry and with researchers, that continuous wave emitters are very unlikely to produce EMI related failures, and little testing with cw sources has been done. Bonney et al., (1973), after testing, considered a continuous wave source at 915 MHz to be hazardous if the field intensity was 75 v/m or more.

4.5 Historical Trends in Pacemakers

The existence of EM hazards to pacemakers has been well known for several years. As a result, researchers have identified hazardous EM sources and manufacturers have worked to harden the devices against those sources of EMI that users might encounter.

The success of these manufacturers' efforts is reflected in a study by Denny et al., (1977). This five year study, involving hundreds of pacemakers showed that the average resistance to interference of pacemakers to a pulsed 450 MHz source increased from 35 v/m in 1973 to 144 v/m in 1976.

4.6 EMC Standards for Medical Electronic Devices

The general class of medical electronic devices contains many sensitive instruments likely to be susceptible to EMI. The Electrocardiograph, for example, is vulnerable to 60 Hz line interference (Huhta and Webster, 1973). Medical devices are used most often in clinics and hospitals in large metropolitan areas. The electromagnetic environment in these hospitals is apt to be polluted by a wide variety of transmitters, appliances, and even by medical electronic devices.

The Bureau of Medical Devices of the Food and Drug Administration has supported a study of electronic devices and the ambient electromagnetic environment in several major hospitals. The results of this study establish guidelines for acceptable emissions from medical devices and safe susceptibility thresholds. These guidelines were published in the report, "EMC Standard for Medical Devices," MDC-E 1385, (1976). The guideline for minimum radiated electric field susceptibility limit from the report is shown here as Figure 6. It covers frequencies from 100 kHz to 1 GHz. It was deemed unnecessary in the report to consider higher frequencies since it is generally known that devices which are safe from hazardous EMI at one frequency will be safe at a higher frequency. The report further recommends specific device performance standards at the industrial, scientific, and medical (ISM) frequencies of 2.45, 5.8 and 24.125 GHz.

It is clear, from Figure 6, that the existing guideline for electric field susceptibility at 1 GHz would permit the manufacture of devices with thresholds (∿7 v/m) that are lower than the field intensities expected near the SPS receiving area (19 v/m). The impact of this recommendation at 2.45 GHz is not clear since threshold levels of most devices increase with frequency. The threshold of devices at 2.45 GHz could conceivably be well above 19 v/m, but there is little data available to establish this.

One manufacturer of medical electronic devices claims their equipment is safe in field intensities of 1 v/m (private communication) while others, without providing supporting data, believe their equipment is safe in field intensities of hundreds of v/m. Most of those people contacted for information about medical device EMI susceptibility believed that by 1990 or so improved manufacturing techniques can produce devices that would be safe in almost any realistic EM environment. A few believed that specific instrument types (diagnostic, for example) should be tested for susceptibility over a wide frequency range.

4.7 Medical Electronics Summary

Demand pacemakers are known to be susceptible to EMI. Their susceptibility thresholds, however, are rapidly increasing because of design improvements, and at ultra high frequencies the average threshold can be in the hundreds of volts per meter range. For these reasons, it seems unlikely that pacemakers would fail in the SPS-cw power beam which is projected to be 19 v/m or less outside the receiving areas.

