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COMPILATION AND ASSESSMENT OF MICROWAVE BIOEFFECTS
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FINAL REPORT
A SELECTIVE REVIEW OF THE LITERATURE ON BIOLOGICAL EFFECTS OF MICROWAVES IN RELATION TO THE SATELLITE POWER SYSTEM

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PREFACE

This report, "A Selective Review of the Literature on Biological Effects of Microwaves in Relation to the Satellite Power System," is the first of two documents prepared for the Department of Energy under a contract for Compilation and Assessment of Microwave Bioeffects. The second document, "An Outline of SPS Research Needs and Study Plan," is published separately but is developed in consequence of data and problem areas identified in the Selective Review.

An overview of the biophysical character of microwave radiation is provided in Appendix A. A glossary of biophysical terms is provided in Appendix B. The reader who is not familiar with principles of physics, engineering, and biology as these disciplines relate to biological effects of microwave radiation will profit by reading the material in the Appendices before reading the Executive Summary and the Review that follows.

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EXECUTIVE SUMMARY

A microwave Satellite Power System (SPS) is being considered by officials of the Department of Energy and of the National Aeronautics and Space Administration as a means of providing a substantial source of electrical energy. Each of several satellites would be inserted into a high, geosyncronous orbit where large vanes that contain collectors of solar energy would be exposed almost continuously to the sun's light. The light would be converted by each satellite to 2450-MHz microwaves that would be beamed to a large rectifying antenna on the earth's surface. After conversion to alternating or direct current, the energy would be fed into power lines for commercial and domestic use.

There are many potential problems that must be addressed and researched before SPS can become a functioning reality: the economic and social costs; the effects of manufacturing processes and rocket effluents on the environment; the extent to which the microwave beam interferes with radio, television and other communications; and the effects of the microwave beam on the ionosphere, to name a few. There is, in addition, the problem of researching and predicting biological effects of microwave radiation on man and on the other forms of life that comprise ecological systems in proximity to receiving antennae.

Potential biological and ecological problems are the focus of a review of the world's scientific literature on biological effects of microwave radiation. The emphasis is on recently reported data and on

the 2450-MHz continuous-wave (CW) radiation that is envisioned for SPS. Two distinct and hitherto unanswered questions are apparent:

1. Will microwave radiation at a relatively high power density ($\sim$23 mW/cm^2) near the center of each rectifying antenna produce disruption, debilitation or death of airborne species that may attempt to fly through the beam? Completely lacking are verified experimental data that would indicate whether none, some, or all of the airborne species can sustain flight through the beam--or, whether none, some, or all will learn to take evasive action.
2. Will continuous microwave radiation at relatively low power densities near the periphery of a rectifying antenna and beyond the area of exclusion produce untoward effects on resident flora and fauna, including human beings? The review of experimental and epidemiological findings revealed that thresholds of relatively short-term radiation for morbid biological effects (e.g., cataracts, heart disease, hematological effects, immunological disturbances, and genetic and developmental defects) are well above the maximal power density (1 mW/cm^2) that is tentatively projected at and beyond the area of exclusion of the receiving antenna. There is a caveat, however, to indications that CW 2450-MHz radiation at 1 mW/cm^2 is safe. No experimental study has ever been performed that even remotely approaches the 30 years or more that SPS would be operative.

The available experimental data indicate that continuous-wave 2450-MHz radiation at power densities below 1 mW/cm^2, which would occur beyond the zone of exclusion, does not result in morbid biological effects, but these data have arisen from studies that do not contain effects of ultra-long-term exposures, and do not permit evaluation of potential for ecological disruption. In addition, the data are mute with respect to consequences for airborne species that may fly over the rectenna, or for terrestrial or airborne species that may ascend or descend to the surface of the rectenna, thereby incurring radiation at power densities that could exceed 20 mW/cm^2. Only intensive experimental study can reveal whether the SPS concept safely can be implemented.

COMPILATION AND ASSESSMENT OF MICROWAVE BIOEFFECTS: A SELECTIVE REVIEW OF THE LITERATURE ON BIOLOGICAL EFFECTS IN RELATION TO THE SATELLITE POWER SYSTEM

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INTRODUCTION

One of many alternate sources of electrical energy that are being considered by the Department of Energy is a microwave-mediated Satellite Power System (SPS). Once inserted into geosynchronous orbit at an altitude of more than 40,000 kilometers, a satellite would collect then convert the sun's energy to 2450-MHz microwaves, which would be beamed to the Earth's surface, where a rectifying antenna ("rectenna") would convert the microwaves to electrical current suitable for industrial and domestic use. The expanse of each rectenna (about 10 by 13 kilometers), the power density of the continuous-wave microwave beam ($\sim$23 mW/cm^2 at center, with fall off to 1 mW/cm^2 or less at the periphery of the rectenna), and the possibility that 20 or more satellite systems will eventually be operating, creates two sets of interrelated problems for biological/ecological assessment. These are 1) the effects of microwave fields of higher intensity on airborne biota (including human beings in aircraft) that may traffic

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the area above the rectenna; and 2) the effects of virtually perpetual fields of much lower intensity on all forms of life at and beyond the rectennae's zone of exclusion. In this review, the scientific literature is examined, not only for biological effects that are pertinent to assessment of SPS, but for hiatuses of knowledge that will have to be filled before SPS can be vouched for operational safety.

GUIDELINES FOR REVIEW

More than a thousand English summaries and two-hundred original (or translated) papers on the biological effects of microwave radiation were initially reviewed with respect to potential impact of the Satellite Power System (SPS) on biological and ecological systems. The references cited in this review are far from exhaustive. The citations were selected to provide a consensus of current views concerning biological effects of microwave radiation; the aim is representation. To insure representation of views of Eastern European scientists, the recently published text by Baranski and Czerski (1976)--both Polish scientists who are familiar with the extensive Soviet literature on microwaves--was used as a point of departure for work published through the middle 1970s. Independent reports are emphasized for the period after 1974. The difficult task of distilling the data of a vast but fragmented literature was eased somewhat by the following guidelines, some of which derive from SPS design criteria:

1. The tentative specification of 2450-MHz (12.25-cm) energy led to an emphasis on works in which radiation at frequencies between 2000 and 3000 MHz was employed; however, this 1000-MHz range was often expanded for the sake of incorporating data on genetic, developmental, and other potentially adverse effects of microwave radiation.
2. The specification of continuous wave (CW) transmission obviates the need for data from many studies in which pulsed radiation was used; however, several reports that contain comparative data on CW and pulsed radiations were reviewed because they reveal an important difference: At any given averaged power density, pulsed radiation is more likely to result in effects, at least in the animal with an intact and functioning nervous system.
3. Emphasis was placed on data of more recent reports. During the past decade, marked strides have been made in the technology of measuring incident microwave fields (densitometry). Indeed, measurements of absorbed energy (dosimetry) were virtually alien to the microwave laboratory until the 1970s (*cf.* Justesen and King, 1970; Johnson and Guy, 1972; Gandhi, 1974; Guy, 1974; Phillips, et al., 1975; and Justesen, 1975b). Power-density numbers reported in the literature prior to the 1970s are frankly suspect. Further, reports of experimental studies in which power densities were measured by accurate instruments

and were validated by dosimetric techniques are quite recent, are relatively few in number, and are confined to the Western literature (*cf.*, e.g., Guy and Korbel, 1972; Phillips, et al., 1975; and Hagan, et al., 1977).

4. Lastly, emphasis has been placed on several findings of effects at low intensities of radiation, some independently confirmed, that need to be addressed in research on SPS impact.

FOCUS OF REVIEW

The review focuses on two questions:

1. What are the effects on human and infrahuman species of sustained, 2450-MHz CW radiations at the lower power densities (<1 mW/cm^2, average) that would be present at the periphery of the rectenna?
2. What are the effects of higher intensity radiations (to $\sim$23 mW/cm^2) of the sort that would be encountered on an intermittent basis by animals that entered the zone of intense radiation or by airborne species (insects, birds, and bats) that ventured into fields above the rectenna?

Either question can be approached, in principle, from the quantitative perspective of threshold, i.e., at what power density does one find reliable evidence of alteration of social behavior? of an individual's behavior? or of systemic function? Unfortunately, the determination of such a threshold would likely raise another, highly pertinent question for which there is no ready answer: How does one differentiate benign effect from hazardous effect? The question of benignity or peril goes to the heart of the issue of philosophy of standards. In the Soviet Union and in several other countries the operating principle is to invoke a maximal permissible limit (MPL) of exposure below which <u>no</u> effects are assumed to occur. The rationale is that any effect <u>might</u> be an adverse effect.

While the principle of no-effect has intuitive appeal, it runs counter to practicability. Such an MPL for electromagnetic radiations in the visible spectrum would leave the human race and most other forms of life starving in darkness. A no-effect MPL for the neighboring infrared spectrum would amount to a decree of death by freezing. But why not a no-effect MPL for the microwaves, upon which the flora and fauna presumably do not depend for nurture and warmth? The answer lies in a well-confirmed datum, which is the limiting case for a biological effect: A single 10-μsec pulse of microwave energy that is absorbed in the head at a dose of no more than 10 μJ/g can result in an acoustic response, the phenomenon known as radio-frequency (RF) hearing, or the Frey Effect (<u>cf</u>. Frey, 1962, with Justesen, 1975a). Given the plausible assumption that a no-effect MPL for occupational exposure would be based on the limiting case of demonstrable perturbation irrespective of the character of the field, i.e., whether continuous wave (CW), or sine- or pulse-modulated, one's attention is directed to the Frey effect. That single, acoustically detectable pulse--which can be construed as a very brief CW transmission--when averaged conservatively over the 8-hour working day, extrapolates to a maximal permissible power density near 350 picowatts per square centimeter. To place this quantity in perspective, one should note that an adult human being emits microwaves* at frequencies between 300 MHz and 300,000 MHz at a rate near 540 nanowatts per square centimeter (Kraus 1966), a rate that is more than three orders of magnitude greater than would be a no-effect MPL based on the Frey effect.

