

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: 7/8/71

Project Title: Study of Microwave Dosimetry

Project No.: A-1347

Project Director: Mr. H. L. Bassett

Sponsor: National Institutes of Health; Public Health Service (DHEN)

Effective June 25, 1971 Estimated to run until: June 24, 1972

Type Agreement: Contract No. NIH-71-2374 Amount: \$ 33,155.00

Reports Required: Interim Progress Reports; Summary Report; Final Summary Report;
Final Comprehensive Report.

Sponsor Contact Persons: Technical Matters
Dr. Donald I. McRee
Project Officer
National Institute of Environmental Health Sciences
P. O. Box 12233, Building 11
Research Triangle Park, N. C. 27709
Phone: (919) 549-8221

Administrative Matters
Contracting Officer
Research Contracts Branch
National Institutes of Health
Building 31, Room 1B63
Bethesda, Maryland 20014
Phone: (301) 496-5581

Assigned to Electronics (Special Techniques) Division

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GEORGIA INSTITUTE OF TECHNOLOGY

Engineering Experiment Station

PROJECT TERMINATION

Date 7/31/73

PROJECT TITLE: **Study of Microwave Dosimetry**

PROJECT NO: **A-1347**

PROJECT DIRECTOR: **Mr. G. K. Huddleston**

SPONSOR: **National Institutes of Health, PHS**

TERMINATION EFFECTIVE: 6/24/73 (Grant Expiration)

CHARGES SHOULD CLEAR ACCOUNTING BY: 6/30/73

Contract Closeout Items Remaining: Final Invoice & Closing Documents
Final Report of Inventions
Government Property Inventory, etc.

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GEORGIA INSTITUTE OF TECHNOLOGY
EXPERIMENT STATION 225 North Avenue, Northwest Atlanta, Georgia 30332

A-1347

22 September 1971

Dr. Donald I. McCree
National Institute of Environmental
Health Sciences
P. O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report Covering the Period
24 June 1971 to 24 September 1971, Georgia Tech
Project A-1347, Contract No. NIH-71-2374,
"Study of Microwave Dosimetry"

Dear Sir:

Efforts during the first quarter have been limited primarily to background study and planning. After meetings with the Project Officer in July and with researchers at the University of Michigan in August, it became practical to finalize plans for the work to be carried out here at Georgia Tech without the possible duplication of the effort at Michigan. This summary report is, in essence, an outline of those plans for the next quarter.

The main emphasis of the project will be the development of a probe suitable for power density measurements over the 1 to 10 GHz band under far-field (plane wave) conditions. The probe will operate on the principle of energy absorption in a lossy substance rather than as an antenna per se. Pyroelectric crystals will play a major role in the probe design, serving as the detector of absorbed energy. Triglycine sulphate (TGS) crystals have been selected as the pyroelectric material to be used in the initial designs; more sensitive materials (and more expensive), such as strontium barium niobate (SBN), will be considered for the final probe design. A sufficient quantity of TGS crystals has been obtained to support initial investigation of detector performance to be undertaken in the second quarter. An FET input operational amplifier has been ordered which will serve as the pre-amplifier required for the crystal detector designs.

Concurrent with the detector design work to be carried out in the second quarter, uniform microwave fields will be established and characterized for testing the probe designs. A number of horn type radiators will be used to establish the uniform fields at selected frequencies. The fields produced by the radiators will be characterized using the XY probe positioner facility at Georgia Tech. For high power applications, a focused beam system is available at 2450 MHz.

A literature search is underway to determine a list of candidate protein film materials to be used in microwave exposure studies. It is anticipated that the testing of candidate films for possible applications in monitoring of microwave fields will continue at a low level throughout the contract period.

Approximately 400 man-hours of engineering and technician time has been expended during the first quarter of the contract period. A graph is attached which shows the projected and actual expenditures of contract funds for the period 24 June 1971 to 30 August 1971. It is anticipated that the contract funds will be sufficient to complete the work delineated in the original proposal.

Respectfully submitted;

H. L. Bassett
Project Director

Approved:

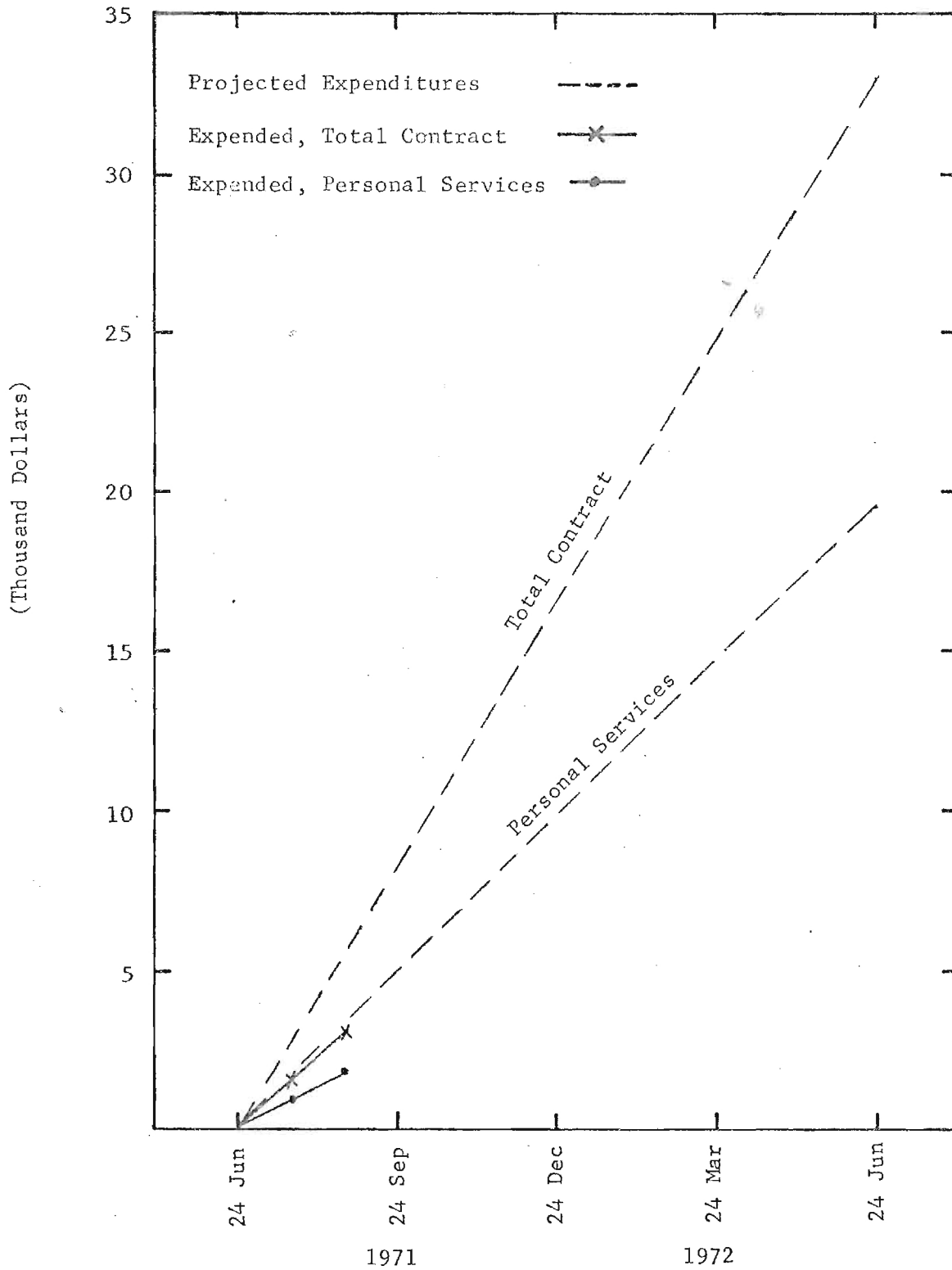
J. W. Dees, Head
Special Techniques Branch

Addressee: In Triplicate

Enclosure: Projected and Actual Expenditures

Project A-1347

Study of Microwave Dosimetry



Projected and Actual Expenditures

A-1347



GEORGIA INSTITUTE OF TECHNOLOGY
EXPERIMENT STATION 225 North Avenue, Northwest Atlanta, Georgia 30332

16 December 1971

Dr. Donald I. McRee
National Institute of Environmental
Health Sciences
P.O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report Covering the Period
25 September 1971 to 24 December 1971, Georgia Tech
Project A-1347, Contract No. NIH-71-2374,
"Study of Microwave Dosimetry"

Dear Sir:

Efforts during the second quarter have been directed toward design and construction of the pyroelectric probe, pre-amplifier, and a horn type radiator for testing and calibrating the probe in the 2.2 - 2.6 GHz frequency band.

Three tryglycine sulphate crystals have been cleaved, polished, and electroded to serve as the pyroelectric element of the probe. A tiny hole has been drilled through the center of each crystal (perpendicular to the 1 cm x 1 cm electroded faces) to accept the insulated center conductor of a length of 0.056" O.D. rigid coaxial cable. The center conductor will be connected electrically to one electrode of the crystal; the outer conductor will be connected to the other electrode and provide the required electrical path and mechanical mounting for the pyroelectric element. This mounting configuration has been selected to minimize probe-field interaction and to provide the means of isolating the pre-amplifier from the vicinity of the measurement region.

Based on results reported in the literature on the use of pyroelectric detectors in the microwave region, design equations have been derived which yield performance data as functions of crystal geometry, electrical properties, pre-amplifier input impedance, and modulation frequency of the incident radiation. The performance data calculated from these equations with the aid of the UNIVAC 1108 computer verify theoretically that very small power densities can be measured--provided that the absorbing cross-section of the pyroelectric element can be made to be on the order of one square centimeter. Rough calculations of the absorbing cross-section of a small, lossy dielectric sphere, combined with the expected small value of loss tangent of TGS in the 1 - 10 GHz band, indicate that a lossy material will be required on one electrode of the crystal to provide efficient conversion of the incident radiation into heat. To obtain the required thermal response, the thermal mass of this material must be small. Various materials are being considered.

The design of the pre-amplifier to be used with the pyroelectric element has been completed. With the exception of some precision resistors used in the

design, all components have been assembled and mounted in a shielded box. The precision resistors arrived in early December and this will permit completion of the construction of this unit. The circuit used is designed to provide a range of input resistances from one megohm to 10,000 megohms and a very small value of input capacitance (about 3 pf).

A horn radiator with rectangular aperture is being constructed in the main machine shop. The horn is designed for operation in the 2.2 - 2.6 GHz frequency band and will be used to establish a uniform field of known power density as determined from measurements made at the input to the antenna. This antenna will be used to calibrate the pyroelectric detector in this frequency band.

Efforts during the next quarter will be focused on testing the pyroelectric probes thus far developed and on the further development of such probes. Following the calibration and testing of the preamplifier and horn radiator, measurements will be made to determine the responsivity and detectivity of the pyroelectric detectors in plane wave fields as functions of power density, microwave frequency, modulation frequency, and orientation. From the results of these measurements, it is anticipated that improved probe configurations will be developed. Plans are currently underway to construct other horn antennas so that testing of the probes can be carried out over the entire 1 - 10 GHz band. An improved crystal mount consisting of a dielectric coaxial line with thin aluminum films serving as conductors is being designed at this time and will be built during the next quarter.

Approximately 1220 man-hours of engineering and technician time have been expended during the first two quarters of the contract period. A graph is attached which shows the projected and actual expenditures of contract funds for the period 24 June 1971 to 30 November 1971. It is anticipated that the contract funds will be sufficient to complete the work delineated in the original proposal.

Respectfully submitted,

H. L. Bassett
Project Director

Approved:

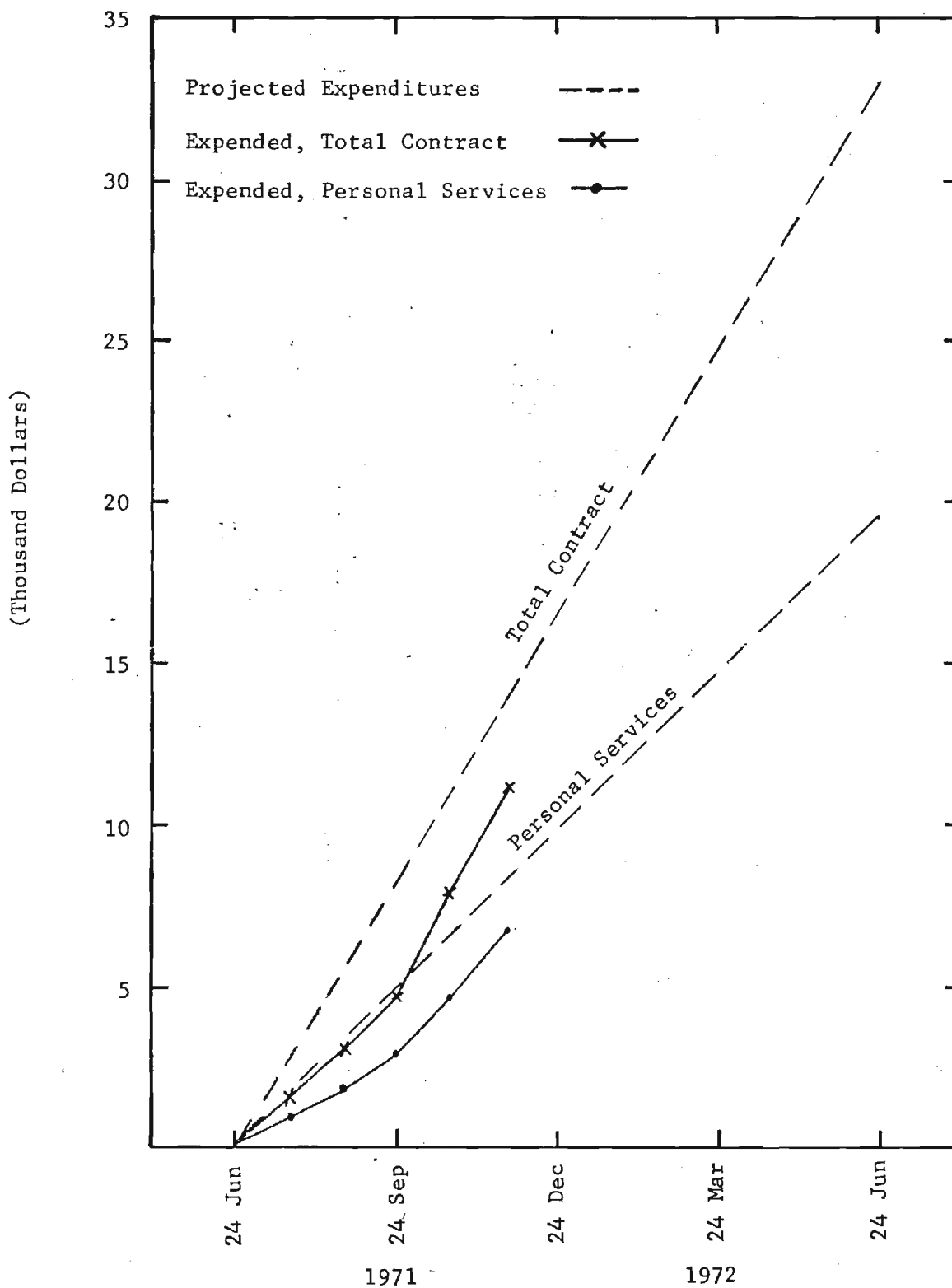
J. W. Dees
Special Techniques Branch

Addressee: In Triplicate

Enclosure: Projected and Actual Expenditures

Project A-1347

Study of Microwave Dosimetry



Projected and Actual Expenditures



GEORGIA INSTITUTE OF TECHNOLOGY
EXPERIMENT STATION 225 North Avenue, Northwest · Atlanta, Georgia 30332

A-1347

20 March 1972

Dr. Donald I. McRee
National Institute of Environmental Health Sciences
P. O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report Covering the Period
25 December 1971 to 20 March 1972, Georgia Tech
Project A-1347, Contract No. NIH-71-2374,
"Study of Microwave Dosimetry"

Dear Sir:

Efforts during the first three quarters have been directed toward the design and implementation of a pyroelectric detector of microwave radiation suitable for measurements of power density in the 1 to 10 GHz frequency band under far-field (plane wave) conditions.

We are pleased to inform you that we have experienced our first real success in this endeavor. Measured responses of the probe have been obtained at only one microwave frequency (9.375 GHz) but the results are very encouraging. Please refer to the enclosed research proposal requesting renewal of the current program for a detailed account of these results.

We have compiled a list of heat sensitive proteins which may have possible applications in microwave dosimetry. As stated in an earlier letter, this effort has proceeded at a low level throughout the project period.

During the final three months of the current project period, we will endeavor to test and calibrate the detector at selected frequencies throughout the 1-10 GHz band. We will undoubtedly encounter problems but are confident we will overcome them.

Approximately 2120 man-hours of engineering and technician time have been expended during the first three quarters of the contract period. A graph is attached which shows the actual and projected expenditures of contract funds for the period 24 June 1971 to 29 February 1972.

