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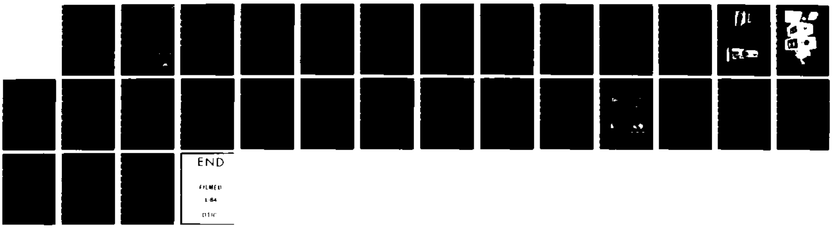

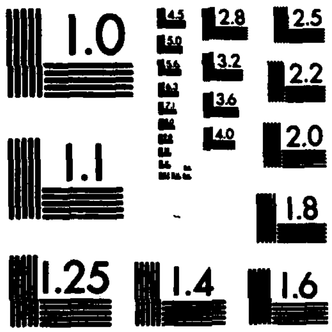
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Report USAFSAM-TR-83-19

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EFFECTS OF LONG-TERM LOW-LEVEL RADIOFREQUENCY RADIATION EXPOSURE ON RATS

VOLUME 3. SAR IN RATS EXPOSED IN 2450-MHz CIRCULARLY POLARIZED WAVEGUIDE

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Brooks Air Force Base, Texas 78235

NOTICES

This final report was submitted by the Bioelectromagnetics Research Laboratory, Department of Rehabilitation Medicine, School of Medicine, University of Washington, Seattle, Washington 98195, under contract F33615-80-C-0612, job order 7757-01-71, with the USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks AFB, Texas. Dr. Jerome H. Krupp (USAFSAM/RZP) was the Laboratory Project Scientist-in-Charge.

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The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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The average SARs for live rats exposed in 2450-MHz circularly polarized waveguides were estimated from the total system loss measured by five power meters and by the use of a correction factor representing the ratio between actual SAR (measured by twin-well calorimetry) and apparent SAR (measured by power meters) for various body masses and five orientations. In the waveguides, the average SAR changed less than threefold when the rats grew from 200 to 700 g and when they moved around in the cage. The ratio of peak to average SAR in the body of the rats was

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VOLUME 3. SAR IN RATS EXPOSED IN 2450-MHz CIRCULARLY POLARIZED WAVEGUIDE

INTRODUCTION

Much of the past work on chronic exposure of test animals involved the use of anechoic chambers, metal capacitor plates, or resonant cavities. With these methods, the energy coupled to each animal is a function of the group size, group orientation, and orientation of each animal within the group, as well as of the presence and orientation of water and food dispensers. In such cases, extrapolating the biological results from animals to humans is virtually impossible.

Guy and Chou (1975) and Guy et al. (1979) have respectively described a 915- and a 2450-MHz circularly polarized waveguide system for exposing a population of animals to a single energy source while maintaining relatively constant and quantifiable electromagnetic energy coupled to each animal. These exposure systems have been used successfully in our laboratory since 1975 for physiological and behavioral studies (Moe et al., 1975; Johnson et al., 1977; Lovely et al., 1977, 1978). The 2450-MHz exposure system produces a specific absorption rate (SAR) in rats that simulates the absorption produced in humans by exposure to 450-MHz radiofrequency radiation (RFR). Therefore, this system was selected for exposing 200 rats to electromagnetic fields throughout their lives (Guy et al., 1980). Since the SAR varies with the normal growth of rats from 150 g to 650 g, the SAR must be determined for various body weights. This report documents the dosimetric measurements on rats exposed in the 2450-MHz circular waveguide system.

METHODS

Exposure System

The exposure system consists of a number of independent waveguides so that each animal has its own exposure cell (Fig. 1). This is a relatively inexpensive and convenient method for exposing a sizable number of animals to RF energy from a single source. The individual waveguides allow the animals to be continuously exposed while unrestrained and living under normal laboratory conditions with access to food and water. Each exposure cell consists of a cylindrical waveguide that is excited by circularly polarized waves that provide relatively constant and easily quantified coupling of the fields to each animal regardless of its position, posture, or movement. Food and water are provided to the animals with negligible perturbation of the fields. The details of the design and operation of the waveguide have been described by Guy et al. (1979).

Apparent SAR Measurement

When an animal is placed in the waveguide (Fig. 1(b)) and is exposed to traveling waves by power fed into the terminal, P_{IN}, some power, P_A, will be absorbed by the animal; some, P_W, will be absorbed by the cage and the waveguide; some will be reflected in the form of both right-hand, P_{RR}, and left-hand, P_{RL}, circularly polarized waves that couple back to the probes on the feed section for the waveguide; and some, P_{TA} and P_{TB}, will be absorbed at the termination terminals. The reflected component P_{RR} can be measured at the reflecting arm of the bidirectional coupler placed between the source and the input probe as CP_{RR}, where C is the coupling coefficient of the bidirectional coupler. The reflected component P_{RL} can be measured directly at the other terminal of the feed transducer. The power level of the incident energy launching the right-hand circularly polarized waves can be measured at the incident wave terminal of the bidirectional coupler as CP_{IN}. The power level of energy transmitted beyond the animal can be measured at the terminals, P_{TA} and P_{TB}, of the termination transducer. The sum of power levels of energy absorbed by the animal, P_A, and the waveguide, P_W, can be obtained from the expression in Fig. 1(b) in terms of the known components of power transmitted to the various terminals of the transducers and the directional couplers. The measured power delivered to the exposure system was derived from five Hewlett-Packard model 432B power meters used to monitor the incident (approximately 300 W), reflected, and transmitted powers. The net energy delivered to the system was integrated by a microcomputer over the exposure period (15-20 s typical).

The apparent average SAR in the rats was calculated by dividing the total system loss ($P_A + P_W$) by the weight of the animal and was normalized to 1-W input power (P_{IN}) to the waveguide.

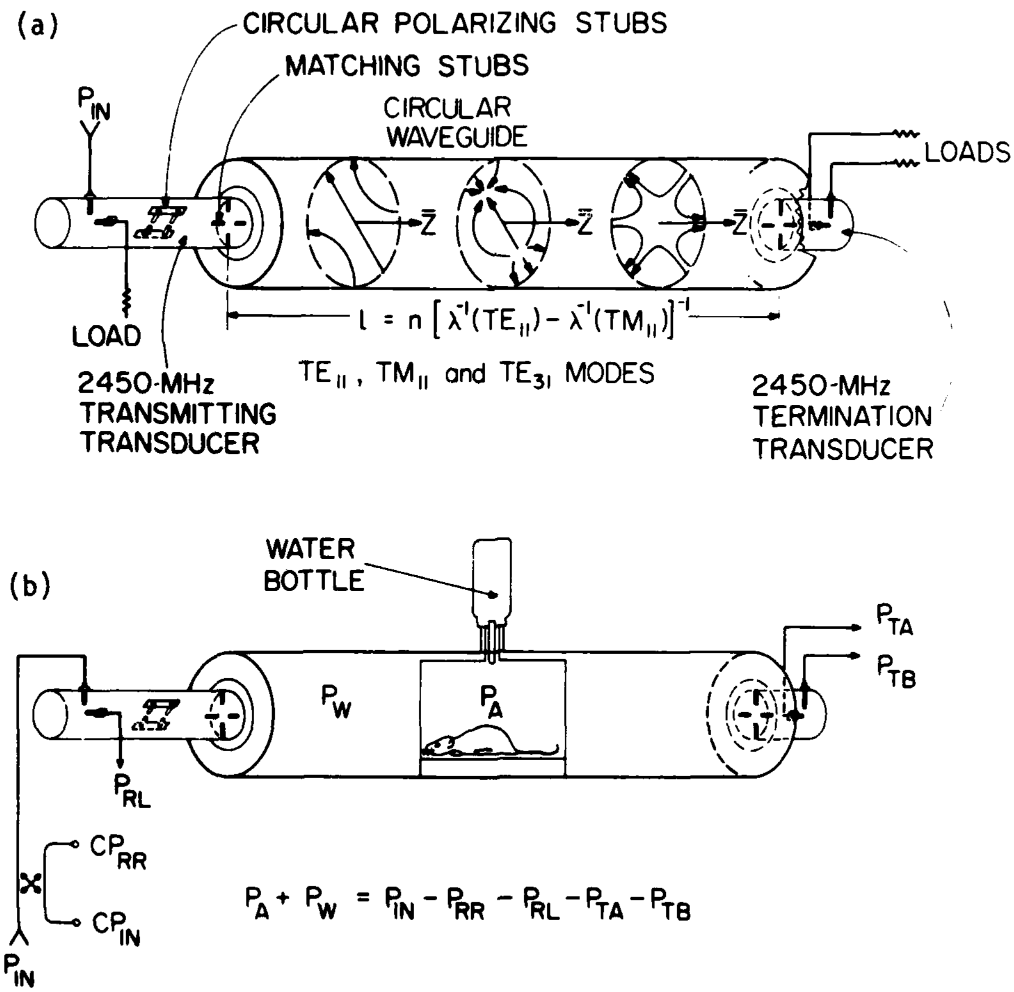

Figure 1. Operation of 2450-MHz exposure waveguide: (a) empty, (b) with animal.