A no-effect MPL for microwaves is putatively impractical; more desirable by far is a no-hazardous-effect MPL--or at least a scientifically sound body of threshold data on hazardous effects by which to make enlightened judgments of benefit and risk.

The problem of differentiating benign from hazardous effect is a formidable one that, unfortunately, few investigators have made an effort to resolve. Its timely resolution might be critical to the success of SPS.

A SELECTIVE SURVEY OF THE BIOLOGICAL LITERATURE

By their nature, the clinical case study and the epidemiological survey are scientifically suspect. Causal connections cannot be established in the case study because of the absence of controls. The survey suffers the ever-present possibility of confounding by spurious correlates of

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* The preponderance of biologically emitted microwave energy occurs at the highest frequencies near the infrared radiations, but the issue of depth of penetration is academic: Each layer of cells in a body is radiating cells of the neighboring layer; the radius of even the largest cell is so much smaller than the shortest wavelength of emitted radiation that the factor of penetration by endogenous microwave energy is irrelevant.

primary variables. That is, workers in areas where there are microwave fields of high intensity may initially differ in character from workers not exposed to such fields. As an hypothetical example, more highly trained, more specialized engineers may be needed in a given setting to create, test, and operate apparatus that generate fields of higher power density. Additional training and specialization necessitate more years in school. More years of schooling result in an older graduate. Older individuals are per se more likely to exhibit symptoms of pathology. A correlation may also (and probably does) exist between the intensity of the ambient microwave field and the quantity of ionizing radiations that are generated by, say, a magnetron or a klystron that operates at high anode voltages. Their defects notwithstanding, the case study and the survey are valuable on two grounds: 1) They generate hypotheses for experimental assessment on infrahuman subjects; and 2) they are the only sources of "data" on long-term human exposures to microwave radiation.

Cardiovascular Response

A most unusual case study was presented by Dr. Milton Zaret at the FDA-WHO Symposium on microwaves, which convened in Poland in 1973 (cf. Zaret, in Czerski, 1974, with Zaret, 1976a). Zaret reported that heart disease is rampant in several Finnish cities in the district of North Karelia, which borders the Soviet Union. He blamed the high incidence of the disease on "electronic smog" from over-the-horizon radar systems on the Soviet side of the border.

Zaret's report has been accepted by some writers as evidence of a connection between chronic exposure to microwaves and heart disease (see, e.g., Bloomquist's 1976 survey on SPS, p. 162), but subsequent reports, both epidemiological and experimental, have all but laid his suspicions to rest. His claims run counter to data uncovered in a long-established program of community control of cardiovascular disease in North Karelia (cf. Puska, 1973, with Tuomilehto, et al., 1976). The identified risk factors are hypertension, a diet high in cholesterol, obesity, and excessive use of tobacco.

There is evidence from experimental studies of animals that the heart is reactive to microwave fields of modest intensity; for example, acute exposures to 10-cm radiation at a power density of 8 mW/cm^2 has been reported to decelerate the beat of the isolated turtle's heart (e.g., Tinney, et al., 1976). However, intact rabbits that were exposed to 2450-MHz radiation at power densities of 20 to 30 mW/cm^2 for four hours a day across 8 to 10 weeks exhibited little difference in concentration of serum cholesterol or of cholesterol in the aortic wall, or in severity of experimentally induced atherosclerotic lesions (Sparks, et al., 1976).

Several occupational surveys have been reported recently by Eastern European authors who state that long-term exposures of workers to microwaves at power densities at or below 1 mW/cm^2: 1) are not associated with deviations of blood pressure from control levels (Czerski and Siekierzynski, 1974); 2) may result in "slight but significant cardiovascular alterations" after 10 years of exposure, but the exposed workers exhibit higher resistance to stress (Bielski, et al., 1976); 3) do not result in reliable deviations of ocular sensitivity (Gabovich and Zhukovskii, 1976) or of ophthalmic pathology* (Artamonova, et al., 1976); and 4) may be interpretationally confounded with such risk factors as smoking, consumption of alcohol, obesity, and overwork (Gus'Kova and Kochanova, 1976).

One of the more ambitious occupational surveys reported to date was undertaken by Siekierzynski, et al., (1976), who studied 507 workers that reportedly had been exposed to fields between 0.2 and 6 mW/cm^2 and 344 workers that were exposed to fields that never exceeded 0.2 mW/cm^2. No differences between the two groups were observed with respect to incidence of gastric or duodenal ulceration, thyroidal function, lens transparency, or work disability in relation to variations in ambient power density of microwave radiation. Age of the subjects--but not the total duration of occupational exposure--was highly correlated with symptoms of dysfunction. The authors concluded that their data do ". . .not support the hypothesis of cumulative effects of microwave exposure. . . ."

Cataracts

Zaret's concern for the possibility of microwave-induced heart disease was antedated by his belief that exposure to microwaves can

* Ophthalmologic examinations are an important part of diagnosis of cardiovascular disease.

result, after many years of delay, in an anomalous cataract of the posterior subcapsular region of the lens of the human eye (see, e.g., Zaret, 1975, 1976b, 1977). Cataracts are readily induced in experimental animals (see, e.g., Carpenter, et al., 1975; and Kramer, et al., 1975), but exposure to fields of high power density (>100 mW/cm^2) and the production of high intraocular temperatures (>41°C) are necessary. The evidence favoring a thermal basis of microwave cataractogenesis is substantial (but see Carpenter, et al., 1977), and is exemplified by work performed on monkeys by McAfee, et al. (1975, 1977). McAfee and his colleagues selectively exposed the heads of <u>awake</u> monkeys by directing the microwave beam to their eyes at a power density that is cataractogenic for <u>anesthetized</u> animals (3-cm wavelength at 350 to 495 mW/cm^2). The monkeys had the choice of "looking" into a radiator for 15-min periods while drinking fruit juice, or of foregoing both the radiation and the liquid. Several animals chose to drink and thereby sustained the radiation, but none exhibited signs of aversive behavior. It is highly likely that convective cooling of the eyes by blood, which flowed to the monkey's head from the larger mass of the shielded portion of its body, maintained the eyes below the thermal threshold of damage. If high power densities of a microwave field are solely responsible for ocular lesions, the monkeys should have developed cataracts. Even after repeated exposures and follow-up observations over a period of 2 yr, lesions of the monkey's ocular apparatus have not been observed by McAfee and his colleagues.

Gonadal Response

The testes and the eyes are more vulnerable to insult from elevation of temperature than are other tissues. Severe testicular damage resulted from whole-body exposures of mice to intense microwave fields (Prausnitz and Süsskind, 1962); the mice were exposed hundreds of times for 4.5 minutes a day to a 3-cm field at 100 mW/cm^2--a nine-minute exposure proved fatal in pilot experiments. A recently reported study of rats by Muraca, et al. (1977) revealed that comparable heating of the rodents' scrota by 2450-MHz CW microwaves or by immersion in water to temperatures of 36, 38, 40 and 42°C resulted in comparable extent of damage at each temperature.

The power densities associated with testicular damage are generally high; Baranski and Czerski's (1976) review of more than 20 reports provides numbers that range from 10 to 400 mW/cm^2. The smaller numbers are associated with long-term, chronic exposure. Only five minutes of irradiation at 400 mW/cm^2 was required to produce testicular damage in mice, which, however, recovered fully within a period of 10 days after exposure. One of the few recent reports that link exposures at low power densities with gonadal dysfunction arose from an epidemiological study conducted by Lancranjan, et al. (1975). Twenty-two of 31 microwave technicians were reported to suffer from a loss of libido and from reduced spermatogenesis after an average of eight years of occupational exposure at "tens to hundreds of microwatts per square centimeter" to microwave radiation at frequencies between 3600 and 10,000 MHz. Both conditions had remitted in most cases three months after exposures were discontinued.

There are no reports of irreversible testicular damage in human beings at power densities below 1 mW/cm^2. An unusual case history has been reported of infarction of a fallopian tube after tubal diathermy was performed in a sterilization procedure (Cordiner, et al., 1976). Histological examination of the fallopian tube subsequent to laparotomy revealed that the infarct resulted from hemorrhagic block, but there were no other abnormalities. The diathermy treatment probably involved power densities in excess of 100 mW/cm^2. The case history is unusual in that it represents the only known report of injury to the reproductive system from clinical application of microwave energy.

Genetics

Chromosomal and mitotic abnormalities in plants and animals are demonstrable consequences of high-intensity microwave radiation (see, the review by Baranski and Czerski, 1976, and the report by Chen, et al., 1974). Recent experimental studies of primitive organisms (Baranski, et al., 1976, and Blackman, et al., 1977), and of infrahuman mammals (Varma, et al., 1977, and Leach, 1976) have confirmed earlier findings that microwave radiation at power densities below 10 mW/cm^2 are not mutagenic, which agrees with findings from epidemiological studies of human beings (see, e.g., Italiano, et al., 1976). Baranski and Czerski (1976) have concluded that there is "...no satisfactory evidence of microwave-induced genetic effects..." (p. 134) at low to modest power densities, but they hint at a caveat that is of critical importance to

SPS: there have not been sufficiently large numbers of mammals tested under truly long-term radiation to warrant a confident denial of microwave mutagenesis at low power densities.

