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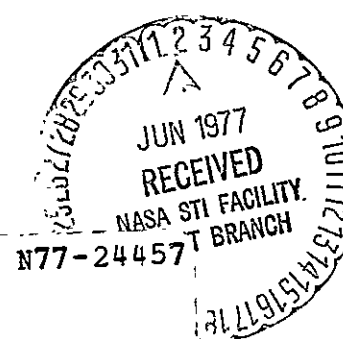
MICROWAVE RADIOMETER FOR SUBSURFACE TEMPERATURE MEASUREMENT

by Ronald A. Porter
and Kenneth P. Bechis

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Prepared for

National Aeronautics and Space Administration
AMES RESEARCH CENTER
Moffett Field, California

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ABSTRACT

A previously developed UHF radiometer¹, operating at a frequency of 800 MHz, has been modified to provide an integral, 3-frequency voltage standing-wave ratio (VSWR) circuit in the radio-frequency (RF) head. The VSWR circuit provides readings of power transmission, at the antenna-material interface, with an accuracy of $\pm 5\%$. The power transmission readings are numerically equal to the emissivity of the material under observation. Knowledge of material emissivity is useful in the interpretation of subsurface apparent temperatures, obtained on phantom models of biological tissue, animals and human subjects, with the radiometer.

The emissivities of phantom models, consisting of lean beefsteak, were found to lie in the range 0.623 to 0.779, depending on moisture content. Radiometric measurements, performed on instrumented phantoms, showed that the radiometer was capable of sensing small temperature changes occurring at depths of, at least, 19 to 30 mm. This is consistent with previously generated data which showed that the radiometer could sense temperatures at a depth of 38 mm.

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In addition, the assistance of Dr. W.A. Williams, of NASA-Ames, with various aspects of the project are gratefully acknowledged.

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Section 1

INTRODUCTION

The basic purpose of the research and development work, described in this report, was to provide a 3-frequency voltage standing-wave ratio (VSWR) circuit in the radio-frequency (RF) head of the UHF radiometer, developed under a previous contract¹. The radiometer operates at a center frequency of 800 MHz. Following completion of this work, it was necessary to test the performance of the VSWR circuit and radiometer, as a whole, by conducting suitable measurements on phantom models of biological tissue. These objectives have been successfully accomplished.

The VSWR circuit provides readings of power transmission, at the antenna-material interface, quickly and accurately, with an absolute accuracy within $\pm 5\%$, referred to a standard laboratory-type slotted line. The power transmission readings are numerically equal to the emissivity of the material under observation. Knowledge of material emissivity is important for proper interpretation of measured apparent temperatures and prediction of theoretical brightness temperatures of phantoms, animals and human subjects.

The emissivities of phantom models, consisting of fresh, lean beefsteak, were found to lie in the range 0.623 to 0.779, at the radiometer operating frequency (800 MHz) depending on the moisture content of the beefsteak. The emissivity increases with decreasing moisture content.

Radiometric observations, performed on instrumented phantom models of biological tissue, showed that the radiometer was capable of sensing small temperature changes occurring at depths of, at least, 19 to 30 millimeters. Similar observations, conducted during the previous project, indicated that it could sense temperatures from a depth of 38 millimeters.

In addition to the VSWR circuit, several other improvements were made in the radiometer. These are summarized in the following paragraphs:

1. The temperature stability of the radiometer RF head was improved; it remains steady within $\pm 0.2^{\circ}\text{C}$, over a period of 30 minutes.
2. The stability of the internal radiometer calibration circuit has also been improved; the calibration signal has been observed to shift only $+ 0.1^{\circ}\text{C}$ over a period of 30 minutes.
3. Certain improvements made in radiometer shielding and grounding, and in lock-in amplifier alignment, have resulted in better signal stability; over a period of 30 minutes, the radiometer output shows a drift of only 0.15°C , in the absence of an input signal.

A set of conclusions and recommendations are presented at the end of this report. It is felt that, with the above improvements, the UHF radiometer will provide highly useful subsurface temperature data during the course of observations on animals and human subjects.

Section 2

MODIFICATION OF UHF RADIOMETER

2.1 OBJECTIVES

The objectives of this portion of the contract work were as follows:

1. Provide a voltage standing-wave ratio (VSWR) circuit, integral with the UHF radiometer RF head, to permit accurate measurement of VSWR at the antenna-material interface, over the operating RF bandwidth of the radiometer.
2. Modify the internal radiometer calibration circuit to improve long-term stability and reduce the calibration signal to a level that is nearer the maximum anticipated difference between the antenna signal and the internal Reference Load signal.
3. Improve the internal temperature stability of the RF head enclosure.
4. Improve the shielding, bonding and grounding of all signal and power wiring, to reduce internally-generated electromagnetic interference to an acceptable level.
5. Modify the Radiometric Data System (RDS) to provide for recording data furnished by two types of thermistor temperature sensors - the existing Yellow Springs Instrument (YSI) Series 400 sensors and the new YSI Series 500 needle probes.
6. Modify the RDS to provide Line Feed and Carriage Return signals for each line of data printed out by the ASR-33 teletype machine. Also, modify the RDS logic circuitry to permit grouping of data characters into groups of four (4) with spaces between successive groups. Finally, the RDS was to be modified to provide an indication that the monitored data is, in fact, being recorded on its magnetic tape.
7. Check the performance of the Princeton Applied Research Lock-In Amplifier and re-align it if necessary.

These improvements will be discussed in the Sections to follow.

2.2 THEORETICAL BASIS FOR VSWR CIRCUIT

The need for this addition to the radiometer was realized during the course of work performed during the previous Contract¹. A VSWR circuit, integral with the radiometer RF front end, would permit convenient and accurate measurement of VSWR at the interface between the antenna and the material under observation. From the readings of VSWR, it is possible to determine the reflectivity, ρ , at the interface from the relation,

$$\rho = \left(\frac{S-1}{S+1} \right)^2 \quad (2-1)$$

in which, S is the measured value of VSWR.

Since the antenna is employed in an active sense, during a VSWR measurement, the quantity being measured is power transmission, τ .

$$\text{Thus, } \tau = 1 - \rho = 1 - \left(\frac{S-1}{S+1} \right)^2 \quad (2-2)$$

$$\text{or } \tau = \frac{4S}{(S+1)^2}$$

Figure 2-1 shows a plot of power transmission as a function of VSWR at the antenna-material interface. It will be noted that the power transmission drops off rather rapidly with increasing values of VSWR.

When the radiometer makes a measurement of apparent temperature, T_A , the value obtained is,

$$T_A = \tau T_M + \rho T_R, \text{ } ^\circ\text{K} \quad (2-3)$$

where,

T_M is the thermodynamic temperature of the material

T_R is the thermodynamic temperature of the radiometer,

and the remaining terms are as previously defined.