Respectfully submitted,

H. L. Bassett
Project Director

Approved:

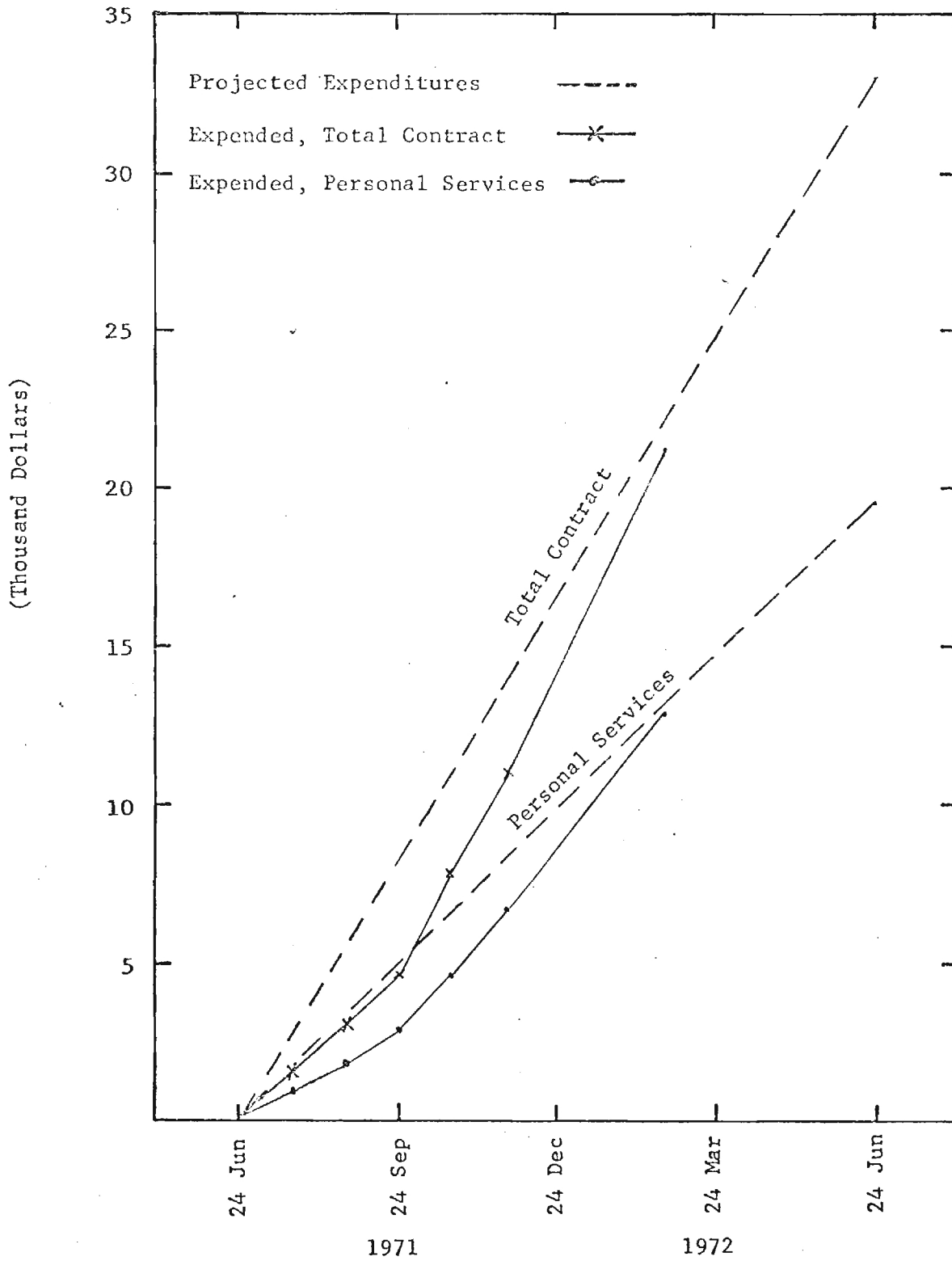
J. W. Dees, Chief
Special Techniques Division

Addressee: In Triplicate

Enclosures: Projected and Actual Expenditures
Research Proposal (Renewal of NIH
Contract No. NIH-71-2374)

Project A-1347

Study of Microwave Dosimetry



Projected and Actual Expenditures

A-1347



GEORGIA INSTITUTE OF TECHNOLOGY

EXPERIMENT STATION 225 North Avenue, Northwest Atlanta, Georgia 30332

June 21, 1972

Dr. Donald I. McRee
National Institute of Environmental Health Sciences
P.O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Final Summary Report Covering the Period 25 June 1971 to 21 June 1972, Georgia Tech Project A-1347, Contract No. NIH-71-2374, "Study of Microwave Dosimetry"

Dear Sir:

The main emphasis of the research efforts supported under this contract has been the development of a pyroelectric probe for making accurate measurements of power density in the 1 to 10 GHz microwave frequency band under far-field (plane wave) conditions. The approach taken in this investigation was influenced largely by the overall research aim of developing a probe capable of making meaningful microwave measurements close to and far from a radiator, inside and outside of biological specimens.

During the first quarter of the program, background study and planning were carried out to determine the method of approach and the scope of the investigation. During the second quarter, several pyroelectric probe designs, including electronics, were implemented with few encouraging results. Efforts to realize a successful pyroelectric probe were continued, and late in the third quarter our first real successes were experienced when probe responses were obtained at selected frequencies in the 8.4 - 9.6 GHz frequency band.

Efforts during the fourth and final quarter of the project period have been directed toward continued development and testing of the pyroelectric probe concept. Improved versions of the detector element have been fabricated and tested at X-band and at 2450 MHz. Probe responses have been obtained at 2450 MHz which strongly indicate that 1 to 10 GHz operation is indeed feasible. A miniaturized version of the preamplifier and an improved version of the post amplifier have been fabricated for delivery to the Project Officer in July. A pyroelectric detector element is currently being mounted. Calibration of the resulting probe at selected frequencies will be carried out before delivery is made.

The results of this investigation have been reported by oral presentations made at two different symposia: The Purdue 1972 Symposium on Electromagnetic Hazards, Pollution, and Environmental Quality, Lafayette, Indiana on 8-9 May 1972; Microwave Dosimetry Workshop, Georgia Institute of Technology - Walter Reed Army Institute of Research, Atlanta, Georgia, on 1-2 June 1972. Summary

papers were submitted in both cases to appear in the formal proceedings of those meetings.

A final comprehensive report of this research program is currently being prepared. Ten bound copies will be delivered to the Project Officer in July to fulfill the reporting requirements of this contract for the project period 25 June 1971 to 24 June 1972.


In May, renewal of the present NIH contract was awarded and notice received at Georgia Tech to continue the studies of microwave dosimetry at approximately the same level of effort as during the first year. The program of research for the coming year is outlined in the request for renewal dated 20 March 1972.

Approximately 3000 man-hours of engineering and technician time have been expended during the period 25 June 1971 to 31 May 1972. A graph is attached which shows the actual and projected expenditures of contract funds for the same period. It is anticipated that approximately 250 man-hours will be expended during June 1972 and that the actual expenditures of contract funds will equal the projected expenditures.

Respectfully submitted,

H. L. Bassett
Project Director

Approved:


J. W. Dees, Chief _____
Special Techniques Division

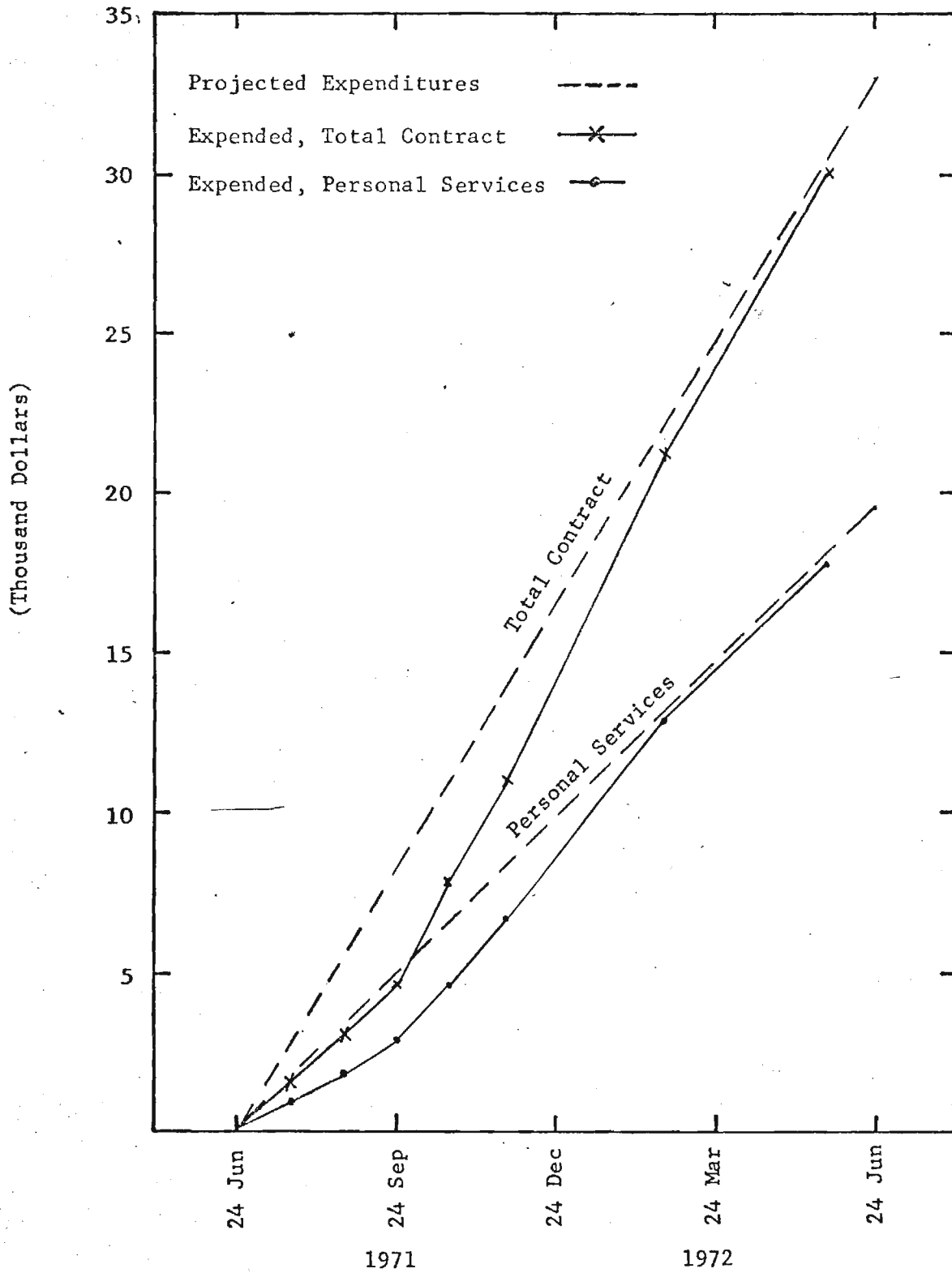
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Enclosure: Graph of Projected and Actual Expenditures

HLB/pw

Project A-1347

Study of Microwave Dosimetry



Projected and Actual Expenditures



26 September 1972

Dr. Donald I. McRee
National Institute of Environmental
Health Sciences
P. O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report No. 5 Covering the Period 25 June 1972
to 24 September 1972, Georgia Tech Project A-1347, Contract No.
NIH-71-2374, "Study of Microwave Dosimetry"

Dear Sir:

Efforts during the fifth quarter included publishing of the final report on the first year's work, a visit to NIEHS to deliver a pyroelectric probe, and technical progress in the area of adapting the probe to measurements inside biological materials.

The final report covering the results of the first year's effort under this contract was completed and delivered on or about 15 August 1972.

On 22-23 August 1972, G. K. Huddleston visited NIEHS for the purposes of delivering a pyroelectric probe and discussing priority of work during the next twelve months. The probe endured the trip and was placed in operation in the irradiation facility at NIEHS. In discussing the priority of work for the coming year, it was mutually agreed that emphasis should be placed on miniaturizing the probe and calibrating it inside of biological materials. Furthermore, application of the probe to measure CW fields, correlation of near-field and far-field responses, and the use of arrays of pyroelectric crystals all should receive low priority.

The adaptation of the pyroelectric probe for measurements of energy absorption inside biological materials will involve essentially three parallel efforts: (1) development of pyroelectric detector elements consisting of pyroelectric crystal, lossy (microwave) material, and thermal and electrical insulation; (2) development of the electronics required to locate the detector element remotely from the electronics; (3) an in-depth theoretical study of the effects of probe construction and properties of the medium in which the probe is placed on the response of the probe to electromagnetic radiation in the 1-10 GHz frequency band.

During the fifth quarter, efforts have been concentrated on (1) and (2) above. An electrometer circuit followed by a bandpass filter centered at the modulation frequency of 2 Hertz has been constructed and tested. Responses have been obtained in the 8-10 GHz frequency band using several

different pyroelectric detector elements mounted on a triax cable approximately three feet long and connected to the electrometer. (Feedback is used in the electrometer circuit to eliminate the effects of the cable capacitance; the bandpass filter is used to attenuate those frequencies in the response different from the modulation frequency and to amplify the response.) Responses have been obtained from TGS crystals having carbon placed on them, indicating the validity of this approach; additional tests are going on to determine the optimum design parameters.

During the next quarter, efforts will be concentrated on (1), (2), and (3) above. In particular, the theoretical analysis will be initiated so that the probe responses measured can be correlated to energy absorbed inside biological materials.

Approximately 1,061 man-hours of engineering and technician time have been expended during the period 25 June 1972 to 31 August 1972. Approximately \$8,738 of the total contract funds of \$66,632 have been expended during this period. It is anticipated that the remaining contract funds of \$24,130 will be sufficient to complete the work delineated in the renewal proposal.

Respectfully submitted,

G. K. Huddleston
Project Director

Approved:

J. W. Dees, Chief
Special Techniques Division

Addressee: In Triplicate



2 January 1973

Dr. Donald I. McRee
National Institute of Environmental
Health Sciences
P. O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report No. 6 Covering the Period
25 September 1972 to 24 December 1972, Georgia Tech
Project A-1347, Contract No. NIH-71-2374, "Study of
Microwave Dosimetry"

Dear Sir:

Efforts during the sixth quarter have been directed toward the develop-
ment of a pyroelectric probe suitable for measurements of microwave energy
density in biological materials. Experimental work at 2450 MHz and
theoretical work have been accomplished.

The experimental effort has included the fabrication and testing of
several pyroelectric elements of small size (~ 2 mm). The pyroelectric
element is mounted on an 1/8-inch diameter dielectric rod about four
inches long; a preamplifier is mounted on the other end of the rod with
electrical connection to the crystal element being provided by conductive
paint applied along the rod. Testing has been carried out by placing the
pyroelectric element inside a waveguide and applying various levels of
modulated microwave power. Responses of the probe to the microwave fields
have been obtained but only at input power levels of about 200 milliwatts.
Various amounts of microwave absorber have been added to the probe to
enhance its power absorbing properties, but no substantial increase in
total probe response has been observed. It is believed that any increased
absorbency is offset by the increase in thermal mass.

Recognizing the thermal nature of the problem, thermal analyses of
various idealized probe configurations have been carried out to determine
the effects of the thermal properties of the probe materials on total
response. Spherical and rectangular probe configurations with variable
amounts of absorber and insulator present have been considered. Computed
results for the rectangular case indicate that the microwave absorber
material added to the pyroelectric element should possess low density,
low heat capacity, and high thermal conductivity in order to enhance
probe response. The study of the thermal properties of the probe is
continuing and will be extended to include more completely the electro-
magnetic aspects of the total problem.

Approximately 900 man-hours of engineering and technician time have been expended during the period 1 September 1972 to 30 November 1972. Approximately \$7,132 of the total contract funds of \$66,632 were expended during this same period. It is anticipated that the remaining contract funds of \$16,998 will be sufficient to complete the work delineated in the renewal proposal.

Respectfully submitted,

G. K. Huddleston
Project Director

Approved:

J. W. Dees, Chief
Special Techniques Division

Addressee: In Triplicate



2 April 1973

Dr. Donald I. McRee
National Institute of Environmental
Health Sciences
P. O. Box 12233, Building 11
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report No. 7 Covering the
Period 25 December 1972 to 24 March 1973,
Georgia Tech Project A-1347, Contract No.
NIH-71-2374, "Study of Microwave Dosimetry"

Dear Sir:

Efforts during the seventh quarter have been directed toward the theoretical aspects of the measurement of microwave energy density in biological materials using the pyroelectric effect and toward the fabrication of a set of pyroelectric probes for the measurement of power density over the 1 to 10 GHz frequency range.

A description of the thermal analyses of pyroelectric probes in biological materials was presented in the proposal to renew the present contract (dated 13 March 1973) and will not be repeated here. Computed results for the rectangular and spherical configurations will be obtained for additional cases of interest during the next reporting period and included in the final report.

A set of pyroelectric probes (including electronics) are being fabricated for use in power density measurements under plane wave irradiation conditions over the 1 to 10 GHz frequency band. Each probe element utilizes a pyroelectric crystal mounted very close to its associated preamplifier. The resonant absorption phenomenon observed in earlier experiments which resulted in very good probe responses will be exploited in designing this set of probes. The single preamplifier unit has been built. The follow-on electronics are under construction. Two crystal elements have been prepared for use at the higher microwave frequencies, and larger crystal elements for use at the lower frequencies are being prepared. The crystal elements comprising the complete set of probes are being mounted so that the appropriate element can be inserted on the preamplifier unit. Calibration of the probes will pose some problem because of the time remaining on the present project period; however,

as much progress as possible will be made in this area. The probe set and electronics will be delivered to the sponsor upon completion of the present project period.

A visit was made by Mr. Huddleston to NIEHS on 30 January. Dr. McRee visited Georgia Tech on 21 March. A proposal for the renewal of the present contract was submitted to NIEHS by Georgia Tech on 13 March 1973.

Approximately 550 man-hours of engineering and technician time have been expended during the period 1 December 1972 to 28 February 1973. During this same period, approximately \$5,680 of the total contract funds of \$66,632 were expended. It is anticipated that the remaining contract funds of \$11,318 will be sufficient to complete the work as delineated in the renewal proposal.

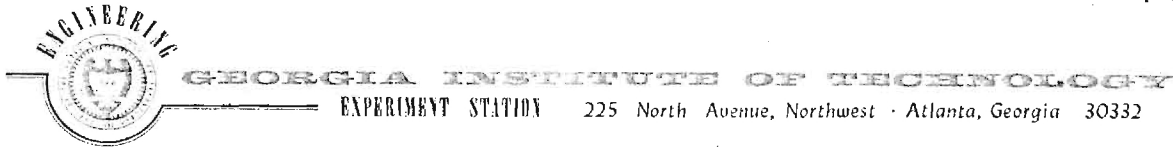
Respectfully submitted,

G. K. Huddleston
Project Director

Approved:

J. W. Dees, Chief
Special Techniques Division

Addressee: In Triplicate



22 June 1973

Dr. Donald I. McRee
National Institute of Environmental
Health Sciences
P. O. Box 12233, Building 17
Research Triangle Park, North Carolina 27709

Subject: Quarterly Progress Report No. 8 Covering the Period 25 March
1973 to 24 June 1973, Georgia Tech Project A-1347, Contract
No. NIH-71-2374, "Study of Microwave Dosimetry"

Dear Sir:

Efforts during the eighth quarter have been directed toward testing of implantable pyroelectric probes, fabrication of a miniaturized pyroelectric probe for free-space applications, and the development of advanced instrumentation for pyroelectric probes. In addition, a final report has been prepared.