Teratology

Baranski and Czerski (1976) reviewed data on teratology in sub-mammalian species and reached the tentative conclusion that thermal effects, including those that are peculiar to the rapid volume heating by microwaves, can explain most of the findings of structural abnormalities of embryo and fetus. Since their review was written (circa 1974), a number of teratological studies of small mammals has been reported. Roberts Rugh and his colleagues have been particularly active in observing the effects of short-term but highly intense doses of 2450-MHz CW microwaves on mice (*cf.* Rugh, et al., 1975; Rugh, 1976; and Rugh and McManaway, 1976*a*,*b*,*c*). Structural abnormalities and resorptions were noted at Cesaerean section (just before term) and functional deficits were noted in surviving pups from other dams, particularly after radiation on the 9th day of gestation. Defects included fetal stunting and exencephaly, and later impairment of defense against thermal stress. Similar structural changes were observed in experimental *and in control* mice by Chernovetz, et al. (1975), who also found evidence that after exposure to highly intense fields 1) mortality of dams is more probable than fetal abnormality; and 2) the virtually complete postpartum mortality of pups that is associated with an earlier maternal injection of a control teratogen, cortisone, is reliably diminished by microwave radiation. A subsequent study of rats by Chernovetz, et al. (1977) revealed that the peak of the dam's body temperature after infrared or microwave radiation is a highly reliable predictor of maternal mortality and fetal resorption.

The studies by Rugh and by Chernovetz and their respective colleagues were performed either in a waveguide or in a multimode cavity, both of which preclude valid measurement of power density, but the rates of energy dosing were usually well in excess of 30 mW/g; this rate of dosing could only be accomplished in the free field at power densities many times higher than 10 mW/cm^2.

Acute exposures of gravid human beings to 2450-MHz CW radiation have taken place for several years in the clinic of José Daels, a Belgian obstetrician. Daels employs the radiation as an analgesic agent during the uterine contractions of labor and reports that his experience with 2000 deliveries* has proven the radiation beneficial to mother and to child. Time in labor is considerably reduced as is maternal demand for narcotic analgesics (cf. Daels, 1973, 1976, with Justesen, 1977). Daels has not reported power densities, but they probably exceed 100 mW/cm^2 at the abdomen since fetal temperature is typically elevated by 1°C after a series of 20- to 60-sec exposures of the mother. Follow-up studies of children who were born in his clinic have not yet been reported by Daels.

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* In a personal communication to D. R. Justesen dated January 2, 1978, Dr. Daels reported that more than 10,000 deliveries have been performed with microwave radiation, and that "careful observation" of children has never revealed a "harmful effect."

The consensus of biological investigators is that the rate of absorption of microwave energy as measured dosimetrically or as indexed by power density is the critical variable for inducement of biological effects for all but short durations (<2 hr) of exposure. Apparent exceptions have been reported by Rosenbaum and his associates (Lindauer, et al., 1974; Liu, et al., 1975), who exposed groups of pupae of the darkling beetle (*Tenebrio molitor*) for periods of time that ranged from 15 min to 8 hr. Power densities of incident radiation were commensurately reduced as exposure duration increased so that the same dose of energy, about 2 J/g, was administered to the pupae of each group. The averaged incidence of teratogenesis (physical malformations) was virtually the same in pupae of all radiated groups (∿24%) and was reliably higher than that in sham-radiated pupae (∿18%). This finding could be taken as evidence for a cumulative effect of radiation at a power density of only 400 $\mu W/cm^2$ after 8 hr of exposure. A possibly confounding influence, however, is the time of confinement during radiation, which varied systematically and inversely with the power density of radiation; i.e., confinement may have interacted with the radiation to produce structural abnormalities. More recent studies by Olsen and his colleagues have tended both to confirm (Olsen, 1977) and to disconfirm (Pickard and Olsen, 1977) the flat dose-response function. In the latter study, a definite threshold of teratogenesis was observed and was associated with a rise of pupal temperature in excess of 10°C.

Development

Published data on the effects of microwave irradiation on development of insects, avians and small mammals have been well reviewed by Baranski and Czerski (1976), who conclude that "...no serious effects are to be expected at power densities below 10 mW/cm^2 under usual exposure conditions" (p. 131). They further note that defects, when observed, are largely the result of hyperthermia. These conclusions, while just, are predicated on relatively short exposures (hours to weeks) and thus do not forecast what might happen to a species that is continuously exposed over generations of time. A more recent investigation by Johnson, et al. (1977) may be a harbinger of ill effects that have not been detected in earlier studies. The authors intermittently radiated rats *in utero* in carefully metered 30-cm CW fields at 5 mW/cm^2 for a total of 180 hours across the 500-hr period of gestation. On some measures, the neonatal pups appeared to be developmentally superior to sham-radiated controls, i.e., averaged body mass was greater and the eyes opened earlier, indicating accelerated growth. The radiated rats were inferior to controls, however, as thermoregulators and were slower in learning to master an escape-avoidance task. As indicated under Behavior, the occurrence of a microwave-induced behavioral "deficit" may provide no clue as to mechanism or behavioral competency in the wild and thus may leave unanswered the question of hazard. Some behavioral tasks are mastered more quickly by animals with *simpler* nervous systems (Hebb, 1958) and it is possible that the radiation produced an accelerated CNS development of Johnson, et al.'s rats. The finding of poorer thermoregulation does cross the boundary of endangerment. There is little doubt that survival of the feral animal would be threatened by a compromised thermoregulatory system. A critical but unanswered question is that of the threshold of impairment: Will prolonged exposures in utero at, say, 1 mW/cm^2 also result in deficits of thermoregulation?

Hematology and Immunology

Extensive work on the mammalian hematopoietic system and its constituents has been carried out, particularly by Eastern European investigators. Kicovskaja (1964, cited in Baranski and Czerski, 1976, p. 137) irradiated rats one hour daily for 216 days with 10-cm microwaves at power densities of 10, 40 or 100 mW/cm^2. Evidence of lymphocytosis, of lymphopenia, and of a slight decrease in number of red blood cells was found at power densities ≥ 40 mW/cm^2. Deichmann, et al. (1964), in contrast, reported evidence of neutrophilia, lymphopenia and increased numbers of red blood cells in rats after single and repeated exposures (for 10 min to 7.5 hr) to 1.25-cm microwaves at power densities that ranged from 10 to 24 mW/cm^2.

Baranski (1971) exposed large numbers of guinea pigs and rabbits to 10-cm radiation at power densities between 3.5 and 7 mW/cm^2 for three hours daily. Overall durations of the intermittent exposures ranged from two weeks to four months and both continuous and pulsed waves were used. The exposures resulted after two to three months in a significant leukocytosis, due entirely to increased numbers of lymphocytes; there was no effect on the number of granulocytes. Bone-marrow examination revealed no significant changes in the myeloid/erythroid ratios, but there was a marked depression both in pronormoblastic and in basophilic normoblastic populations of cells and a shift to more mature forms. The mitotic index of erythroid cells, as determined after administration of colchicine, was severely depressed in microwave-exposed animals. Pronounced structural changes were also noted in the nuclei of normoblasts, but no such effects were seen in precursors of granulocytes. Examination of lymph-node and of spleen-impression smears revealed a marked increase in lymphoblasts and in reticular cells, and abnormalities of nuclear structure were observed that were similar to those observed in normoblasts. After termination of radiation, the blood picture gradually returned to normal. The overall impression one gains in reading Baranski's report is one of stimulation of the lymphoid system, the response being much more pronounced to pulsed than to CW radiation.

Miro, et al. (1974) exposed mice for 150 hours to pulsed, 10-cm microwaves at a level near 20 mW/cm^2; the authors reported an apparent stimulatory effect of irradiation on the reticulohistiocytic system. They made their determinations by histological analyses and by observing uptake of ^{35}S-methionine into proteins of liver, spleen and thymus.

Czerski et al. (1974a) exposed guinea pigs four hours daily for 14 days to 2950-MHz pulsed microwaves at a power density of 1 mW/cm^2. These daily exposures were started either at 0800 or at 2000 hours to permit study of possible alterations in the circadian rhythm of bone-marrow mitoses as determined after the arrest of mitosis by colchicine. No effects were seen on precursors of granulocytes and only minimal effects were found on the erythroid series, but pronounced phase shifts were noted in the pool of stem cells. Included in the latter category were early normoblasts, myeloblasts, lymphoblasts, and other unidentified blasts. The study was then extended; a large group of inbred Swiss albino mice was exposed once for four hours at 0.5 mW/cm^2 to pulsed 2950-MHz microwaves--a frequency at which the mouse exhibits resonant absorption of microwaves. Another group of mice was used to determine body temperature immediately after comparable exposures. No significant increases of body temperature were found during the 4-hr exposure. The results of the study on mice were similar to those in the experiment on guinea pigs. The diurnal rate of proliferation of the stem-cell population of exposed animals was amplified and the phase shifted from that of controls. In another study the investigators exposed rabbits daily for two hours (for a total of 74 or 158 hours) to 2950-MHz pulsed or continuous waves at 3 mW/cm^2 and found an impairment of red-cell production as determined by ferrokinetic studies (Czerski, 1974b). In this study the effects of pulsed waves were more pronounced than were those of continuous-wave radiation.