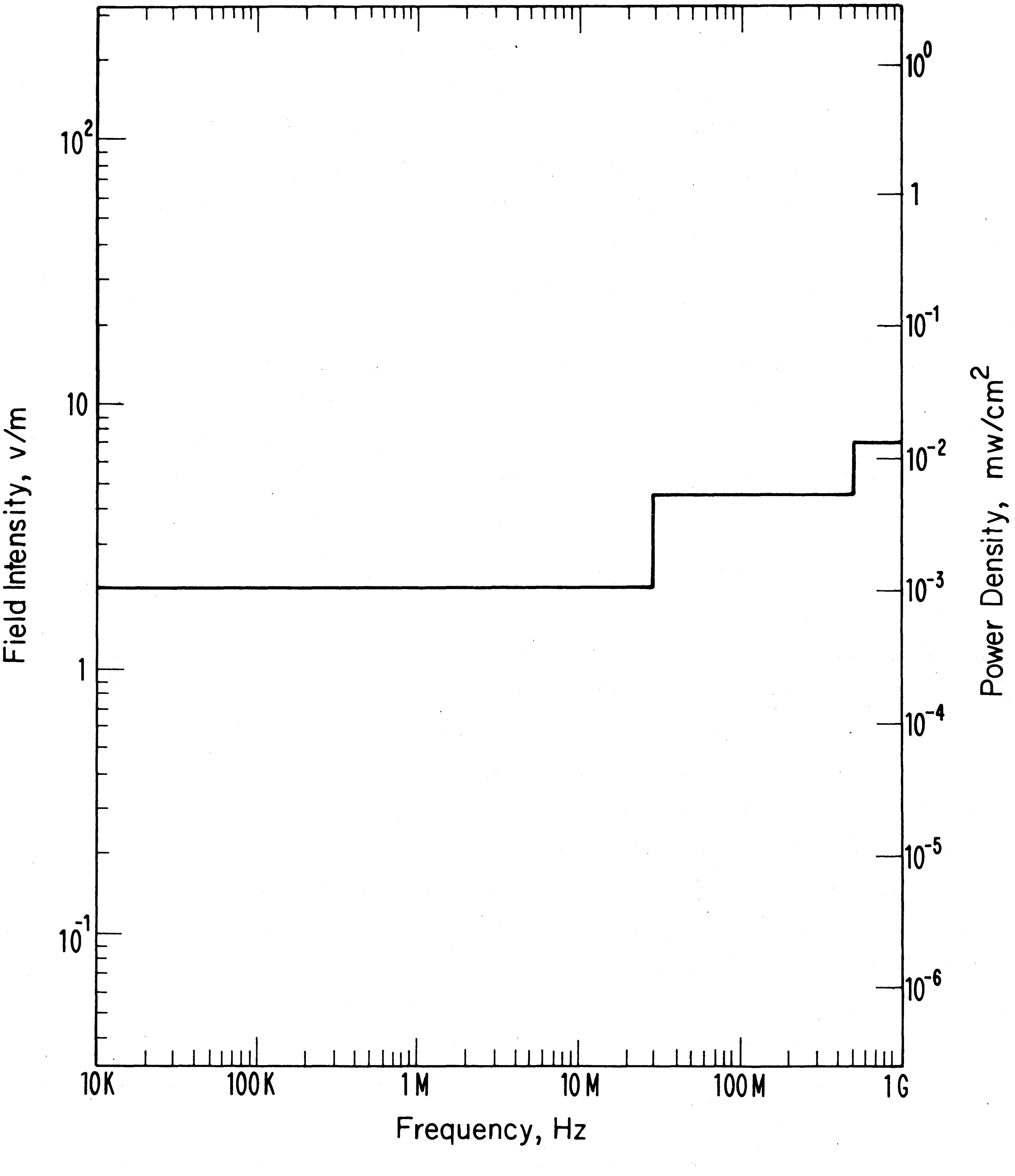

Figure 6. Recommendations for minimum electric field susceptibility limits for medical electronic devices.

It is commonly, although not universally, believed that all medical devices will be hardened to the threat of EMI from UHF sources in a few years. This belief stems in part from the fact that the electromagnetic interference susceptibility of electronic devices usually decreases with increasing source frequency. There is little specific data to support this for devices other than pacemakers, however.

The existing guideline for minimum radiated electric field susceptibility limit for medical devices recommends a susceptibility threshold of not less than 7 v/m at 1 GHz. This value is applicable to sources modulated in accordance with report MDC-E 1385, but does not directly relate to the cw SPS power beam at 2.45 GHz. Devices, then, which meet the existing guideline, could conceivably fail in the region immediately outside the SPS receiving areas.

Consideration should be given to the questions of the compatibility of the general class of medical electronic devices with the SPS power beam. An existing government agency, the Bureau of Medical Devices of the Food and Drug Administration, has responsibility for medical device standards. To avoid duplication of effort or conflicts, any future work regarding compatibility should be coordinated with this agency.