Very encouraging results have been obtained for a pyroelectric probe immersed in water and irradiated at 2450 MHz. Measured responses have been obtained which establish the feasibility of such probes. Details of the experiment are included in the final report.

A miniaturized pyroelectric probe was fabricated for measuring power density in free space under far-field conditions. This probe consists of a preamplifier mounted permanently on one end of a $\frac{1}{4}$ -inch diameter Plexiglas tube approximately 12 inches long with the necessary power and signal wires inside the tube. Unfortunately, the preamplifier became inoperative at the time calibration of the probe was to begin, and insufficient time remained to construct another probe. Consequently, no calibration data have been obtained.

Advanced instrumentation for processing the signals produced by the pyroelectric probes has been built and tested. The instrumentation works very well and overcomes the problems of stray (60 Hertz) pick-up. Probe voltages less than one millivolt are easily detected and displayed as a constant value. Minor modifications are presently being made to perfect the electronics.

The final report covering the period 25 June 1972 to 24 June 1973 has been prepared and is presently in the final stages of printing. It is anticipated that the final report will be transmitted by 24 June 1973.

Mr. Huddleston visited Dr. McRee at NIEHS during 19-20 June 1973 for the purpose of demonstrating the advanced instrumentation and the probes developed during this second year of effort. Responses obtained for a particular lossy probe when placed in the variable frequency irradiation system at NIEHS indicated the desirability of calibrating this probe at Georgia Tech for subsequent use at NIEHS. This probe would be used to complement the NBS probe presently on order. This probe will be calibrated over the 8-10 GHz frequency band (where the NBS probe is expected to have shortcomings) and at 2450 MHz during the time remaining on the project. The probe and instrumentation will be shipped to NIEHS in the near future.

Approximately 630 hours of engineering and technician time have been expended during the period 1 March to 1 June 1973. During this same period, approximately \$5,800 of the total contract funds of \$66,632 were expended. It is anticipated that the remaining contract funds of \$5,400 will be sufficient to cover the expenses incurred during June 1973.

Respectfully submitted,

Gene K. Huddleston
Project Director

Approved:

J. W. Dees, Chief
Special Techniques Division

Addressee: In Triplicate

STUDY OF MICROWAVE DOSIMETRY

by

H. L. Bassett, G. K. Huddleston, and B. W. Nolte

15 August 1972

Technical Report No. 1

on

Georgia Tech Project A-1347

Prepared For

National Institute of Environmental Health Sciences

Research Triangle Park, North Carolina 27709

Contract NIH-71-2374

1972



Engineering Experiment Station

GEORGIA INSTITUTE OF TECHNOLOGY

Atlanta, Georgia

Technical Report No. 1
on
Georgia Tech Project A-1347

STUDY OF MICROWAVE DOSIMETRY

H. L. Bassett, G. K. Huddleston, B. W. Nolte

15 August 1972

Prepared for

National Institute of Environmental Health Sciences
Research Triangle Park, North Carolina 27709
Contract NIH-71-2374

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

The feasibility and implementation of triglycine sulfate pyroelectric detectors for microwave dosimetry applications have been investigated. Theoretical and experimental results have been obtained which demonstrate the practicability of free-space microwave radiation detection using the pyroelectric effect. Two rather successful triglycine sulfate probes have been implemented and some of their characteristics determined under far-field conditions in the 1 to 10 GHz frequency band.

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SECTION I

INTRODUCTION

1. Background

Nonionizing radiation interacts with biological materials. The question is - what is the nature of this interaction, and does it constitute a hazard [1]? There are reasons to believe that hazards do exist (e.g., see [2]) and laws have been passed to protect the public from "unnecessary" exposure to "harmful" radiation emitted from electronic products. The quotation marks have been used to point out that the conditions which constitute a "necessary" exposure and the level of radiation which is "unharmful" have not been clearly defined on the basis of carefully obtained scientific data. Nevertheless, controls, regulations, and standards are being established to protect the general public and workers from the possibly harmful effects of nonionizing radiation. How these controls, regulations, and standards are being established is of great concern and importance to the agencies responsible for establishing and enforcing them, to the groups and individuals that must abide by them, to the agencies and officials responsible for public and occupational safety and health, and to the users of electronic products.

Electromagnetic fields in the frequency spectrum between 1 MHz and 100 GHz have special biological significance since they can readily be transmitted through, absorbed by, and reflected at biological tissue boundaries in varying degrees, depending on body size, tissue properties, and frequency. The frequency range receiving the most attention in terms

Fortunately, researchers in electromagnetic engineering and the biological sciences have begun to bridge the gulf that separates the two sciences, and a better quantitative understanding of the mechanisms of interactions should result. Such understanding is of paramount importance in developing and establishing indisputable standards of safe exposure; furthermore, such an understanding is necessary before meaningful microwave dosimetry can be done.

At the present time, it appears that some of the fundamental problems of microwave dosimetry have been recognized. For example, as in ionizing radiation dosimetry, the difference is made clear in microwave dosimetry between "exposure dose" and "absorbed dose". The accurate measurement of exposure dose and absorbed dose has also been recognized as a fundamental problem of microwave dosimetry. Prior to the establishment of dose-effect relationships, accurate measurements of dose must be made. Furthermore, the establishment of meaningful standards requires the simultaneous specification of practical procedures and instruments to measure nonionizing radiation levels and to relate the measurements to possibly harmful effects in man.

In addition to the lack of measuring instruments, there exists a lack of measurement techniques particularly adapted to microwave dosimetry as well as a lack of knowledge of what parameter or parameters are to be measured and at which location in space. For example, at the present time it appears that some biological effects of nonionizing radiation are related to the conversion of electromagnetic energy to thermal energy within biological tissues on a local and/or global scale. Wacker and

aim stated above has influenced the approach taken in the current investigation in that the results obtained here must contribute to the accomplishment of the overall aim.

3. Method of Approach

The type of probe chosen for this investigation operates on the principle of energy absorption in a lossy substance rather than as an antenna per se. A pyroelectric crystal serves as the absorber of microwave energy and the detector of same. The pyroelectric detector is a thermal detector whose response depends not on the rise in temperature due to energy absorption but rather on the rate of change of temperature with respect to time. Pyroelectric detectors have a number of interesting properties which are discussed in Section II.

The method of approach taken was based on a number of considerations. First, since the probe should be "small", it was judged that the processes of microwave energy collection, absorption, and detection should all take place in the probe itself as an inherent property of the probe material. Second, to minimize the scattering properties of the probe, it was deemed desirable to avoid the use of materials in the probe construction which are good conductors at the microwave frequencies of interest. Third, in order to obtain a probe response essentially independent of orientation in the field, it was desired that the probe should be realizable in a spherical configuration. Fourth, since one aim of the research was to develop new techniques and detectors, and since work was currently being carried out elsewhere on other types of probes (magnetic loops, electric dipoles,

SECTION II

THEORY

1. General

Of the 32 known crystal classes, 10 out of 21 without a center of symmetry exhibit spontaneous polarization; i.e., alignment of electric dipoles within domains of the crystal. The spontaneously polarized crystals are called pyroelectric since the value of the spontaneous polarization is temperature-dependent. The one-time application below the Curie point of a sufficiently high dc potential in a direction parallel to the crystal's ferroelectric axis aligns the dipoles into a single domain. Removal of the field will cause most of the domains to remain aligned in the same direction, and the crystal exhibits remanent polarization [6].

The pyroelectric effect is the change in spontaneous polarization that occurs upon uniformly heating or cooling a polar crystal that is free of stress [7]. When a pyroelectric crystal is subjected to a small uniform change in temperature, a polarization proportional to the change in temperature is produced. Observation of variations in the polarization of a pyroelectric material that is free of stress constitutes detection of a change in temperature of the material. In the case where thermal energy is transferred to the crystal by electromagnetic radiation, detection of that radiation is effected via the pyroelectric effect.

The pyroelectric detector belongs to the class of thermal detectors. However, it will be seen that pyroelectric detectors differ fundamentally

Materials which exhibit pyroelectric properties include tourmaline, barium titanate (BaTiO_3), lithium sulfate ($\text{Li}_2\text{SO}_4 \cdot \text{H}_2\text{O}$), and triglycine sulfate [$(\text{NH}_2\text{CH}_2\text{COOH})_3 \cdot \text{H}_2\text{SO}_4$], abbreviated TGS. Triglycine sulfate was used exclusively in this investigation.

2. Statement of the Problem

Figure 1 illustrates the salient features of the pyroelectric detector. The crystal element consists of a thin flat slab of pyroelectric crystal with conducting electrodes of area A on the two faces of the crystal normal to the spontaneous polarization axis (denoted by the vector \underline{P} in the figure). The crystal is connected as shown to a preamplifier which serves to transform the rather high impedance of the crystal to a low impedance to facilitate further instrumentation. The incident microwave radiation (plane wave with P_M mW/cm^2) is amplitude-modulated at the source with modulation frequency f_M corresponding to modulation period $T_M = 1/f_M$. The microwave energy is converted to thermal energy via ohmic losses in the crystal itself (and possibly in the electrodes) which causes the temperature of the crystal to vary periodically in time at the same frequency as the modulation waveform. The time variations of temperature cause a pyroelectric current to flow which is proportional to the rate of change of temperature with time. The voltage produced at the electrodes is applied to the input of the preamplifier. The output of the preamplifier is derived in what follows.

The electromagnetic, thermal, pyroelectric, and electronic aspects of the detector are embodied in the equivalent circuit model shown in Figure 2.

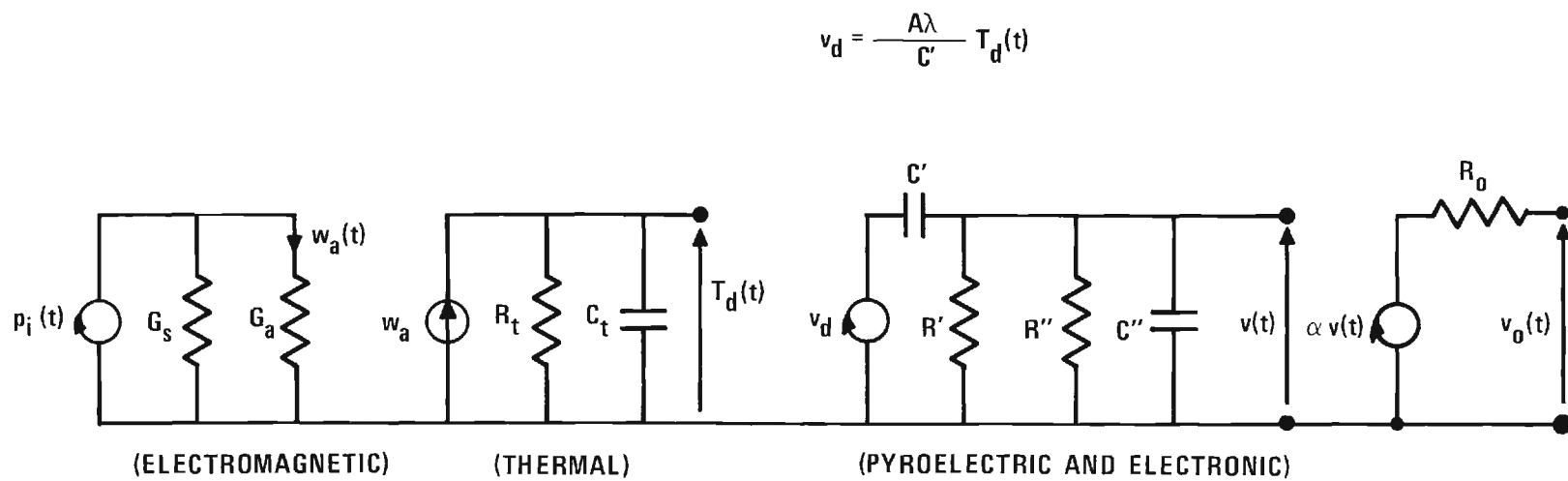


Figure 2. Equivalent Circuit Model of Pyroelectric Detector

The units of C_T are joules per degree Centigrade or watt-second per degree Centigrade. Perhaps more important than R_T and C_T taken separately is their product $\tau_T = R_T C_T$, the thermal time constant of the detector. In the equivalent circuit model of Figure 2, the absorbed power $w_a(t)$ is represented by a current source which drives the parallel R_T, C_T thermal circuit to produce the voltage $T_d(t)$ which represents the temperature response of the detector as a function of time.

After Cooper [10] and Stanford [7], the equivalent circuit model of the pyroelectric crystal consists of a temperature-dependent voltage source in series with the capacitance of the electroded crystal shunted by the leakage resistance of the unit as shown in Figure 2. The leakage resistance R' of the parallel-plate capacitor formed by electroding the slab of pyroelectric material is given by

$$R' = \frac{a}{\sigma A} \quad (2)$$

where σ = dc leakage conductance of the material plus the ac loss conductance

and where the other symbols have been defined in equation (1). The electrical capacitance of the crystal element is given by

$$C' = \frac{\epsilon_r \epsilon_0 A}{a} \quad (3)$$

where ϵ_r = relative dielectric constant of the material in the direction of the spontaneous polarization axis

ϵ_0 = permittivity of free space ($= 8.854 \times 10^{-14}$ farads/cm).

The temperature dependence of the voltage source $v_d(t)$ is given by

where R_e = electrical resistance of the parallel combination of R'

$$\text{and } R'' \left(R_e = \frac{R'R''}{R' + R''} \right),$$

C_e = electrical capacitance of the parallel combination of C'
and C'' ($C_e = C' + C''$).

The important function of the preamplifier is to transform the rather high impedance of the crystal detector to a low impedance without introducing excessive distortion and noise from the preamplifier itself.

3. Complex Frequency Domain Analysis

The objective of the analysis of the equivalent circuit model of Figure 2 is to determine the voltage $v(t)$ at the input of the preamplifier as a function of the incident radiation $p_i(t)$ and the parameters of the circuit model. A frequency domain analysis based on sinusoidal amplitude modulation of the incident radiation is presented in [10]. For the purposes of the present investigation wherein square-wave modulation of the incident radiation is anticipated, a complex frequency domain analysis using Laplace transforms [11] is deemed appropriate and will be used.

Applying the method of Laplace transforms to the linear system of Figure 2 yields the following expression for the temperature response in the s -domain

$$T_d(s) = \frac{G_a P_i(s)}{C_T} \frac{1}{s + 1/\tau_T} \quad (7)$$

where $P_i(s)$ = Laplace transform of $p_i(t)$ and the other variables have been previously defined. The corresponding Laplace transform of the voltage $v(t)$ (denoted $V(s)$) is given by

detector starting at time $t = 0$. The time domain voltage response of the detector to such excitation consists of the sum of a steady-state (periodic) response $v_{ss}(t) = v_{ss}(t + T_M)$ and a transient response $v_h(t)$ which decays with increasing time t . That is, the total response is given by

$$v(t) = v_{ss}(t) + v_h(t). \quad (12)$$

Applying the methods of Laplace transforms for periodic excitations as described in Chapter 15 of [11] results in the following expression for the steady-state voltage response of the detector to square wave excitation:

$$v_{ss}(t) = \frac{P_M G_a A \lambda}{C_T C_e} \left(\frac{\tau_T \tau_e}{\tau_T - \tau_e} \right) \left\{ \left[\frac{e^{-t/\tau_T}}{D_T} - \frac{e^{-t/\tau_e}}{D_e} \right] u(t) + \left[e^{-\frac{(t - T_M/2)}{\tau_e}} - e^{-\frac{(t - T_M/2)}{\tau_T}} \right] u(t - T_M/2) \right\} \quad (13)$$

where

$$D_T = 1 + e^{-T_M/2\tau_T}$$

$$D_e = 1 + e^{-T_M/2\tau_e}$$

and $u(t)$ is the unit step function. It is understood that Equation (13) is valid only for $0 \leq t \leq T_M$ but gives the periodic response of the detector for any complete period since $v_{ss}(t) = v_{ss}(t + nT_M)$, where n is any integer greater than zero and T_M is the period of the modulated incident radiation. The transient part of the total response is given by

$$v_h(t) = \frac{P_M G_a A \lambda}{C_T C_e} \left(\frac{\tau_T \tau_e}{\tau_T - \tau_e} \right) \left\{ \frac{e^{-t/\tau_T}}{D_T} - \frac{e^{-t/\tau_e}}{D_e} \right\} u(t) \quad (14)$$

where $D_1 = 1 + e^{-\beta_T/2\beta_T}$

$$D_2 = 1 + e^{-\beta_T/2}$$

Equation (20) facilitates the study of the steady-state response in terms of the parameters defined by Equations (15)-(18) in which the relative sizes of the time constants and the period of modulation, and the ratios of the crystal resistance and capacitance to those of the preamplifier are brought into perspective. The absolute time scale is determined from the relation

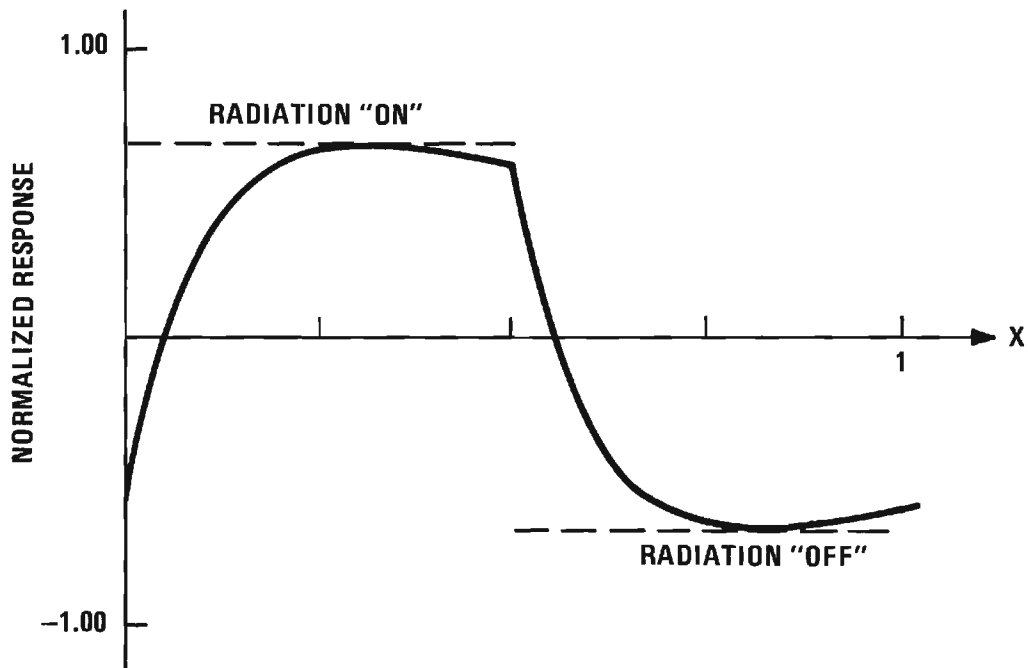
$$T_M = \frac{\epsilon_r \epsilon_0}{\sigma} \beta_T \frac{\beta_e}{\beta_e + 1} (1 + \beta_c) \quad (21)$$

where ϵ_r , ϵ_0 , σ have been defined previously as properties of the pyroelectric material and free space. It is also noted that the factor $G_a P_M \lambda / (J \rho c_p \sigma A)$, which is a function of the crystal properties and the amplitude of the incident radiation, affects only the amplitude of the steady-state response and not the shape. Hence, many salient features of the response can be studied independently of the type of material used and the electromagnetic properties of the detector.