Actual SAR Measurement

Twin-well calorimetry has been used by many investigators for measurement of the average SAR in laboratory animals exposed to electromagnetic fields (Phillips et al., 1975; Blackman and Black, 1977; Allen and Hurt, 1979; Cairnie et al., 1980). The operation of the twin-well calorimeter may best be understood from its construction.

The two brass cylinders in the back of Fig. 2(a), each large enough to hold an animal, illustrate the inner components of the calorimeter. Each cylinder is surrounded by an array of thermocouples attached to the outer wall and connected in series so that the individual voltages are additive. The right cylinder array, however, is connected to the left-cylinder array so that the voltages are subtractive. Thus, if both cylinders are at the same temperature, the total output voltage from the pair is zero. Any temperature difference between the cylinders would result in a net voltage output from the thermocouple arrays. The twin wells are surrounded by an oval cylinder (Fig. 2(b)) designed to be held at constant temperature by a circulating fluid. The air gaps between all cylinders are filled with foam (Seal Guard 184). Two completed calorimeters with inlet and outlet ports for the circulating fluid are shown in Fig. 3. Two sizes were used in this study: One had wells with internal dimensions of 20.3-cm length by 6.74-cm diameter and was used for the rats, which weighed between 100 and 650 g; the other had wells with 25.4-cm length by 9.8-cm diameter and was used for stabilization.

The two twin-well calorimeters were connected in series to a constant-temperature circulator (Fig. 4). The temperature of the circulating water was kept at 30.5°C. One calorimeter was used to stabilize the temperature of two rat carcasses of similar body weight; the other calorimeter was used to measure the microwave energy absorbed by the exposed carcasses. Pairs of rats of similar body mass were overdosed with 200 mg/kg (i.p.) of pentobarbital and placed in the stabilizing calorimeter for at least 7 h. The rats were then put in exposure and control waveguides; after a short, high-power exposure, they were immediately placed in the measuring calorimeter. The voltage output of the thermocouple array in the calorimeter was sampled by a Fluke 8005A

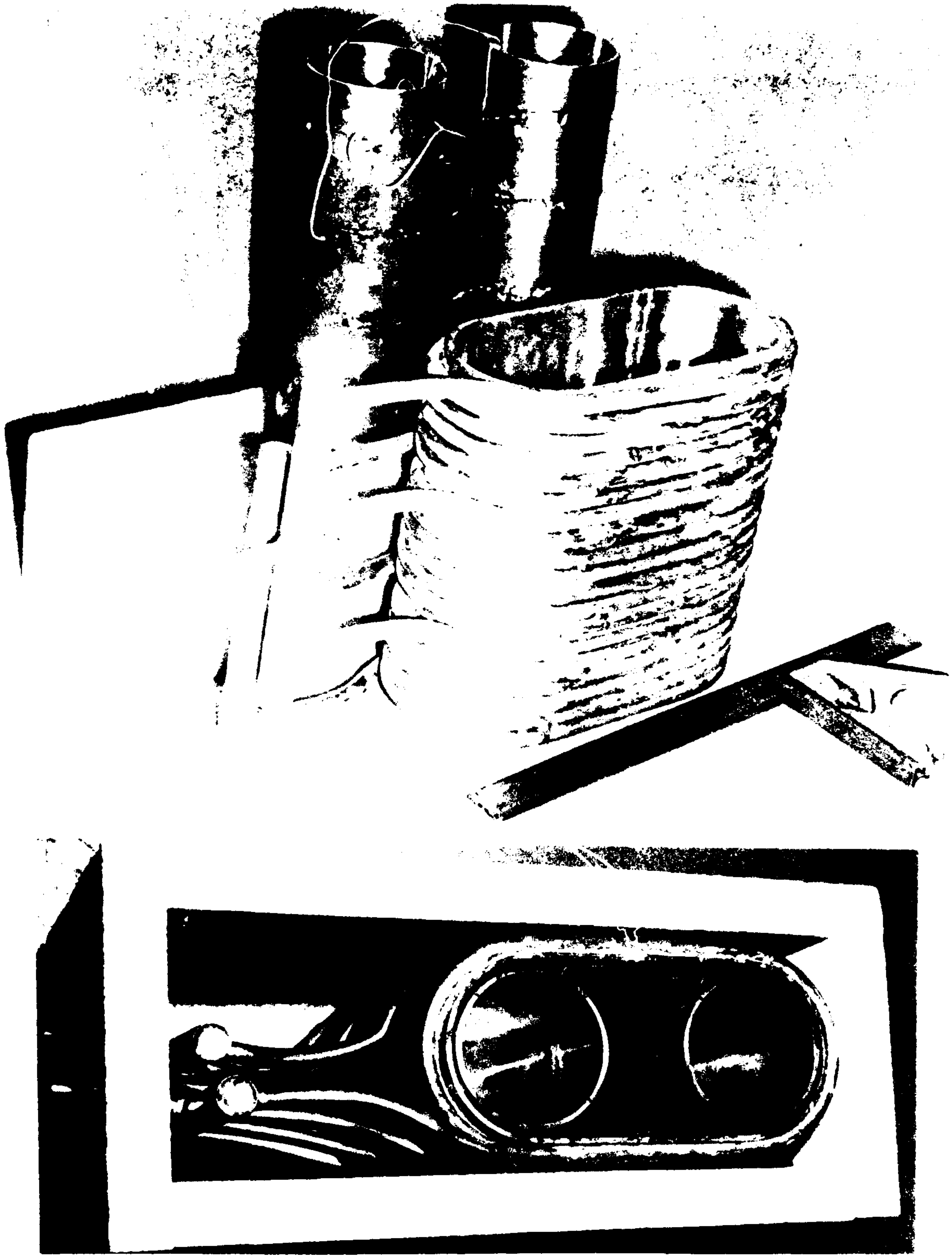

Figure 2. Twin-well calorimeter: (a) before enclosure; (b) before insulation is placed between the two cylinders and the outer cylinder.

