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Project Summary

Responses of Airborne Biota to Microwave Transmission from Satellite Power System (SPS)

Studies were conducted to determine whether 2.45 GHz microwave radiation (as would be produced by the proposed Satellite Power System) constitutes a hazard to exposed avian species or influences their survival. Several species of birds were used to study a number of endpoints: aversion/attraction to the microwave field, change in migratory orientation, social interactions, lethality, thermoregulatory responses, molt, foraging behavior, nesting and reproduction, and effect on bird flight. In several cases the birds responded simply to an additional thermal insult. Some of the effects found could alter the survivability of the birds if sufficiently high microwave fields are encountered. For a few endpoints, including foraging behavior, migratory orientation and social interaction, it was not clear if the modified response was thermally based. However, these changes were judged to be small and probably not critical to survival.

This Project Summary was developed by EPA's Health Effects Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

In an effort to find a reliable pollution-free energy source as an alternative to fossil fuels, the Department of Energy has actively examined a number of possible energy sources. One such source involves collecting the energy of the sun by a network of satellites and transmitting it in the form of microwave energy (2.45 GHz) to rectennas on the earth's surface. In assessing the environmental impact of this proposed Satellite Power System (SPS), the effects of microwaves on airborne biota is an important consideration. The focus of this report is on the avian species since birds are commonly found in areas likely to be selected as rectenna sites. Further, their complete freedom of movement precludes preventing their exposure during flights across the area or when landing on the rectenna.

The goal of this program is to determine whether microwave irradiation adversely alters a wide range of complex avian behaviors that are essential to their survival. Effects of 2.45 GHz microwaves have been studied extensively in mammalian species, e.g., rats, mice, rabbits and monkeys, but very little information is available for birds. Avian species, generally, have higher rates of metabolism (especially during flight), stand on two feet and have an elongated neck that increases the amount of isolation between the head and thorax. All of these anatomical features can be expected to increase the susceptibility of birds to hyperthermia, vestibular and neuromuscular dysfunction as well as more subtle altered behaviors, e.g., inappropriate migratory behavior due to interference with normal astronomical or geomagnetic clues.

In this study the experiments were designed to provide, where possible, dose-response data for a variety of different migratory and non-migratory behavioral and physiologic endpoints. Non-migratory behaviors include breeding, flocking, feeding and social interaction among birds. Effects of microwaves on migratory behavior were evaluated by comparing the orientation of irradiated and non-irradiated birds (that normally migrate) during the time of seasonal migrations. Finally, experiments were carried out to determine if birds are able to perceive and respond to microwave irradiation, the relationship between dose and changes in body temperature under a variety of ambient conditions, and the relationship between dose and lethality.

Summary Text

Exposure Facilities

Microwave exposures were conducted in both indoor (laboratory) and open field areas. The microwave irradiation facilities were designed to provide plane-wave illumination with a power density variation of ± 0.5 dB maximum over the cages, and/or flight area, during all acute and short-term chronic studies. The radiating source for all experiments was a standard-gain horn which provided linearly polarized radiation.

The acute-exposure field studies (at Manomet Bird Observatory) required only the illumination of a 15 x 15 x 15 cm microwave-transparent cage. Thus, horn-to-cage spacing of 1.37 meters provided the required power density uniformity using a simple overhead mounted horn. By varying the horn-to-platform spacing, and by adjusting the microwave power generator control, the power density at the surface of the platform could be varied from about 1 mW/cm^2 to over 100 mW/cm^2. For orientation studies, the horn was placed on the ground and the subjects were raised on a microwave-transparent platform 2.74 meters above the horn.

The Arthur D. Little (laboratory) facility required the uniform, simultaneous illumination of multiple cages of approximately 1.0 x 1.0 x 0.6 m each. Four such cages were uniformly illuminated with a horn-to-cage spacing of at least 7.3 meters. At this spacing, a power density of 25 mW/cm^2 was acheived with a total radiated power of about 4.6 kW. The Cober S6F generators, which are 6 kW microwave power sources, provided adequate power margin. Measurements indicated the presence of 180 Hz amplitude modulation which may reach 60 percent at low generator output, <1 kW, but declines to about 40% above 3 kW output.