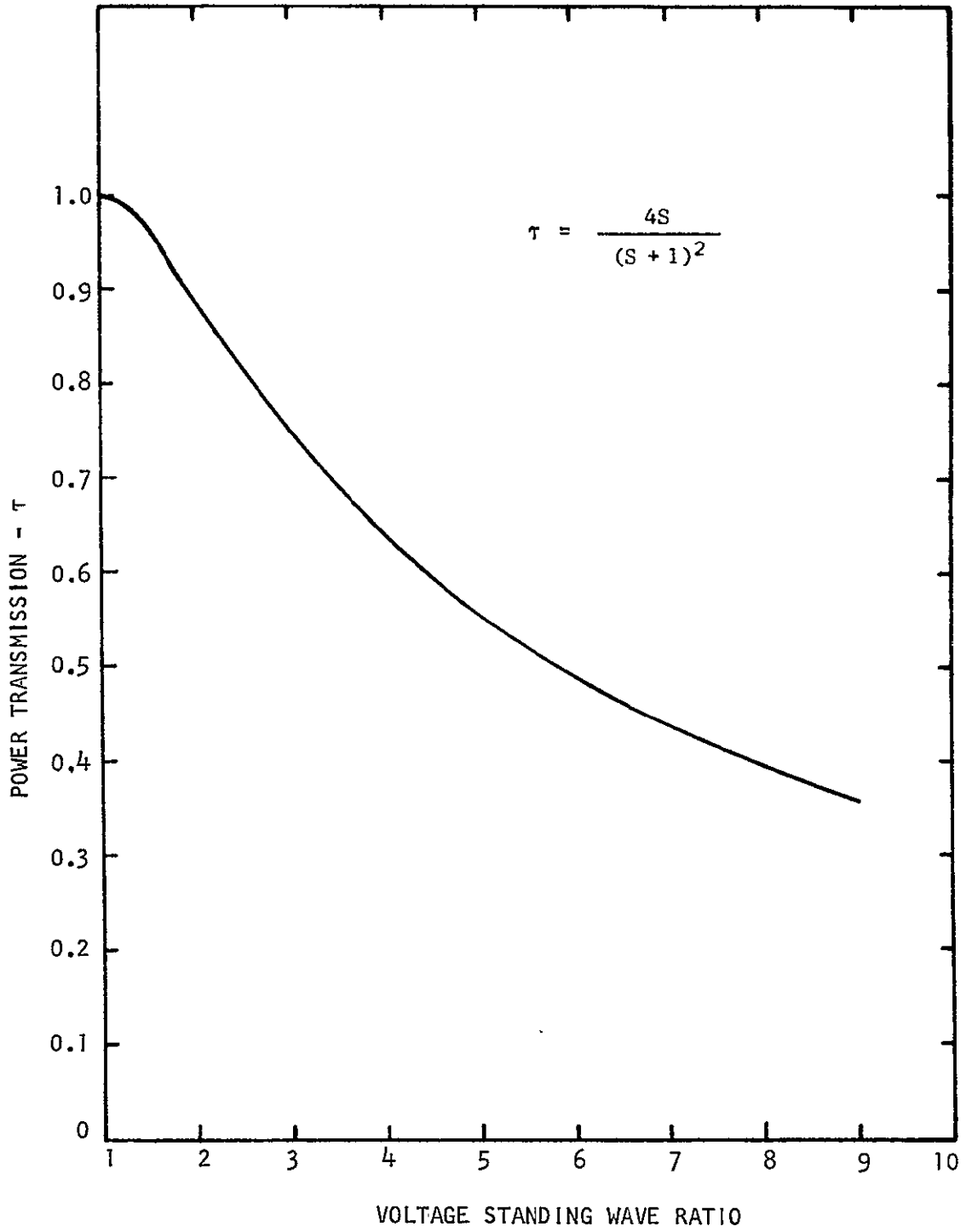


Figure 2-1 - Power Transmission versus Voltage Standing Wave Ratio

If now a typical VSWR of 2.5:1 were obtained, during a given measurement on a phantom model or patient, the corresponding value of τ would be 0.81, as shown in Figure 2-1. Thus, $\rho = 1 - \tau = 0.19$. Substituting typical values of T_M and T_R in Equation (2-3) we have,

$$T_A = (0.81 \times 309) + (0.19 \times 311)$$

or

$$T_A = 309.4^\circ\text{K}.$$

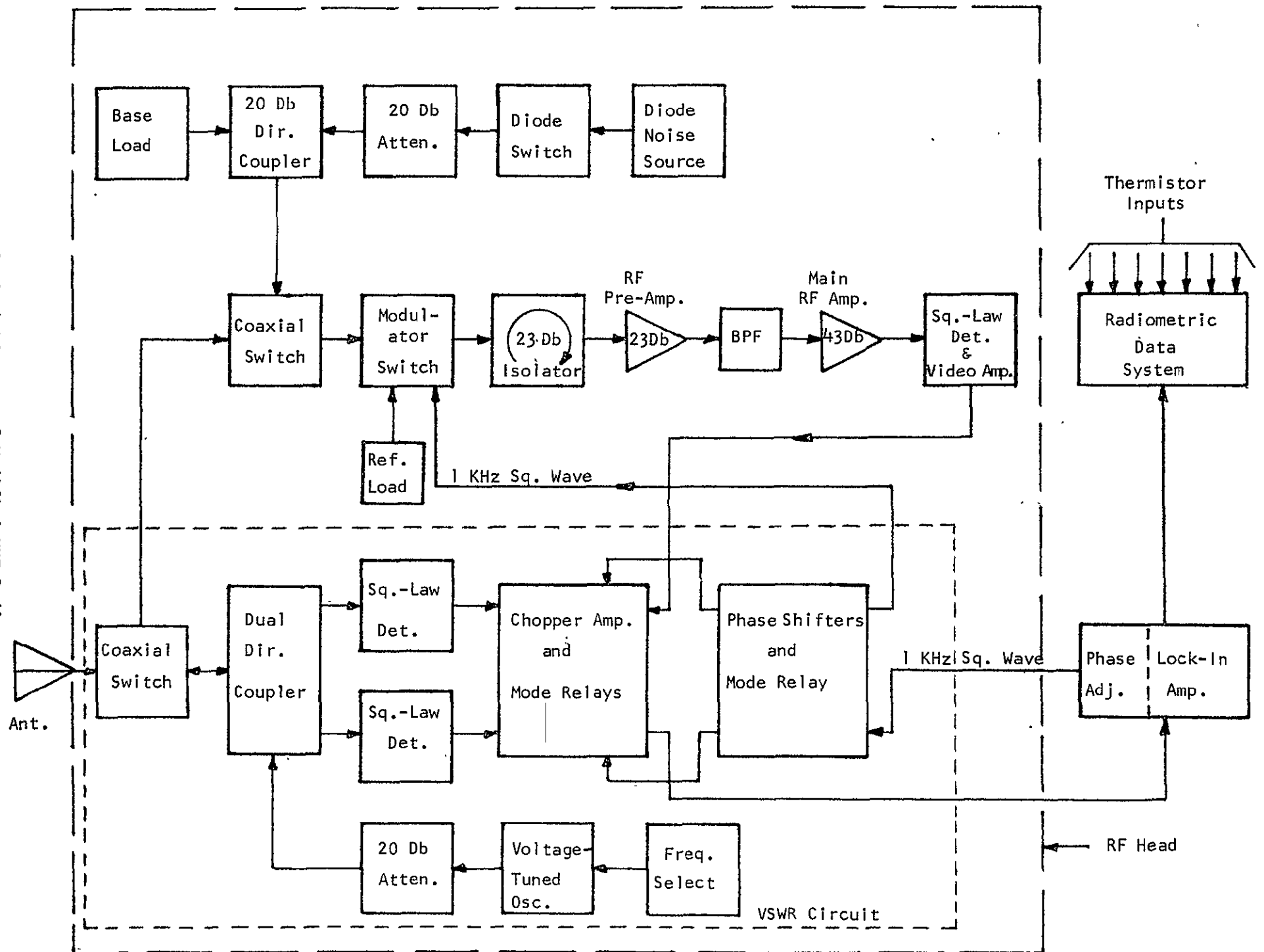
This example shows that a reflectivity of 0.19, at the antenna-material interface, represents (0.19×311) or 59.1°K of the total observed apparent temperature. It is clear, therefore, that knowledge of the magnitude of the reflected component facilitates interpretation of measured apparent temperatures.

2.3 DESCRIPTION OF VSWR CIRCUIT

The transmission at the antenna-material interface may be measured, automatically at three points in the operating frequency band and displayed on the digital indicators located on the RDS. A block diagram of the circuitry required to perform this measurement is included in Figure 2-2. This measurement technique compares the reflected energy with the transmitted energy. Synchronous detection of the resultant signal provides a readout of the difference in power levels of the transmitted and reflected signals. This circuitry utilizes the same video processing circuitry as the radiometer, which results in a saving of hardware. All of the additional hardware required to perform this function is housed within the radiometer RF head.

Referring to Figure 2-2, a voltage-tuned, solid state oscillator generates continuous-wave energy over the operating RF frequency band of the radiometer. The oscillator is manually controlled to generate any of three fixed operating frequencies: one frequency at the radiometer band center and the other two at the band edges. The oscillator drives a 20 Db dual-directional coupler; the direct coupler output is connected to the radiometer antenna by a mechanical coaxial switch. The two coupler outputs represent the total power delivered to the antenna and the power reflected from the antenna-material interface. The transmission, τ , is the

Figure 2-2 - Functional Block Diagram of Modified UHF Radiometer
2-5



difference between these power levels. Both the forward and reflected powers are directed to square-law detectors, thus producing voltages which are directly proportional to the input power levels. These voltages are now compared at a 1,000 Hz rate by means of a square-wave chopper. The 1,000 Hz signal is, then, amplified and switched to the RDS to be recorded on its magnetic tape.

The three frequencies, at which the voltage-tuned oscillator operates, are 705, 768 and 832 MHz. Now, it will be recalled from Section 3.4.2 in Reference 1 Report that, to eliminate interference from UHF television stations, it was necessary to introduce various filters into the radio frequency (RF) section of the radiometer. In the Boston area, Channels 38, 44 and 56 operate at frequencies in the range 614 - 725 MHz; and, in the NASA-Ames area, Channel 54 operates at 716 MHz. Thus, the following 3-db operating bandwidths were provided by the RF filters, for these locations:

At NASA-Ames: 755 - 830 MHz

In Boston area: 700 - 830 MHz

Due to the restricted RF operating bandwidth at NASA-Ames, only the two upper frequencies, F2 and F3, in the voltage-tuned oscillator, need be used at that location. In the Boston area, the lowest frequency, F1, was used initially, since the useful RF bandwidth extended down to 700 MHz at that location, when using the appropriate RF filters. Later, when phantom measurements were being conducted, the filter to be used at NASA-Ames was installed and retained in the radiometer throughout the measurements.