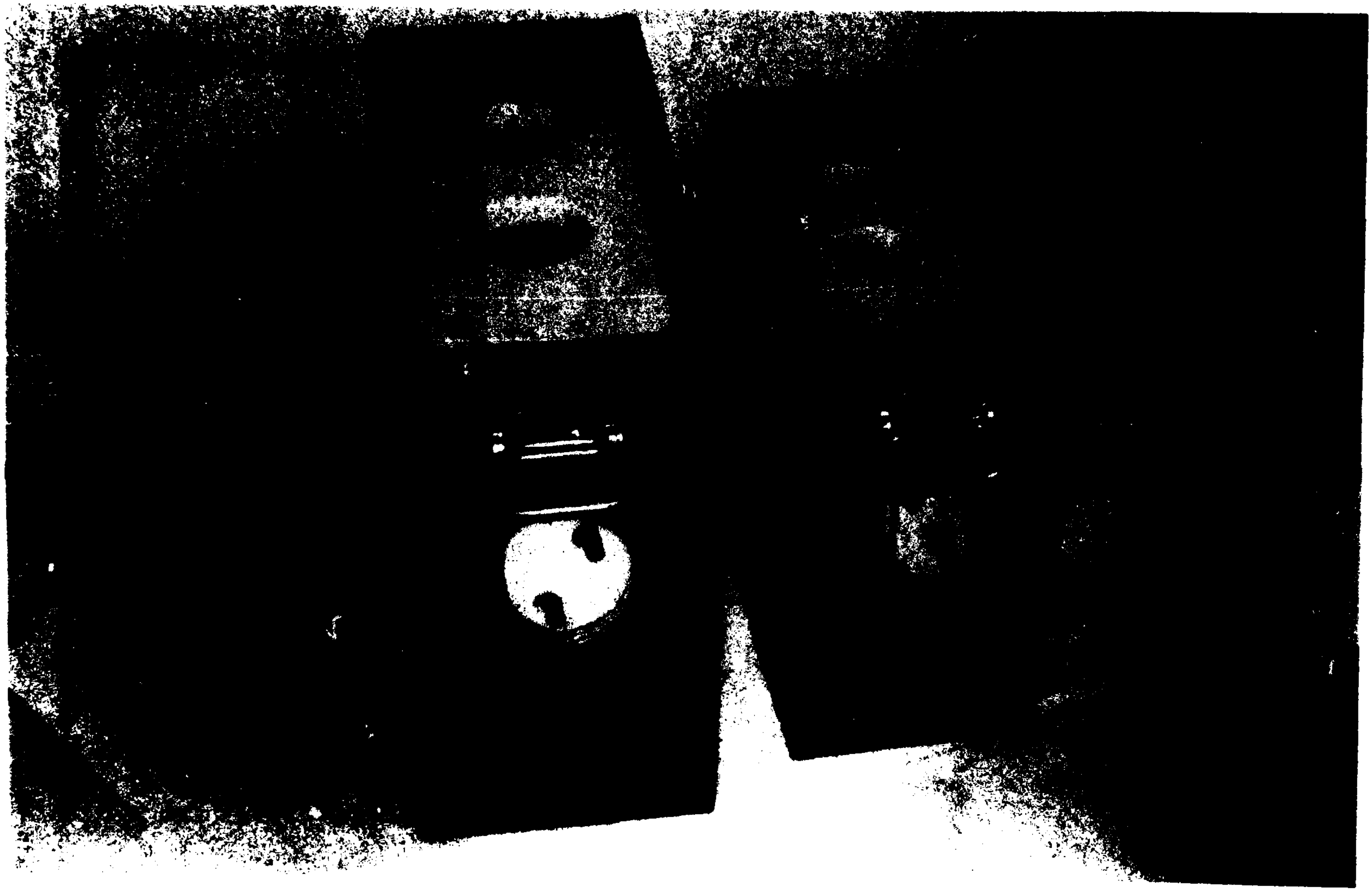

Figure 3. Two finished twin-well calorimeters.

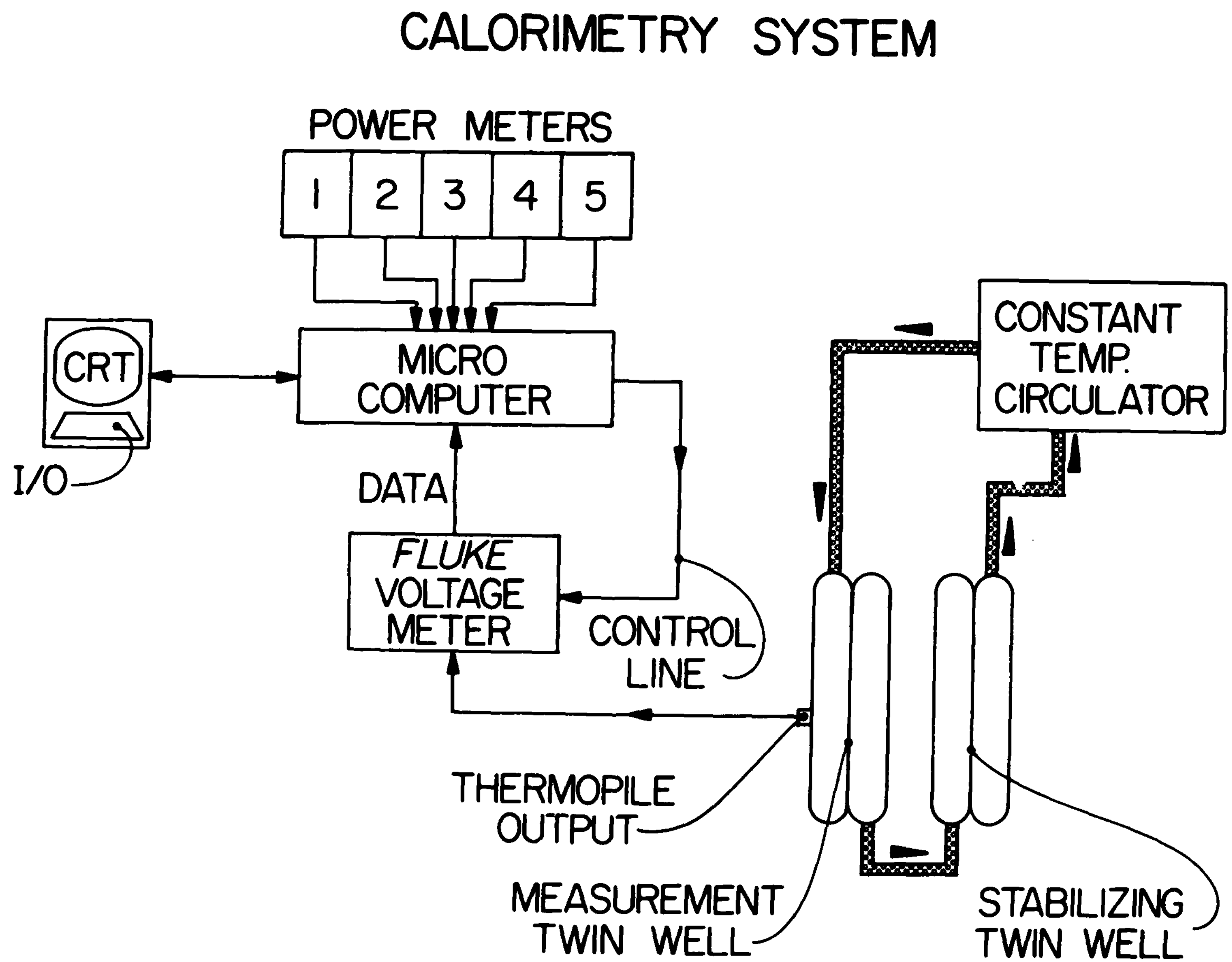

Figure 4. Diagram of the twin-well calorimetry system.

voltmeter as a function of time and integrated by a Z-80-based microcomputer coupled to the voltmeter by an IEEE interface. All data and SAR computations from a series of twin-well calorimet asurements were stored on 5-inch floppy disks for subsequent display terminal or printer output.

This system was calibrated with a known amount of ice at $0^{o}C$ and was checked by the addition of a known amount of heat to one of the two identical phantom bodies contained in the twin-well calorimeter. The approximate shape and weight of rats were simulated by the use of rubber condoms filled with a 0.9% NaCl solution. The phantom to which heat was added was exposed either at the center or along the edge of the plastic cage, and its average SAR was determined as described above. This data was compared with the average SAR calculated on the basis of the average temperature rise measured in the phantom by means of a Vitek 101 probe. The data agreed closely, indicating the accuracy of the twin-well calorimeter system.

SAR Pattern in Rats

The SAR patterns in the sagittal plane of the rats exposed in the center of the waveguide were measured by the thermographic technique (Guy et al., 1976). Each animal was cast in a block of polyfoam and bisected sagittally. Silk screens were placed between the bisected interfaces to provide electric contact between the two halves of the body. The bisected foam blocks were placed together and exposed in the waveguide, with the animal facing either toward or away from the microwave source. Before and after the exposure, thermograms of the bisected plane were taken. The SAR pattern was calculated from the data on temperature rise.

RESULTS

Average SAR

Whole-system absorption and animal absorption in terms of percentage of incident power were determined for 246 rats at different positions in the exposure waveguide. The results are shown in Figs. 5 through 9. The rats were exposed in five orientations:

Rat position

1 At center axis of the waveguide, facing the food tube and the light source; head away from transducer.

2 At far corner of cage; head away from transducer.

3 At side of cage; head away from transducer.

4 Transverse to waveguide axis.

5 Diagonal to waveguide axis; head away from transducer.

The data for position 1 are shown in Fig. 5. The upper line is the least-squares fit for the percentage of absorbed power per watt of incident power, determined by the five-power-meter measurements for the system containing rats of different body weights. The lower curve illustrates the percentage of absorbed power in the rat as measured by the twin-well calorimeter. The percentage of waveguide loss was determined from the difference of the two curves. The data for rats exposed in positions 2, 3, 4, and 5 are shown in Figs. 6, 7, 8, and 9 respectively. Position 3 (Fig. 7), in which the rats were exposed at the side of the cage, resulted in the lowest absorption. Position 5 (Fig. 9), in which rats were exposed diagonally, resulted in the highest absorption. Waveguide loss varied on the average from approximately 20% of incident power for the smallest rat to 8% for the largest; when no rat was in the cage, the loss was about 10% for all waveguides tested. The percentage of waveguide loss depended not only on the body weight of the rat, but also on its position.