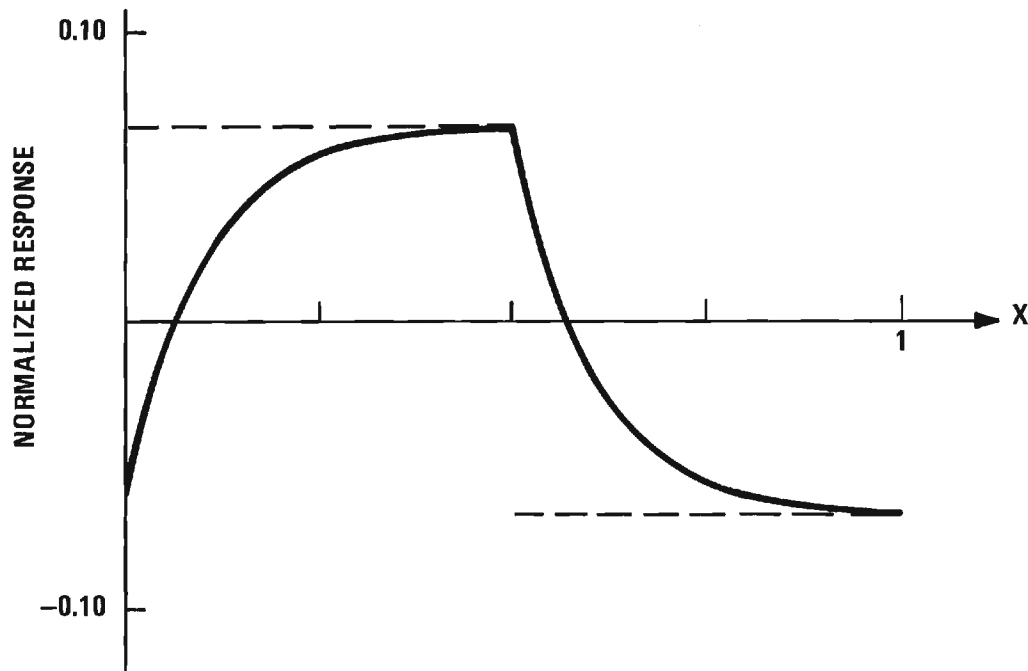
Further examination of Equations (15)-(20) reveal that the thermal and electrical time constants can be expressed as fractions of the period of modulation as follows

$$\tau_e = \frac{1}{\beta_T} T_M \quad (22)$$

$$\tau_T = \frac{\beta_T}{\beta_T} T_M \quad (23)$$



(a) $\beta_e = 10, \beta_T = 10, \beta_\tau = 10$



(b) $\beta_e = 0.1, \beta_T = 10, \beta_\tau = 1000$

Figure 3. Normalized Steady-State Responses of Pyroelectric Detector for Square-Wave Excitation for Different Values of Detector Parameters

time constant; the response resembles a triangular wave which becomes more triangular as τ_e is made longer relative to the period. These responses have been presented and discussed to provide a qualitative "feel" for the detector response.

An idea of the order of magnitude of the amplitude of the detector response for a given absorbed power ($P_{M a}$) can be obtained by using the physical constants of TGS given in Table I. Let the area A of the electroded surface of the crystal be 1.0 cm^2 for convenience. Using the quality factor Q in Table I and the maximum value of the normalized response in Figure 3(a) of 0.416 results in a detector "peak-to-peak responsivity" of

$$\frac{v_{\text{ptp}}}{P_{M a}} = Q(2)(0.416) = 1.08 \times 10^3 \frac{\text{volts}}{\text{watt}} . \quad (24)$$

Using $\beta_c = 0$ in Equation (21) reveals that the period of the modulation waveform is $T_M = 34.64$ milliseconds, corresponding to the modulation frequency $f_M = 28.87$ Hz for the response in Figure 3(a). Now, a typical figure for the minimum detectable power (using synchronous detection in a narrow bandwidth) of a pyroelectric detector using TGS is about 10^{-9} watt in a narrow bandwidth. Using this as the absorbed power in Equation (24) yields about one microvolt as the peak-to-peak voltage output of the detector. Further assuming that the absorbing cross section of the detector is about 0.01 of its physical area A implies that the detector should be capable of detecting down to about 10^{-4} mW/cm^2 incident power density (with a signal-to-noise ratio of unity). Some liberties have been

of the radiator is not practical.) In what follows, a similar analysis is presented for the case of sinusoidal modulation of the incident radiation. The results obtained below still apply for square-wave modulation when only the fundamental frequency component of the detector response is considered.

4. Frequency Domain Analysis for Sinusoidal Excitation

The response of the detector represented by the equivalent circuit model of Figure 2 to sinusoidal amplitude modulation of the incident radiation can be obtained directly from the system function given in Equation (9) by replacing s everywhere with $j\omega$. Doing this results in the system function in the ω -domain; viz.,

$$H(j\omega) = \frac{G_a A \lambda}{C_T C_e} \frac{j\omega}{(j\omega + 1/\tau_T)(j\omega + 1/\tau_e)} \quad (25)$$

Multiplying numerator and denominator by $\tau_T \tau_e$, using Equation (6) and the relation $\tau_T = R_T C_T$, and cancelling common terms results in

$$H(j\omega) = G_a A \lambda R_T R_e \frac{j\omega}{(1 + j\omega\tau_T)(1 + j\omega\tau_e)} \quad (26)$$

For incident radiation given by

$$p_i(t) = P_M' (1 + k \cos \omega_M t) \quad (27)$$

where $0 \leq k \leq 1$ (k is the modulation index) and where

$$\omega_M = \frac{2\pi}{T_M} \quad (28)$$

the steady-state voltage response of the detector is given by

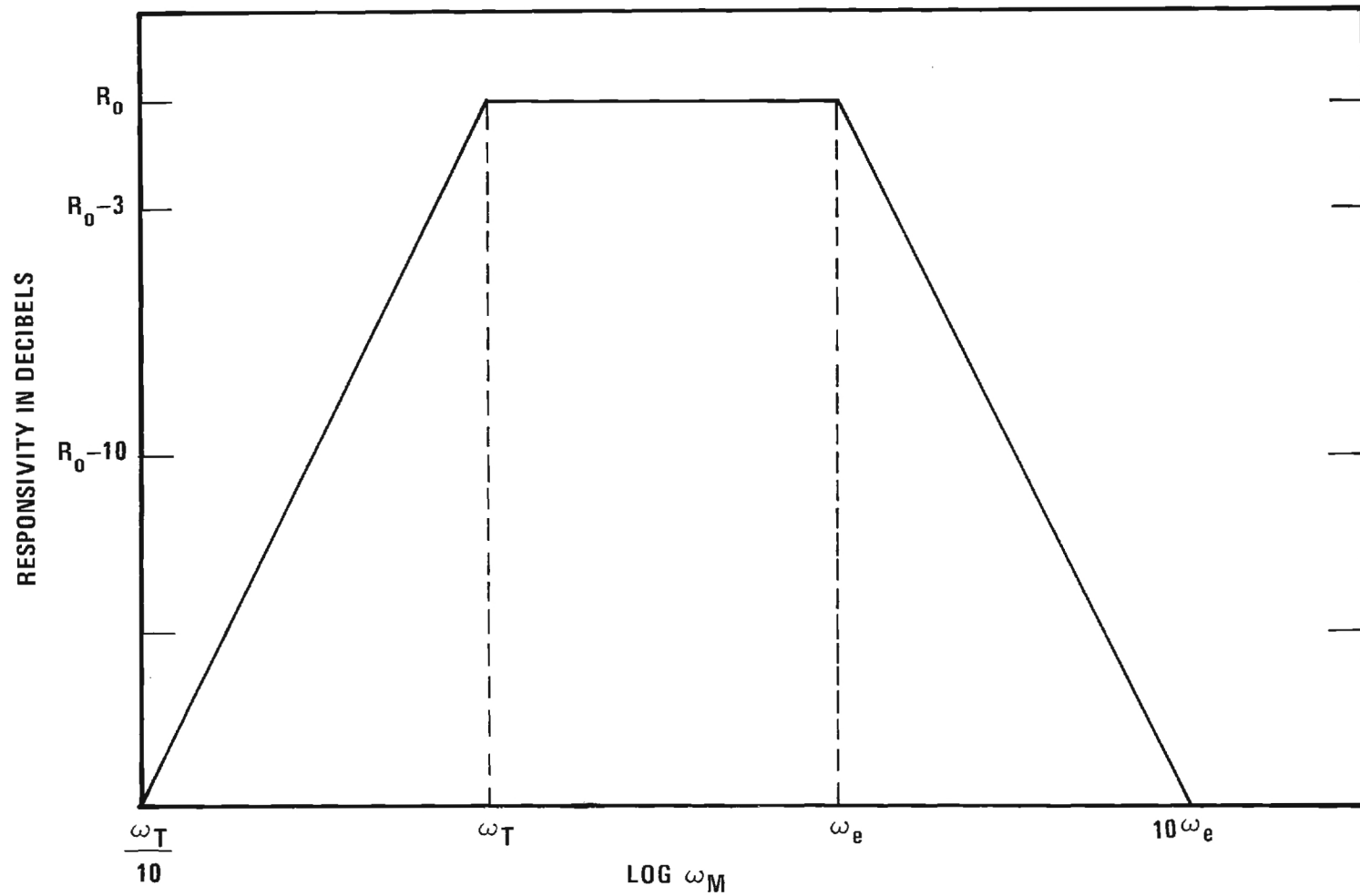


Figure 5. Bode Plot of Responsivity of Pyroelectric Detector for Sinusoidal Excitation

detector for sinusoidal excitation. For ω_M in the interval $\omega_T < \omega_M < \omega_e$ (ω_e is always larger than ω_T for the cases considered in this investigation), the response is relatively constant as indicated by the flat portion of the graph. For $\omega_M > \omega_e$, the response is attenuated at the rate of 20 dB per decade; the same is true for $\omega_M < \omega_T$. Hence, for a given detector, there exists a band of modulation frequencies for which the response is maximum and fairly independent of ω_M . From Equation (33), it is apparent that ω_e can be increased by decreasing β_e to yield a flat response over a wider band of frequencies; however, the expression for R_o in Equation (35) shows that the amplitude of the response is reduced according to $20 \log \omega_e$. Equation (35) also reflects the dependence of the response on the modulation index k and the absorbing cross section G_a . It is noted that other types of thermal detectors are limited in their frequency responses by their thermal time constant; the pyroelectric detector does not suffer this limitation.

There is a definite correlation between the frequency response of the detector shown in Figure 5 and the response to square-wave modulation of incident radiation illustrated in Figures 3 and 4. But this correlation will not be belabored here. It is important to point out, however, that even though the incident radiation may be square-wave modulated, the detection scheme used may make use of the frequency response as shown in Figure 5. That is, the response of the detector to the square wave excitation may be passed through a narrow-band filter centered on ω_M (to reduce the ever-present noise) and synchronously detected using a lock-in amplifier or similar device. Passing the detector voltage through the

SECTION III
EXPERIMENTAL RESULTS

1. General

The experimental portion of the investigation comprised the fabrication of several pyroelectric detectors (including electronics) and the measurement of their responses to square-wave, amplitude-modulated microwave radiation at selected frequencies in the 1 to 10 GHz frequency band under far-field (plane wave) conditions. The input parameters of interest for a given detector include microwave frequency, modulation frequency, incident peak power density, and orientation of the probe in the field. The output parameters of interest include output waveform shape and peak-to-peak amplitude of the voltage response. From the measurements of these input and output parameters, other parameters were derived which quantify the performance of each detector in terms of the parameters discussed in Section II.

In the present section, two different pyroelectric detectors are described (designated Probe #1 and Probe #2), and their measured performances presented. The details of detector fabrication and measurement procedures are discussed in Appendices I and II. This section is concluded with a discussion of the measured results.

It is appropriate to discuss some terms and nomenclature common to both detectors. The term "detector" will be understood to include the pyroelectric crystal with conducting electrodes and its preamplifier. The term "probe" will be understood to mean those parts of the detector

of a probe to meet the objective stated in Section I had to proceed at the rate at which information became available from the experiments. Emphasis was initially placed on crystal fabrication and mounting. Instrumentation problems due to the high impedance of the crystal arose and required that emphasis also be placed on preamplifier design and implementation. The net result was that not all desirable characteristics of the probe could be realized simultaneously in the first few attempts. The results obtained thus far, however, do indicate the feasibility and practicality of the approach taken as well as the steps to take to realize pyroelectric probes having desirable probe characteristics.

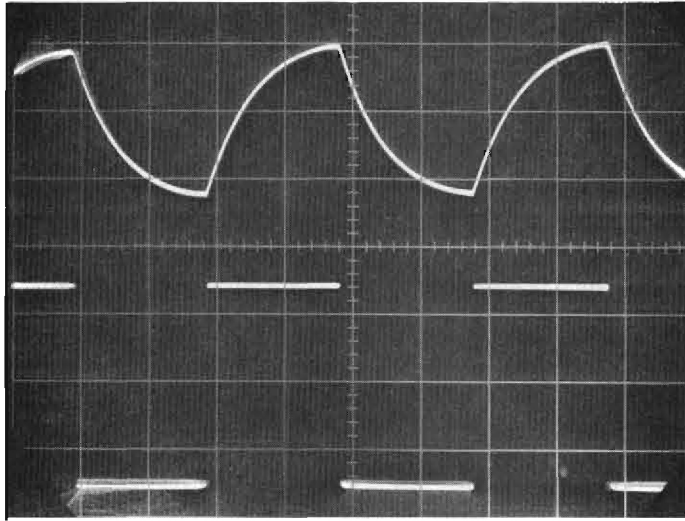
2. Experimental Results - Probe #1

Figure 6(a) is a photograph of Probe #1. The glass bulb at one end encloses the pyroelectric crystal to prevent noisy responses due to fluctuating air currents in the test environment. At the other end of the cylindrical aluminum probe body is the preamplifier unit. The probe body provides a rigid mount for the sockets into which the crystal mount and preamplifier unit are inserted. The 3/16" aluminum tubing entering the probe body at a right angle houses four #30 AWG insulated wires which provide power to the preamplifier and carry the signal away from the probe to the post-amplifier. Figure 6(b) shows a photograph of the crystal mount with the glass bulb removed to expose the crystal. The aluminum foil surrounding the crystal was installed to reduce the pick-up of extraneous signals (60 Hertz and 120 Hertz signals, primarily) by the high-impedance device. In operation, the probe is placed in the field so

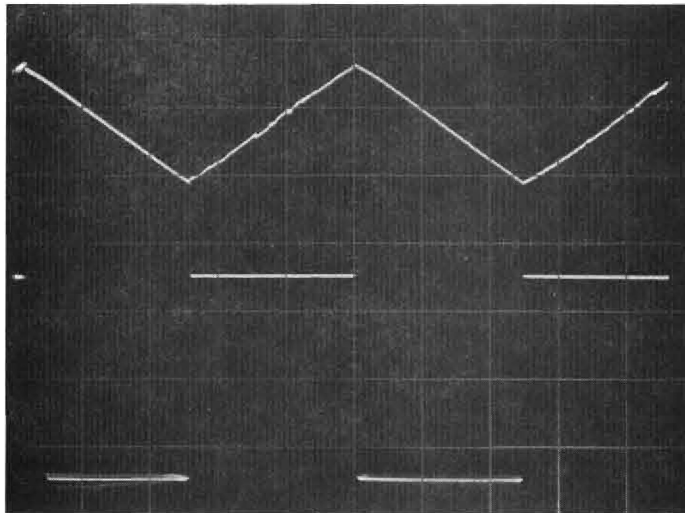
that the incident radiation is normally incident on the face of the crystal seen in Figure 6(b) so that maximum response is obtained. The aluminum tubing was oriented transverse to the electric field of the incident TEM wave so that its effects on perturbing the field were hopefully minimized.