5. SPS INTERFERENCE TO INTEGRATED CIRCUITS

Although the possibility of interference from microwave energy to integrated circuits has been recognized for some time, actual measurements of the effects are relatively sparse (Roe, 1975). Fortunately, a few measurements do exist that enable one to calculate the potential for interference to a few types of integrated circuits. The following will discuss the potential interference problems to three different types of integrated circuits.

Interaction between microwave energy and integrated circuits can occur in various ways. Catastrophic failures have been produced in integrated circuits when the power coupled into the leads of the devices is of the order of 1 to 100 watts for 500 microseconds. These failures are typically due to bonding wire melting, metallization failure, and junction shorting. Nondestructive interaction, however, typically occurs at power levels that are orders of magnitude less than those necessary for catastrophic failure. This nondestructive interaction or interference is the subject of interest here.

The predominate interference mechanism in integrated circuits is believed to be rectification of microwave energy by the various pn junctions found on all devices. This rectified current can inhibit or induce state changes or change the quiescent operating point of the device. Changes of the quiescent operating point can be particularly harmful in noise environments since they reduce the noise immunity of the device.

Basic rectification theory states that the rectified current in a pn junction is

$$I_r = \eta\, P_{rf}\ \text{(ABSORBED)} \tag{2}$$

where η is the rectification efficiency and P_{rf} is the rf power absorbed into the junction. The theory also tells us that in the microwave frequency range

$$\eta = \frac{\eta_o}{f^2} \tag{3}$$

where η_o is a constant dependent on junction construction and bias conditions, while f is the frequency of the rf energy. In other words, junction efficiency is inversely proportional to frequency squared.

The theory is useful since it allows one to extrapolate measurements that are made at frequencies other than the 2.45 GHz SPS frequency. Assume, for example, that a measurement is made at frequency f_1, where the device absorbs a power P_{rf1}, and produces a rectification current I_{R1}. Further assume that this is the level of current where interference effects are first noted (interference threshold). Thus, one can write that

$$I_{R1} = \frac{\eta_o}{f_1^2}\, P_{rf1}. \tag{4}$$

If the threshold measurement were made at a different frequency, f_2, one should expect that the same interference threshold would be reached when

$$I_{R1} = \frac{\eta_o}{f_2^2}\, P_{rf2} \tag{5}$$

or

$$\frac{P_{rf1}}{P_{rf2}} = \left(\frac{f_1}{f_2}\right)^2 . \tag{6}$$

While these formulas are approximate, they do show that interference threshold can be expected to vary as the square of frequency.

Measurements were made at 0.91 and 3.0 GHz on three types of integrated circuits, a 7500 bipolar NAND gate, a 4011 CMOS NAND gate, and a 5474 flip flop (Roe, 1975). A summary of these measurements is given in Table 5, where the interference thresholds are defined as that point where deviation in the device normal or quiescent operating conditions are first noted. It should also be noted that these measurements were made on a number of devices of the same type and the values shown are representative of those devices that were most susceptible to interference.

Table 5. Summary of Interference Threshold Measurements on Integrated Circuits

Device	Measured Interference Threshold	Measurement Frequency	Estimated Interference Threshold 2.45 GHz
7400 NAND GATE	2 mw (3.0 dBm)	0.91 GHz	14.5 mw (11.5 dBm)
4011 NAND GATE	10 mw (10.0 dBm)	3.0 GHz	6.7 mw (8.3 dBm)
5474 FLIP FLOP	20 mw (23.0 dBm)	3.0 GHz	13.3 mw (11.2 dBm)

Before interference estimates can be made, the coupling mechanism between the SPS microwave beam and integrated circuits must be understood. This subject is effectively treated in a report by Ditton (1975) which examines the coupling of microwave energy through shielded and unshielded wires connected to various ports of an integrated circuit, including power supply connections.

The maximum power coupled into an integrated circuit by a connecting wire is given by

$$P_{rf}\ (\mathrm{MAX}) = P_d \cdot a_e \cdot s_e$$

where

$P_{rf}(\mathrm{MAX})$ = maximum coupled power in mw,

P_d = incident field density in mw/cm^2,

a_e = effective aperature of the connecting wire in cm^2,

and

s_e = shielding effectiveness of any shielding around the wire.