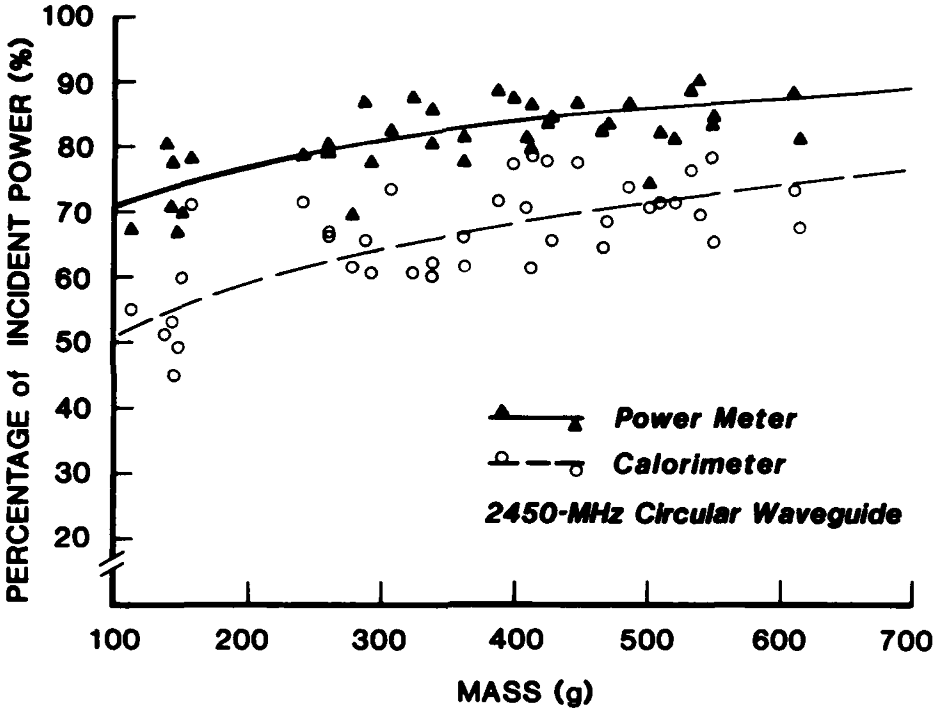

Figure 5. Percentage of power absorption as a function of body mass for a rat exposed with its long axis parallel to the axis of the cage and head away from the transducer (position 1).

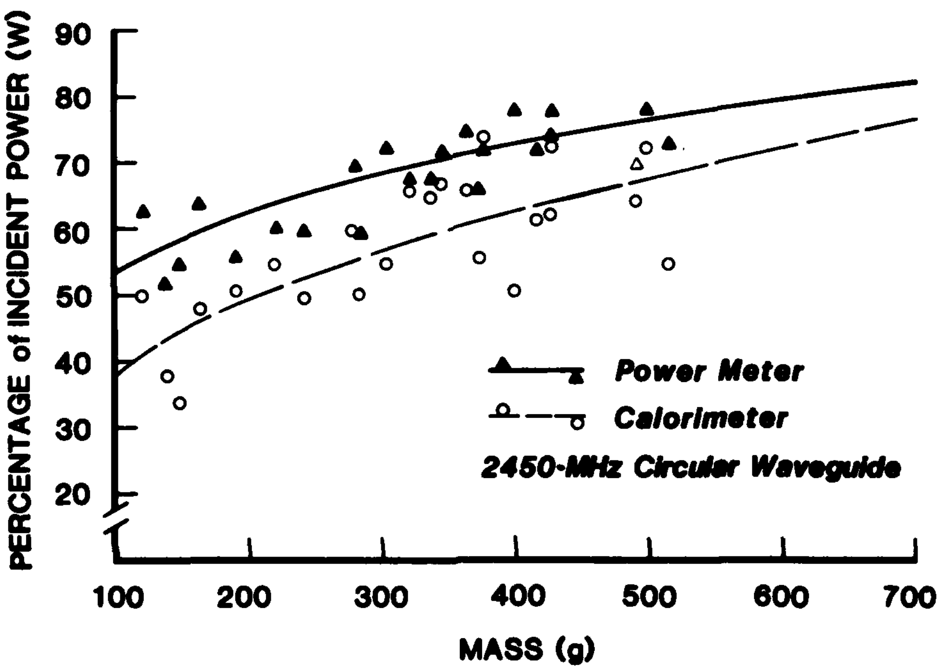

Figure 6. Percentage of power absorption as a function of body mass for a rat exposed at the far corner of the cage with head away from the transducer (position 2).

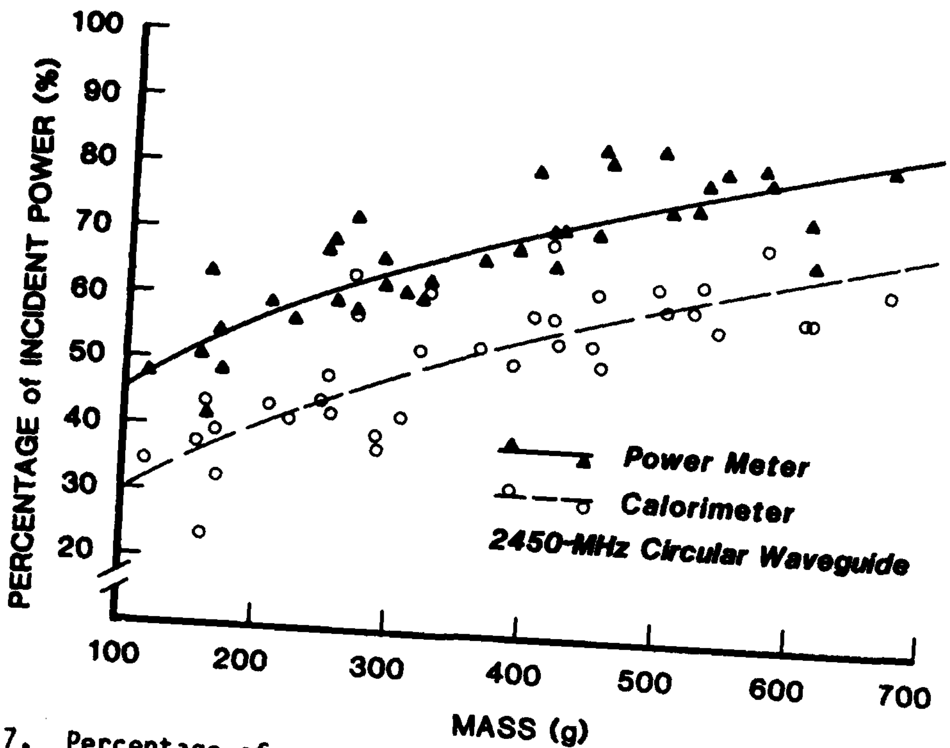

Figure 7. Percentage of power absorption as a function of body mass for a rat exposed at the side of the cage with head away from the transducer (position 3).