Comparisons made against VSWR data, obtained with a laboratory-type slotted line, show that the maximum error in the data obtained with the radiometer VSWR circuit is within $\pm 5\%$.

Figures 2-3, 2-4 and 2-5 provide plots of power transmission versus voltage reading at each of the three frequencies used in the VSWR circuit, respectively. As stated in Section 2.2, the relationship between power transmission and reflectivity is given by,

$$\tau = 1 - \rho \quad (2-4)$$

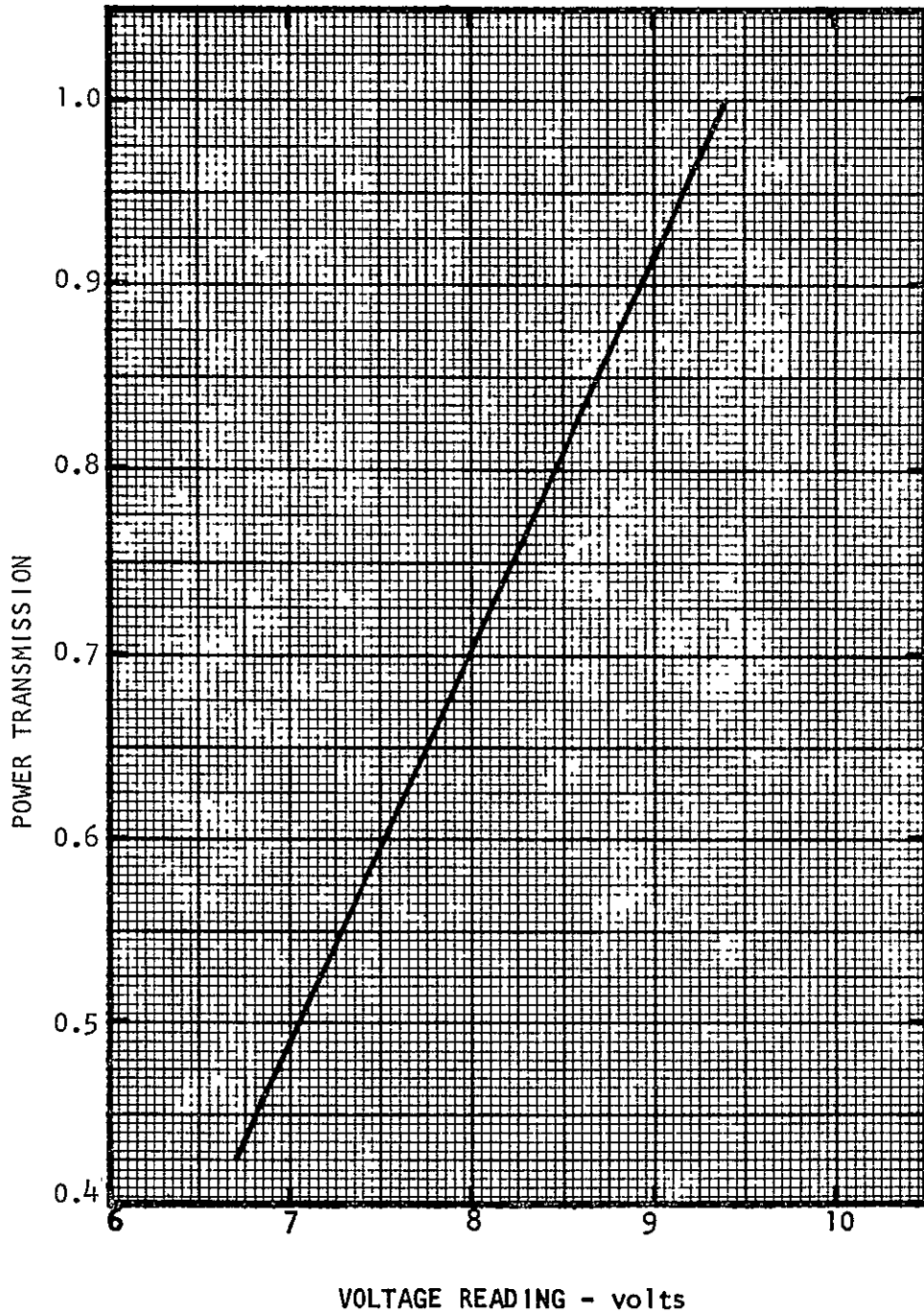


Figure 2-3 - Power Transmission versus Voltage Reading at Frequency F1 (705 MHz)

Note: This frequency and chart applicable only to measurements performed at Radiometric Technology, Inc.

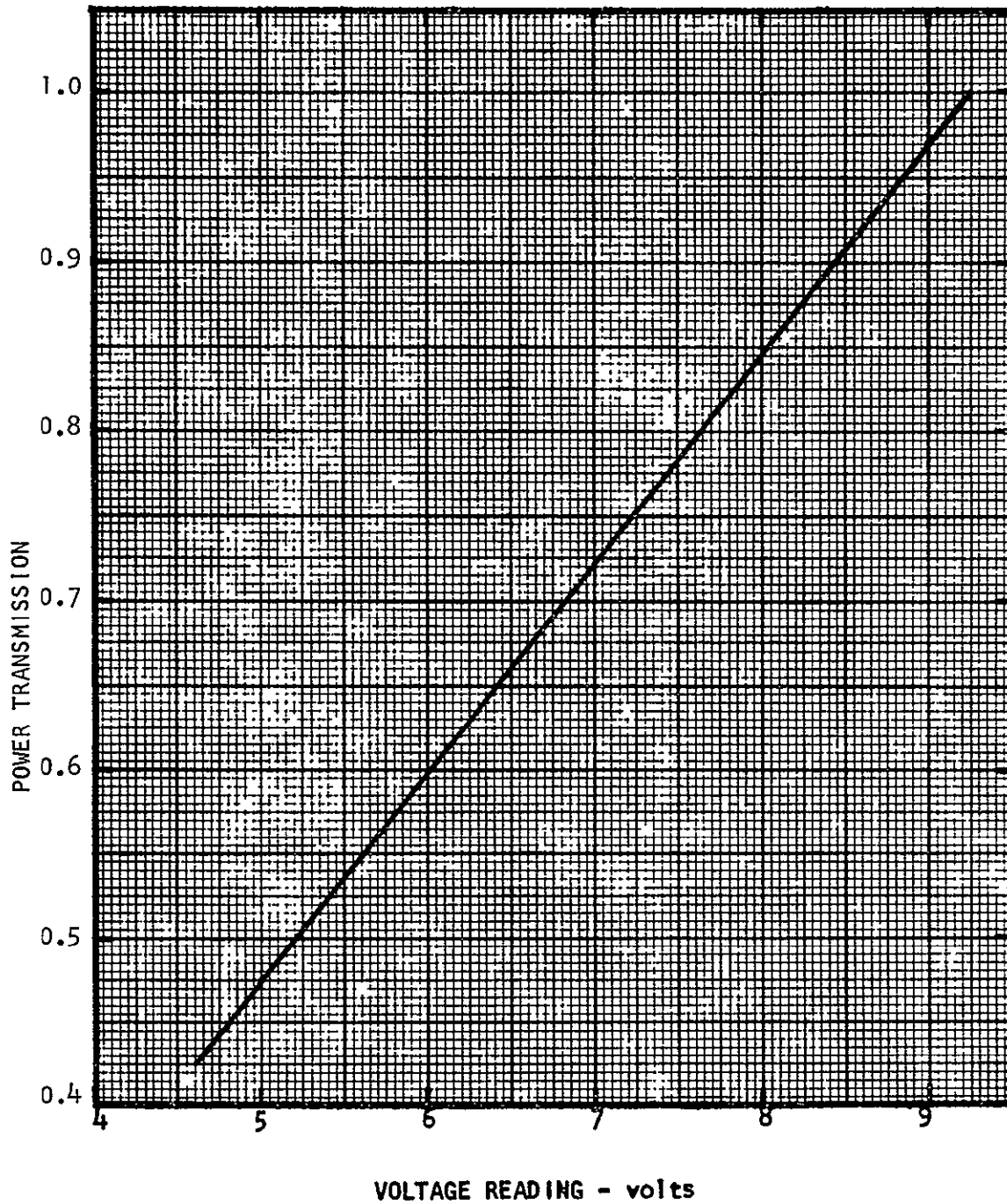


Figure 2-4 - Power Transmission versus Voltage Reading at Frequency F2 (768 MHz)