The horns were positioned for overhead illumination. This configuration, shown in Figure 1, yielded a power density

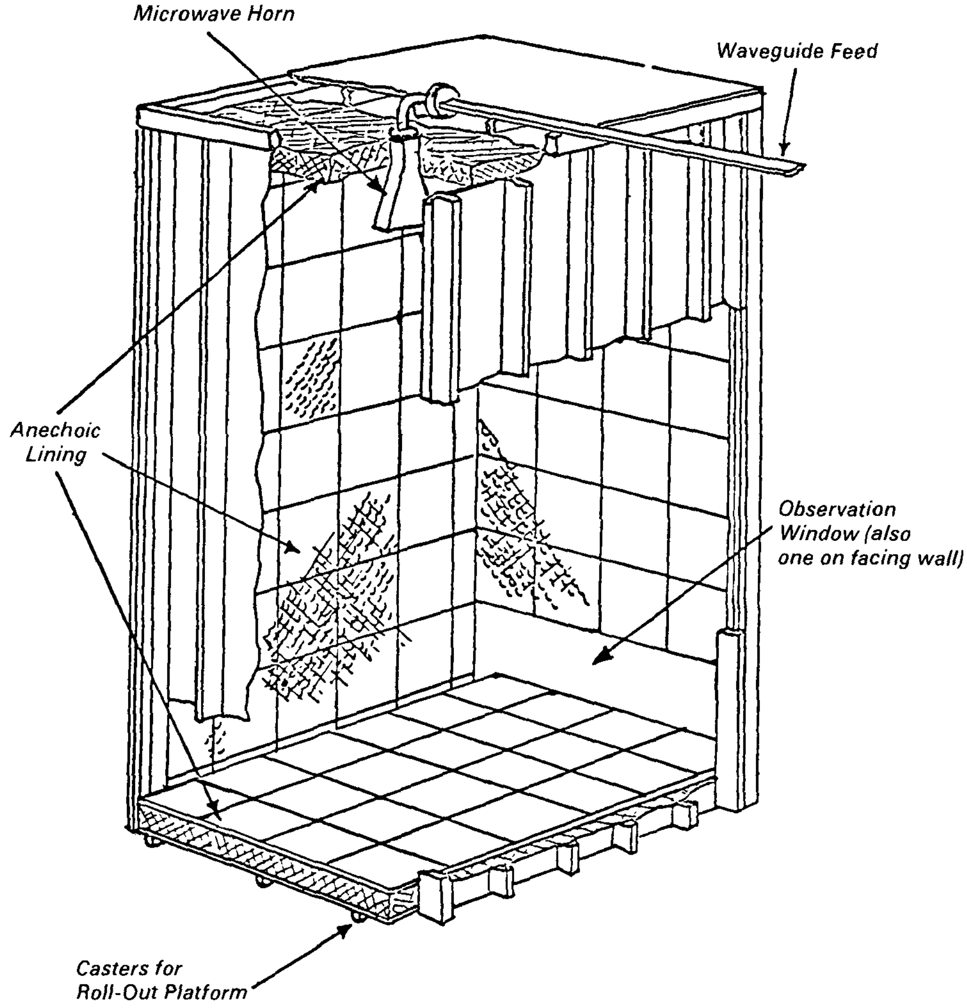


Figure 1. *Microwave irradiation chamber—final design.*

variation of ± 1 dB over a floor space of 4' x 6'. A total of five irradiation chambers were used, together with two replicas for housing and heating the control birds. Three of the chambers were operated at 0.1, 1.0 and 10 mW/cm^2, for chronic studies. Another chamber was operated at 25 mW/cm^2 for subchronic exposure studies while the fifth was used in conjunction with the wind tunnel and for those studies involving acute exposures.

An open-jet wind tunnel for study of birds in flight was designed and built. The wind tunnel and flight chamber configuration (Figure 2) consisted of two fans, placed side by side, followed by a honeycomb flow straightener, a contraction nozzle, a second flow straightener, the working chamber, and finally an outlet diffuser. Upstream fans were used so that the air velocity in the flight chamber could be controlled by restricting the air flow to the fans through the use of blocking lattice-works of different open area placed in front of the air inlet. This technique allowed the use of constant speed fan motors rather than the variable speed motors used in tunnels with downstream fans.