The rather bulky probe configuration shown in Figure 6(a) is not desirable from an electromagnetic point of view. However, at the outset of the probe design phase of the investigation, it was decided to relegate the electromagnetic scattering problem to a secondary position and concentrate on crystal/preamplifier design and fabrication so that the sensitivity of the TGS material to microwave radiation could be determined experimentally. The probe configuration in Figure 6(a) facilitated such measurements in that it allowed easy interchange of several pyroelectric crystals having different thicknesses, electrodes, and mounting arrangements. The probe body and preamplifier shown in Figure 6(a) were used with Probe #1 and Probe #2 described herein; the two probes differed only in the crystals and mounting arrangements used.

The preamplifier consisted of an FET-input operational amplifier (Analog Devices type AD-506K) connected as a voltage follower. This particular unit was selected because of its small input capacitance (~ 2 pf.), high input resistance ($\sim 10^{12}$ ohms), and particularly for its low bias and offset currents (~ 10 pA maximum). Other desirable features included size (TO-99 package) and no requirement for external compensation of offset voltage. The voltage follower configuration with unity gain was selected to give high input impedance and to eliminate the use of

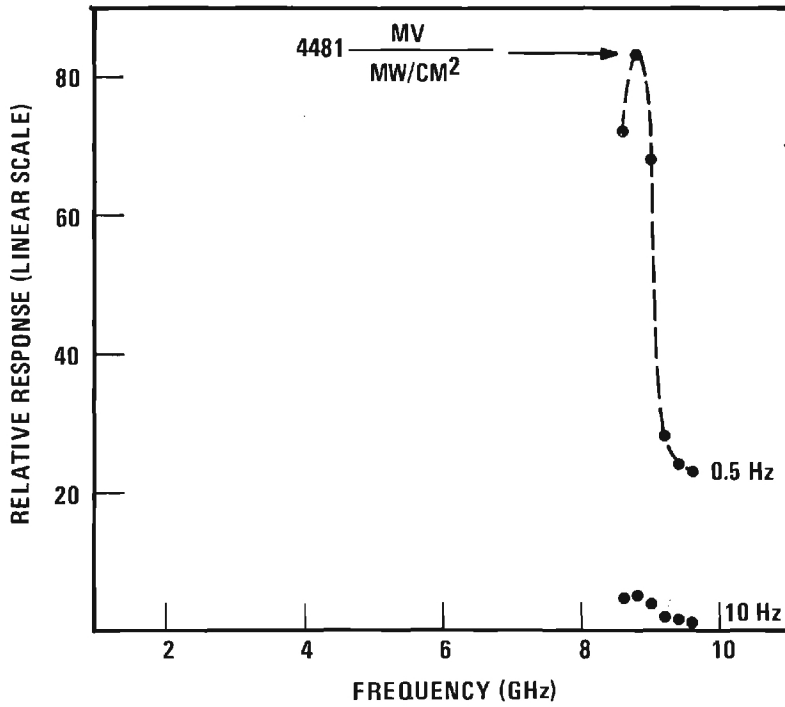


(a) $f_M = 0.5$ Hz

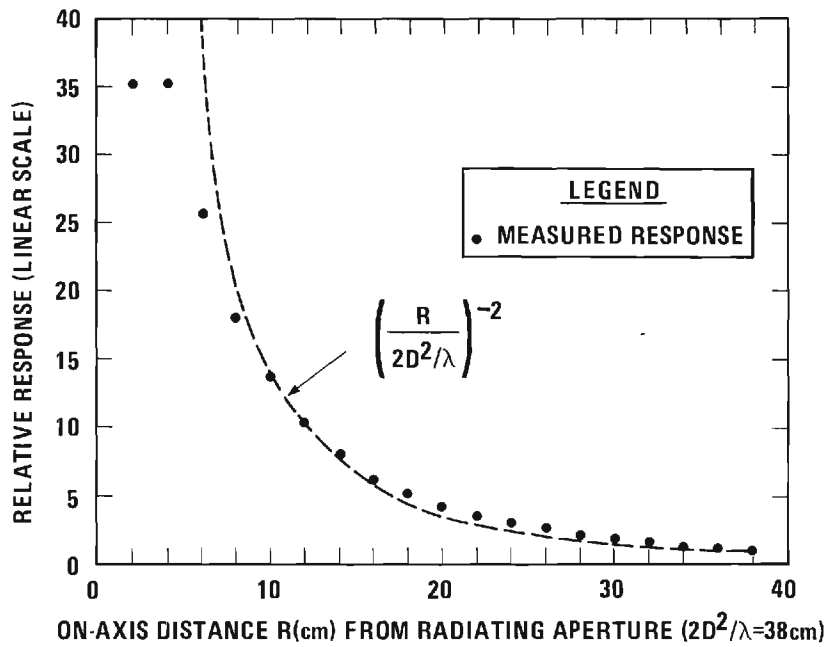


(b) $f_M = 10$ Hz

Figure 7. Photographs of Steady-State Responses of Probe #1 at 9.375 GHz

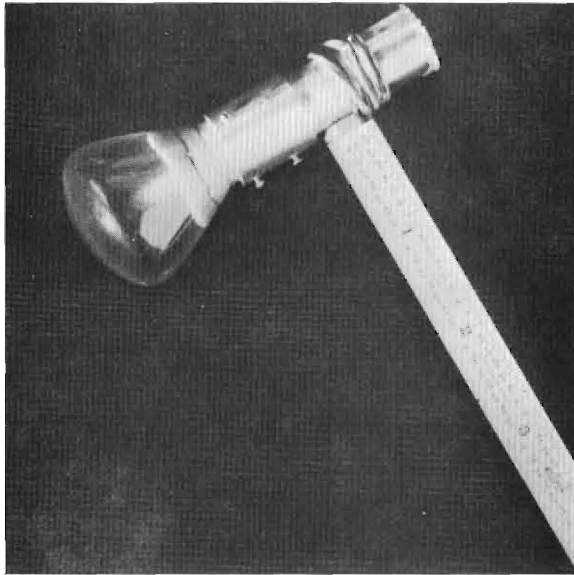


(a) RELATIVE RESPONSE OF PROBE #1 VERSUS MICROWAVE FREQUENCY.

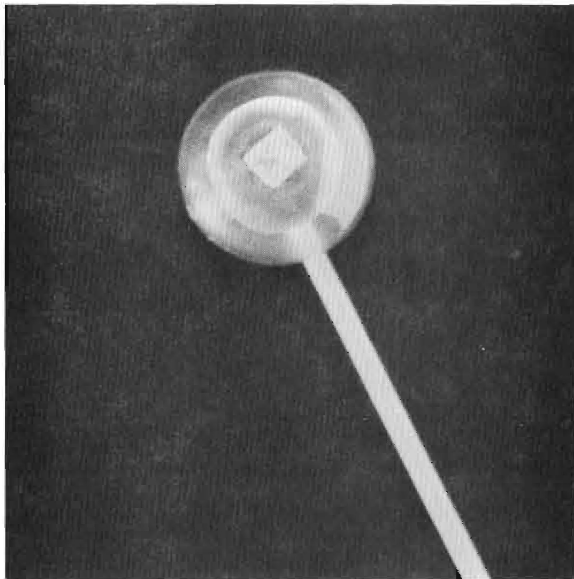


(b) RELATIVE RESPONSE OF PROBE #1 VERSUS DISTANCE FROM RADIATING APERTURE.

Figure 8. Measured Responses of Probe #1

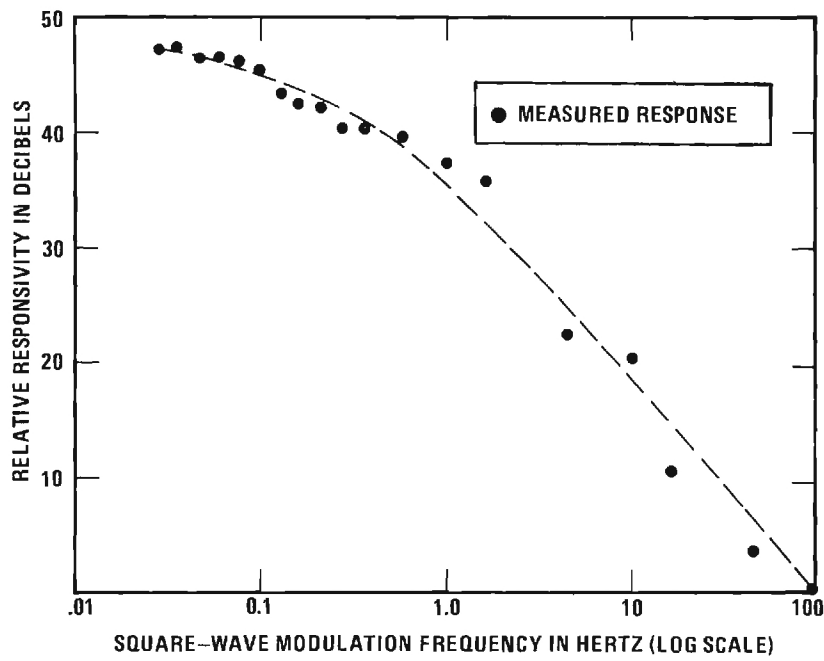


(a) SIDE VIEW.

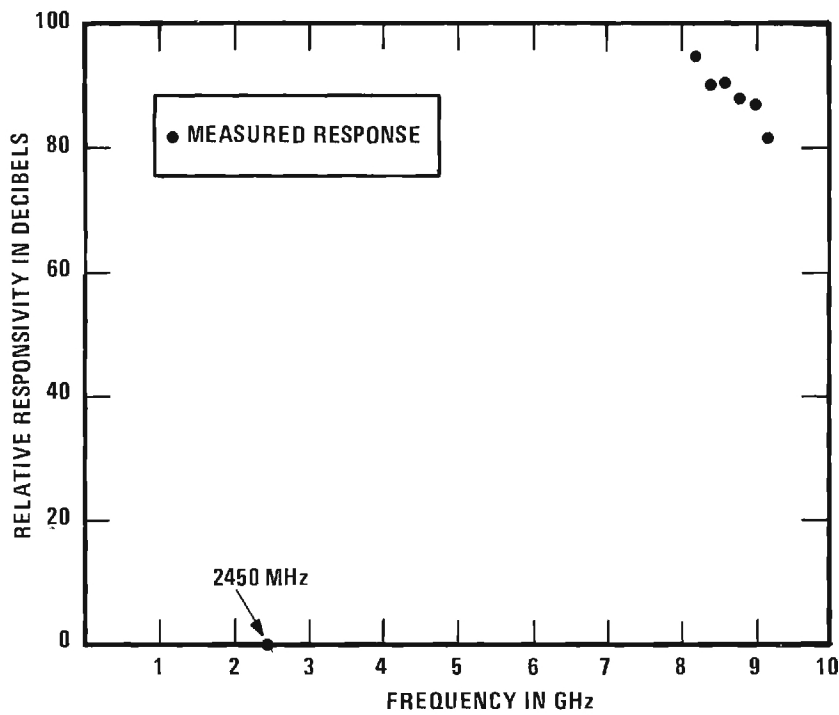


(b) FRONT VIEW SHOWING CRYSTAL.

Figure 9. Photographs of Probe #2



(a) RELATIVE RESPONSIVITY VERSUS MODULATION FREQUENCY AT 8.2 GHz.



(b) RELATIVE RESPONSIVITY AT SELECTED MICROWAVE FREQUENCIES (fm = 1.0 Hz).

Figure 10. Measured Results for Probe #2.

crystal of Probe #2 was poled in various ways and some variations in responsivity were noted. No definitive experiment has yet been performed to determine the responsivity as a function of poling conditions, but efforts are underway to do so. In addition, an experiment is being designed to determine the long-term stability of the pyroelectric probe.

The pyroelectric detector will not respond to continuous wave microwave radiation. That is, the incident radiation must be amplitude-modulated either at the source or at the detector. Consideration is being given to methods of providing the required modulation external to the source so that continuous wave microwave radiation may be detected.

Although the responses obtained for the pyroelectric probe under plane wave conditions are encouraging, no information is available for the response of such a probe immersed in a dielectric medium other than free space (e.g., biological material). It appears that the pyroelectric crystal element must be isolated both electrically and thermally from the medium in which it is immersed in order to obtain the desired sensitivity. Efforts are planned which will help determine the applicability of pyroelectric detectors to microwave measurements inside of biological materials. A dosimeter which simulates part of the human anatomy and which utilizes a pyroelectric detector has been conceived.

5. Other Work

Concurrent with the investigation of the pyroelectric detector, a low-level effort has been continued to investigate the possible applications of heat-sensitive proteins to microwave dosimetry. The aim here is to ascertain the feasibility of developing an organic dosimeter which could

APPENDIX I

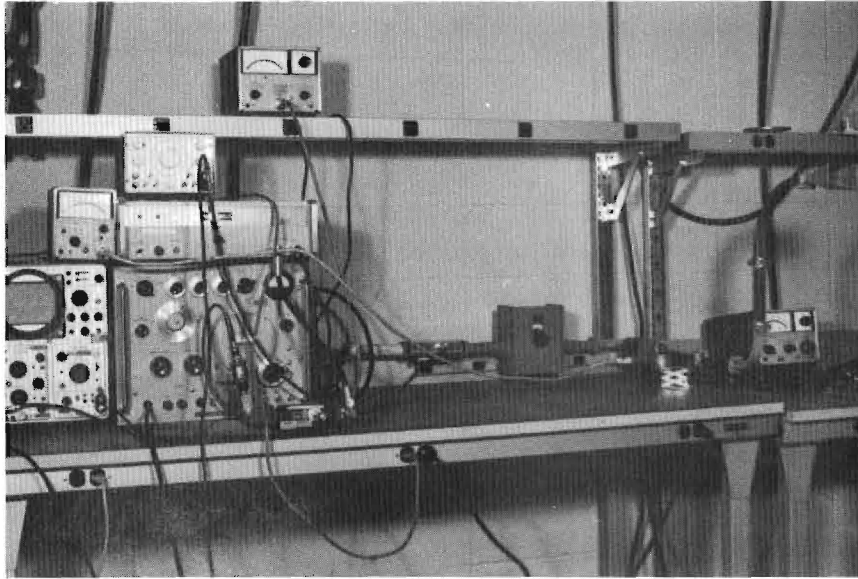
MICROWAVE FIELD GENERATION AND RESPONSIVITY MEASUREMENTS

The measurement of the responses of the pyroelectric probes used in this investigation required the establishment of uniform (plane wave) microwave fields of known power densities in the 1 to 10 GHz frequency band. The systems and techniques used to establish such fields and measure the probe responses are described in this appendix. A description of the microwave system and the method of determining power densities are included.

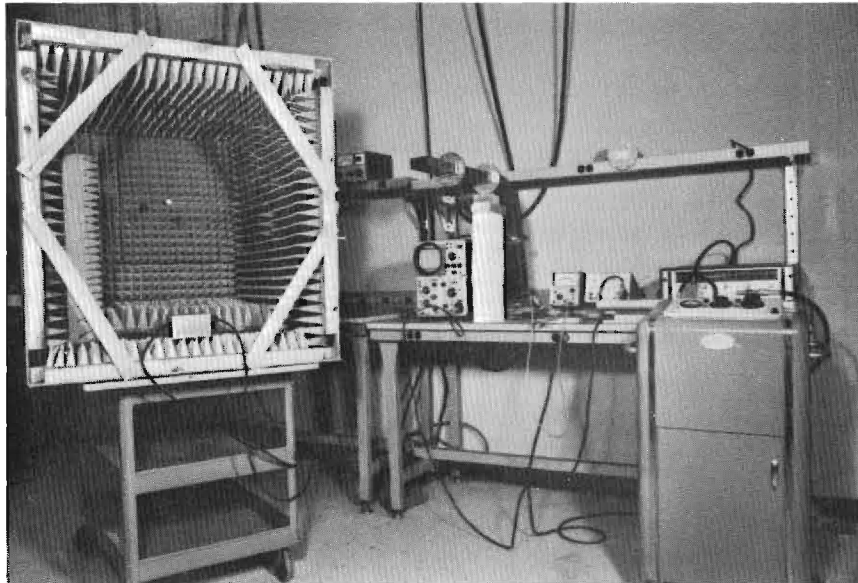
1. Description of Microwave System

The X-band system (Figure I-1(a) and Figure I-2(a)) uses a signal generator as the microwave source. The output power is on the order of 1 mW to 50 mW and is amplified by a traveling wave tube (TWT) to a maximum power level of 1 watt. A PIN modulator and audio oscillator provide the on-off square-wave modulation of the microwave field. Isolators are used to prevent reflections in the system from interfering with the power measurement scheme. A standard gain horn is used as a transmitting antenna. To reduce reflections and standing waves, a small anechoic chamber is used (Figure I-2(b)).

The S-band measurement system (Figure I-1(b) and Figure I-2(b)) is similar in design to that used at X-band. A high-power, 2450 MHz magnetron is used as a signal source, from which 1 watt of microwave power is used. The remaining power is coupled into a dummy load. A PIN modulator and audio oscillator provide the square-wave modulation of the microwave field. The transmitting antenna is an open-end waveguide.



(a) PHOTOGRAPH OF X-BAND MEASUREMENT SYSTEM



(b) PHOTOGRAPH OF S-BAND MEASUREMENT SYSTEM

Figure I-2. Photographs of Microwave Systems.

This expression for power density does not depend on the characteristics of the receiver.

From $|\Gamma_t| = \frac{VSWR - 1}{VSWR + 1}$, it can be seen that considerable error may be introduced if the VSWR is different than unity and neglected. The VSWR is determined by slotted line measurements at the frequencies of interest.

The transmitting antenna at X-band is a standard gain horn whose gain, G_t , has been calibrated as a function of frequency. At S-band, the gain G_t of the open-end waveguide must be calculated as a function of frequency using [12]

$$G_t = \frac{8}{\pi(1 - |\Gamma_t|^2)} \frac{\kappa}{\beta_{10}} \left| 1 + \frac{\beta_{10}}{\kappa} + \Gamma_t \left(1 - \frac{\beta_{10}}{\kappa} \right) \right|^2 \frac{ab}{\lambda}, \quad (4)$$

where

$$\kappa = 2\pi/\lambda,$$

$$\beta_{10} = 2\pi/\lambda_g \quad (\lambda_g = \text{waveguide wavelength in cm}),$$

a = width of waveguide in cm, and

b = height of waveguide in cm.