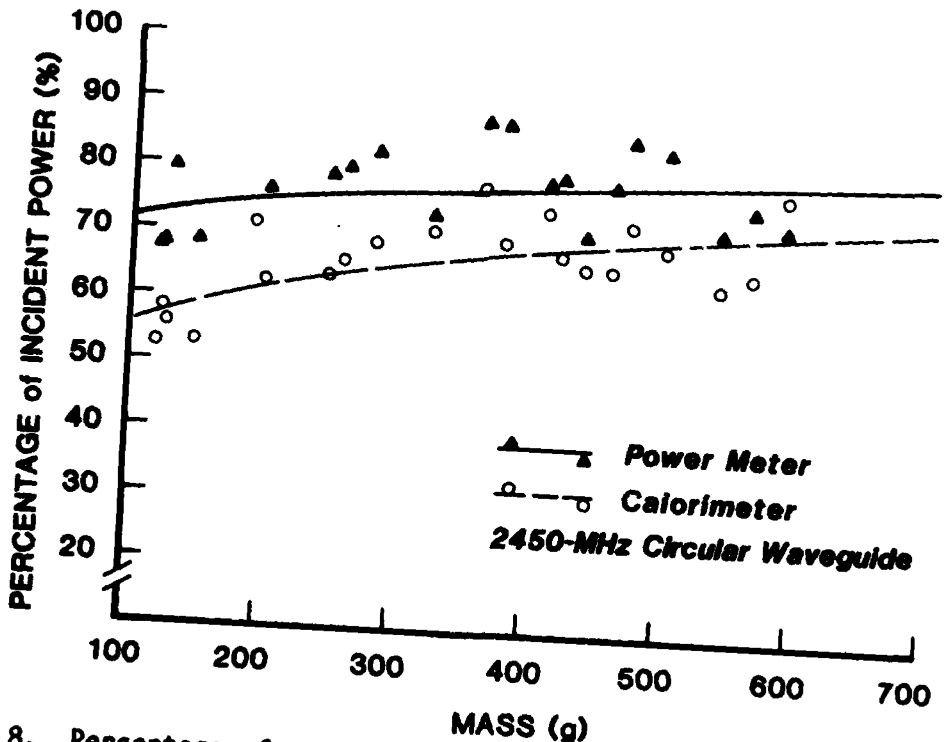

Figure 8. Percentage of power absorption as a function of body mass for a rat exposed with body axis transverse to the axis of the cage (position 4).

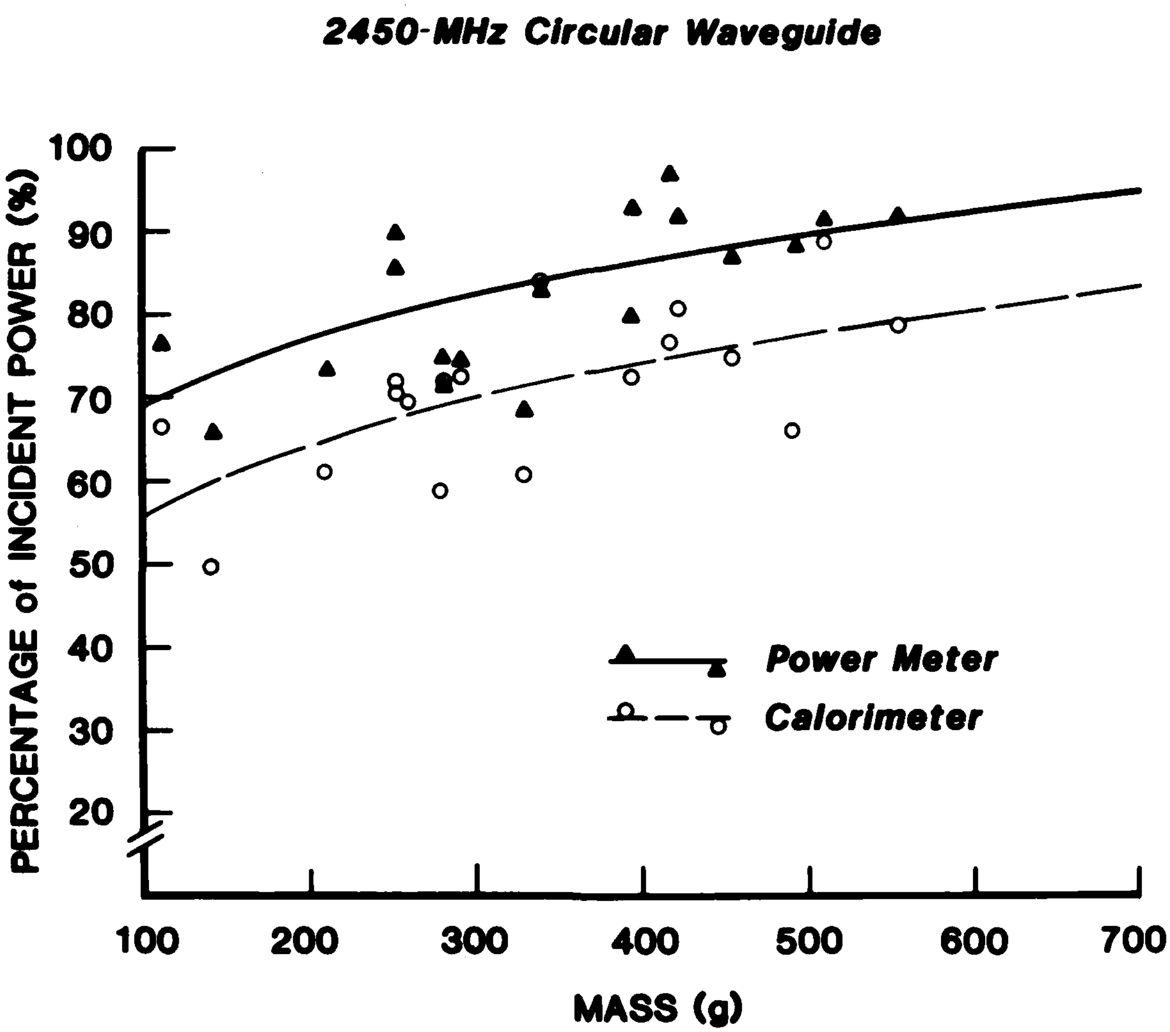

Figure 9. Percentage of power absorption as a function of body mass for a rat exposed diagonally to the cage axis with head away from the transducer (position 5).

The smaller animals experienced a higher average SAR than the larger ones did, and exposure of the smaller ones resulted in a proportionally higher power loss in the system. In Fig. 10, the curves illustrate the calculated average apparent SARs (with no consideration of waveguide loss) for the rats as a function of mass and position for a 1-W input power to the waveguide.

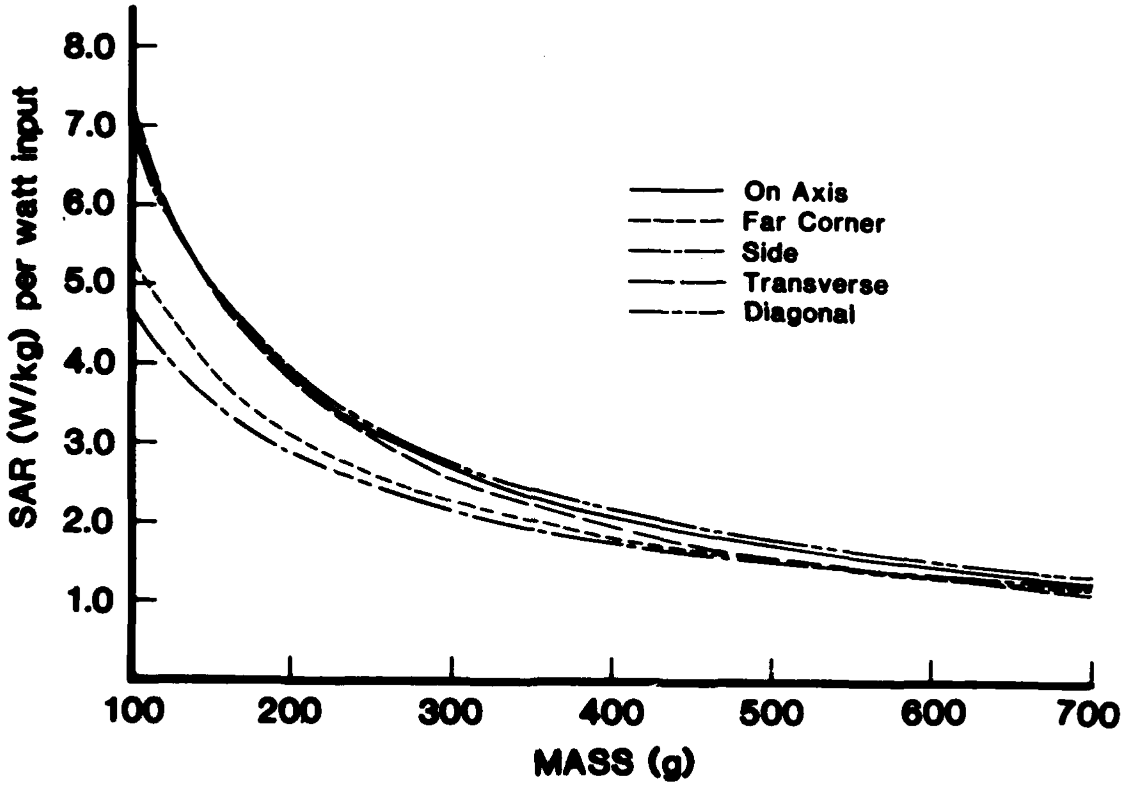

Figure 10. Apparent SARs (least-squares curves with no consideration of waveguide loss), measured by five-power-meter method as a function of exposed-animal mass and position in waveguide for 1-W input power.