The finding of shifts in the circadian rhythm of the blood-forming system at power densities near 1 mW/cm^2 may be among the most reliable of physiological indicants that biological systems are responsive to relatively weak microwave fields. A similar phase-shift in the circadian rhythm of body temperature was observed in rats by Lu, et al. (1977) after exposing them at 1 mW/cm^2 to 2450-MHz CW radiation for one to eight hours. The implications of such field-induced shifts, which represent perturbations of the biological clock, are not clear, but are reminiscent of the work of Wever (1974) who claims that man-made electromagnetic radiations can interfere with "natural" fields of solar and terrestrial origin that he postulates to be regulators of circadian biological rhythms.

A recent spate of studies has been focused directly on immunological effects of microwave irradiation. Paradoxically, positive effects are often reported in association with radiation at power densities above 10 mW/cm^2 (see, e.g., Luczak, et al., 1976; Szmigielski, et al., 1976a, 1976b; and Wiktor-Jedrzejczak, et al., 1976a,b,; 1977b) and include enhanced phagocytic activity, an increase in the population of complement-receptor-bearing lymphocytes, and augmentation of antiviral responses. In contrast, Shandala and his colleagues (1977) reported that one month of daily, 7-hr exposures of rats to microwave radiation at much lower power densities near 500 $\mu W/cm^2$ resulted in impaired immunological competency and in induction of autoimmune disease. Of particular interest to the immunologist is that Shandala's control rats were generally maintained in warm quarters, while experimental animals were removed daily from the quarters and were taken to a laboratory where they were radiated in an environment that was "bitterly cold." Since sham-radiation controls were not employed, it is not possible to determine whether radiation, cold-stress, or both were responsible for reported effects.

Cerebrovascular Response

It has been known for many years that any of a variety of stresses--e.g., electroconvulsive shock and fever borne of infectious disease--will increase the permeability of the blood-brain barriers (BBB). Sutton and Nunnally (1973) reported that hyperthermia induced by 2450-MHz CW radiation can breach the rat's barriers. Subsequently, Frey, et al. (1975) and Oscar and Hawkins (1977) reported that nonhyperthermic, 1.2- to 1.3-GHz pulsed radiations (<500 $\mu W/cm^2$ averaged power density) also breach the rat's barriers. While Frey, et al. found that CW radiation at the same frequency had no effect, even at a power density of 2.4 mW/cm^2, Oscar and Hawkins reported a reliable enhancement of BBB permeability at a power density of 0.3 mW/cm^2. Perhaps resonance is a factor (the rat will resonate at 1.2 GHz if appropriately aligned with respect to the field). Adding more confusion to these findings is the report by Merritt (1977) that attempts by him to replicate the findings of Frey, et al., and of Oscar and Hawkins, were futile. Since the functional role(s) and the mechanisms of the BBB are still a matter of scientific debate--as are means of quantifying the degree of BBB permeability after cerebral insult--the unsettled nature of the findings is hardly surprising. Of import to SPS is that no evidence of increased permeability has been obtained in the wake of 2450-MHz CW radiations at or below 1 mW/cm^2.

Endocrinology

Response of the endocrines of rats to whole-body CW irradiation at decimeter wavelengths has been studied extensively in recent years, but the lion's share of the reports is based on short exposures at modest to high power densities ($\geq$ 10 mW/cm^2), e.g., see Lotz and Michaelson, 1975; Guillet, et al., 1975; Houk, et al., 1975; Guillet and Michaelson, 1977; Travers and Vetter, 1976; and Mikolajczyk, 1977. Increased titers of corticosterone and of luteinizing hormone were observed. In other studies, Vetter (1975) found that serum protein levels increased as a function of power density, indicating an alteration of protein synthesis or catabolism. Levels of thyroid hormone were found by Vetter to decrease as power density of the 2450-MHz CW radiation was increased from 5 to 25 mW/cm^2. In agreement is the finding of Lu, et al., (1977), who reported that serum thyroxine levels were transiently elevated after exposure of rats at 1 mW/cm^2, and were depressed after exposure at 20 mW/cm^2. None of the reported alterations was irreversible or resulted in morbidity.

Behavior

Two judgments can be made about the mammalian behavioral response to microwave radiation; one is its high sensitivity, the other, its poor specificity with respect to locus and mechanism. On one hand, behavior is the most sensitive litmus of biological reactivity. The human being or the infrahuman animal with unimpaired audition can "hear" a single pulse of radiation that deposits only 10 μJ/g of energy in the head (cf. Frey, 1962, with Justesen, 1975a, and Chou, et al., 1977). The corresponding rise of intracranial temperature per pulse is less than 5 X 10^{-6}°C

(Guy, et al., 1975). On the other hand, behavioral manifestations of microwave radiation provide virtually no insights into <u>mechanisms</u>. The litmus of behavior is achromatic; it gets lighter or darker, but is lacking in the red or green hues that would signal, respectively, deleterious or benign effects. It follows that the <u>analytical</u> utility* of behavior lies in providing signposts, usually in the form of data on thresholds, that can direct and anchor an investigator's attack on mechanisms of reaction in, for example, the function and morphology of the CNS and the endocrines.

The focus of the section on behavior is upon thresholds. As already indicated, the threshold of perception of rectangularly pulsed microwave radiation is near 10 μJ/g per pulse (typical averaged- and peak-power densities at threshold are, respectively, 120 $\mu W/cm^2$ and 40 mW/cm^2 <u>for an extended series</u> of pulses [Guy, et al., 1975]). The perceptual threshold of CW and sinusoidally modulated radiations, which lack the sharp "attack" and high peak density required of the thermoelastic wave of pressure that presumably results in radiofrequency (RF) hearing (<u>cf.</u> White, 1963, with Foster and Finch, 1974) is considerably higher, about 35 mJ/g (King, et al., 1971), which would require a plane-wave power density near 5 mW/cm^2.

Reduced rates of locomotor activity of rats were reported to occur at power densities of very-high-frequency (VHF) radiation near 1 mW/cm^2 (Korbel, 1970). However, as described under <u>Ecology</u>, Korbel's exposure

* Behavior per se may be a critical factor in the survival of a species that is radiated in an intense microwave field. Successful behavioral thermoregulation and escape or avoidance behaviors may spell the difference between death or survival of, say, a small bird that flew into the center beam of SPS.

system precluded accurate determination of power densities, which apparently were much higher than measured values because of multipath radiations (see Guy and Korbel, 1972). More recent studies of rats' locomotor behavior, in which dose rates or power densities were more accurately measured, revealed that locomotor activity was reliably augmented immediately after 1-hr periods of exposure to 2450-MHz CW radiation in a cavity (Mitchell, et al., 1977). The rats were dosed at a rate of 2.3 mW/g, which is roughly equivalent to the rate at which energy would be absorbed from a plane-wave at a power density between 5 and 10 mW/cm^2. Contrasting with this finding is another reported by Roberti, et al. (1975), who exposed rats to 3000-MHz microwaves (either CW or pulsed) at averaged power densities between 0.6 and 26 mW/cm^2 for a cumulative total of 185 or 408 hours. No reliable differences of activity between experimental and control animals were found. The apparent conflict of findings between the study by Mitchell, et al., and that by Roberti, et al., probably inheres in a difference in their scheduling of behaviorial measures. The bulk of measurements by Roberti, et al. were obtained after termination of radiation treatments, while those of Mitchell, et al. were closely interspersed during a succession of treatments. Considered in sum, the data of the two studies indicate that locomotor activity of rats may be affected acutely by 12-cm radiation at power densities in excess of 5 mW/cm^2, but lengthy exposures, even at relatively high power densities, have negligible carryover.

When microwave radiation is programmed as a potentially disruptive stimulus, the character of the behavior chosen for study strongly influences the threshold of disruption. For example, tasks that required rats to press a lever at a very low rate or at a very high rate in order to maximize the pay-off of a food reward became reliably more difficult when incident 2860-MHz CW radiation was elevated to power densities between 5 and 10 mW/cm^2 (Thomas, et al., 1975). Another task, one that involved alternate pressing of two levers by a rat that was being exposed to 2450-MHz CW radiation, was not rendered more difficult until power densities were elevated to 15 mW/cm^2 (Gage, 1976). When a low-demand operant response was the task (a licking response or nodding of the head for a food reward), behavioral disruption in the form of work stoppage by hungry rats was not observed until dose-rates of 2450-MHz radiation were increased to 8-10 mW/g (cf. Justesen and King, 1970, with Lin, et al., 1977), which would require radiation at power densities well in excess of 20 mW/cm^2.

A field-induced disruption or attenuation of work by an animal carries no warrant that the microwave radiation is perceptually noxious--that it will produce escape from or avoidance of the field at, say, the threshold power density of work stoppage. In order to demonstrate nociceptive (irritating or painful) properties, one must give the animal a choice of remaining in or transiting from the potentially noxious field. Whether the highly dense field will induce aversive behavior is a critical question for SPS--especially for airborne animals that may fly through the center of the beam. Some earlier reports of studies of mice appeared to indicate that these tiny rodents will learn to avoid intense 2450-MHz CW fields. Close scrutiny of the reports revealed, however, that neither avoidance nor escape as technically defined was demonstrated. The mice were located in an opaque waveguide and readings of reflected power were used to index rates of energy absorption. At high initial levels of forward power that resulted in dose rates near 60 mW/g, there invariably followed a reduction of energy absorption by a mouse--to a dose rate between 40 and 45 mW/g. The investigators interpreted the reduction as evidence of avoidance behavior.* Perhaps the mice were purposively adopting postures and orientations in the waveguide that permitted _partial escape_ from radiation, but just as likely is the induction of heat prostration and collapse of the animal, which would result in a reduced absorptive cross section and a commensurate reduction in the rate at which microwave energy is absorbed.