For flight training and exposure of Budgerigars, a 1.0 x 0.6 x 0.6 m cage with four solid transparent sides and two screened ends was placed in the airstream of the wind tunnel approximately 0.54 m from the outlet honeycomb flow-straightener. The flow was adjusted to provide a velocity of 37 km/h at the level of the training perch, and a variation of $<$ 2.4 km/h was measured over the remainder of the cage.

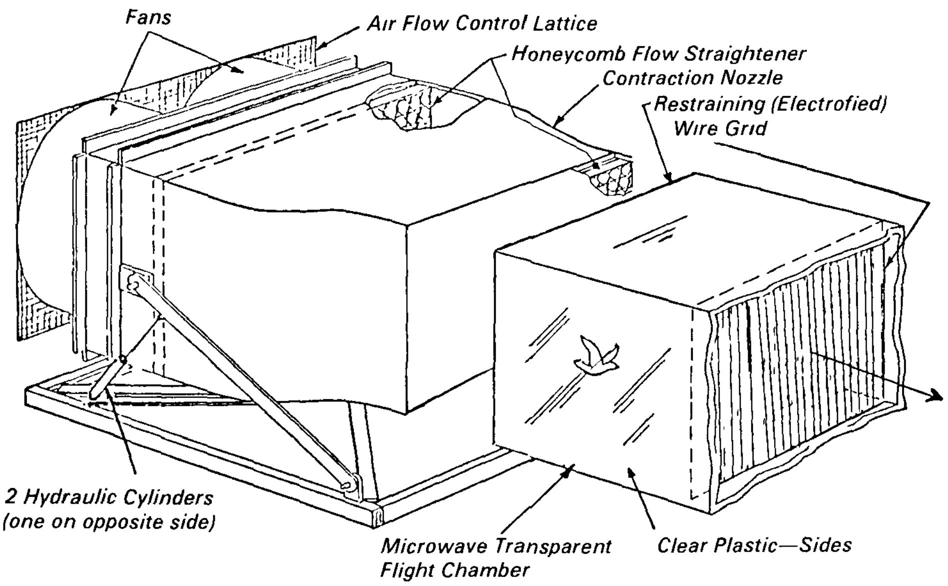


Figure 2. *Wind tunnel and flight chamber.*

Aversion/Attraction

These experiments determine if birds can perceive the presence of microwave irradiation by observing whether House Finches (*Carpodacus mexicanus*) and Blue Jays (*Cyanocitta cristata*) exhibit an attraction or an aversion to the field when exposed to power densities of 10, 25, and 50 mW/cm^2.

At all three power densities, House Finches showed non-random movement within the test cage based on the number of times that birds were observed in the microwave-irradiated or in the non-irradiated areas. At 10 mW/cm^2, House Finches exhibited behavior consistent with attraction to the field by perching more often in the exposed areas of the cage during microwave irradation than in the shielded areas. House Finches, at a power density of 25 or 50 mW/cm^2, were observed to perch more frequently in the non-irradiated areas of the cage, suggesting an aversion to the microwave field (Table 1). Blue Jays also showed non-random movement within the test cage at all exposure levels. Birds were observed in the exposed areas of the cage significantly fewer times than in the microwave shielded areas (Table 2). These results indicate that Blue Jays exhibit an aversion to microwave irradiation at all three power densities. Based on these results, birds exposed to microwave irradiation at a rectenna site would appear to be capable of responding to the field by either avoidance or attraction depending upon the power density of the field and the ambient conditions of temperature, humidity, wind speed and solar radiation.

Thermoregulatory Behavior

To investigate the relationship between microwave exposure and the onset and duration of patterns of thermoregulatory behaviors, a series of experiments were carried out with House Finches (small bird - 17 to 24 g) and Blue Jays (medium-sized bird - 75 to 100 g) at each of five power densities: 0.1, 1, 10, 25 and 50 mW/cm^2. Cages were arranged so that the birds sitting on the perch were oriented perpendicular to the E vector of the microwave field. To quantify thermoregulatory behavior, birds were observed for one or more of four distinctive postures which represent behavioral responses to increasing thermoregulatory stress.

Cloacal temperature was used as a measure of body temperature. Each bird's temperature was monitored continuously before, during and after 10 minutes of exposure to microwave radiation. Ambient temperatures generally remained within ± 2° (20°C) and there was essentially no air movement (wind) over the restrained birds.