The curves in Fig. 11, obtained from twin-well calorimetry measurements, illustrate the actual SAR least-squares curves as a function of mass and position. Note that the calculated average SAR for rats exposed in the the diagonal position (position 5) varies, per watt input, from 5.60 W/kg for a 100-g rat to 1.17 W/kg for a 700-g rat. The least-squares plot of SAR data for rats exposed at the side of the waveguide, where coupling is the least, indicates an SAR of 3.00 W/kg for a 100-g rat and 1.00 W/kg for a 700-g rat.

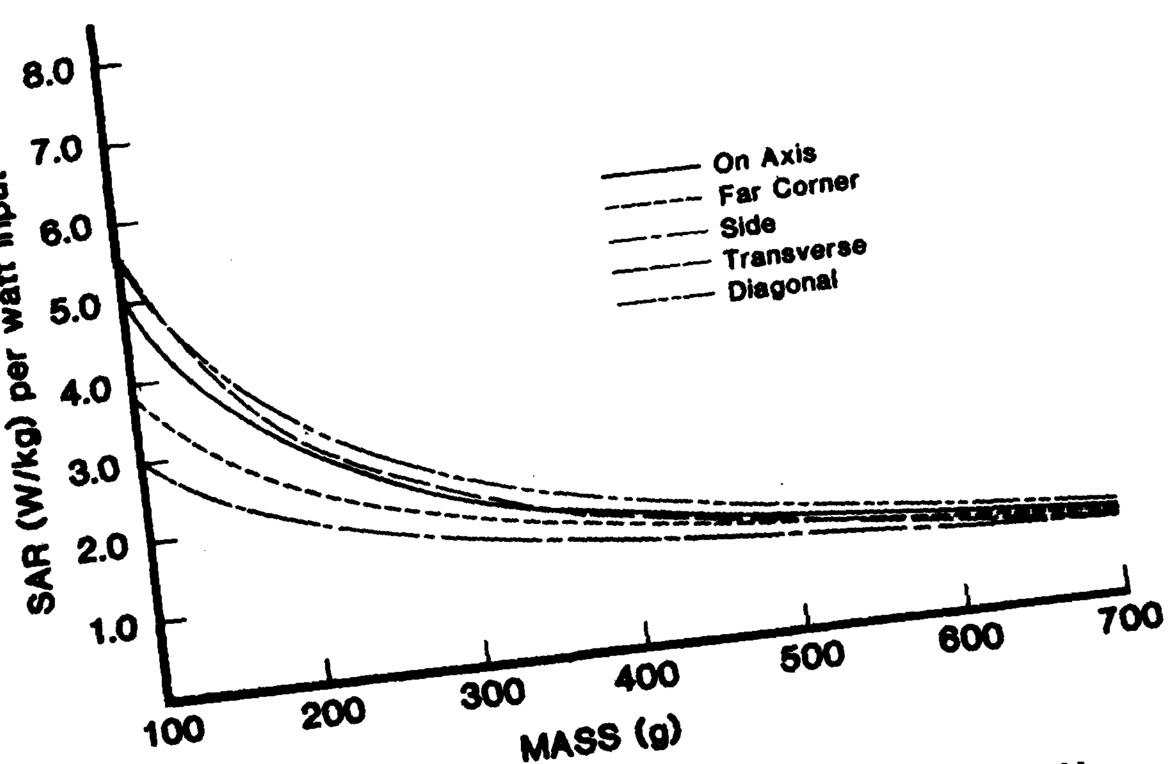

Figure 11. Actual SARs (least-squares curves), measured by twin-well calorimetry, as a function of exposed-animal position in waveguide for 1-W input power.

Figure 12 illustrates the average apparent and actual SARs for all five positions (if we assume that equal time was spent in all positions). The actual SAR as averaged over all five exposure positions varied from 4.60 W/kg for a 100-g rat to 1.07 W/kg for a 700-g rat.

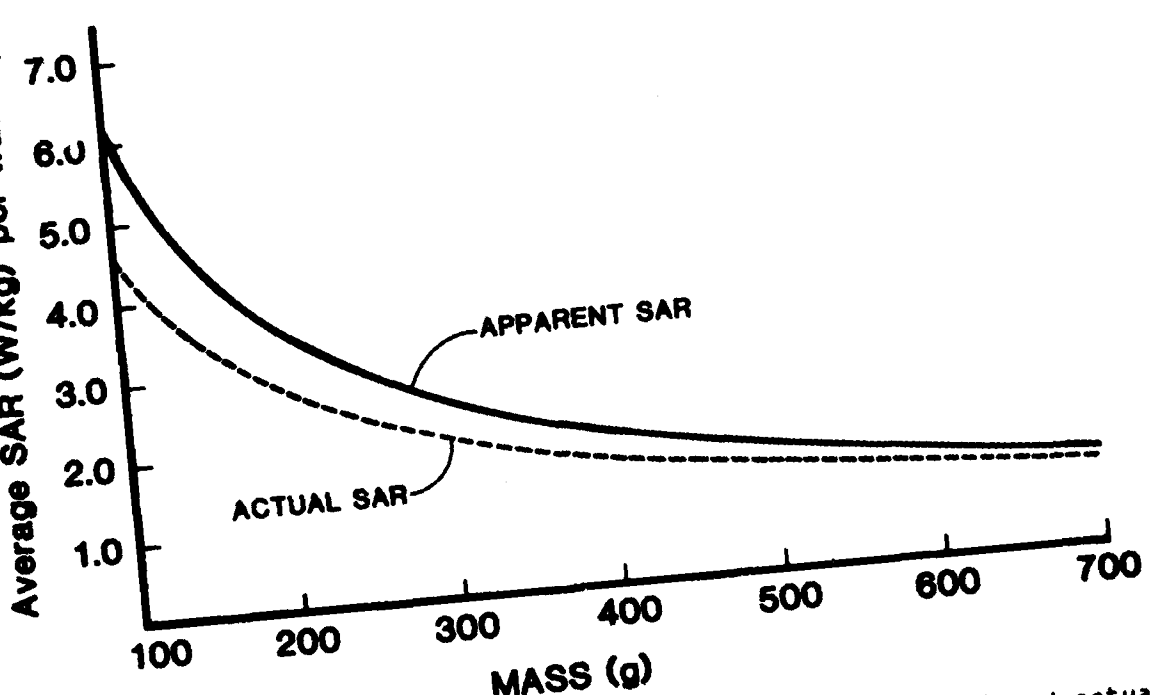

Figure 12. Averages of apparent (five-power-meter measurements) and actual (twin-well calorimeter measurements) SARs for all five positions for exposed animals in waveguide for 1-W input power.

The ratio of the actual SAR to the apparent SAR is plotted in Fig. 13. This ratio can be used as a correction factor to convert the apparent SAR measured from live rats to actual SAR.