Appropriate tests of aversive behavior have been conducted (_cf._ Frey and Feld, 1975, with Hjeresen, et al., 1976). Rats were placed in a shuttlebox, one half of which was shielded from radiation. The tests revealed that, while the rats did not avoid the radiated area, they did _tend to escape_ from it when it was radiated with pulsed fields (130-300 mW/cm^2 peak density, 0.4-0.9 mW/cm^2 averaged density). In contrast, the rats were not reactive to CW fields at a power density of 2.4 mW/cm^2.

The noxious quality of a stimulus can also be determined by an experimental procedure that results in learned aversions to an originally appetitive stimulus, such as saccharin in solution. Lovely and Guy (1975) exposed rats to 30-cm microwaves for 10 min at one of several

* To avoid an agent, the animal must _prevent_ contact. In the study cited, reduction of dose rate occurred but avoidance of the field was not possible.

power densities from 5 to 45 mW/cm^2. Twenty-four hours later, control rats and others exposed at power densities below 25 mW/cm^2 maintained a strong preference for saccharin over water; the rats exposed at 25 to 45 mW/cm^2 exhibited significant reductions in intake of the saccharin solution. The implication is that short periods of fairly intense irradiation can create an experimental malaise, of unknown duration and intensity, and that the learned aversion persists for at least a day.

A final study of interest also involves conditioning (Bermant and Justesen, 1976, and Bermant, et al., 1977). Rats were exposed to intense 2450-MHz radiation (>200 mW/g) for short (<3-min) periods in a multimodal cavity; radiation continued until colonic temperatures were increased by 1.5°C. Antecedent to each bout of radiation was the presentation for 30 seconds of a sonic stimulus. After 200 pairings of the sonic conditional stimulus (CS) with the microwave unconditional stimulus (US), the rats were subjected to measures of experimental extinction, i.e., the US was omitted to permit observation for indications of conditional ("learned") hyperthermia. Strong indications of Pavlovian conditioning were observed; indeed, the rats exhibited a small (∿0.5 to 1.5°C) but virtually unextinguishable hyperthermia that was elicited whenever they were brought to the conditioning lab--or even when they were picked up in the vivarium by their trainer (but not by a stranger). The generality of this hyperthermal conditioning has not been established, but the data do demonstrate that short periods of highly intense radiation can leave a lasting imprint on the central nervous system.

Nervous System

Behavior is a scientific portal to the nervous system and much of the world's literature on neurological effects of microwave irradiation has dealt more nearly with the "Conceptual Nervous System"--with inferences based on behavior--than with concrete elements of the Central Nervous System and their response to radiation. Examples of inferential neurologizing abound in the Eastern literature (see e.g., Tolgsakja and Gordon, 1973) and center upon the induction of the neurasthenic syndrome in human beings by exposures of many years' duration in reportedly weak fields. Restlessness, insomnia, irritability, headache, and impotence are frequently cited as elements of the syndrome, but little substantiation has appeared in the Western literature. This discrepancy has been interpreted variously as a failure of candid medical reporting in Western countries, as a function of differing medical philosophies, East vs West, and as a failure of Eastern-bloc countries to enforce their occupational standards of exposure (see Justesen, 1977).

Many laboratory studies have been reported on the neurohistological and electrophysiological responses of animals to microwave irradiation, but in the bulk of these studies, chronically indwelling brain electrodes were used, which can distort and enhance incident fields, thereby introducing artifact. One recent series of studies conducted by Adey and his colleagues has captured the interest of neurophysiologists because of apparent freedom from artifact and of indications that the nervous system is selectively responsive to weak fields below the extremely-low-frequency band (i.e., sub-ELF fields) or to microwave fields that are modulated at sub-ELF frequencies (cf., e.g., Adey, 1975; Gavalas, et al., 1970; Kaczmarek, et al., 1974; and Bawin, et al., 1975, with Blackman, et al. 1977). Electromagnetic radiation at frequencies that range from sub-ELF through the microwaves are capable of altering the flux of calcium ions in cortical tissues of isolated brains, but only when the sub-ELF carrier frequency or the sinusoidal modulation of higher radio-frequency radiations is near natural "biological" frequencies between 5 and 25 Hz (e.g., near the 8- to 16-Hz range of the electroencephalogram (EEG) "alpha" rhythm). The effect occurs to very-high-frequency (VHF) radiations at averaged power densities near 1 mW/cm^2 and appears to be an analog of subtle but reliable shifts of timing behavior that are seen in intact monkeys during exposure to comparable fields (Gavalas, et al., 1970).

Because the efflux of ions (and, presumably, the alteration of the primate clock) are modulation-frequency-dependent, this now independently confirmed phenomenon may be considered irrelevant to SPS. However, as Clarke and Justesen (1977) have pointed out, a field that is not modulated by its source can nonetheless be modulated by the behaving animal as it moves in and about the field. In addition, respiration, myocardial contraction, movements of limbs (especially of the avian's wings in flight) are often highly rhythmic and in many cases cross the range of the brain's "biological" frequencies, the possibility of disruptive neurochemical perturbations by weak CW fields must be assessed.

Ethology

Ethology, the study of the behavior of a species in the natural setting, is almost without representation in the microwave literature. Professor F. N. Willis of the University of Missouri (Kansas City) performed an unpublished study in 1970 on a herd of young guinea pigs that had been subjected to short (10-min) periods of intense 2450-MHz radiation ($\sim$30 mW/g). The dominance hierarchy and other ethological measures of the exposed herd of animals were carefully charted and compared to measures from sham-radiated animals. No reliable differences were observed. More recently, Clarke (1977) performed research for his Ph.D. dissertation at the University of Kansas on chickens (*Gallus gallus*) that had been conventionally incubated, except during the second 24 hours of gestation, when eggs of the experimental flock were incubated in a 2450-MHz CW microwave field at a dose rate of 100 mW/g; microwave incubation occurred in an environment at normal temperatures and with forced-air cooling of eggs. Clarke obtained a full battery of ethological measures on the animals, which were observed as young adults, but found only one behavioral difference between radiated and control flocks. Measures of dominance when the two flocks were merged revealed a reliable incidence of heightened submissiveness among radiated cocks and hens. The implication of this diminished ranking in the pecking order is unclear but, if caused by embryonic radiation, it was the result of fields of power density well in excess of 100 mW/cm^2.

Ecology

Ecological assessment of microwave radiation has never been attempted and, in virtue of the tremendous complexities inherent in multibiotic systems, will pose the most difficult and time-consuming challenge in the evaluation of SPS impact. The data of several studies _may_ provide some insights into ecological problems, but the reader is cautioned about the intrusion of what Justesen and King (1970) have referred to as _emergence_. Simply put, as a system becomes more complex, there is an increased likelihood that data based on its elements as studied in isolation cannot be generalized to the system as a whole. To illustrate within the conceptual frame of the individual organism: The dose of microwave irradiation in a cancerous rat that completely eradicates a malignant tumor will enhance growth of the malignant cells when they are cultured _in vitro_, which may indicate that whole-body hyperthermia of the cancerous animal not only heats the malignancy, but can also have a stimulatory effect on immunological mechanisms (Marmor, et al., 1977). The example well illustrates the phenomenon of systemic emergence, or what is often called _biological amplification_. By extension, the complex of biota that coexist interdependently in the natural setting will likely exhibit _ecosocial amplification_ of a "stimulus" that perturbs the ecosystem.

Given the caveat of emergence, one can turn to findings that, at the least, have heuristic value for ecological studies. Burks and Graf (1975) collected data over a 19-year period on birds that were killed by collisions with a TV-antenna tower 300 meters in height. They concluded that the antenna's electromagnetic interference with navigational "signals" from the earth's natural E and H fields resulted in attracting the birds to the tower. Tanner and his colleagues (cf. Tanner, et al., 1967, with Romero-Sierra, 1969) have reported on effects of microwave radiation on parakeets in flight. Their data indicate that 9300-MHz pulsed radiations (40-mW/cm^2 average, 4-W/cm^2 peak) produced aversive behaviors--although the birds were hungry they often, but not always, avoided a sector of the beam where food was located. Whether the birds were responding to the averaged or to the peak component of the field is unknown since no experimental studies have been reported on effects of unmodulated microwaves on birds in flight.

Extensive work has been performed on avian embryos (McRee, et al., 1975) and adults (Krueger, et al., 1975). McRee, et al. observed for effects of 2450-MHz CW radiation at 30 mW/cm^2 (14-mW/g dose rate) on embryos of Japanese quail. Separate groups of 57 eggs were radiated for 4 hours during the 1st, 2nd, 3rd, 4th, or 5th day of gestation, or during all 5 days. Controls were incubated under standard conditions. Two days after hatching, the baby quail were weighed, decapitated, and then examined for structural deformities. Hemograms were obtained. None of the endpoints (hatchability, body mass, teratology, hematology) differed greatly among the six irradiated and six control groups.