House Finches and Blue Jays show behavioral responses to microwave-induced heat stress which are good indicators of increased cloacal temperatures during microwave irradiation. For both species, studies of behavior and cloacal temperature indicate that there is no observable thermoregulatory stress induced by microwave irradiation of 10 mW/cm^2 or less. At 25 mW/cm^2 the larger Blue Jays show more signs of stress than House Finches. At 50 mW/cm^2, both House Finches and Blue Jays exhibit signs of thermal stress and show significant elevation in cloacal temperature during 10 minutes of irradiation. Blue Jays showed the larger behavioral response (Figure 3) suggesting that they must expend more energy for heat dissipation than House Finches for similar rises in cloacal temperature. Both species experienced significantly greater elevation in cloacal temperature when the longitudinal axis of the body was oriented parallel to the E vector compared

Table 1. *Aversion/Attraction of Birds to Microwave Fields - House Finches*

		**Number of times House Finches were observed in Area A or B*		
Power Density	*Cage Area*	*Pre-exposure*	*Exposure*	*Post-exposure*
a) 10 mW/cm^2	*A Shielded*	*1104*	*906*	*861*
	B Exposed	*792*	*992*	*912*
	$\bar{X}$ ambient temperature = 23.4°C; $\bar{X}$ relative humidity = 72%			
	X^2 = 51.3, df = 2, $p < 0.01$			
b) 25 mW/cm^2	*A Shielded*	*876*	*1133*	*959*
	B Exposed	*889*	*691*	*735*
	$\bar{X}$ ambient temperature = 22.4°C; $\bar{X}$ relative humidity = 68%			
	X^2 = 56 98, df = 2, $p < 0.05$			
c) 50 mW/cm^2	*A Shielded*	*860*	*993*	*925*
	B Exposed	*1012*	*721*	*806*
	$\bar{X}$ ambient temperature = 21.1°C; $\bar{X}$ relative humidity = 47%			
	X^2 = 53 05, df = 2, $p < 0.01$			

**The total number of observations of House Finches in a symmetrical cage with two quadrants shielded from, and two quadrants exposed to, microwave irradiation at 10, 25, and 50 mW/cm^2. The null hypothesis being tested with a X^2 analysis (3x2 X^2 contingency tables, df = 2) is that the frequency of observations in the shielded and exposed areas of the cage is independent of the pre-exposure, exposure, and post-exposure periods. Observations were made every six seconds during the last ten minutes of each 30-minute period (pre-exposure, exposure, and post-exposure periods). Birds were observed continuously through a pre-exposure, exposure and post-exposure period. Each of 10 birds was tested twice.*

Table 2. *Aversion/Attraction of Birds to Microwave Fields - Blue Jays*

Power Density	*Cage Area*	**Number of times Blue Jays were observed in Area A or B*		
		Pre-exposure	*Exposure*	*Post-exposure*
a) 10 mW/cm²	*A Shielded*	*875*	*961*	*996*
	B Exposed	*926*	*805*	*678*
	$\bar{X}$ ambient temperature = 19.1°C; $\bar{X}$ relative humidity = 44%			
	X^2 = 41.76, df = 2, $p < 0.01$			
b) 25 mW/cm²	*A Shielded*	*716*	*1070*	*708*
	B Exposed	*887*	*661*	*766*
	$\bar{X}$ ambient temperature = 19.5°C; $\bar{X}$ relative humidity = 50%			
	X^2 = 110.58, df = 2, $p < 0.001$			
c) 50 mW/cm²	*A Shielded*	*791*	*1113*	*1009*
	B Exposed	*947*	*663*	*762*
	$\bar{X}$ ambient temperature = 19.6°C; $\bar{X}$ relative humidity = 53%			
	X^2 = 108.22, df = 2, $p < 0.01$			

**The total number of observations of Blue Jays in a symmetrical cage with two quadrants shielded from, and two quadrants exposed to, microwave irradiation at 10, 25, and 50 mW/cm². The null hypothesis being tested with a X^2 analysis (3x2 X^2 contingency tables, df = 2) is that the frequency of observations in the shielded and exposed areas of the cage is independent of the pre-exposure, exposure, and post-exposure periods. Observations were made every six seconds during the last ten minutes of each 30-minute period (pre-exposure, exposure, and post-exposure periods). Birds were observed continuously through a pre-exposure, exposure, and post-exposure period. Each of the 10 birds was tested twice.*

to perpendicular orientation. At 50 mW/cm², parallel orientation proved lethal for some House Finches after 9 minutes of irradiation even though the ambient temperature did not rise above 24°C.