In many instances, the connecting wire is more than a 1/2 wavelength long (a wavelength is 12.2 cm at 2.45 GHz), which means that it tends to act like a long wire antenna. Thus, the wire typically has a multilobe radiation pattern with the number of lobes increasing with increasing wire length. The complexity of this lobe structure is compounded by the fact that the wire is terminated in a mismatched (and often variable) impedance.

Experiments have shown that one can expect to see a distribution of received power depending on orientation of wire of

$$P_{rf}(avg) = \frac{1}{10} P_{rf}(max) \quad (7)$$

where the average received power is $P_{rf}(avg)$ (Ditton, 1975). These experiments have also shown that the effective aperture, a_e, of a wire whose length is greater than $\lambda/2$ is approximately equal to the aperture of a 1/2 wave dipole or

$$a_e = 0.13 \lambda^2, \quad (8)$$

where λ is the wavelength of the incident field. Note that the effective aperture is not a function of wire length, but only the wavelength of the incident field. Thus, the absorbed power does not increase with increasing wire length.

A summary of the values of $P_{rf}(max)$ and $P_{rf}(min)$ that can be expected at various locations around the SPS rectenna is shown in Table 6. Based on experimental data, this table uses a shielding effectiveness of 1.0 (0 dB) for unshielded wire and 10^{-4} (-40 dB) for shielded wire.

Table 6. Estimates of the Maximum Power $P_{rf}(max)$ and Average Power $P_{rf}(avg)$ that can be Coupled into an Integrated Circuit through a Length of Wire Greater than $\lambda/2$

Location	Power Density P_d	$P_{rf}(max)$ Unshielded	$P_{rf}(max)$ Shielded	$P_{rf}(avg)$ Unshielded	$P_{rf}(avg)$ Shielded
Center of Rectenna	23.0 mw/cm^2	26.5 dBm	-13.5 dBm	16.5	-23.5
Edge Rectenna 5 km from Center	1	12.8	-27.2	2.8	-37.2
Exclusion Fence 5.7 km from Center	0.10	2.8	-37.2	-7.2	-47.2
First Side-lobe 9.0 km from Center	0.08	1.9	-38.1	-8.1	-48.1
Second Side-lobe 13.0 km from Center	0.03	-2.4	-42.4	-12.4	-52.4
Third Side-lobe 17.0 km from Center	0.01	-7.1	-47.1	-17.1	-57.4

The difference between $P_{rf}(max)$ in Table 6 and the threshold values shown in Table 5 is given in Table 7. Positive numbers mean that the coupled power exceeds threshold and interference can be expected. Similarily, the difference between $P_{rf}(avg)$ and the threshold values is given in Table 8.

Table 7. Difference between P_{rf}(max) and Interference Threshold Values Shown in Table 5

LOCATION	7400 NAND GATE		4011 NAND GATE		5424 FLIP FLOP	
	UNSHIELDED	SHIELDED	UNSHIELDED	SHIELDED	UNSHIELDED	SHIELDED
Center of Rectenna	+15.0	-25.0	18.2 dB	-21.7 dB	15.3 dB	-24.7 dB
Edge of Rectenna 5 km from Center	+1.3	-38.7	4.5	-35.5	1.6	-38.4
Exclusion Fence 5.7 km from Center	-8.7	-48.7	-5.4	-45.4	-8.4	-48.4
First Side-lobe 9.0 km from Center	-9.6	-79.6	-6.4	-46.4	-9.3	-49.3
Second Side-lobe 13.0 km from Center	-13.9	-53.9	-10.7	-50.7	-13.6	-53.6
Third Side-lobe 17.0 km from Center	-18.6	-58.6	-15.4	-55.4	-18.3	-58.3

Table 8. Difference between P_{rf}(avg) and Interference Threshold Values Shown in Table 5