Kreuger, et al. (1975) examined for effects of 260-, 915-, and 2435-MHz CW radiation on separate flocks of mature domestic chickens

(Gallus gallus), each of which consisted of one cock and four hens. The power density of the 12-cm radiation was reported to be 1 mW/cm^2 and the period of irradiation, which was continuous, was 12 weeks. Neither fertility nor hatchability of eggs was affected. No abnormalities were noted except for poorer quality of egg shells from hens that were irradiated by 2435-MHz microwaves. Since fragility of the egg shell of a feral species could threaten its survival, the data of Kreuger, et al. and the means by which their data were generated are of more than passing interest in view of the small value of the reported power density. Power density was not measured but was calculated. The flock was not exposed to plane waves but received multipath radiations in a metal cage with the configuration of an inverted funnel. Microwave energy was fed into the cage from an opening in its truncated overhead. In effect, Kreuger, et al., constructed a low-Q cavity not unlike that of Guy and Korbel (1972), who discovered that power densities, which measured less than 1 mW/cm^2 inside their cavity, failed by orders of magnitude to predict the much higher quantities of energy that were actually absorbed by simulated biological targets. These seeming kinks in the methodology of Kreuger, et al. do not relieve the concern that prolonged irradiation at seemingly low power densities may be harmful; it is quite possible that feral animals in certain environments near the periphery of an SPS rectenna would also encounter multipath radiations.

Most studies of biological effects of microwave radiation have been focused on the fauna. Studies of flora for the greater part have been performed at high power densities in efforts to assess effects on seed germination or on weed-killing potential. One study that has ecological import has been reported by Barthakur (1976), who observed stomatal responses of bean leaves and of leaves of the water hyacinth to 2450-MHz microwaves at power densities from 0 to 200 mW/cm^2. Even in darkness--and with and without activation of an airstream--the leaves of both plants responded to the thermal stress of radiation with transpirational cooling, which led to decrements of temperature that were as much as 10°C. Plants, at least of some species, are apparently quite capable of thermoregulating over a considerable range of ambient temperatures--and in the absence of photic stimulation.

Airborne Biota

As currently projected, the power density of the microwave beam will be at least 20 mW/cm^2 within an approximate 2-km radius of the rectenna's center (Bloomquist, 1976, p. 163). A bird that attempted to fly along a path through the center of the beam would travel a distance of nearly 4 km through fields within which rates of energy absorption could double or treble because of resonance, i.e., a small avian with a long axis that approximates 5 cm would, given parallel alignment to the vector of the E-field, be resonant in a 2450-MHz field. Even neglecting the factor of resonance, it is doubtful that an animal could survive such a flight because of the added thermal burden. The possibility that early encounter with the beam near the periphery of the antenna might produce evasive behavior cannot be assessed in the light of extant data. Some work has been performed on approach-avoidance behaviors of reptiles and of mammals during exposure to microwave irradiation, but, as indicated earlier, no controlled experiments that bear on aversive behaviors of airborne avians in a CW field have been reported.

Some reptiles, such as the pit viper, have highly specialized means of detecting sources of thermal energy (Gamow and Harris, 1973). Many infrahuman mammals, on the other hand, are demonstrably insensitive even to large, rapid increases of skin temperature. The nociceptive (pain) threshold of skin temperature of the domestic cat, for example, is about 52°C (Kenshalo, 1964). Recently completed studies of the rodent in intense 2450-MHz fields indicate either that aversive behavior only takes place after the animal has been severely compromised thermally (Monahan and Ho, 1977), or that aversion is wholly lacking (Carroll, Levinson, Clarke, and Justesen, unpublished studies).

Whether the airborne avian possesses a fine thermal sensitivity, and whether such a sensitivity, if present, would be used to avoid excessive radiation, are open questions.

Lethality

Few studies have been performed on lethality of 2450-MHz microwaves. Rugh (1976) radiated mice with 2450-MHz CW energy of sufficient intensity to produce death in less than 8 minutes. Although he reported age-modulated threshold doses in J/g (43.9 to 47.8 for males; 39.3 to 42.9 for females), the reported values are overestimations because of his method of indexing mortality. Forward power and reflected power were monitored while the animals were radiated in a waveguide; with moving animals, the readout from the reflected-power meter continuously changed. Rugh used as the measure of mortality cessation of change in the readings of reflected power. Since a lethal dose of hyperthermalizing radiation can occur before or shortly after onset of a lengthy bout of convulsive activity, and since Rugh timed mortality from onset of radiation until cessation of activity, many if not all of his animals had sustained a mortal dose well before the time of reported mortality.

A rather ingenious method of assessing lethality--one that fortuitously predicts an LD-50 under certain conditions (see Justesen, et al., 1977)--was developed and reported by Phillips, et al. (1975). The animal is timed from onset of radiation to onset of a _grand mal_ convulsion. By use of this strategem, Phillips et al. determined convulsive latencies for mice and rats that ranged in mass from 29 to 560 grams. At any given dose rate between 25 and 210 mW/g, the latency to convulsion was essentially independent of the animal's mass; convulsive doses ranged narrowly between 22 and 30 J/g for latencies that ranged between 100 and 1200 sec.* Subsequent studies by Justesen, et al. (1977) confirmed that the averaged dose to convulsion for a normal rat under standard environmental conditions is near 25 J/g, given a dose rate of 100 mW/g. These

* The energy dose is a time-intensity product that often can be used to predict a biological response to intense radiation over a relatively short period of time--milliseconds to as long as one or two hours. At lower power densities and longer durations of exposure, the predictive value of the energy-dose number breaks down. For example, a mouse irradiated in a 2450-MHz field at 1 mW/cm^2 would accumulate a 25-J/g dose after six to seven hours, but no untoward heating would occur because the animal easily would be able to dissipate the thermal product of the absorbed radiation during this period.

doses and dose rates, which are based on exposures to 12-cm radiation in multimodal cavities, are in good agreement with data on lethal dosing of rats in the free field for which the extrapolated range of power densities that corresponds to the range of dose rates of Phillips, et al. is 50 to 500 mW/cm^2 (see Dordevic, 1975). Dordevic also attempted to determine the absolute power-density threshold of lethality in rats that were exposed to a 2400-MHz field. Under restraint, the animals expired within two hours while exposed to radiation at a power density of 30 mW/cm^2. One notes again that small birds with a major axis the length of which approximates half of the wavelength of a 25-mW/cm^2, 2450-MHz field, i.e., with a long axis near five centimeters, effectively will be exposed to radiation at a power density in excess of 50 mW/cm^2 (see Gandhi, 1974, and Gandhi, et al. 1977, for especially good accounts of biological "resonance" and of other factors that can result in enhancement of absorption of microwave energy).

Exposure Systems and Dosimetry

Much of the experimental literature on biological effects of microwave radiation is based on poorly engineered exposure facilities, inadequate environmental control, poor dosimetry or no dosimetry, improper methodology, and instrumentation ill-suited for collection of biological data during radiation. The literature is rife with reports on a wide variety of species and on *in vitro* preparations in which biological effects are related solely to radiation intensities as expressed in units of mW/cm^2. Power density as a measure of the intensity of the incident microwave field is not impugned. Power-density numbers as determined by a well-crafted probe in a well-designed, electrically anechoic chamber are an indispensable measurement in biological studies of the effects of plane wave (uni-path) radiation. No longer acceptable, however, are experiments in which measures of power density have not been validated against dosimetric measures that, minimally, provide numbers on averaged quantities or rates of whole-body energy absorption and, ideally, provide data on averages, peaks, and anatomical distributions of absorbed energy. The twofold necessity for densitometry and dosimetry goes beyond the intra-laboratory calibration of the former by the latter. Only by establishing the goodness (or poorness) of fit between measures of incident and absorbed energy over the range of the microwave frequencies and under a variety of physical environments can the scientist provide the public-health practitioner with the laboratory data by which he or she can understand and properly utilize measures of power density in the real world.

Exposure apparatus has varied from well-engineered anechoic chambers to ordinary antenna sources in rooms with reflective surfaces that have conspired for unknown or unacknowledged multipath radiation; and from resonant cavities and transmission lines to various sources of near-zone reactive fields. Exposures have involved single animals, groups of animals, and the presence of scattering devices such as conductive leads to instrumentation, thermocouples, thermistors, food, water bottles, and metallic floors. The target preparation has varied from suspensions of single-cell organisms to large animals, including man. Frequencies of radiation and parameters of modulation have varied considerably and often have not been specified. Environmental temperature, humidity, and air velocity have varied considerably. In many cases modulation of the microwave radiation has been intentional, other times unintentional, sometimes known, and sometimes unknown. The reported power densities of incident fields may have been estimated, calculated, or measured directly. The latter may or may not have been done properly by taking into account reactive fields, multiple scattering, nonlinearities of the measuring instrument, harmonics, and modulation of the source. Since thresholds of biological effects are dependent on so many factors, it is impossible to interpret with precision the results of the bulk of the world's literature on biological effects of microwaves, or to draw firm conclusions concerning the significance of reported biological effects for SPS--or, for that matter, for any microwave source.

The problems that are borne of the manifold inadequacies of instrumentation,* of dosimetry, and of specification have contributed heavily to the public's misunderstanding of microwaves, to controversy among scientists, and to the international disparity of microwave-exposure standards, which range by orders of magnitude. If investigators continue to limit their research to a quest for a correlation between some biological effect and a power density, the goals of understanding and predicting

* One of the reviewers admonished the writers, and correctly so, that inadequacy often lies more in the user than in the instruments he or she uses.

biological effects of microwave radiation will never be realized. Any and all investigations that are undertaken for SPS should be thoroughly grounded on dosimetric principles and practices that ensure a return of useful and confirmable data.