Foraging

Behavior involving the ability of birds to search for and manipulate food was studied in the White-throated Sparrow (*Zonotrichia albicollis*). This experiment was designed to quantify the impact of the SPS system on the foraging behavior of a small avian species by using a standard optimal foraging laboratory study technique. Three basic experiments were performed: acute multiple (brief) exposures conducted at power densities of 0.0, 0.1, 10.0 and 25.0 mW/cm² for 2, 20 or 200 minutes; 7-day exposures conducted at power densities of 0.0, 0.1, 1.0, 10.0, and 25.0 mW/cm²; and 4-week exposures conducted at power densities of 0.0 and 25.0 mW/cm².

For the acute multiple exposures, foraging efficiency was found to be influenced by changes in ambient temperature and relative humidity, but no acute effects were found that correlated with dose levels of microwave exposure. Seven-day continuous exposures resulted in no significant differences in foraging behavior between sham- and microwave-treated birds. Significant differences in foraging efficiency were found among birds receiving different power densities but, again, the differences were not found to be dose-related. Birds exposed in the 4-week studies showed no significant differences in foraging efficiency between pre-exposure, exposure, and post-exposure periods despite significant differences in ambient room and exposure chamber temperatures. When compared to (parallel) sham control birds, microwave-treated birds showed a significantly lower search efficiency during the post-exposure period; however, this one difference should not indicate differential survival between control and microwave-treated birds.