The power P_i incident at the transmitting antenna may be measured by coupling a fraction of the power in the transmission line to a power meter (Figure I-1(a) insert). If

P_1 = power at port 1 in mW,

$P_2 = P_i$ = power at port 2 incident at transmitting antenna in mW,

P_3 = power at port 3 indicated on the power meter in mW, and

C_c = coupling ratio of coupler,

Since the square-wave modulation rate of the microwave field is slow (down to 0.1 Hz), the voltage response and waveshape were observed on a storage oscilloscope, which also facilitated the photographing of the responses with a Polaroid camera.

The circuit diagram for the pre-amplifier and post-amplifier are shown in Figure I-3. The pre-amplifier utilized an FET-input operational amplifier Analog Devices Type AD-506K. A Fairchild U6A7741393 operational amplifier was used in the post-amplifier circuit. The post-amplifier was provided with selectable voltage gains ranging from 1 to 25 in increments of 5.

APPENDIX II

PREPARATION OF TRIGLYCINE SULFATE CRYSTALS AND DETECTOR FABRICATION

This appendix describes the fabrication of the triglycine sulfate (TGS) crystals and the crystal mounts used in this investigation.

The growth of TGS crystals has been discussed by Konstantinova, Sil'vestrova and Aleksandrov [14], Koldobskaya and Gavrilova [15], and Beerman [16]. Large single crystals of TGS can be obtained from aqueous solution by slowly lowering the temperature while keeping the solution supersaturated. TGS crystals are normally transparent. Opaque areas within the crystal are indicative of water inclusions, vacancies, or other defects in the crystal lattice. Such defects are generally the result of lowering the solution temperature too rapidly. The growth rate of the crystal is not the same in all directions. Consequently, the predominant face of the crystal tends to grow in the form of a parallelogram. The b-axis, or spontaneous polarization axis, is usually along the longer diagonal across the face of the crystal in this case. This is not always true, however, and the orientation of the b-axis becomes even more difficult to ascertain visually in larger crystals, which tend to assume more irregular shapes. X-ray examination of the crystal is therefore desirable to ensure acceptable lattice structure and proper determination of the b-axis orientation. TGS crystals are also commercially available.*

*Note: One commercially prepared crystal was obtained for this investigation from the Crystal Division, Gould Laboratories, 540 E. 105th Street, Cleveland, Ohio 44108.

later detector as shown in Figure II-1(a). The leads were bonded to the electrodes with Hanovia #13 flexible silver adhesive.

Several detector packages were assembled using the crystal mount illustrated in Figure II-1(b). This particular mount was designed to mate with a socket on the main body of the probe. Signal connection is through the metal pin and the common connection is secured through the overlapping aluminum with a screw. Originally, the crystals were placed on a polyurethane pedestal for support. In the interest of isolating the crystal as much as possible both electrically and thermally, later units used two to four small nickel wires for support instead of the polyurethane base. Attempting to obtain even better isolation, it was found possible to support the crystal satisfactorily by only the electrode leads (using the Hanovia silver adhesive for bonding).

A thin glass dome, not shown in Figure II-1, was placed over the crystal and epoxied to the Lexan base in each case to protect the crystal and insulate it from temperature fluctuations in its environment. A layer of silver was deposited on the inner surface of the glass dome from the base up to the height of the mounted crystal. This shield was then connected to the system ground through the aluminum sleeve of the mount in order to reduce stray 60-cycle pickup from the sides and back of the detector.

The detectors in this study were poled at various field strengths in the range 400-1000 volts/cm. Most of the detectors were poled at ambient temperatures, although some were poled at temperatures above the

Curie point and allowed to cool with poling voltage applied. Effects of poling at various potentials and/or different temperatures were not quantitatively studied in the course of this particular investigation.

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STUDY OF MICROWAVE DOSIMETRY

by

H. L. Bassett, G. K. Huddleston, and J. B. Langley, II

24 June 1973

Technical Report No. 2

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Georgia Tech Project A-1347

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Research Triangle Park, North Carolina 27709

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ABSTRACT

The feasibility and implementation of pyroelectric probes for microwave dosimetry applications in the 1-10 GHz frequency band have been investigated. Experimental results have been obtained which demonstrate the practicability of an implantable pyroelectric probe at 2450 MHz. The effects of lossy material added to triglycine sulphate crystals have been studied. Improved instrumentation for pyroelectric probes has been developed. Miniaturization of free-space pyroelectric probes has been implemented.

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SECTION I
INTRODUCTION

This report covers the second year of a two-year program of research to develop new detectors and techniques which can be used to measure the energy absorbed in a biological specimen placed in either near or far microwave fields ranging from 1 GHz to 10 GHz.

During the first year, efforts were directed toward the development of a pyroelectric probe suitable for making accurate power density measurements over the 1 to 10 GHz frequency band under far-field (plane wave) conditions. The results of these efforts are presented in Reference 1.

During the second year, efforts were undertaken to increase the bandwidth of the probes developed in the first year. The results of these efforts are presented in Section II below. The main thrust, however, of the second year's efforts was to develop an implantable pyroelectric probe. The results of these efforts are presented in Section III below. Other efforts during the second year included the development of better instrumentation for the pyroelectric probes and the miniaturization of pyroelectric probes for free-space applications. The results of these efforts, and recommendations for future work, are presented in Section IV below.

SECTION II

RESULTS FOR LOSSY FREE-SPACE PROBES

1. Introduction

Earlier efforts directed at developing pyroelectric probes suitable for power density measurements under plane wave conditions [1] showed that such probes are inherently narrow banded as indicated by the graphs in Figure 1. These graphs show the relative response of two such probes developed earlier and described in [1]. The peak responsivities occurring at approximately 8.2 GHz for both probes are attributed to resonant absorption by the dielectric bodies comprising the pyroelectric crystal elements of the probes.

The dimensions and electrical properties (dielectric constant and conductivity) of dielectric bodies immersed in free space influence the frequencies at which resonant absorption occurs. This statement is illustrated rather well for a spherical, lossy dielectric sphere by Figure 4 of [2]. For fixed values of microwave frequency, dielectric constant, and conductivity, resonant absorption occurs at specific radii of the sphere as indicated by the peaks in the graph of relative absorption cross section versus sphere radius. For the simple spherical geometry, it can be shown that the absorption peaks are related to the natural modes of oscillations of the sphere [3]. For small values of conductivity, the resonant absorption peaks may be rather large and sharply defined; for larger values of conductivity (a more lossy material), the absorption peaks are smaller and less well defined. For certain combinations of dielectric

constant and conductivity, the absorption cross-section of the sphere may be rather constant over a large range of radii. Similar statements apply for a spherical body of fixed dielectric properties and radius over a range of microwave frequencies.

One of the first tasks of the current investigation was to determine the effects of lossy material on the response of pyroelectric probes. This task was undertaken for two reasons: (1) the addition of lossy material to the probe might provide for a "flatter" response over a broader microwave frequency range; (2) the addition of lossy material might enhance the response of the probe so that smaller crystal elements suitable for measurements inside biological materials could be implemented. Obtaining flat responses for free-space probes would lead to a pyroelectric probe suitable for power density measurements under plane wave conditions over a broader microwave frequency range.

The effects of lossy material on probe response was determined experimentally as described below.

2. Description of the Probes

Two probes were fabricated as shown in Figure 2 and designated as Probes #3 and #4. Probe #3 consisted of a 3 mm diameter by 0.4 mm thick disc of triglycine sulphate material. Electrodes of conductive silver paint were applied to the two faces of the disc in the usual manner. The electroded crystal was mounted on a Lexan base occupying the center portion of the aluminum holder shown in Figure 2(a). Electrical connections to the electrodes were made using conductive paint and 10 mil nickel wire; the

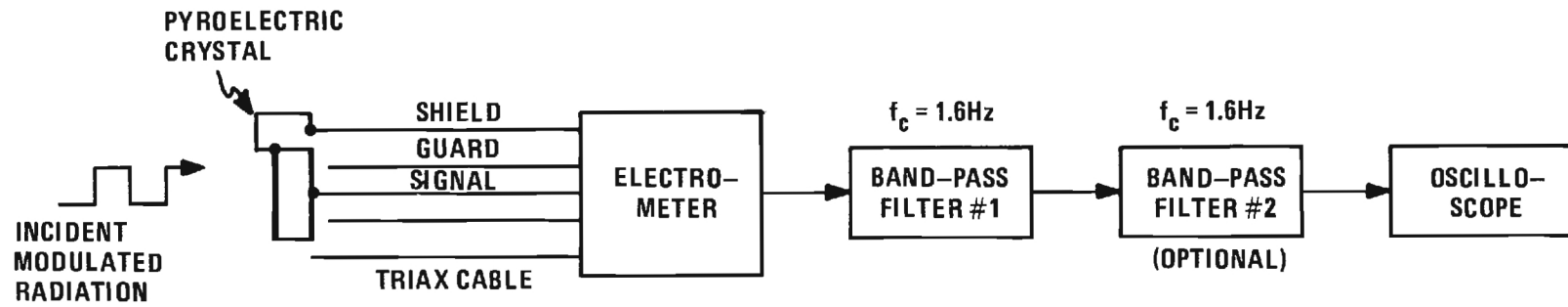
signal connection was made to the rear electrode using nickel wire and a center conductor pin embedded in the Lexan base; the ground return connection was made to the front electrode by the nickel wire and conductive paint applied to the Lexan base and extending to the aluminum holder. A mixture of powdered carbon and conductive adhesive was applied to the front electrode and allowed to harden in the hemispherical form shown. The crystal was poled by applying 40 volts between the electrodes for an arbitrary period of about 30 minutes. Probe #3 was deliberately made small so that the effects of the lossy material on enhancing probe response could be determined.

Probe #4 consisted of a 6 mm x 7 mm x 2 mm thick slab of triglycine sulphate material. Aluminum electrodes approximately 2000 Å thick were evaporated onto the large faces of the crystal. The electroded crystal was mounted directly on the center pin conductor imbedded in the Lexan base. Nickel wire was bonded to the top electrode and aluminum holder to make the ground return connection. A carbon mixture was applied to the top electrode of Probe #4 as shown in Figure 2(b). Probe #4 was constructed to be similar to Probe #2 [1] for which good responsivities were obtained earlier (Figure 1). The crystal of Probe #4 was poled in a similar manner as Probe #3.

A two-inch diameter styrofoam sphere was hollowed out and placed over the crystal elements to protect them from damage and to provide thermal shielding from the air currents in the test environment.

3. Instrumentation

In earlier experiments using Probe #2 [1], a preamplifier was located very near to the crystal element. The preamplifier serves to transform the



6

Figure 3. Block Diagram of Instrumentation Used With Probes #3 and #4.

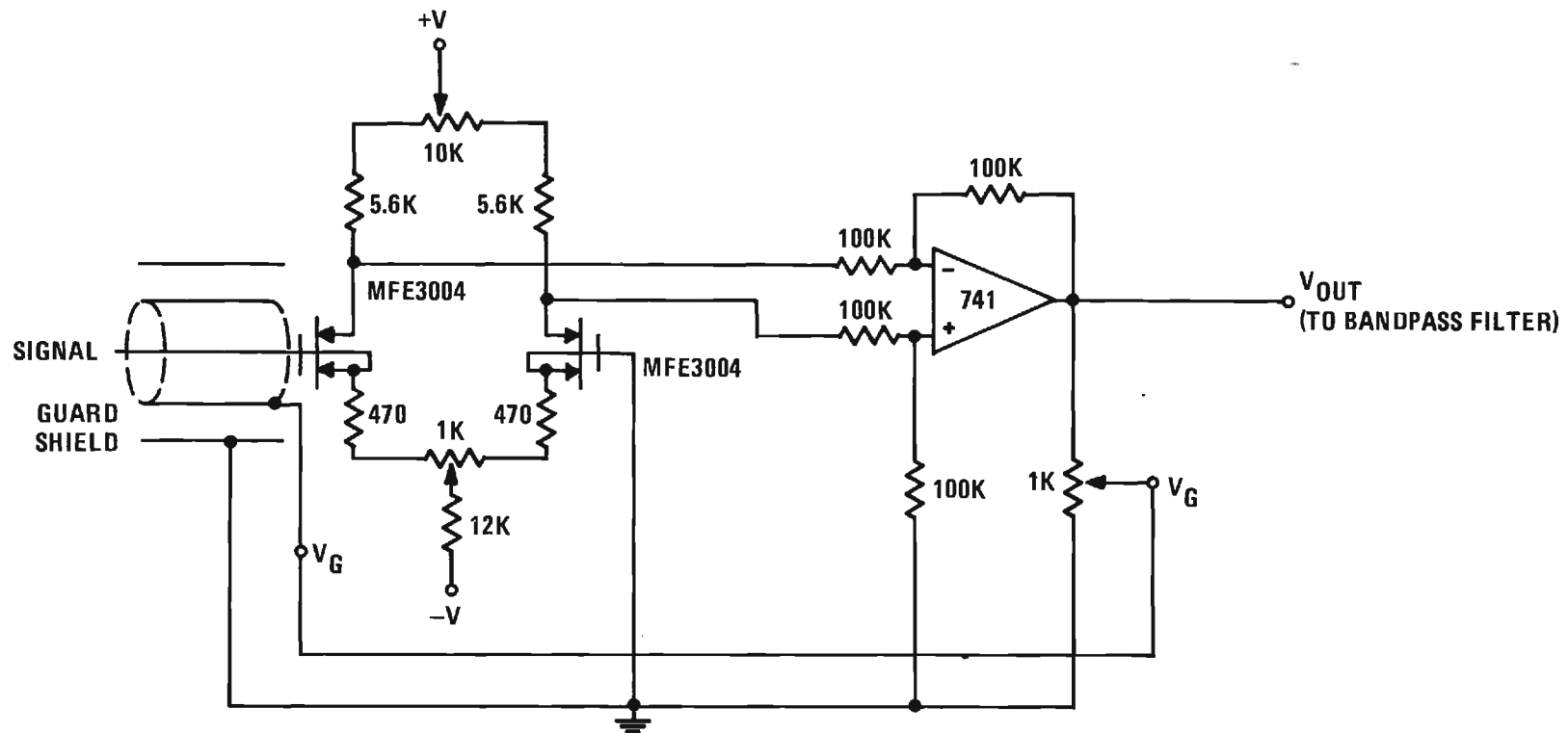
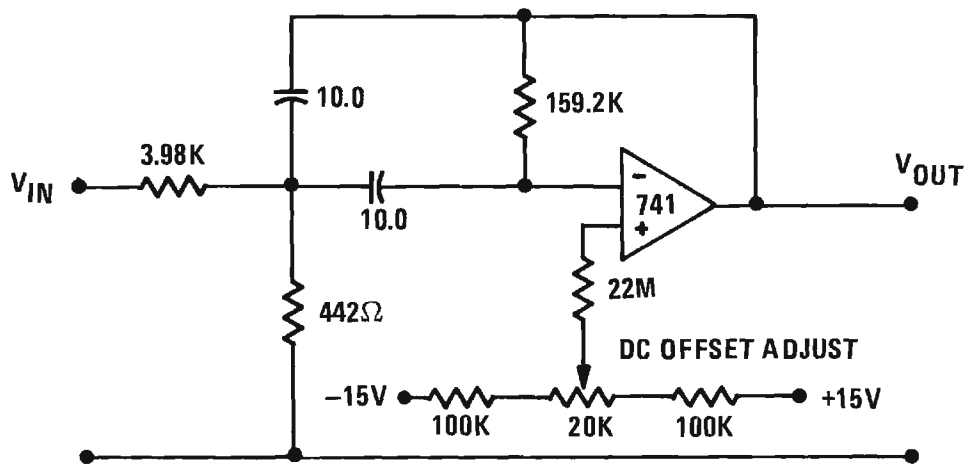


Figure 4. Schematic Diagram of Electrometer.



(ALL CAPACITANCES IN MICROFARADS)

Figure 6. Schematic Diagram of Band-Pass Filter #2 (Gain of 10 at 1.6 Hz).

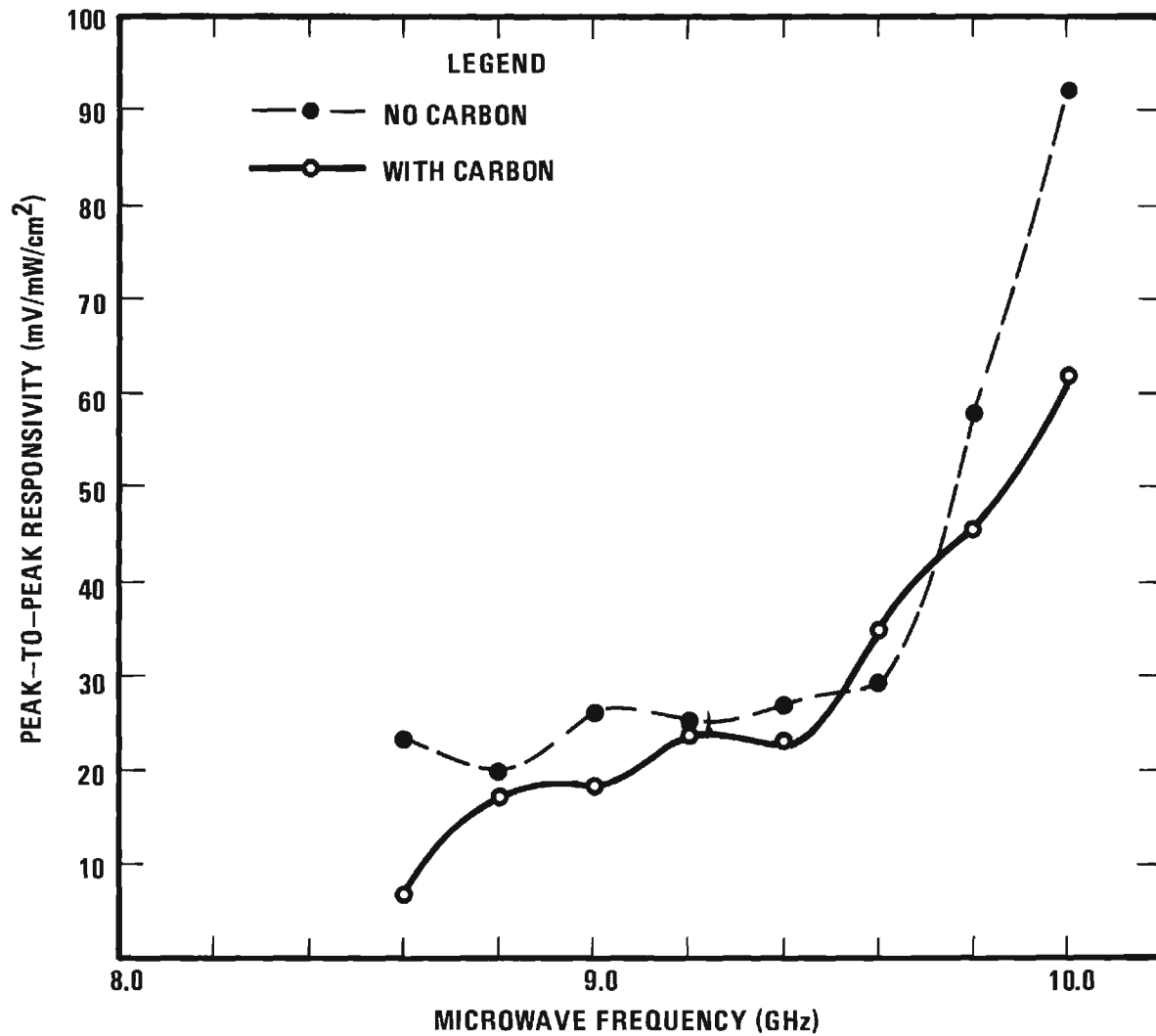


Figure 7. Measured Responses of Probe #3 Before and After Lossy Material Applied ($f_M = 0.85$ Hz).