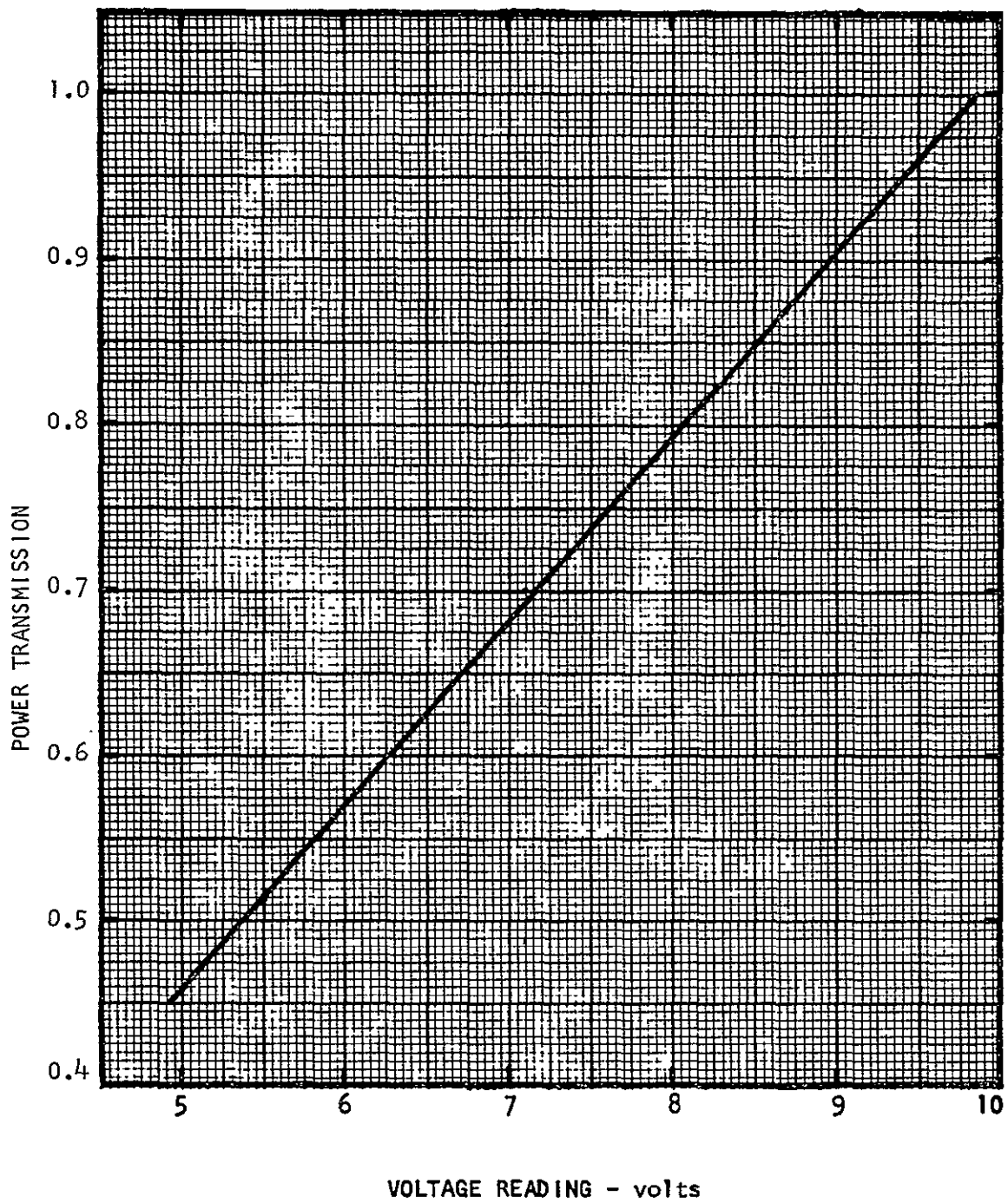


Figure 2-5 - Power Transmission versus Voltage Reading at Frequency F3 (832 MHz)

Now, it is also true that, under conditions of thermal equilibrium, the relationship between the emissivity and reflectivity of a material is given by,

$$e = 1 - \rho \quad (2-5)$$

Thus, it follows that the power transmission, τ , and emissivity, e , are numerically equal. Accordingly, the power transmission value, obtained from Figure 2-3, 2-4 or 2-5, may also be read as an emissivity value of the particular material under examination. In other words, a measurement of power transmission, at the antenna-material interface, provides direct information on the emissivity of the material. Knowledge of the emissivity is very useful in data interpretation, as is shown in Section 3.

2.4 MODIFICATIONS TO RADIOMETER CALIBRATION CIRCUIT

In the original calibration circuit, appearing in Figure 3-3 of Reference (1) report, it was necessary to keep the noise diode switched off at all times, except for the time interval when the calibration signal increment of $+ 53.1^{\circ}\text{C}$ was required. It was discovered that this intermittent operation of the noise diode caused it to operate in an unstable manner; the calibration signal was, therefore, not as stable as desired.

To eliminate this problem, a microwave diode switch was placed in series with the noise diode, as shown in Figure 2-2, to permit shutting off the calibration signal without switching off the operating voltage from the noise source. Thus, the diode operates continuously; this results in better long-term stability in the calibration signal. As shown in Figure 2-6, the calibration signal shifted upward by only 0.1°C over a period of 30 minutes. These favorable results are also considered to be due, in part, to the improved temperature stability of the RF head.

Concurrently with the above modification, a reduction was made in the calibration signal level to bring it nearer the maximum anticipated difference between the antenna and the internal Reference Load signals. This was accomplished by increasing the value of the series attenuator from 16 Db to 20 Db. This reduced the calibration signal increment from $+ 53.1^{\circ}\text{K}$ to $+ 13.82^{\circ}\text{K}$. The exact value was deter-