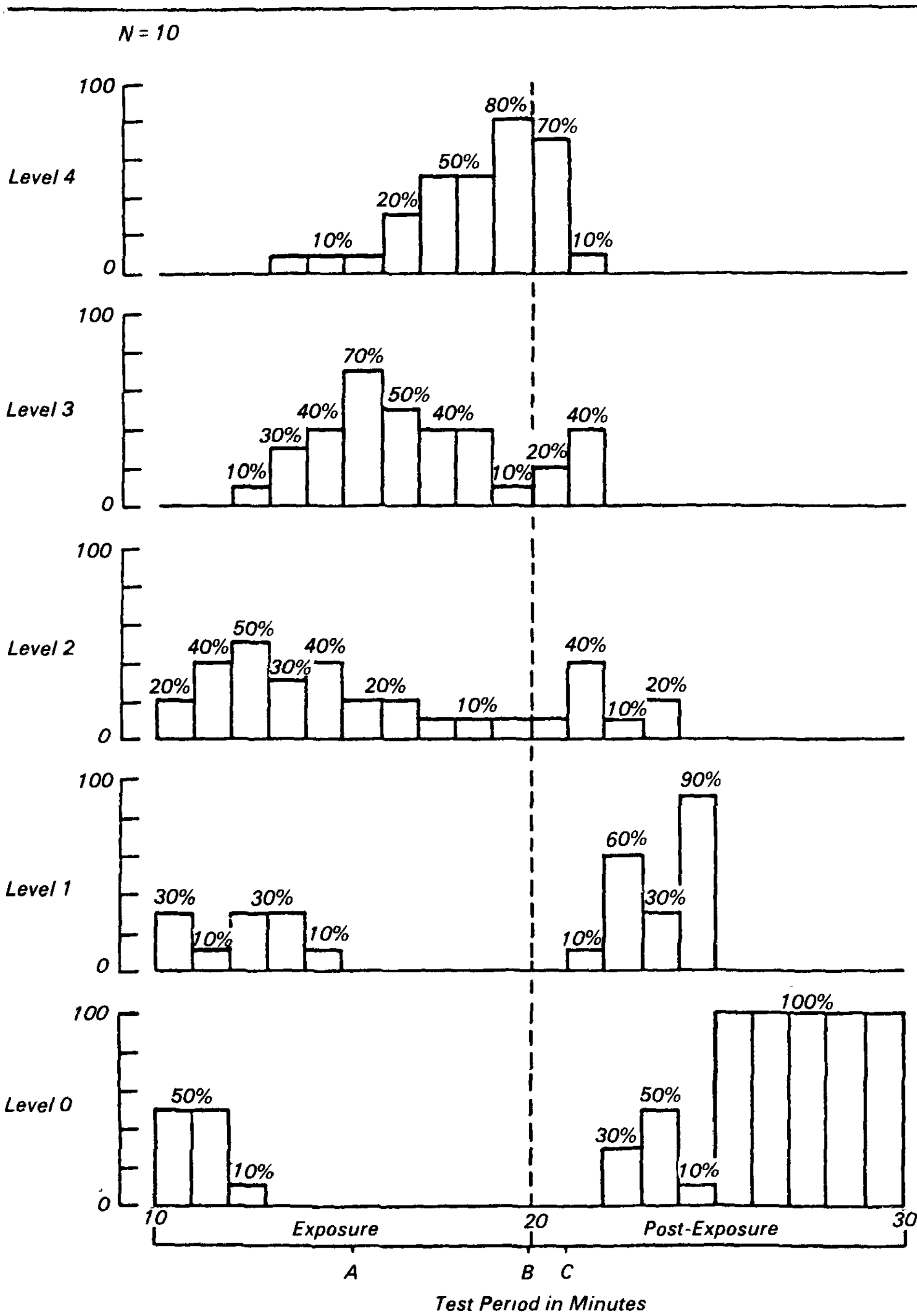
Orientation

These experiments were carried out to determine whether microwave irradiation disrupts the ability of birds to mitigate properly. Associated with premigratory preparation is an increased nocturnal activity. This nocturnal restlessness, known as "Zugenruhe" may, in captivity, have a directional component which reflects the true direction of the intended migration. This research was designed to answer the questions of whether exposure to microwaves impairs premigratory restlessness, influences the ability of a bird to maintain directional movements during migration, or alters the chosen direction of orientation. The procedures developed by Emlen and Emlen (1966) were used to study avian orientation. The "Emlen cage" consists of an inverted cone made of polystyrene (for microwave transparency) lined with blotting paper. The narrow base to the cage is centered around an ink pad while the top of the cage is covered by a transparent material, usually plastic hardware cloth. The caged bird·therefore has a clear view of th night sky and will leave an ink footprint o the blotting paper each time it makes a attempt to escape. This record of th bird's activity provides data on th directional preference of that bird.

Microwave exposure did not chang the quantity of nocturnal activity, o "Zugenruhe," exhibited by White-throate Sparrows. Approximately one-third of a birds tested maintained direction behavior, regardless of cloudcover o other environmental variables. Micro waves did not affect the ability of birds t maintain oriented movements. Als microwaves (Figure 4) did not affect th specific directional preferences of non randomly orienting birds grouped unde various cloudcover conditions. The non treated birds, however, showed thei movements to be non-randomly distri buted on nights with clear skies and on a nights combined. The same distribution of microwave-treated birds were found t be random. Therefore, while the mea angles, or preferred directions wer statistically the same, the microwave treated birds showed a greater dispersio of chosen directions around the mear This is a significant finding which can b attributed to microwave exposure. Hence we conclude that although there was n significant change in directional prefe ence by birds under exposure to micrc waves at the power densities projecte for use by the SPS, the increase dispersion of those treated birds repre sents an influence which must b considered as potentially hazardous t migratory birds in the absence of mor definitive experimental data.

Bird Flight

The average size of many commo avian species (5 cm in length) is such th many birds should have a maximu microwave absorption efficiency at 2.4 GHz. During prolonged flight birds ar often near the limit of their ability dissipate metabolic heat. Therefore th effect of the additional heat load impose by a microwave field was studie Budgerigars were trained to fly in a win tunnel and exposed to microwave radia tion at 50 mW/cm². Each experiment subject was flown for two 10-minut periods a day, a control flight and microwave flight with a minimum of 3 minutes of rest between the flights. I normal flight, the bird's legs wer observed to be aligned close to the bod and parallel to its axis. Under condition of thermal stress or hyperthermia, th bird dropped its legs to expose its toes an



(A = five minutes after onset of irradiation; B = ten minutes after onset of irradiation; C = one minute after termination of irradiation.)