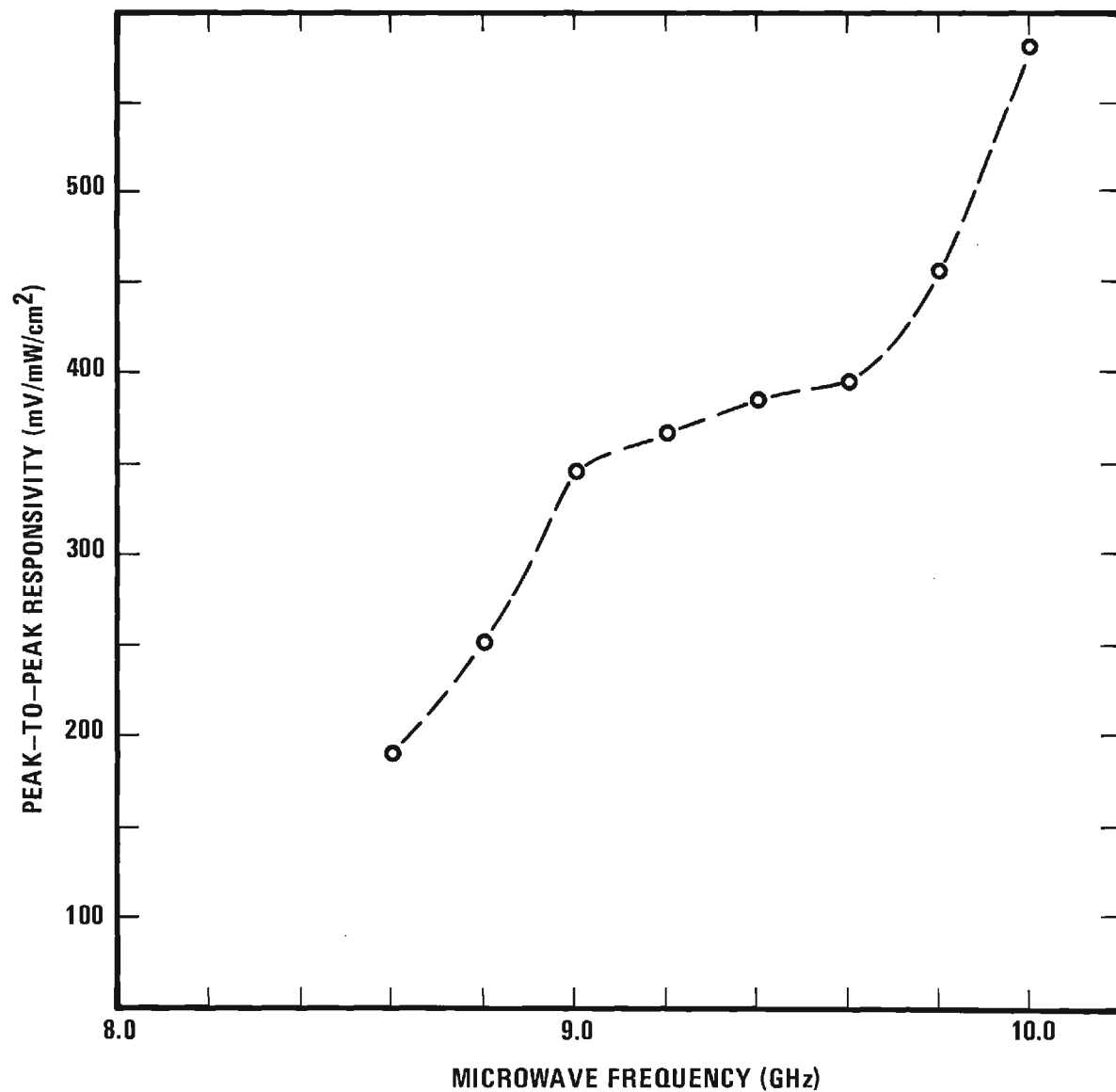


Figure 8. Measured Responses of Probe #4 ($f_M = 4$ Hz).

Although the addition of the lossy material to Probe #3 failed to produce the desired effects, certain positive results were obtained. The responses obtained for Probe #3 indicate that small crystal elements are practical for use in such microwave probes; since the size of the probe is important from an electromagnetic viewpoint, this is an encouraging result. Secondly, the instrumentation scheme was partially successful; earlier attempts to remove the electronics from the vicinity of the crystal did not employ voltage feedback and were not successful. However, a number of problems were experienced with the instrumentation scheme used with Probe #3. Adjustment of the feedback voltage to the guard of the triax cable was critical and depended on the position of the cable. That is, if the cable were moved, the feedback voltage would have to be readjusted to again minimize the effects of the cable capacitance. Movement of the cable caused a spurious output of the electrometer which was manifested as "ringing" in the bandpass filter sections. The extreme care that had to be exercised in the use of the electrometer/detector unit dictated that a more practical method of instrumentation be sought for such small crystal elements.

SECTION III

IMPLANTABLE PYROELECTRIC PROBES

1. Introduction

Another task undertaken during the current investigation was to determine the suitability of pyroelectric devices for the measurement of microwave energy absorption in biological materials. This task involved the fabrication of two probes using small pyroelectric crystal elements and the measurement of probe responses at 2450 MHz under controlled irradiation conditions as described in subsequent paragraphs. Immediately below, some considerations important to such measurements are presented.

The power absorbed by a biological material (e.g., muscle tissue) irradiated with microwave energy at a fixed frequency depends on the frequency, shape and dimensions of the material body, electrical properties of the material, orientation of the body in the field, and on the relative locations of the source and the body. If, however, the electromagnetic field and the electrical properties of the material are known everywhere throughout the body, then the real power absorbed at each point \underline{r} (assuming no magnetic losses) is given from Poynting's theorem [4] as

$$P_a(\underline{r}) = \frac{\sigma_c(\underline{r}) \underline{E}(\underline{r}) \cdot \underline{E}^*(\underline{r})}{2} \left(\frac{\text{watts}}{\text{m}^3} \right), \quad (2)$$

where

$\sigma_c(\underline{r})$ = electrical conductivity of the medium at the microwave frequency of interest, and

$\underline{E}(\underline{r})$ = electric field intensity at the point \underline{r} and (*) denotes complex conjugate (sinusoidal steady state).

As an alternative probe configuration, consider a thin disc of pyroelectric crystal with its circular faces perpendicular to the spontaneous polarization axis and electroded with vacuum deposited aluminum or carbon ($\sim 1000\text{\AA}$ thick). Let hemispherical masses of absorbing material (with electrical properties similar to those of the biological imbedding material) be placed on the two circular faces of the crystal to form an overall spherical shape. Let this structure be mounted at the end of a dielectric rod which serves as a handle, and let conducting paths be provided from the crystal electrodes along the rod to a preamplifier unit mounted on the other end of the rod. Let a thin protective coating be applied to the structure to provide waterproofing and electrical and thermal insulation. The resulting structure comprises one configuration of an implantable pyroelectric probe conceived during the course of this investigation.

When placed in a biological material and irradiated with microwaves, the absorbing material on the faces of the crystal absorbs an amount of power proportional to $\underline{E} \cdot \underline{E}^*$ in the material with the constant of proportionality being the electrical conductivity of that material at the (radian) frequency ω_c of the microwave radiation ($\omega_c = 2\pi f_c$). Since the pyroelectric material responds to the time rate of change of temperature, the radiation must be amplitude modulated so that the temperature of the absorbing material and the crystal are periodic in time, producing a periodic voltage waveform between the faces of the crystal having the same frequency ω_m as the modulating waveform. The pyroelectric voltage produced is applied to the high resistance input terminals of the preamplifier via the conducting leads along the dielectric rod. The output of the preamplifier may be processed as in the case of the free-space probes.

Some of the factors discussed above were applied to the design and fabrication of two implantable pyroelectric probes. These probes were subsequently tested to determine the feasibility of the approach. The results obtained are described below.

2. Description of the Probes

Photographs of the two implantable pyroelectric probes (designated Probes #5 and #6) are shown in Figure 9. Probe #5 consists of a pyroelectric crystal disc (5.7 mm diameter x 1.47 mm thick) with silver conductive paint electrodes. A mixture of carbon and conductive adhesive was placed on each crystal face and allowed to harden. The crystal element is mounted on the end of a 1/8-inch diameter Plexiglas rod approximately 4 inches long. The preamplifier (Analog Devices AD506K) is mounted on the other end of the rod. Silver conductive paint applied in shallow grooves along the rod provide the necessary electrical paths from the crystal element to the input of the preamplifier. The preamplifier is an FET-input operational amplifier connected as a voltage follower as described in Appendix I of Reference 1. Clear acrylic spray was applied to the structure to provide a protective coating. The crystal was poled by removing the preamplifier from the socket and applying 40 volts between the appropriate pins for approximately thirty minutes. A three-conductor (#28) shielded cable is used to provide power ($\pm 15V$ dc) and signal paths between the preamplifier and post-amplifier; the cable shield provides a ground return path.

Probe #6 is similar to Probe #5 with the exceptions of the dielectric rod and protective coating. The dielectric rod of Probe #6 is a 3/16-inch

diameter Teflon rod approximately $1\frac{1}{2}$ inches long. It was found that smaller diameter Teflon rods were too flexible, causing breaks in the conductive paint electrical paths applied in grooves along the rod. The completed structure was dipped into a Teflon-base paint (Dexter Corporation X-500) to provide a protective coating. Teflon was chosen for the rod and coating because of its excellent electrical and thermal insulating properties. Clear acrylic spray was applied over the Teflon coating to ensure waterproofing of the probe. Waterproofing is important since triglycine sulphate is water-soluble.

3. Instrumentation

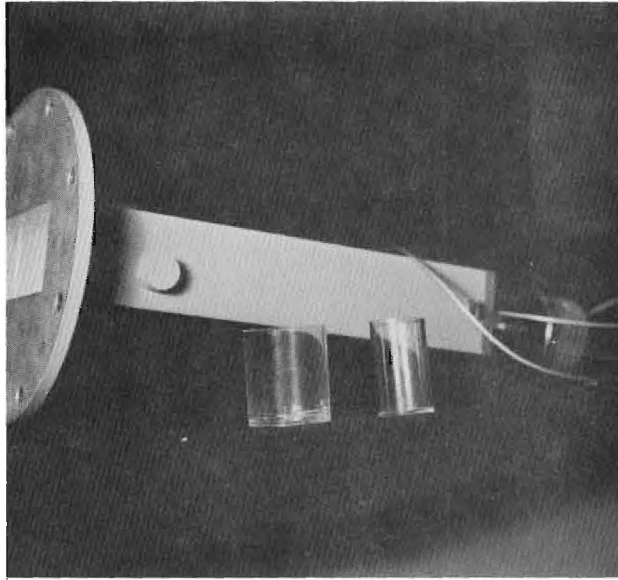
A block diagram of the set-up used in testing Probes #5 and #6 is shown in Figure 10. The test probe was placed in the sliding short waveguide section through a $\frac{1}{4}$ -inch diameter hole centered in one broad side of the waveguide with the preamplifier being located outside as illustrated in Figure 10. Incident and reflected microwave power (2450 MHz) at the input of the E-H tuner was monitored via the dual directional coupler and power meters. The incident power was modulated by the in-line PIN modulator driven by a Wavetek audio generator to produce square wave amplitude modulation of the fields at the probe. With the probe in place and power applied, the E-H tuner and sliding short were adjusted to minimize the reflected power and, hence, maximize the power delivered to the load. The load in this case was the probe and any other lossy material in the waveguide. The output of the preamplifier was amplified by the post-amplifier (described in Appendix I of Reference 1) and viewed on an oscilloscope.

A "closed" irradiation system was used so that the fields in the probe could be intensified without the use of high input microwave power and so that the net power absorbed by the probe could be measured. The combination of E-H tuner and sliding waveguide short facilitate the adjustment of the field intensity at the probe location by positioning a maximum of the voltage standing wave there. Neglecting any small losses due to imperfect conductivity of the waveguide walls and radiation from the access hole in the sliding short section, all of the microwave power not reflected at the input of the E-H tuner must be absorbed by the probe structure; i.e., the crystal and dielectric rod. Low loss materials were chosen for the dielectric rods so that most of the power absorbed would be confined to the lossy material on the crystal faces and to the crystal itself.

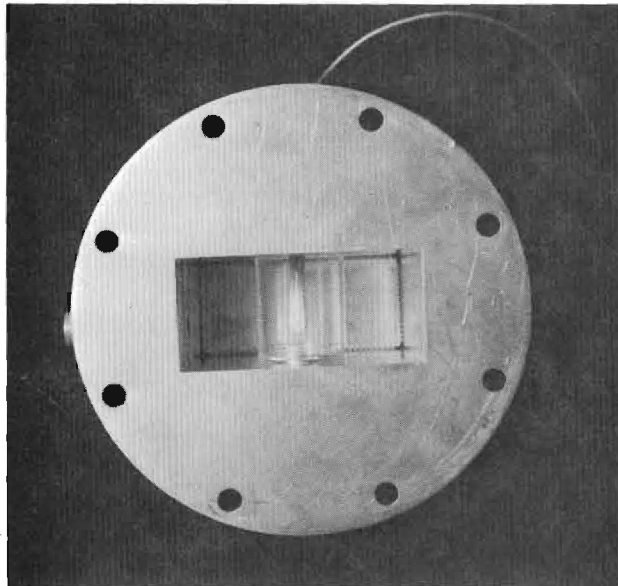
4. Measured Results

Probe #5 was fabricated and tested before Probe #6. The results obtained were not very encouraging. With Probe #5 inserted in the waveguide and power applied, the adjustment of the E-H tuner to minimize the reflected power was very critical. Measurable responses of the probe were obtained only for input powers exceeding 200 mW, of which about one-half was reflected. Additional amounts of absorbing material were added to the crystal, but no substantial increase in response was obtained.

It was felt at the time that the lack of response of Probe #5 was due to the capacitance of the leads connecting the crystal and preamplifier. Consequently, Probe #6 was constructed using a shorter dielectric rod of lower dielectric constant to reduce the capacitance. Preliminary testing



(a) Vials and Sliding Short.



(b) Large Vial and Probe #6 in Sliding Short Section.

Figure 11. Photographs of Plastic Vials and Sliding Short Waveguide Section Used With Probe #6.