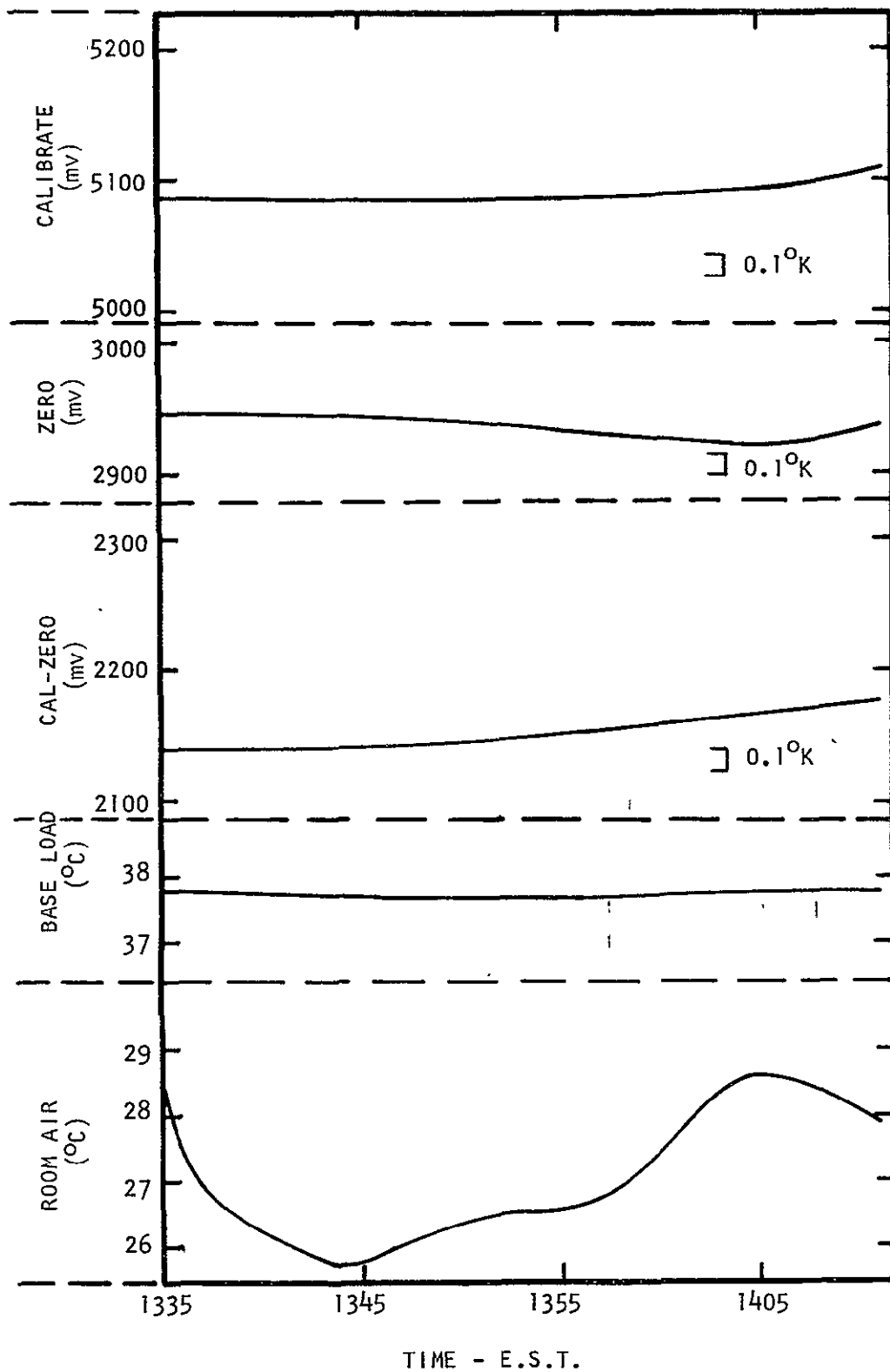


Figure 2-6 - Stability Test on UHF Radiometer

mined with the aid of the hot termination signal, furnished by an Airborne Instruments Laboratory Type 70 Standard Noise Generator, and a precision coaxial -type variable attenuator. The hot termination signal, in this unit, is held at $373.2^{+1}0\text{K}$.

2.5 IMPROVED RF HEAD TEMPERATURE STABILITY

It was observed, during work reported in Reference (1) that long-term radiometer stability and good absolute accuracy are dependent on close control of the temperature within the RF head enclosure. To improve the temperature stability of the RF head, additional effort was devoted to the achievement of finer control by the internal temperature controller and to better thermal insulation within the RF head.

Wherever possible, additional 0.95 cm-thick thermal insulating material was attached to the inner walls of the RF head. In some areas, components were moved away from the walls to provide sufficient space for the extra insulation. Thermal tests were, then, conducted and the temperature controller was adjusted to provide finer control. However, it was found necessary to switch off the heater, after a period of 30 minutes, and allow the heat from the active components to bring the RF head temperature to 38°C . At a room temperature of approximately 27°C , a stable temperature was achieved within 45 minutes. The active components provide sufficient heat to maintain the RF head at a stable temperature over extended periods of time.

As shown in the Base Load plot, in Figure 2-6, these improvements resulted in a temperature stability of $\pm 0.2^{\circ}\text{C}$, within the RF head, over a period of 30 minutes, following initial warmup. It will be noted that the room temperature varied by approximately 3°C in the same interval of time.

2.6 IMPROVED SHIELDING, BONDING AND GROUNDING

During early tests with the radiometer, it was noted that the output signal tended to drift when the input was switched to Zero. In the Zero condition, the radiometer input circuitry is at a null. Since it was being operated in an RF screen room, the observed output drift could not have been caused by externally generated electromagnetic interference. Thus, it was clear that the effect was caused by some instability within the system.

During the course of an extensive investigation, it was observed that the system as a whole did not have a common ground of sufficiently low impedance. Instead of using No. 18 gauge copper wire and the steel structure of the system as a common ground, it was found that heavy copper braid was required to connect the ground points of the various system components. The copper braid has dimensions of 1.25 X 0.16 cm.

In addition to the above modification, all cable shields were thoroughly checked, to ensure that they were properly bonded to their connectors. All negative return wires were also checked for satisfactory connections. Following completion of, both, the system ground and bonding work, it was observed that the radiometer output signal drift was measurably reduced. This is indicated by the Zero plot in Figure 2-6, wherein the output voltage drift is equivalent to an apparent temperature change of less than 0.15°C over a period of 30 minutes.

2.7 ACCOMMODATION OF NEW THERMISTOR SENSORS IN RADIOMETRIC DATA SYSTEM

During the initial development phase, the Radiometric Data System (RDS) was designed to accept only the Series 400 thermistor sensors, furnished by the Yellow Springs Instrument Co. (YSI). This was considered to be convenient since these sensors may be readily interchanged without the need for individual calibrations of temperature versus resistance. Unfortunately, the 4-mm diameter of the Series 400 needle probes was found to be excessive, for easy insertion into phantom models and live tissue. Thus, it became clear that the RDS should be modified to accommodate the fine needles available in the YSI 500 Series thermistor probes, even though these probes require individual calibrations.

Four (4) Model 513 thermistor needle probes have been furnished for use with the RDS. The needles in these probes are No. 20 gauge (0.812 mm). Each probe has a separate temperature-versus-resistance calibration chart. RDS input Jack Nos. 10 thru 13 have been assigned to these probes. In addition, a separate 160.0-microampere constant current source was wired into the RDS for use with the probes. Finally, the data reduction program RAD10M was modified to incorporate the probe calibration data. This modification provides automatic conversion and printout of all data obtained with the Model 513 needle probes.

2.8 MODIFICATION OF RDS LOGIC CIRCUITRY

The original RDS design did not provide for the insertion of Line Feed and Carriage Return signals, at the beginning and end, respectively, of each line of data printed by the ASR-33 teletype machine. It was necessary to insert these signals manually with the teletype keyboard; this was a tedious and time-consuming procedure. In addition, all of the data characters were played back and printed in a continuous series, without any breaks between data samples. If an error appeared anywhere in a given line of data, it was impossible to determine which data sample was affected. Accordingly, it was necessary to discard the entire line of data; if several lines contained errors, a considerable amount of data was lost in this manner.

One other shortcoming was inherent in the original RDS design: there was no indication that the measured data was, in fact, being recorded on the magnetic tape, even though the tape cassette reels were actually rotating. On one occasion, an entire set of measured data was lost due to improper performance of the magnetic tape recorder.

The RDS logic circuitry was modified to provide for automatic insertion of Line Feed and Carriage Return signals at the beginning and end, respectively, of each line of characters. In addition, provision was made, in the logic circuitry, for grouping the millivolt data characters into groups of four (4) with spaces between successive groups. Finally, a Write Protect indicator lamp was added to the recorder circuitry, to provide an indication that the measured data is, in fact, being recorded on the magnetic tape. When the lamp is lit, one is assured that the data is being recorded.

2.9 LOCK-IN AMPLIFIER PERFORMANCE CHECK

A complete performance check was conducted on the Princeton Applied Research Model 120 Lock-In Amplifier, to ensure proper operation. Experience has shown that these units require periodic re-alignment, which was, in fact, the case with this particular unit. Consequently, the Lock-In Amplifier was completely re-aligned, in accordance with the procedure given in the Instruction Manual. The unit met all performance specifications, following completion of this work.

Section 3

MEASUREMENTS ON PHANTOM MODELS

3.1 PREPARATION OF PHANTOM

The three phantom measurements, to be described in this Section, were set up by following the same general procedure. To avoid duplication, this procedure is presented below. When the setup for a given phantom measurement differs from the basic procedure, the difference is noted in the description of that particular experiment.

1. The day before the phantom measurement was to be made, a large 15 X 20 cm, flat piece of fresh, uniformly lean, beefsteak, 4 cm thick, was obtained at a local meat market.
2. At the same time, four thinner pieces of lean beefsteak were also obtained. Each piece had dimensions of 15 X 20 cm, but was only approximately 1 cm thick. To ensure a uniform thickness, the beefsteak was sliced on the butcher's slicing machine.
3. The thick piece of beefsteak was thoroughly sealed in Saran wrap. The beefsteak slices were also wrapped, together, in Saran wrap. In this manner, loss of moisture was avoided from the test samples. All beefsteak samples were left in the laboratory overnight, to permit them to reach room temperature prior to initiation of radiometric measurements.
4. Prior to conducting measurements the following day, the microwave radiometer was set up in accordance with the procedure given in Appendix A, - Section A-1.
5. The large piece of beefsteak was unwrapped so that one of its flat surfaces was exposed. The meat was placed with this surface uppermost, on the observation table, keeping the plastic wrapping on the bottom surface and around the sides of the sample.

The layout of the phantom model, showing the arrangement of the heater element, thermistor sensors and radiometer antenna, is presented in Figure 3-1. The detailed procedure for positioning the heater element, thermistor sensors and radiometer antenna is given in Appendix A, Section A-2. This includes information on electrical connections, heater current adjustment, power transmission measurement and radiometric measurement procedures.