Figure 3. *Percentage of Blue Jays showing stress at each of the five thermoregulatory response levels during and after irradiation with 50 mW/cm².*

tarsa-metatarsus to the airstream. In addition, during thermal stress, birds flew with their mouths open (gaping). If a Budgerigar showed evidence that it was clearly unable to maintain flight for the full 10 minutes, the experiment was terminated. Thermoregulatory behavior after flight was ranked according to severity.

When irradiated at 50 mW/cm^2, birds began to show high levels of stress at ambient temperatures above 26°C and demonstrated an inability to fly for 20 mintues at air temperatures above 32°C. After exposure at air temperatures above 33°C, Budgerigars required at least 10 minutes to recover fully after flight. At air temperatures above 28°C the birds irradiated during flight generally showed higher body temperatures than without exposure. Based on these data, a microwave field of 50 mW/cm^2 could impair bird flight in the field, forcing the bird to engage in thermoregulatory behaviors and land prematurely. The long post-flight cooling period might adversely affect a bird's ability to forage or escape predators. A 50 mW/cm^2 power density is approximately equivalent to an 8°C rise in ambient temperature to a flying Budgerigar.

Reproductive Behavior

In view of the likelihood of birds entering and nesting within the SPS rectenna site, it was essential to determine the effects of microwave irradiation on reproductive success. Bird behavior for six breeding pairs of Zebra Finches were characterized as random, maintenance, feeding, reproductive, aggressive or thermoregulatory. Birds exposed to continuous microwave radiation (25 mW/cm^2) were able to breed successfully. Although the irradiated pairs of Zebra Finches produced fewer eggs and fewer fertile eggs, there was no significant difference in the number of fledglings produced by the irradiated and control pairs of birds. This may simply show that the Zebra Finch already has the ability to compensate for environmental factors which may affect its reproductive success.

The effect of 25 or 50 mW/cm^2 microwave irradiation on embryonic development in bird eggs exposed when incubating parents are absent from the nest was studied by irradiating fertile Coturnix Quail eggs twice a day for 30 minutes throughout the 17-day normal incubation period (for this species). The hatchability of eggs irradiated by 25 mW/cm^2 did not differ from that of control eggs. No significant differences were observed in the rates of growth of chicks hatched from control and 25 mW/cm^2 exposed eggs during the first 26-28 days post-hatch nor from control and 50 mW/cm^2 exposed eggs during the first 15 days post-hatch. No evidence of teratogenesis was observed as indicated by the absence of deformed chicks hatched from eggs that had been irradiated at 25 or 50 mW/cm^2. Based on these data, microwave irradiation by 25 mW/cm^2 should not notably reduce egg hatchability in the field.