LOCATION	7400 NAND GATE		4011 NAND GATE		5424 FLIP FLOP	
	UNSHIELDED	SHIELDED	UNSHIELDED	SHIELDED	UNSHIELDED	SHIELDED
Center of Rectenna	5.0	- 35.0	+8.2	-31.7	5.3	-34.7
Edge of Rectenna 5 km from Center	-8.7	-48.7	+5.5	-45.5	-8.4	-48.4
Exclusion Fence 5.7 km from Center	-18.7	-58.7	-15.4	-55.4	-18.4	-58.4
First Side-lobe 9.0 km from Center	-19.6	-59.6	-16.4	-56.4	-19.3	-59.3
Second Side-lobe 13.0 km from Center	-23.9	-63.9	-20.7	-60.7	-23.6	-63.6
Third Side-lobe 17.0 km from Center	-28.6	-68.6	-25.4	-65.4	-28.3	-68.3

As shown in the summary in Table 9, interference to the 3 representative types of integrated circuits can be expected at the center of the rectenna and at field as low as 1 mw/cm^2. However, interference is not expected at locations beyond 5.7 km from the center or in field of 0.1 mw/cm^2 and weaker. Shielding with a shielding effectiveness of -40 dB should effectively eliminate interferences at all locations.

6. CONCLUSIONS

This study has briefly assessed the circumstances under which interference might be expected between the solar power satellite and general electronics equipment. The study includes devices such as TV receivers, AM/FM receivers, electronic calculators, handheld transceivers, and cable TV components. Also examined were medical electronic devices with specific emphasis on pacemakers and site security devices such as proximity detectors and TV security cameras.

Generally, the study has found very little experimental data in this subject area. Many of the following conclusions are based on interference studies by the Georgia Institute of Technology at frequencies of 420 to 450 MHz and 3.1 to 3.5 GHz. Even though these frequencies are different than the 2.45 GHz proposed for SPS, they do provide a valuable insight into the interference thresholds that might be expected. Interference threshold, as defined here, is the field intensities where some undesirable interaction is first noted.

On the average, most of the equipment had interference thresholds in microwave fields of 10^{-2} mw/cm^2 or greater. Exceptions to this were television receivers, under specific circumstances, and FM/FM stereo receivers. The circumstances that caused television receivers to have significantly lower interference thresholds were that, in some instances, the interference frequency was a spurious response of certain TV frequencies. The average interference threshold during those instances was 8×10^{-5} mw/cm^2. In contrast, the average interference threshold for those tests when there was no spurious relationship was 3×10^{-1} mw/cm^2. A mathematical analysis of the problem showed that the television channels that are most likely to be spuriously related to the SPS frequency is VHF channel 8, and UHF channels 28 and 29.

Average interference thresholds for FM/FM stereo receivers were 5×10^{-3} mw/cm^2. While the cause for this slightly lower threshold is not known, there was no reason to suspect that these lower thresholds were caused by spurious responses. Some improvements in interference susceptibility in receivers could be obtained by improving the shielding effectiveness of the receiver cabinets, increasing the power line filtering, and by filtering and shielding the signal input leads. These improvements were typically of the order of 2 to 17 dB.

Table 9. Summary of Susceptibility of 3 Types of Unshielded Integrated Circuits to 2.45 GHz SPS Interference

LOCATION	POWER DENSITY Pd	7400 NAND GATE	4011 NAND GATE	5474 FLIP FLOP
Center of Rectenna	23 mw/cm^2	Exceeds threshold, max and avg orientation	Exceeds threshold, max and avg orientation	Exceeds threshold, max and avg orientation
Edge of Rectenna 5 km from Center	1	Exceeds threshold, max orientation only	Exceeds threshold, max and avg orientation	Exceeds threshold, max orientation only
Exclusion Fence 5.7 km from center	0.10	Below threshold	Below threshold	Below threshold
First Sidelobe 9.0 km from center	0.08	Below threshold	Below threshold	Below threshold
Second Sidelobe 13.0 km from center	0.03	Below threshold	Below threshold	Below threshold
Third Sidelobe 17.0 km from center	0.01	Below threshold	Below threshold	Below threshold

Significantly more information is available on the susceptibility of pacemakers at microwave frequencies. Generally, experiments have shown that pacemakers are safe in fields of 75 volts/meter (1.5 mw/cm^2) or less. The only indication of failures in fields below 75 volts/meter is from a study by Georgia Institute of Technology where failures in fields as low as 40 volts/meter (0.5 mw/cm^2) were observed at 3.1 to 3.5 GHz in 10% of a population sample. One must note, however, that the bulk of the experimental data to date on the susceptibility of pacemakers has been collected in either pulsed or amplitude modulated microwave fields. In any event, there is a growing body of evidence that suggests that pacemakers are not likely to be affected by the much lower microwave fields found outside of the immediate rectenna area.