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APPENDIX A

BIOPHYSICAL ASPECTS OF MICROWAVE RADIATION--A TUTORIAL

Electromagnetic radiations extend from just above dc (direct current) to the high-energy cosmic rays. These radiations, in the order of increasing frequency, include the radio-frequency waves, infrared energy, visible light, ultraviolet energy, X-rays, and gamma radiations. Microwaves, which occupy the upper portion of the radio-frequency (RF) spectrum, are situated just below the infrared, and oscillate at frequencies that range from three-hundred millions to three-hundred billions of cycles each second. Since light and the other electromagnetic waves travel through space at a constant velocity near three-hundred millions of meters per second, the wavelength of a radiation can be calculated by dividing its frequency into the constant of velocity. The wavelengths of radiations in the microwave spectrum range, with increasing frequency, from one meter to one millimeter. The microwave frequency selected for the Satellite Power System (SPS), 2.45 billions of cycles per second (2450 Megahertz or 2450 MHz), has a wavelength near 12.25 centimeters, about five inches. The wavelength of 12.25 cm holds only for 2450-MHz radiations in a vacuum or in air. When radiation enters and propagates in a liquid or solid medium, its frequency does not change but its velocity decreases; therefore its wavelength is shorter. In a medium with the properties of a biological body, the radiation's wavelength decreases about 85%. A 2450-MHz radiation has a wavelength near 1.75 cm (about two-thirds of an inch) as it propagates through living tissue of high water content.

The wavelength of a microwave radiation determines the depth to which it will enter a medium. The longer the wavelength, the greater the depth of penetration. Since waves of infrared energy are so short (less than a millimeter in length), their effective penetration is no deeper than the skin. Depending on frequency, microwaves can penetrate tissues to varying depths. A 2450-MHz microwave can penetrate about 1.75 cm into muscle tissue, although most of the energy is absorbed in the first few millimeters. Penetration would be greater in fatty tissue because its water content, and thus its density, is lower. It is this relatively greater depth of penetration by microwaves at longer wavelenths that has raised questions about potential biological hazards, particularly for smaller animals whose vital internal organs are more likely to absorb microwave energy than are the same organs of larger animals and man, which are more deeply located.

Wavelength is important in another respect. An adult human being in a 2450-MHz field will absorb only about half of the microwave energy that is incident on him. The remainder is scattered. As the longest dimension of an animal* approaches one-half of the wavelength of a radiation, more of the incident energy is absorbed. When there is a close match--when, for example, a small bird or rodent in a 2450-MHz field has a body length near five centimeters--a phenomenon known as

* That is, the electrical length of an animal, which is about 80% of its physical length.

resonance can occur. Not only may the animal absorb all of the incident radiation, its absorptive cross-section (the energy absorbing area of the body) may increase severalfold.

The gentle rubbing of the rim of a fine crystal glass with a finger will generate a loud, ringing note--an example of mechanical resonance. Electrical resonance is similar, but to comprehend its implications for SPS, a bit of an excursion into electromagnetic theory is required. Even as a rock thrown into a quiet pond will generate waves, the movement of charged particles such as the flow of electrons in a conductor will generate a wave, albeit of an electromagnetic character. The wave has two components that are at right angles to each other and to the line of propagation of the wave. One component is the electrical or E field; the other is the magnetic or H field. Further, even as a flow of electrons in a conductor can generate the two propagating fields, any conductor (including a biological body) that intercepts the fields will undergo induction of electrical currents. Microwaves at 2450 MHz therefore induce electrical currents in the biological body that absorbs them. In addition, the molecules of water in a body attempt to vibrate at the same frequency as the absorbed microwaves, but because of water's viscosity, friction occurs, which results in heating. Indeed, both the conductive and frictional effects of microwave energy on a biological body result in heating.

The amount of radiant energy that is converted to thermal energy in a body depends to a great extent on the intensity of the incident electromagnetic wave. But there are other factors. The geometry of the body is important in two respects. First, the absorptive cross-section can vary: a snake moving headlong into a propagating wave would present a small absorptive surface, while its broad side would present a much greater area for absorption of energy. Second, the orientation of a body with respect to the E and H fields of an approaching electromagnetic wave is an important factor. More energy is imparted when the long axis of a biological body is parallel to the E field. Maximal transfer of energy occurs when the long axis and the E field are perfectly parallel. By implication, a biological body of a given length will reach maximal resonance when its major axis is parallel to and is a little less than half the wavelength of the E field of an approaching electromagnetic wave. Small birds of 5-cm length that might fly into a 2450-MHz field would be at maximal resonance only if their longest axis--sometimes defined by the body proper, sometimes (but more briefly) defined by the momentary length of flapping wings--were parallel to the E field.

As already indicated, absorption of electromagnetic energy by a biological body results in translation of radiant into thermal energy. If the absorbed radiation is sufficiently intense, the body's temperature will rise noticeably. This is not to say that intense fields produce only thermal effects, while weak fields produce "nonthermal" (athermal) effects. Absorption of any amount of radiation results in heating, but an elevation of temperature may be so slight as to escape detection--or a change of state in the absorbing medium (e.g., from solid to liquid) may result in latent heating, which is not associated with a rise of temperature. Further, this is not to say that there are no athermal effects of microwaves. There indeed may be transitional athermal effects at the molecular level from radiation pressure or field forces, but the ultimate fate of all absorbed microwaves is thermal in nature.

It is of great importance to recognize that thermal transactions involve more than temperature. Heat and temperature are not identical. Temperature is the averaged kinetic energy of a system of molecules. Heat is thermal energy in transit from one body to another or--in the case of heating by microwaves--heat results from propagating electromagnetic energy that, in flowing from a source to an absorbing body, undergoes translation from radiant to thermal energy. The flow of energy is appropriately called a flux. One can impart a large amount of microwave energy to a biological body without increasing its averaged temperature. That is, one can arrange to cool the body by a flux of chilled air or liquid. If there is a balance of fluxes in a body--if the heating from absorbed energy is exactly offset by the loss of thermal energy--the result is a steady-state in the average temperature. Such an equilibrium has been used by biologists in the microwave laboratory, but many of them, in utilizing the method of equivalent temperatures, have claimed that effects produced thereby are "nonthermal" in nature. However, an effect produced by a flux of thermalizing energy--or by the inevitable gradients of temperature that attend strong thermal fluxes--is just as much a thermal effect as that born of a change of temperature. It cannot be stressed too strongly that 1) heating of a biological body, even by intense microwave radiation, does not necessarily result in a rise of averaged temperature; and 2) that heating of a body, whether the averaged temperature increases or not, is a thermal transaction.

The term "radiation" carries negative connotations. Gamma- and X-radiation bring memories of the horrors of Hiroshima and Nagasaki. Small wonder, then, that "microwave radiation" is feared by many persons. It will prove helpful to the reader if he or she will recall that all forms of electromagnetic energy that propagate through space at the velocity of light are, by definition, radiant energy, which is to say "radiation." Microwaves and the other RF radiations share one important property in common with X- and gamma-radiations: all impart an increase in <u>kinetic</u> energy when absorbed by an object. The kinetic energy of a body is determined by the rate of motion of its molecules. Temperature by definition is the average of the kinetic energies of a body's molecules.

Microwaves differ greatly from X- and gamma-rays in another respect. The difference lies in what is called <u>photon</u> energy. Whereas kinetic energy is the measure of a molecule's rate of motion, the photon energy of a radiation provides a measure of its ability to produce molecular <u>disruption</u>. As the frequency of an electromagnetic radiation increases, so too does its photon energy, which is the potential of a wave to strip electrons from molecules. A molecule so disrupted is said to be "ionized," hence the reference to X- and gamma-rays as ionizing radiations. The photon energy of a microwave radiation of even the highest frequency is so small that ionization of biological materials cannot occur unless extremely high temperatures are produced that would reduce the body to a pile of ash.

The increase of kinetic energy of a biological body, that is, the elevation of the body's temperature, when excessive, is the only undisputed hazard of continuous-wave microwave radiation. If dissipation of thermal energy were prevented, the increase of a body's temperature would be roughly proportional to the intensity of the radiation. At microwave frequencies, the intensity of radiation is usually measured in terms of what engineers refer to as <u>power density</u>, which is the amount of electromagnetic energy that flows through a measured area of space per unit of time. The basic quantity of energy is the joule (J), about four of which are required to increase the temperature of one gram of water by one Celsius degree (°C). If one joule of energy were being transferred continuously to a body every second of time, the rate of energy transfer would be termed one watt of power; that is, power is the amount of energy per unit of time that is transferred from one medium to another. Power density, therefore, is a temporal measure of the <u>concentration</u> of energy that is flowing through a given area.

The current occupational standard--the Maximal Permissible Limit--for continuous exposure to microwave radiation in the U.S. is ten milliwatts per square centimeter (10 mW/cm^2). The body of a large human male has a maximal cross-sectional absorptive area near one square meter, which is 10,000 cm^2. At a power density of 10 mW/cm^2, the power of radiations that are incident on the man's body is about 100 watts. At 2450 MHz, nearly half of the incident radiation is scattered--not absorbed--which means the man is absorbing the microwaves at a rate near 50 watts. If the man's body mass is 100 kilograms (220 pounds), he is being dosed with microwaves at the rate of 0.5 milliwatts per gram (0.5 mW/g) of body tissue. Since the resting metabolic rate of an adult male is about

2 mW/g, and his maximal (active) metabolic rate is near 10 mW/g, it can be seen that 2450-MHz microwaves at a power density of 10 mW/cm^2 result in a rate of heating that is well within his ability to regulate his temperature, at least under normal environmental conditions. If the 2450-MHz microwave field had a power density of 100 mW/cm^2, the man would be absorbing energy at a rate near 500 watts and the resulting dose rate would be 5 mW/g. This dose rate is within man's regulatory limits for short periods of exposure, but is approaching a dangerous level if the man is performing vigorous work, is overinsulated by clothing, or is in an environment in which the temperature or humidity is so high as to preclude effective cooling by evaporation and conduction.