In the three phantom measurements, described in this Section, the YSI Model 402 white vinyl-covered thermistor probes were used instead of the Model 513 needle probes, as suggested in Appendix A, Section A-2.

Prior to performing the radiometric measurements, the power transmission was measured at the antenna-phantom interface, following the procedure given in Appendix A, Section A-2.

3.2 RADIOMETER TEMPERATURE SENSITIVITY

The minimum detectable temperature sensitivity, ΔT , of the radiometer, during the phantom measurements, was as follows:

Output time constant = 3 secs: $\Delta T = 0.064^{\circ}\text{K rms}$

Output time constant = 10 secs: $\Delta T = 0.032^{\circ}\text{K rms}$

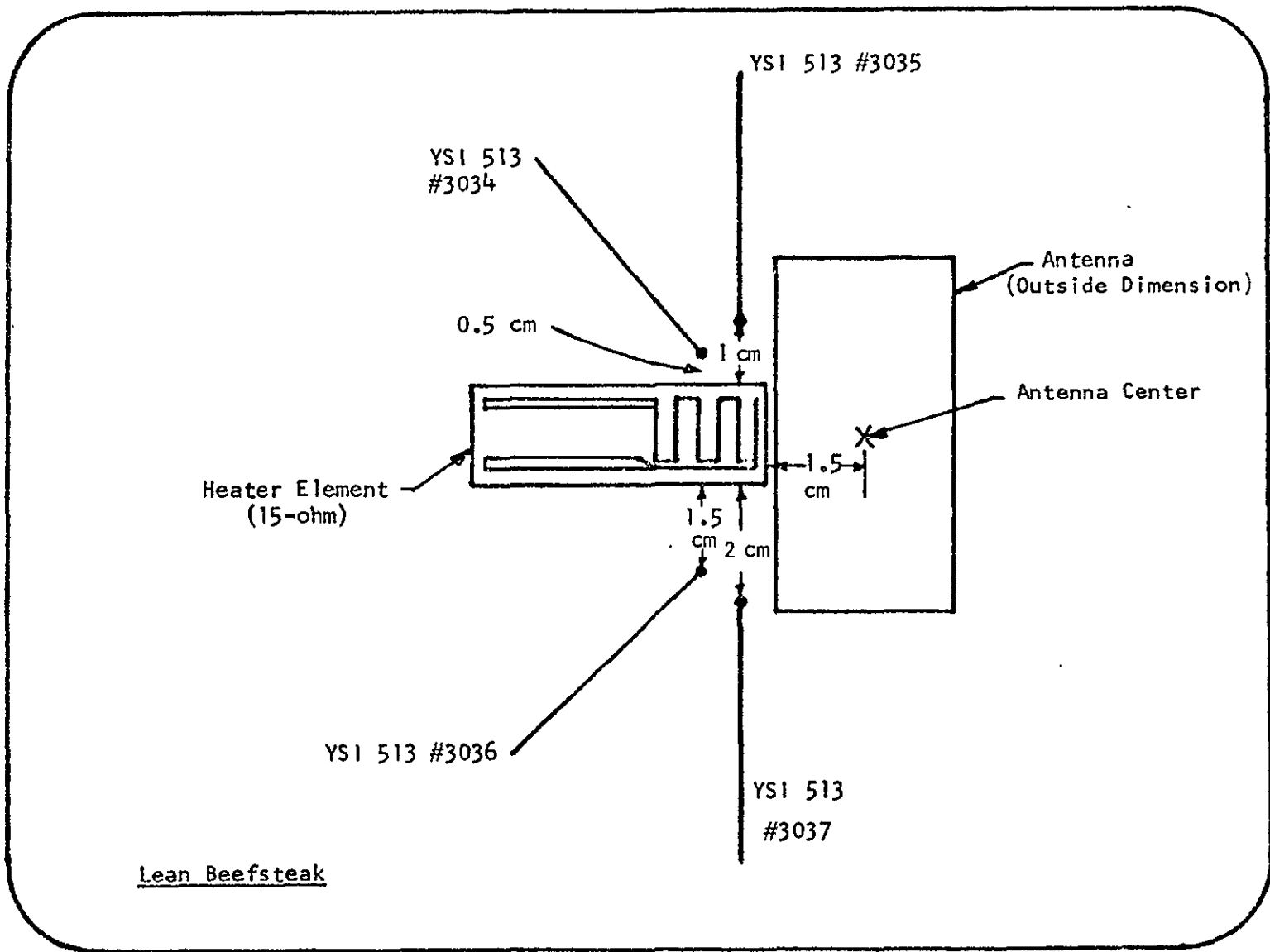
An output time constant of 3 seconds was used in Phantom Measurement No. 1. Thus, the value of ΔT was $0.064^{\circ}\text{K rms}$ in this measurement.

In the case of Phantom Measurements Nos. 2 and 3, the output time constant was of 10 seconds duration, giving a ΔT of $0.032^{\circ}\text{K rms}$.

The average value of the conversion factor, used in converting the radiometer output voltage to degrees Kelvin, $\Delta T/\Delta V$, was $1^{\circ}\text{K per } 155 \text{ mv}$, or $6.45^{\circ}\text{K/volt}$.

Figure 3-1 - Layout of Phantom Model (Full Scale)

3-3



Lean Beefsteak

3.3 SELECTION OF HEATING ELEMENT FOR PHANTOMS

Based on experiments performed during the previous Contract¹, it was realized that the heating element, used in the phantom, should produce a temperature elevation of at least 1°K, at a distance of 1 cm from the heater, within a relatively short period of time i.e., within 10-15 minutes after application of power. To achieve this response, a test was performed using a Minco Products, Inc., thermofoil heating element, with a resistance of 5 ohms.

An instrumented phantom was set up, as shown in Figure 3-1, to check the suitability of the 5-ohm heater. A 6 VDC power supply was connected to the heater element; the current was limited to a maximum of 400 ma. A thick layer of lean beefsteak was placed on top of the heater element and array of thermistor sensors. The temperature elevations, within the phantom, were monitored at frequent intervals during and following the application of power to the heater element. It was found that the 5-ohm heater took over 45 minutes to raise the meat temperature by 1°K, at a distance of 1 cm from the heater. Since this was considered to be too slow, a 15-ohm heating element was substituted for the 5-ohm element, and the experiment repeated. This time, it took only 10 minutes to raise the meat temperature, 1 cm away from the heater, by 1°K. Also, it took only 15 minutes to raise the meat temperature, 0.5 cm away from the heater, by 4°K. Because of the thermal inertia of the meat, these temperature elevations were maintained for up to 10 minutes after the heater was turned off; this turned out to be important, because it was desired to conduct radiometric observations on the first phantom with the antenna placed directly over the heater, under two operating conditions: with the power applied to the element and with power switched off. As a result of the satisfactory performance obtained with the higher resistance heater, it was decided to employ the 15-ohm heater element in all further measurements. The dimensions of the heating portions of this element are 1 X 1.3 cm.

3.4 PHANTOM MEASUREMENT NO. 1

Phantom Measurement No. 1 was set up in accordance with the procedure given in Section 3.1 and Appendix A, Section A-2, except for the following items:

- a) The four thin pieces of lean beefsteak were slightly thinner than 1 cm.
- b) The YSI Model 402 thermistors were used instead of the YSI Model 513 needle probes.
- c) The orientation of the antenna, relative to the heating element differed from that shown in Figure 3-1 in that the long axis of the antenna was placed parallel to, rather than perpendicular to, the long axis of the heating strip. Also, the antenna was placed directly over the heating strip, instead of off to the side.

The results of Phantom Measurement #1 are shown in Figures 3-2 thru' 3-5. The millivolt output values and thermistor-sensed temperatures are plotted over elapsed time. The period of time, during which the heating element was on, is indicated by vertical bars at the foot of each chart. The temperatures measured by the thermistor attached to the heating element, as well as meat temperatures at distances of 0.5, 1, 1.5, and 2 cm from the heater, are also shown. T_A is the apparent temperature sensed by the radiometer. The T_A values, in degrees Centigrade, are computed with the aid of data reduction program RAD10M from the millivolt output data furnished by the radiometer.

Important points to note which, in general, apply to all the subsequent phantom measurements, regardless of the thickness of the beefsteak layer between the heater and the antenna, are:

- a) The closer a thermistor is to the heater, the faster and higher the meat temperature it senses will peak.
- b) The heater temperature does not remain at a constant high level, even if the current remains constant; rather, it operates in cycles with sharp peaks in temperature, followed by a slow exponential-like decay. The reason for this is not clear, except that the cyclical behavior is probably related to the operating mode of the regulating circuit in the power supply. The temporal temperature variations, at a distance of 0.5 cm from the heater, appear to be smooth and unaffected by the cyclical behavior of the heater temperature.