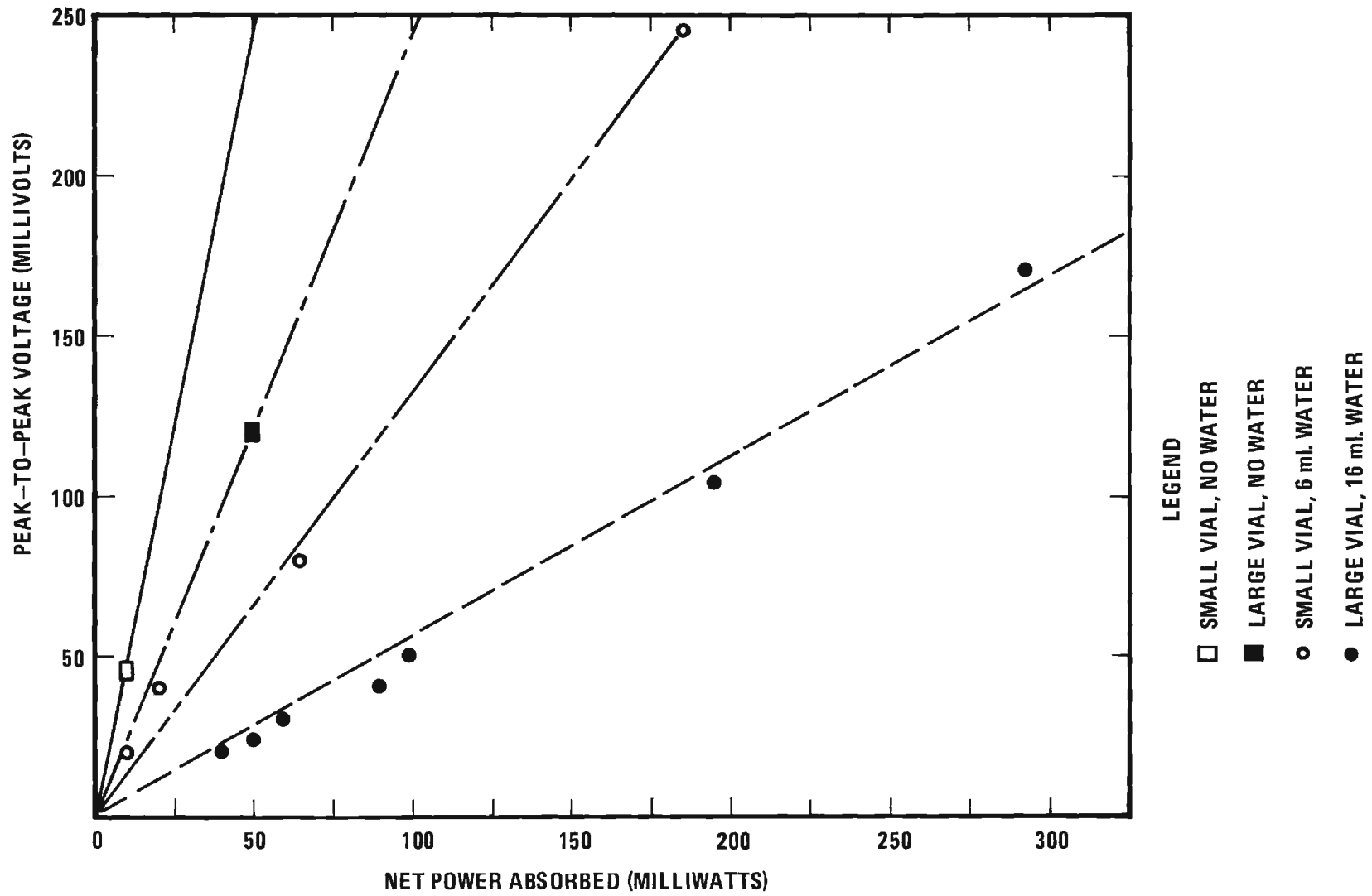


Figure 12. Response of Probe #6 in Water and Air at 2450 MHz ($f_M = 1.0$ Hz)

power densities, or rather $\underline{E} \cdot \underline{E}^*$, were accurately known for the two cases, the responsivities of the probe should be identical. Nevertheless, the assumption of uniform power dissipation in the two vials yields surprisingly accurate results.

It is also informative to relate the values of responsivity obtained above to the values of the fields that may be found in biological materials under typical irradiation conditions. Consider first the point (195, 105) of Figure 12 for the large water-filled vial. Dividing by the volume of 16 ml yields an average power density of 12.2 mW/cm³. From Equation (2), the average value of $\underline{E} \cdot \underline{E}^*$ is given by

$$\overline{\underline{E} \cdot \underline{E}^*} = \frac{2 \overline{P}_a}{\sigma_c} , \quad (4)$$

where the upper bars denote average values. From [7], a typical value of the loss tangent of water is $\tan\delta = 0.157$ at 3.0 GHz and 25°C. The value of the conductivity σ_c needed to evaluate Equation (4) follows from the relation

$$\sigma_c = \epsilon_r \epsilon_0 2\pi f \tan\delta , \quad (5)$$

where

$$\begin{aligned} \epsilon_r &= \text{dielectric constant of water,} \\ &= 78.8 [7], \\ \epsilon_0 &= 8.854 \times 10^{-14} \text{ farads/cm, and} \\ f &= \text{microwave frequency} = 2.45 \times 10^9 \text{ Hz.} \end{aligned}$$

Using the resulting value of $\sigma_c = 0.0169$ mhos/cm in Equation (4) yields an average value of $\underline{E} \cdot \underline{E}^*$ of 1440 (mV/cm)². From Table I and Figure 2 of

\hat{e} , \hat{h} embody the spatial variations of the fields. Let magnetic loss in the probe be zero so the power dissipated in Joule heat is given by Equation (3) above. Assume that the probe is "small" so that \underline{E} is constant in V , the volume of the probe. Then Equation (3) reduces to

$$P_a \approx \frac{\sigma_c \underline{E} \cdot \underline{E}^*}{2} V . \quad (8)$$

The power absorbed by the probe varies as a function of time because of the low frequency modulation of the microwave field; viz.,

$$P_a(t) = \frac{\sigma_c E_o^2 V}{2} \rho^2(t) , \quad (9)$$

where $\rho(t)$ is a square wave of unit amplitude and average value of one-half.

For simplicity, let the thermal properties of the probe be characterized by a thermal capacity C_T and a thermal resistance R_T , where the product $\tau_T = R_T C_T$ is the thermal time constant of the probe. As the power absorbed by the probe varies periodically in time according to Equation (9), the average spatial temperature $T_d(t)$ of the crystal element also varies periodically at the same frequency as the modulating waveform. (Note, however, that for sinusoidal modulation of the absorbed power, the temperature of the crystal would vary periodically at twice the frequency of the sinusoidal modulation.) The steady-state voltage response of the probe then follows from the analysis done earlier [1] for free-space probes; viz., Equation (13) of Reference 1 gives the response when the product $P_M G_a$ is replaced by the product $\eta \sigma_c E_o^2 V/2$ where η ($0 < \eta < 1$) is an efficiency factor which accounts for the fact that the crystal itself may not receive

Some results of this analysis for the special (unrealizable) case of perfectly insulated outer boundaries of the microwave absorber are shown in Figure 13 for the values of the parameters shown in Table I. The pyroelectric voltage response (vertical axis, Figure 13) is normalized by the microwave power absorbed per unit volume in the absorber region; absolute values of response are shown at two selected points for reference. The normalized response is graphed as a function of the thickness of each absorber region for two values of thermal conductivity of the absorber regions.

The two graphs of Figure 13 illustrate the dependence of the detector response on the thermal properties of the absorber region. In the lower graph ($k_1 = k_2$), increasing the thickness of the absorber region does little to enhance the response. In the upper graph ($k_2 = 1000 k_1$), the response is enhanced by increasing the thickness of the absorber region, but a point of diminishing returns is evident. These results demonstrate that the absorbing material used in an implantable pyroelectric probe should possess good thermal conductivity so that the heat generated can flow unimpeded into the crystal element, thus causing maximum variations in the temperature of the crystal. The amount of absorbing material is also important.

6. Conclusions

From the results presented above, it is concluded that implantable pyroelectric probes are feasible. Measurable responses have been obtained using such a probe immersed in a biological liquid; viz., water. Extrapolation of the average responsivities obtained to the conditions expected

TABLE I
 PHYSICAL CONSTANTS OF MATERIALS USED
 IN STRUCTURE OF FIGURE 13

Pyroelectric Material

Thermal conductivity:	$k_1 = 7.0 \text{ mW/cm-}^\circ\text{C}$
Density:	$\rho_1 = 1.69 \text{ g/cm}^3$
Heat capacity:	$C_{p1} = 0.975 \text{ joules/g-}^\circ\text{C}$
Electrical conductivity:	$\sigma_{xx} = 1 \times 10^{-9} \text{ mhos/cm}$
Dielectric constant:	$\epsilon_{rxx} = 43.0$
Crystal thickness:	$2a = 0.4 \text{ cm}$
Pyroelectric coefficient:	$\lambda = 2.2 \times 10^{-6} \text{ coul/cm}^2\text{-}^\circ\text{C}$
Electrode area:	$A = 1.0 \text{ cm}^2$

Absorber Material

Thermal conductivity:	$k_2 = (\text{see Figure 13})$
Density:	$\rho_2 = 1.0 \text{ g/cm}^3$
Heat capacity:	$C_{p2} = 1.0 \text{ joules/g-}^\circ\text{C}$

Electronic

Ratio of preamplifier resistance to crystal resistance:	$\frac{R''}{R'} = 100$
Ratio of preamplifier capacitance to crystal capacitance:	$\frac{C''}{C'} = 0.0$

SECTION IV

OTHER WORK

1. Advanced Instrumentation

It was suggested in the last section that more sophisticated instrumentation is needed to process the output of the preamplifier used with the pyroelectric probe. One of the main reasons for this suggestion is that the output voltage waveform of the preamplifier is corrupted by stray 60 Hertz pick-up. Such pick-up is characteristic of high input impedance devices operated in unshielded environments. Shielding can and has been used [1] to reduce the stray pick-up; however, shielding that is effective for 60 Hertz signals is also effective for microwave signals. Hence, some form of electronic filtering is desirable to eliminate or reduce the corruption of the desired signal. It is also desirable to process the periodic signal so that a direct read-out representation of the signal strength is provided.

Efforts were undertaken late in the current investigation to provide such instrumentation as illustrated in the block diagram of Figure 14. The output signal of the preamplifier is applied to the input of a bandpass filter with a center frequency gain of ten at 1.6 Hz; the gain of the filter is 40 dB below the center frequency gain at 60 Hz. The bandwidth (0.8 - 2.5 Hz) of the filter is narrow so that only the fundamental frequency component of the 1.6 Hz periodic input signal is transmitted. Hence, the waveform at the output of the filter is sinusoidal in shape whereas the input signal from the preamplifier typically has the form of that shown in Figure 7(a) of Reference 1. A schematic diagram of the filter is shown in Figure 6 above.

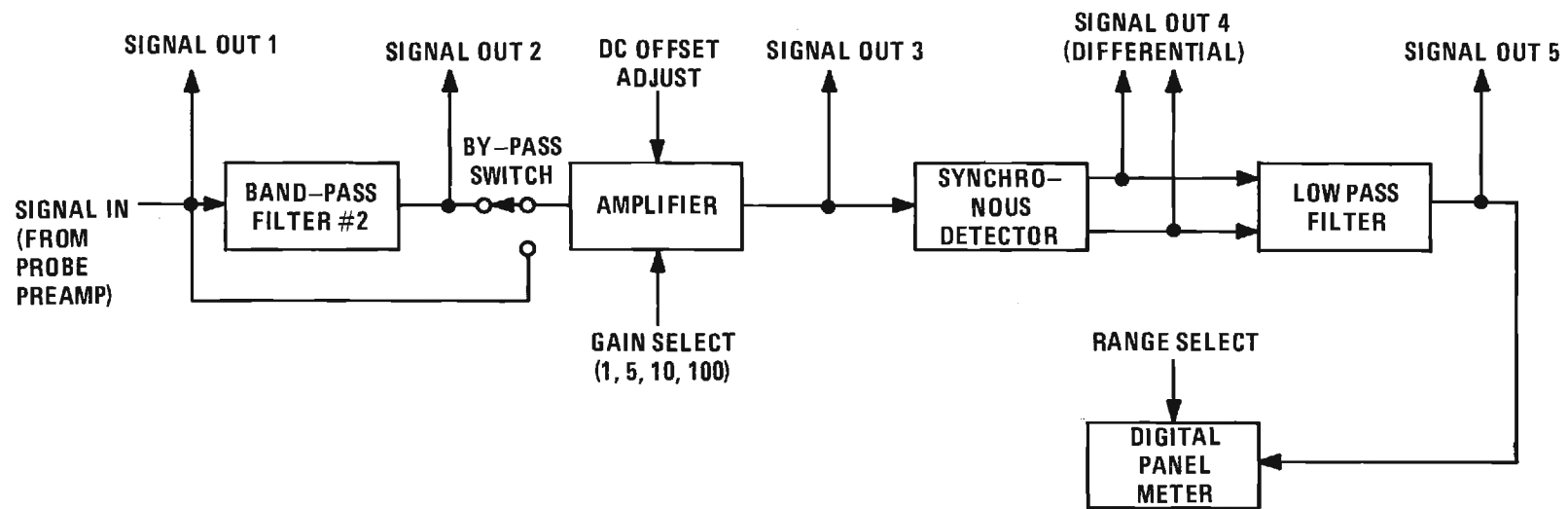


Figure 14. Block Diagram of Advanced Instrumentation for Pyroelectric Probes.

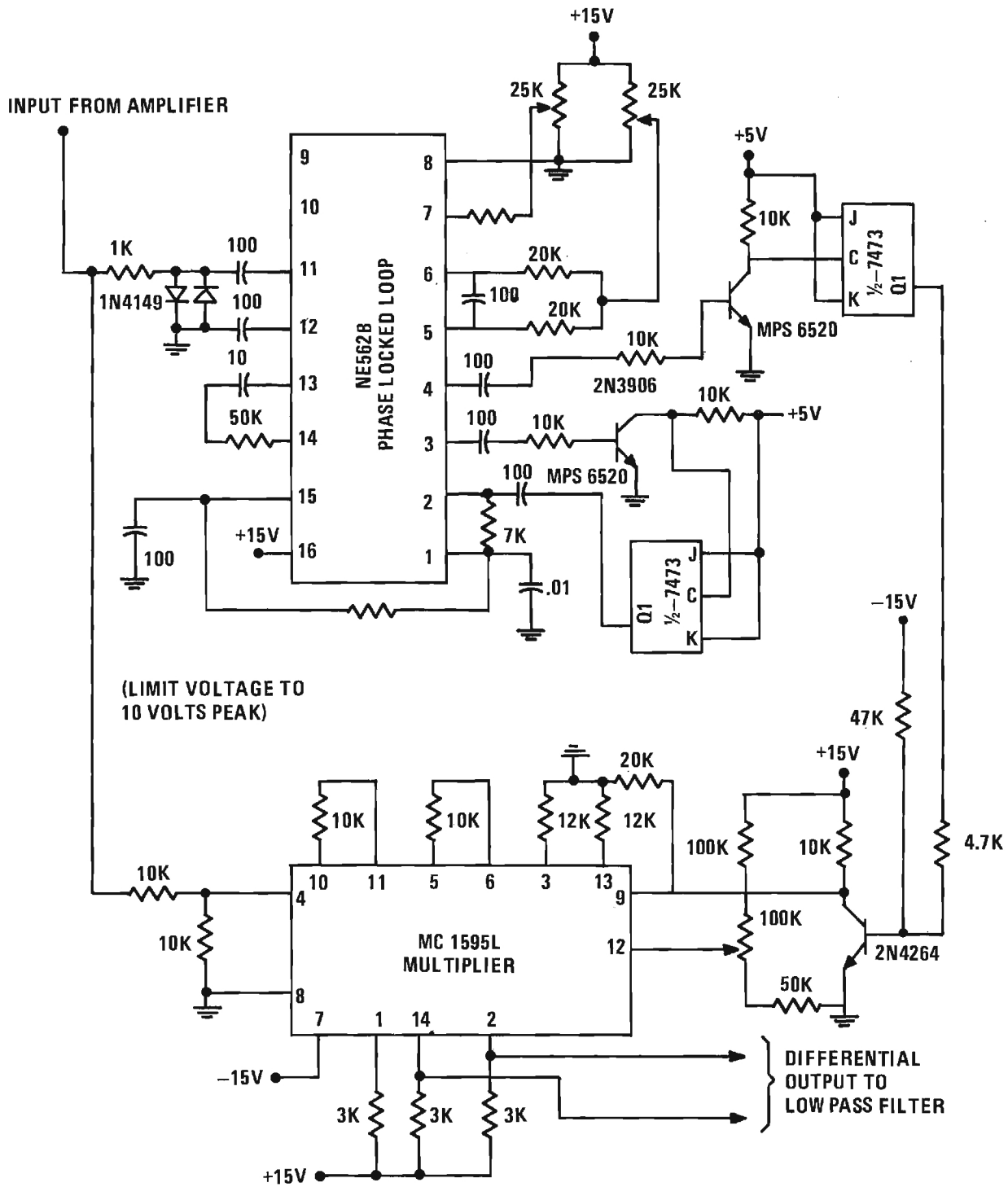


Figure 16. Schematic Diagram of Synchronous Detector (1.6 Hertz Operation).

that the output of the synchronous detector is differential and that an oscilloscope with differential input is required to view the complete rectified wave. A by-pass switch is also provided so that the bandpass filter can be by-passed, if desired.

The instrumentation described above has been constructed, but no performance data were available at the time of this writing.

2. Miniaturized Free-Space Pyroelectric Probes

Although the rather bulky probe configurations described in Section II have served to establish the feasibility of pyroelectric probes for free-space applications, they are not desirable from an electromagnetic viewpoint. Consequently, some efforts have been initiated during this investigation to reduce the size of the probes.

The result of the efforts to miniaturize free-space pyroelectric probes is shown in Figure 17. The probe shown there consists of the pre-amplifier (AD506K) permanently mounted on one end of a 3/16-inch diameter plexiglas tube approximately 12 inches long. The pins of the preamplifier are exposed to accept a standard 8-pin socket (TO-5 case). Four #30 AWG kynar insulated wires are wire-wrapped to the pins of the AD506K and run through the inside of the plexiglas tube to the 8-pin socket mounted on the other end. A 6-foot length of #28 AWG 5-conductor shielded instrumentation cable (Belden #9640-25) with mating sockets provides the connection between the probe and follow-on electronics. The crystal element is mounted on the pins of a standard 8-pin socket for easy mating with the preamplifier. A coating of Teflon is applied over the crystal to provide protection and

some insulation from air currents in the test environment. This configuration was chosen so that the preamplifier could be mounted as close as possible to the crystal element and so that any number and sizes of crystal elements could be easily interchanged.

No testing of the probe shown in Figure 17 has been accomplished at the time of this writing.

3. Future Work

The feasibility of pyroelectric probes for use in the detection of microwave energy in the 1 to 10 GHz frequency band, inside and outside of a biological material, has been established. However, it is clear that further refinements in the fabrication of these probes are possible and should be undertaken, especially for implantable pyroelectric probes. Further study and experimentation is also needed to calibrate an implantable pyroelectric probe inside of a biological material; indeed, a suitable method of calibration must be found. Efforts should also be undertaken to determine the effects of the probe on the fields being measured in different biological media. Experimental procedures which combine the characteristics of particular irradiation systems and those of pyroelectric probes may then be developed from the results of these studies for use in microwave dosimetry.

It is worthwhile at this point to review the particular merits and demerits of pyroelectric probes for microwave dosimetry applications. First, the pyroelectric probe is a dielectric structure as opposed to a conducting structure; however, conducting elements are required for instrumentation

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