A final topic of interest lies in what commonly are called "hotspots." Irrespective of the kind of electromagnetic field in which an absorbing body is placed--that is, whether the propagating wave has a fixed polarization (E and H fields remain in the same planes with respect to the earth's horizon), an elliptical polarization (E and H fields rotate continuously around the line of propagation), or is complexly mixed in a waveguide or in a multimodal cavity (for example, in a microwave oven)--the rule is that the energy is not uniformly absorbed. Some regions of the body absorb more energy than others. At a frequency of 900 MHz, for example, radiation of a solid sphere that is constructed to model the human head results in a marked concentration of energy at the center of the sphere. Radiation at other frequencies of bodies of the same or differing shape typically results in greater capture of energy near the proximal surface, with the depth of penetration increasing, as mentioned before, at longer wavelengths. Geometrically irregular bodies like that of the human being tend to capture more energy at places of marked anatomical transition, for example, where neck and shoulder meet, at the armpit, and at the crotch. Whether a concentration of energy is sufficient to result in an excessive elevation of temperature is a function of many variables: the power density, polarization, and frequency of radiation; movement and orientation of the radiated body; and the rate at which blood flows through and cools the radiated tissue. In general, at low to modest power densities, say from 1 to 10 mW/cm^2, cooling of tissues by blood is sufficiently rapid that an excessive rise of temperature probably will not occur. However, if the body is stationary in a field of fixed polarization, the continuous concentration of electromagnetic energy at some locus is an <u>electrical</u> hot spot. If there are athermal effects at low levels of electromagnetic radiation--effects unrelated to thermal flux, thermal gradients, or rise of temperature--they might well arise from <u>electrical</u> hotspots in, say, the sensitive nervous tissues of heart or brain. One hastens to add, however, that while electrical hotspots can and do occur in a biological body during radiation, no one has ever isolated them experimentally in a living animal in the sense of demonstrating them as an exclusive cause of some biological effect.

Appendix A is concluded at this point; the reader may wish to consult the glossary of Appendix B before proceeding to the review.

APPENDIX B

GLOSSARY OF BIOPHYSICAL TERMS*

[Energy] Dose: The quantity of electromagnetic energy in joules that is imparted per unit of mass to a biological body. In formal use, the unit of mass is the kilogram (2.2 lb) and the dose is stated as joules per kilogram (J/kg). For convenience in working with small animals or with small samples of tissue, many researchers prefer to use joules, millijoules, or even microjoules per gram (J/g, mJ/g, or μJ/g) as working units. Dose is synonymous with "Specific Absorption" (SA), q.v.

[Energy] Dose Rate: The amount of electromagnetic energy that is imparted per unit of mass and per unit of time to a biological body, i.e., (formally) watts or joule-seconds per kilogram (W/kg) or (informally) watts or milliwatts per gram (W/g or mW/g). Synonymous with "Specific Absorption Rate" (SAR), q.v.

Continuous Wave (CW): Refers to an unmodulated electromagnetic wave. When a wave is abruptly turned "on" and "off," the resulting burst is referred to as a pulsed wave.

Far and Near Fields: The E and H fields of an electromagnetic wave that is propagating in a uniform medium are always at right angles to each other and to the line of propagation; however, waves near an emitting source are complex in the sense that relative strengths of E and H fields

* Medical terminology is not covered in the glossary as definitions are readily obtained from a standard dictionary.

can each vary greatly. A given body in the near field may therefore absorb little or much energy. Beyond the near field, i.e., in the far field, the relative strengths of E and H fields do not change relative to each other (although their absolute strengths diminish as distance from a point source increases).

Field Force: The electric field of a propagating electromagnetic wave will introduce a force on any charged atom (ion) or a polarized molecule such as water. The force is akin to that observed when one "charges" a rubber comb and picks up pieces of paper. Like charges (when two objects are both positive or are both negative) repel; opposite charges attract. The amount of field force introduced by a microwave field in a biological body is relatively very small, but is much stronger than that produced by radiation pressure (q.v.).

Free Field: A free (or open) field is generally considered to be an electromagnetic wave that is propagating in a vacuum or in air.

Giga: Prefix denoting billion(s), i.e., 1,000,000,000 or 10^9.

Hertz (abbrev., Hz): The cyclical rate at which a wave of energy rises from zero to maximum in the positive direction, falls past zero to reach a maximum in the negative direction, and then returns to zero; equivalent to frequency in cycles per second.

<u>Hotspot</u>: Electromagnetic waves are seldom, if ever, absorbed uniformly by a biological body. Greater uniformity of absorption over time can occur if a radiated animal moves or is moved about in the field of a plane wave, if the animal is radiated in a well-stirred multimodal cavity (microwave oven), or if it is radiated in an elliptically polarized field. Especially for the case of an immobilized animal in a plane-wave field, concentrations of energy will occur that are called <u>electrical</u> hotspots. If the field is sufficiently intense to overcome local cooling by flow of blood through affected tissues, a <u>thermal</u> hotspot will also occur.

<u>Joule</u>: Under the International System, the basic unit of all forms of energy. As a thermal unit, one joule equals 0.239 calories. Since the calorie is defined as the energy required to heat one gram of water from 4 to 5°C, 4.184 joules is the equivalent of one calorie.

<u>Kilo</u>: Prefix denoting thousand(s), i.e., 1000 or 10^3.

<u>Mega</u>: Prefix denoting million(s), i.e., 1,000,000 or 10^6.

<u>Modulation</u>: When a continuous series of waves of electromagnetic energy is modified by pulsing, or by varying its amplitude, frequency, or phase, the waves are said, respectively, to be pulse-, amplitude-, frequency-, or phase-modulated. In order to convey information by radiating electromagnetic energy, it must be modulated.

<u>Multipath Radiation</u>: In contrast with a so-called plane wave, which flows in a straight line through space, an area or volume where electromagnetic waves arrive from different directions because of reflection or multiple sources is said to be the site of multipath radiation. The cavity of a microwave oven exemplifies the case of <u>intended</u> multipath radiation.

<u>Plane Wave</u>: The wave emanating from a point source is an expanding sphere. A segment of the wave at a great distance (with respect to wavelength) from the source may have little curvature relative to the dimensions of a small target and can therefore be treated as a moving plane.

<u>Point Source</u>: A source of radiation that is small in size with respect to its distance from a radiated target. The "inverse-square law" holds for a point-source radiation, i.e., the intensity of the field decreases rapidly, as a function of the square of the distance from the source.

<u>Polarization</u>: The E and H fields that comprise a propagating electromagnetic wave may be fixed in relation to the earth's horizon, or they may rotate. By convention, the vector of the E field is related to the earth's horizon: if the two are perpendicular, the wave is said to be vertically polarized; if parallel, horizontally polarized. When the E and H fields are continuously rotating with respect to the horizon, the wave is said to be elliptically polarized.

Power: The quantity of energy per unit of time that is generated, transferred, or dissipated. The unit of power, the watt (W), is defined as one joule per second (J/s).

Power Density: The quantity of electromagnetic energy that flows through a given area per unit of time. The quantity of energy is complexly related to the strengths of the E and the H fields. Formally, power density is specified in watts per square meter (W/m^2), but by tradition it is usually expressed in milliwatts per square centimeter (mW/cm^2). The power density of energy that is radiated by a source is technically termed "radiance," while that of energy incident on a body is termed "irradiance." In common usage, power density is synonymous with "irradiance," i.e., it is taken to mean the time rate at which electromagnetic energy is incident on a body per unit of surface area.

Radiation Pressure: All propagating electromagnetic waves exert a very slight pressure on an absorbing object. The vane radiometer, which has black (absorbing) surfaces on one side and polished metal (reflecting) surfaces on the other side of its vanes, therefore rotates when illuminated by an intense light. Radiation pressure differs from a field force (q.v.) in that it is produced on all absorbing objects.

[Electrical] Resonance: A metal conductor or a biological body in a free field will absorb energy maximally when the E field of the incident electromagnetic wave is parallel to the conductor's or body's long axis and the electrical length of either is one-half the wavelength of the incident radiation. The electrical length of most biological bodies is about 80% of the physical length. The case of maximal absorption is technically known as "resonance."

Scatter: When an electromagnetic wave is incident on a body, the energy it carries may be absorbed or it may be reflected, refracted, or diffracted from the body. "Scatter" refers collectively to all components of non-absorbed energy. Unlike mechanical reflection, where energy is exchanged between two colliding bodies, virtually no energy is imparted to a body by an electromagnetic wave unless it is absorbed.

Specific Absorption (SA): The quantity of electromagnetic energy in joules that is absorbed per unit of mass of an absorbing body; exposed formally in joules per kilogram (J/kg); often, informally as millijoules or joules per kilogram (mJ/g or J/g). Synonymous with (energy) dose, q.v.

Specific Absorption Rate (SAR): The quantity of electromagnetic energy that is absorbed by a body per unit of mass during each second of time; expressed formally in watts per kilogram (W/kg); often, informally, as milliwatts or watts per gram (mW/g or W/g). "Specific Absorption Rate" is being considered by the National Council on Radiation Protection and Measurements as the official nomenclature for expressing the dose rate of radio-frequency electromagnetic radiations. Synonymous with (energy) dose rate, q.v.