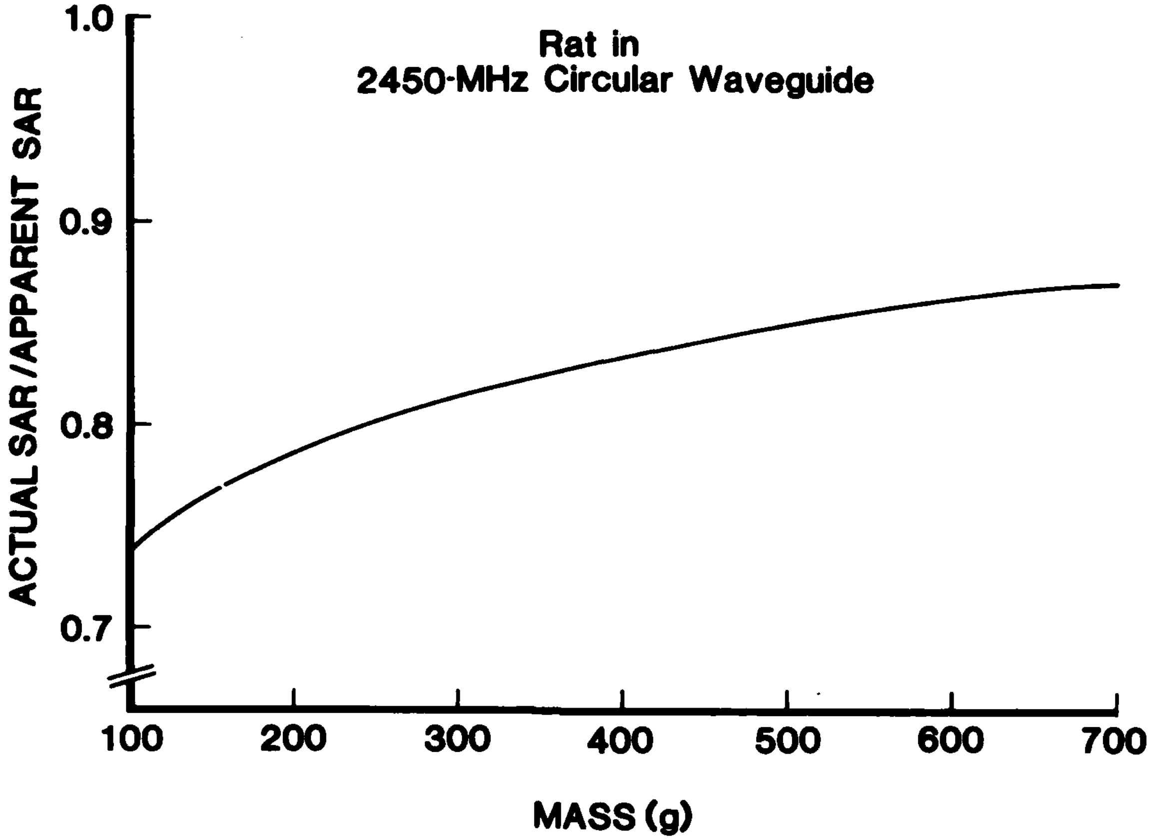

Figure 13. SAR correction factor (actual SAR/apparent SAR) as a function of mass based on average of five positions.

SAR Distribution

Figure 14 shows the SAR distributions as lines of constant SAR normalized for 1-W input for a 324-g rat cadaver exposed in two positions along the axis of the waveguide: (a) anterior: peak SAR, 4.39 W/kg; average SAR, 2.05 W/kg; and whole-body power loss, 0.66 W; and (b) posterior: peak SAR, 6.08 W/kg; average SAR, 1.94 W/kg; and whole-body power loss, 0.63 W.

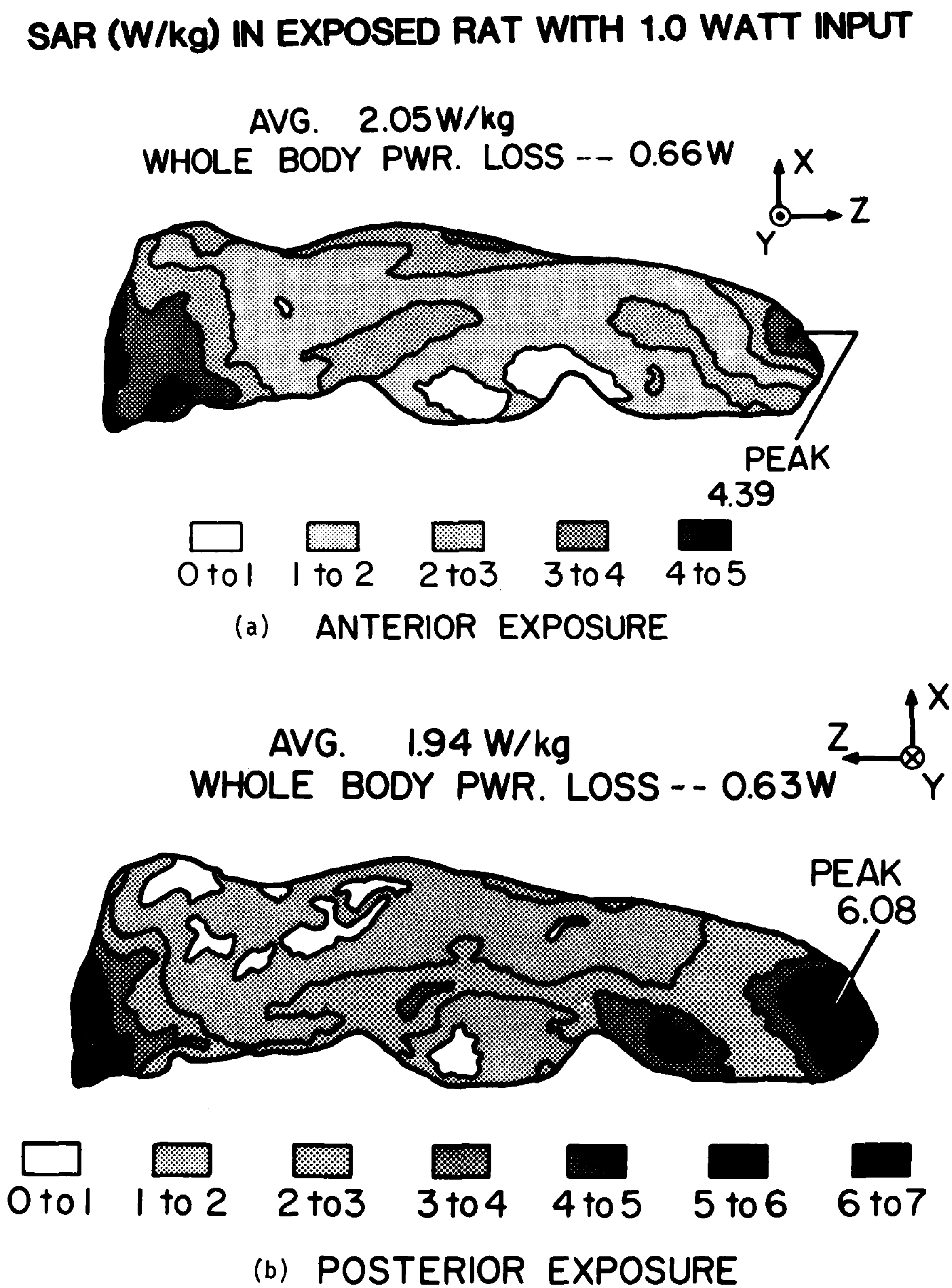

Figure 14. Computer-processed thermographic recording of SAR in cadaver of a 324-g rat exposed along axis of the waveguide chamber.

Estimated Average SARs in Chronically Exposed Rats

In the chronic study, 100 rats were exposed 21 h a day to 0.480 mW/cm^2, 2450-MHz fields for their lifetimes (Guy et al., 1980); the actual SARs in the rats were estimated from the apparent SAR measurements by five power meters. The mean SARs, based on the exposure-waveguide system loss as a function of body mass, are shown in Fig. 15. A five-power-meter measurement for the normal daily 21-h exposure period was made on each waveguide. Each point in the figure represents the average for all animals within a 5-g interval. The solid curve in Fig. 15 is a least-squares fit of the apparent SAR, with no waveguide loss; and the dashed curved line is the calculated average net SAR for the live rat, based on the correction factor curve of Fig. 13. The average SARs for the live exposed rats over the first year of exposure are shown in Fig. 16. The results show that the SARs calculated from the data for the live animals are very close to but slightly less than the values calculated from the measurements on the dead rats (calculated from Fig. 12). Inherent in the latter, however, is the assumption that the animals spent equal time in the five possible positions, whereas in fact they spent more time at the side or corner of the cage, where they absorbed less energy during exposure, than in other orientations (as indicated in Fig. 11).

DISCUSSION

Average SARs and SAR patterns have been obtained in rats exposed to 2450-MHz circularly polarized fields. The average SAR in rats varied with their body mass and their orientation in the waveguide (Fig. 10). The largest variation occurred when the animals were smaller than 200 g. For larger adult rats, the average SAR varied from 2.73 W/kg at 200 g to 1.07 W/kg at 700 g for 1-W input to the waveguide. At different postures for 200-g rats, the SAR varied from 2.00 W/kg at the side to 3.2 W/kg at diagonal exposure. For larger rats, the variations were smaller for different postures. The waveguide loss changed not only with the mass but also with the orientation of the animal.