Studies of the performance of other types of medical electronic devices in interference are generally inconclusive. Current guidelines are that medical electronic devices should be able to operate in fields of 7 volts/meter (0.01 mw/cm^2) at frequencies of 1.0 GHz or higher without undue interference. Laboratory confirmation of whether or not existing equipments meet these guidelines is not available.

The study of the performance of three integrated circuits in microwave fields provided a valuable insight into the mechanisms that produce interference in these types of devices. Basically the interaction of integrated circuits and microwave fields in the GHz region is due to the rectification of microwave energy in the numerous pn junctions that are found on these devices. These rectification currents change the normal quiescent operating points of the junctions which reduces noise immunity or causes a state change. Estimates were made as to the 2.45 GHz field intensities that would produce interference in 7400 bipolar NAND gates, 4011 CMOS NAND gates, and 5474 flip flops. These estimates are based on data taken at frequencies of 910 MHz and 3.0 GHz. The conclusions are that the devices would generally not be affected by SPS fields of 0.1 mw/cm^2 or below. The estimates showed that all these devices potentially could be affected in SPS field intensities of 1.0 mw/cm^2. It is interesting to compare the integrated circuit interference estimates with actual tests of an electronic calculator that uses similar integrated circuits. The electronic calculator had a measured interference threshold at 3.1 to 3.5 GHz of 0.1 mw/cm^2, which is identical to the projections for the individual circuits.

All of the site security devices examined had an interference threshold of 10^{-1} mw/cm^2 or greater. This included radar intrusion detectors, microwave motion detectors, proximity detectors, security detectors, infrared detectors, and seismic detectors. None of these devices should be affected by SPS signal levels unless they are within the exclusion fence at a rectenna site.

7. ACKNOWLEDGEMENT

The authors wish to acknowledge the support for this investigation provided by the U.S. Department of Energy under the direction of F. A. Koomanoff, Chief, Environmental and Resource Assessment Programs, Solar Technology, Washington, D.C., Contract No. DE-A106-79RL10077.

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FORM **NTIA-29**
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

	1. PUBLICATION NO. NTIA Report 81-65	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Analysis of Interference Between the Solar Power Satellite and General Electronics Systems

5. Publication Date
February 1981

6. Performing Organization Code

7. AUTHOR(S)
John R. Juroshek and Francis K. Steele

8. PERFORMING ORGANIZATION NAME AND ADDRESS
National Telecommunications & Information Administration
Institute for Telecommunication Sciences
325 Broadway
Boulder, CO 80303

9. Project/Task/Work Unit No.

10. Contract/Grant No.

11. Sponsoring Organization Name and Address
U.S. Department of Energy
Washington, D.C. 20545

12. Type of Report and Period Covered

13.

14. SUPPLEMENTARY NOTES

15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The concept of collecting solar energy in an orbiting, geostationary, solar power satellite (SPS) and then beaming this power to earth via a focused microwave beam at 2.45 GHz has received considerable attention in recent years. This report examines some of the potential interference problems that might exist between SPS and general electronics equipment. The report specifically considers the possibility of interference to conventional consumer electronic devices such as TV receivers, AM/FM stereo receivers, electronic calculators, and FM mobile receivers. Also included are estimates of the field intensities that would be required to produce interference in three different types of integrated circuits. The report also examines the potential for interference to medical electronics devices, with specific emphasis on pacemakers and site security devices such as proximity detectors and security TV cameras.

16. Key Words *(Alphabetical order, separated by semicolons)*

Key words: electromagnetic compatibility; interference; satellites; solar power

17. AVAILABILITY STATEMENT

☒ UNLIMITED.

☐ FOR OFFICIAL DISTRIBUTION.

18. Security Class. *(This report)*
UNCLASSIFIED

19. Security Class. *(This page)*
UNCLASSIFIED

20. Number of pages
32

21. Price:

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981—779-148/269 Region No. 8