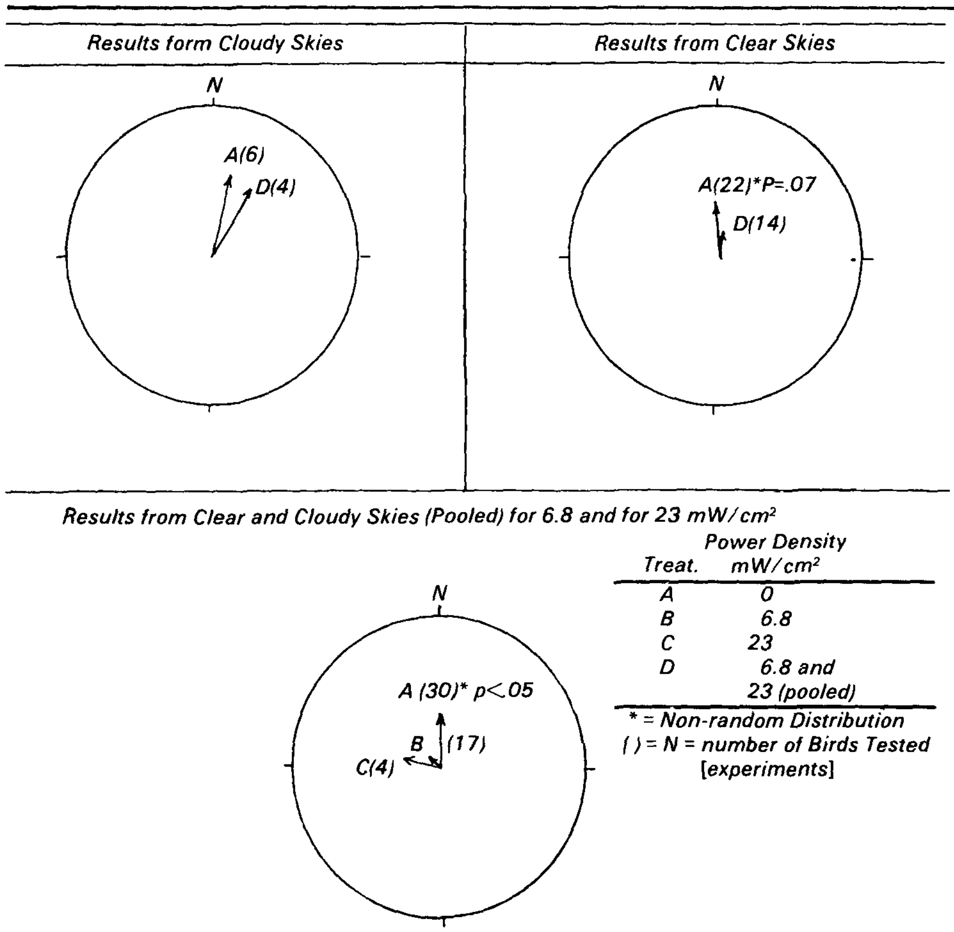


Figure 4. *Mean directions exhibited by groups of birds under various conditions of cloudcover and microwave exposure (6.8; 23 mW/cm²).*

Social Interaction

The White-throated Sparrow (*Zonotrichia albiocollis*) and the Dark-eyed Junco (*Junco hyemalis*) were studied to assess the effects of acute microwave radiation on the behavior and position of birds within a flock dominance hierarchy. Initial observations provided basic flock structure data and the dominance order within the flock. Encounters between birds were classified as either active agression or avoidance.

Initially one and later two birds from five-bird hierarchies were exposed. Ultimately, 17 birds from 12 flocks were exposed to 4 combinations of microwave power and duration, in addition to 3 sham control birds from 2 additional flocks. Although the irradiated birds maintained their positions in the hierarchies (with one exception), some appeared to have changed their level of aggression after exposure at 25 mW/cm^2. These changes, however, are not considered inconsistent with survival of birds at an SPS rectenna site.

Lethal Levels of Microwave Irradiation

The lethal level of microwave irradiation for the Dark-eyed Junco exposed at an ambient temperature of 7 to 13°C appears to be on the order of 150-160 mW/cm^2 over 7 ± 0.5 minutes based on exposures at 130, 150 and 160 mW/cm^2. Power densities of 100 to 130 mW/cm^2 for up to 20 minutes result in no observable signs of heat stress other than gaping. Exposure to near lethal levels of microwave irradiation results in stress-related behaviors that are characterized by gaping, panting, crouching and loss of muscular coordination or equilibrium. The rapid onset of gaping has been observed at all power levels from 25 mW/cm^2 to 160 mW/cm^2 beginning as soon as 30 seconds after the start of exposure.

Molt of Birds Exposed to Microwave Radiation

Molt was chosen as a sensitive indicator of the possible deleterious effects of microwave irradiation on the endocrine and autonomic nervous systems of birds. House Finches were studied to determine if continuous microwave exposure alters molting.

All control and exposed birds completed the molting process. The time required for the last half of molting was essentially the same for the controls and the birds exposed to 1 and 10 mW/cm^2. The rate of molting was slower in the two birds that were exposed to 25 mW/cm^2. Whether the slower rate of molting resulted from microwave exposure or some other variable (e.g., the birds used in these experiments had already started molting when trapped and the change in environment from the wild to the laboratory may have affected the molting process) will require additional study.

An examination of control birds and those exposed at 25 mW/cm^2 revealed no observable gross or histopathologic changes in any of the major organs that could be attributed to microwave treatment. Similarly, each bird was observed for changes in muscle tone, righting reflex, vestibular function, pupillary response to light, corneal opacity and response to pain (cornea). No differences were observed between control and irradiated birds.

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The complete report, entitled "Responses of Airborne Biota to Microwave Transmission from Satellite Power System (SPS)," (Order No. PB 84-141 191; Cost: $32.50, subject to change) will be available only from:
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