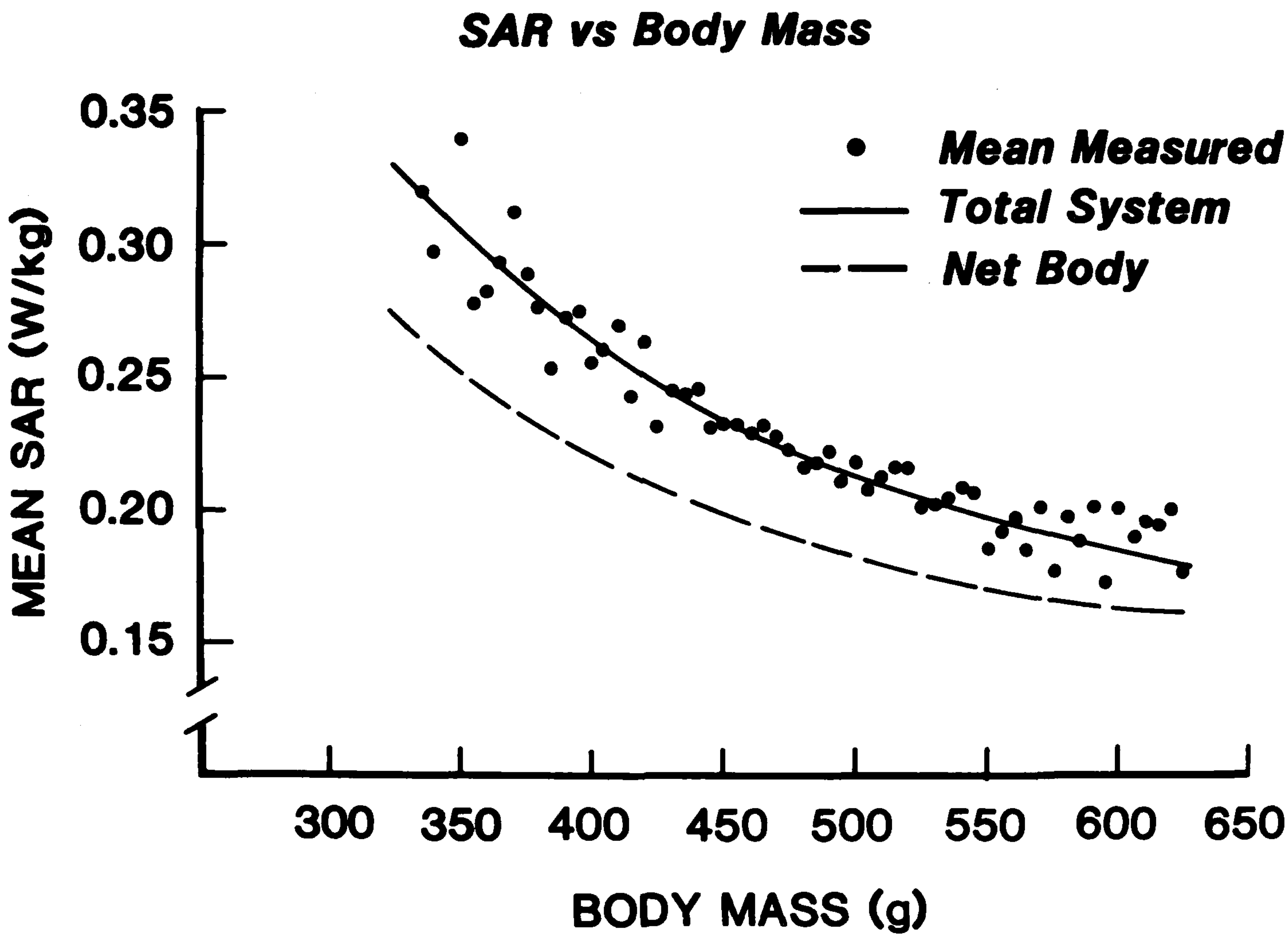

Figure 15. Measured average SARs based on total system loss and calculated net-body average SAR based on empirical correction factor for first-year exposure period (each point is a 7-day average of seven waveguides).

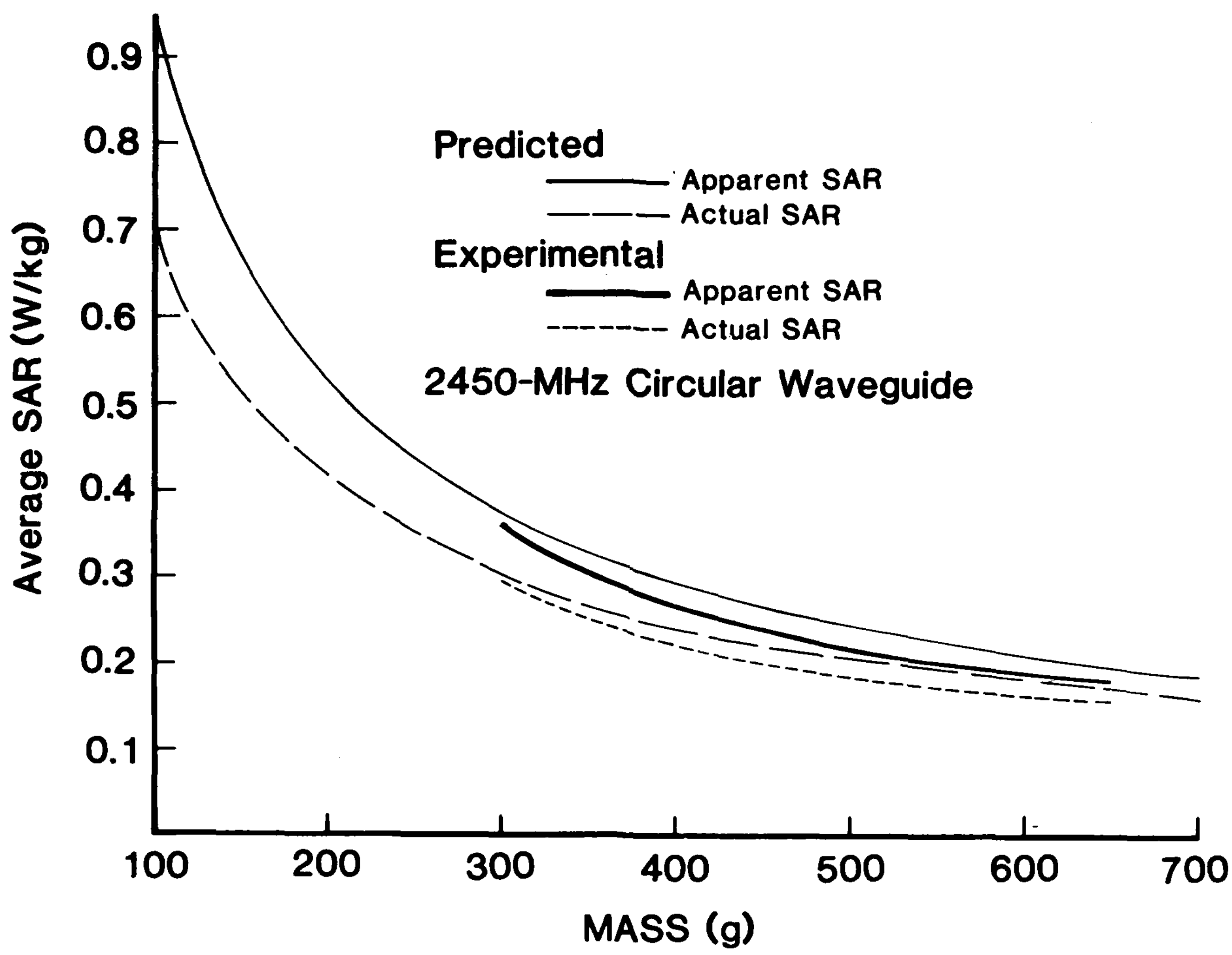

Figure 16. Average SAR values measured for dead rats (predicted) compared with average SAR values measured for free-roaming exposed rats, averaged over weekly periods during first-year chronic exposure (incident power density of 0.480 mW/cm^2).

From the chronic-study measurements (Fig. 16), the experimental apparent SARs were slightly lower than the predicted SARs, if equal time was assumed in the five orientations in the waveguide. Prediction will be more accurate if the percentage of time spent in various orientations can be determined; nevertheless, the measured apparent SARs (and therefore the actual SARs) were within 5% difference from the predicted SARs. This accuracy is satisfactory. The peak SARs obtained by the thermographic technique were only about 2 to 3 times higher than the average SARs (Fig. 14). This ratio of peak to average SAR in rats is much less than that in man exposed to 450 MHz because of the extremities of man. Whether the tail or the feet of the rat has a higher SAR than the body cannot be determined because the thermographic technique cannot provide accurate data in small objects. Despite this limitation, the data presented in this report on average SAR and SAR pattern should be useful for researchers using this type of circular waveguide to estimate the dosimetry in their exposed rats.

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