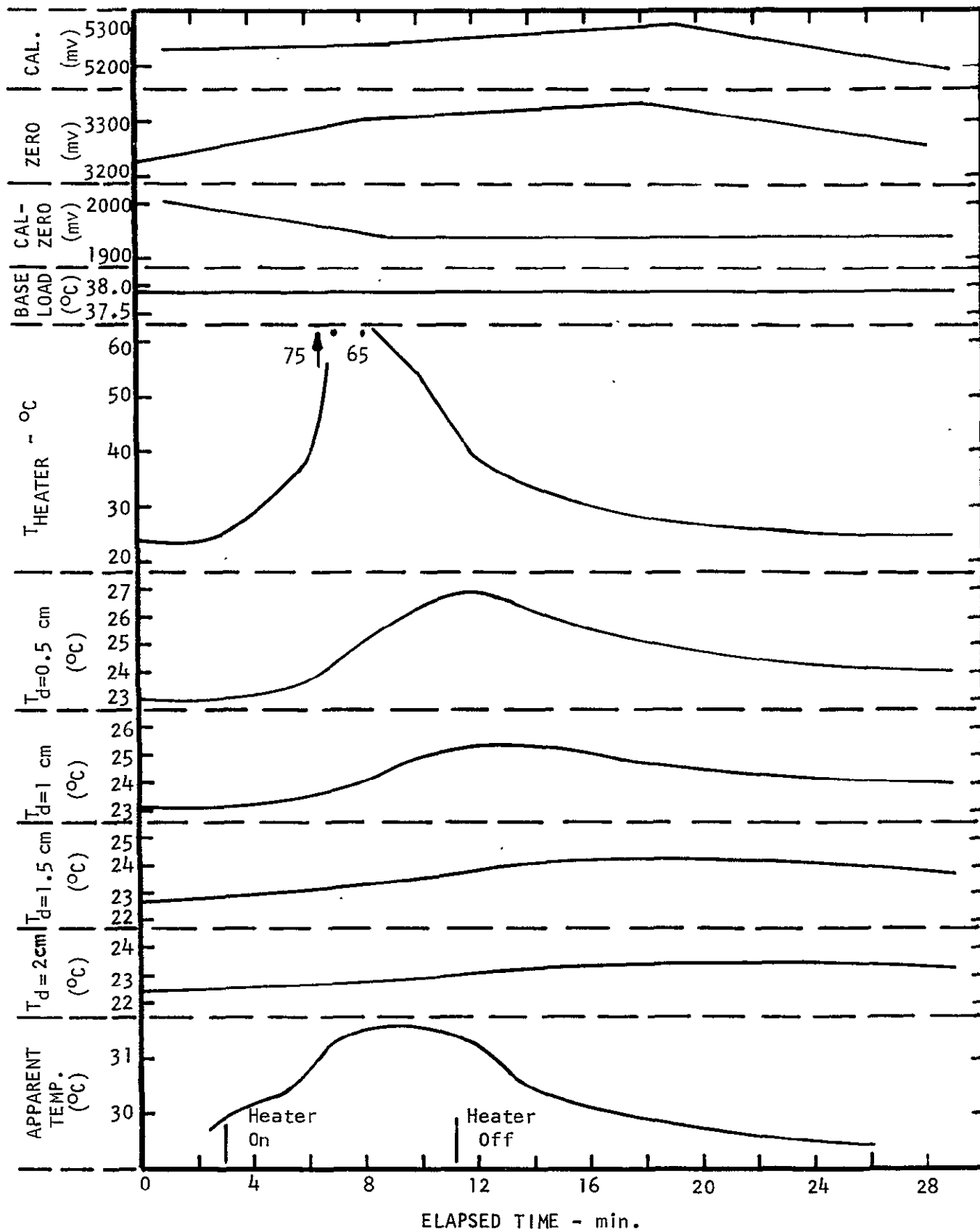


Figure 3-2 - Phantom Measurement No. 1 - Beefsteak Layer Thickness = 5 mm

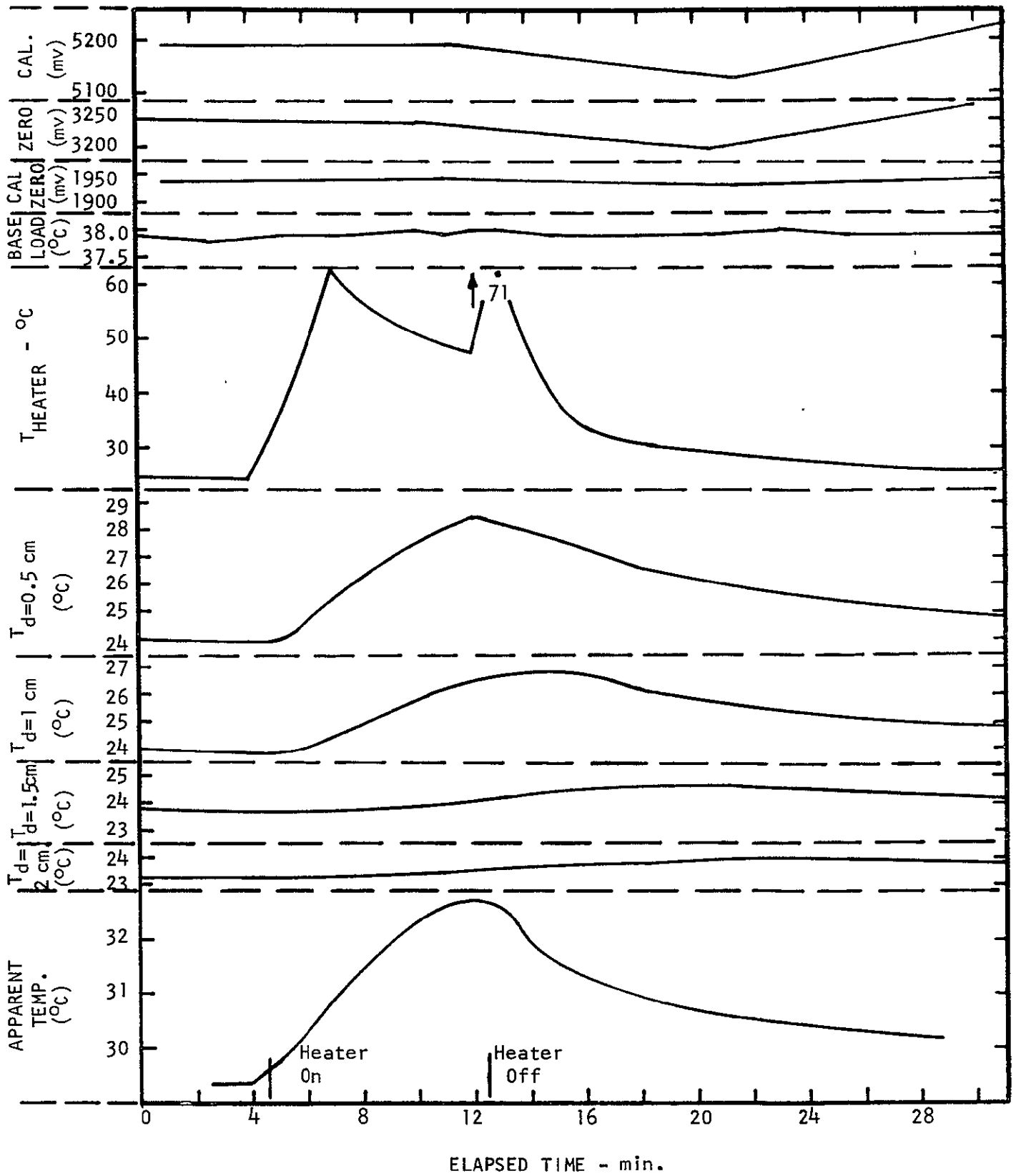


Figure 3-3 - Phantom Measurement No. 1 - Beefsteak Layer Thickness = 9 mm

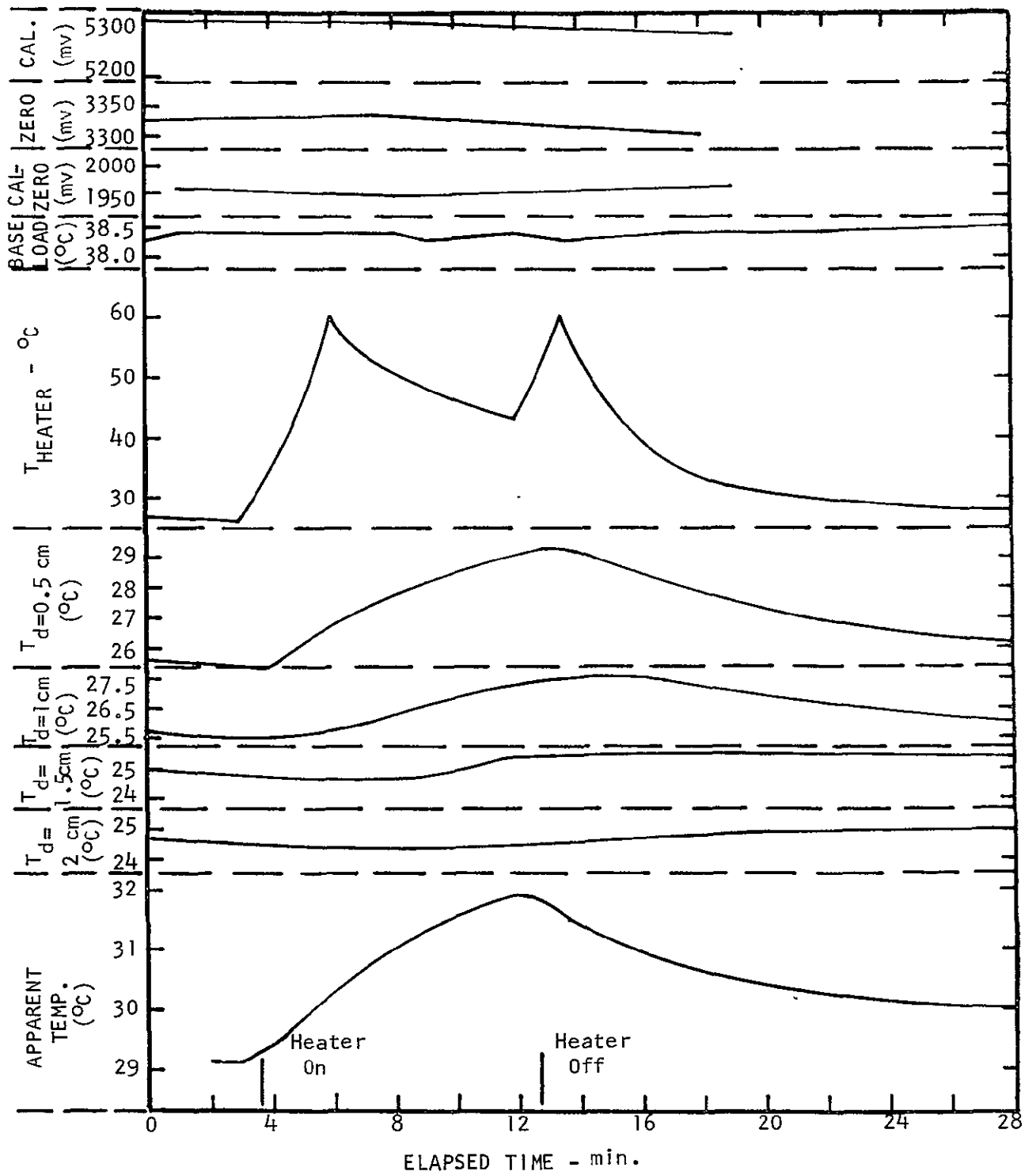


Figure 3-4 - Phantom Measurement No. 1 - Beefsteak Layer Thickness = 12 mm

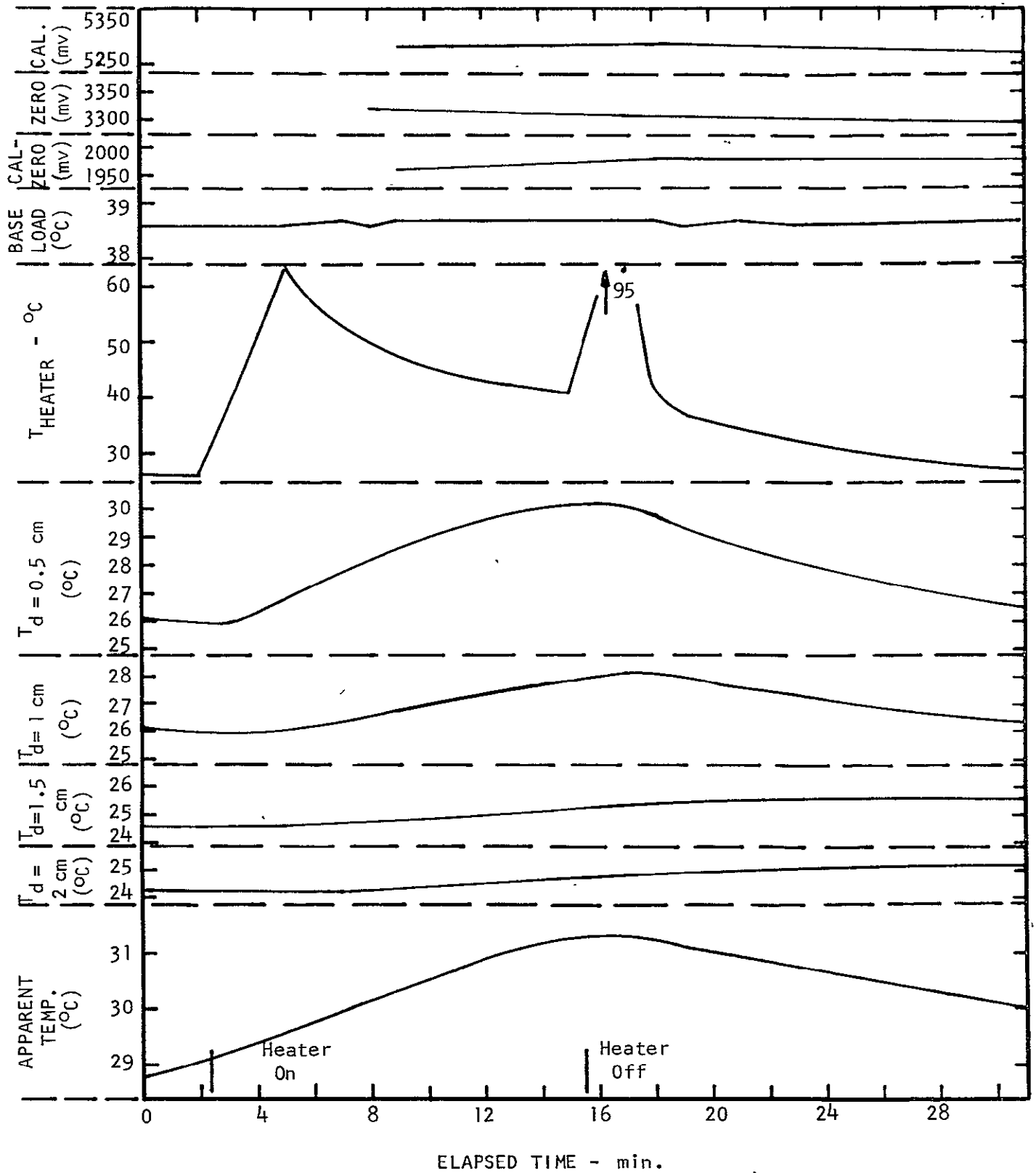


Figure 3-5 - Phantom Measurement No. 1 - Beefsteak Layer Thickness = 24 mm

c) The thermal conductivity of the meat is assumed to be isotropically uniform; that is, the heat from the heating element is considered to propagate equally efficiently in all directions. Thus, although no thermistor sensors were positioned in vertical profile, it is assumed that the temperature is the same 1 cm above the heating element as it is 1 cm horizontally away from it. This is considered to be a reasonable assumption because the meat samples were uniformly moist in all three dimensions.

d) The depth from which the radiometer is sensing temperatures in the beefsteak may be determined by comparing the over-all shape, and especially time of maximum temperature, of the apparent temperature curve, T_A , with the four thermistor temperature plots. If, the T_A curve is most similar in shape and phase to the 1-cm thermistor curve, then the radiometer is most likely sensing temperature variations from a depth 1-cm above the heater. Now, if the total meat thickness between the heater and antenna is 3 cm, then the radiometer is sensing temperatures from the 1-cm level through 2 cm of beefsteak.

Examination of the data in Figures 3-2 thru 3-5, reveals that the T_A curve is most similar to the curve for the 0.5-cm thermistor. This conclusion follows from the close correspondence of the maxima and the rate of decay of the two curves, especially in Figures 3-3 thru 3-5. Since the greatest thickness of beefsteak, above the heating element, was 24 mm (Figure 3-5) the radiometer sensed temperatures through a meat thickness of (24-5) mm or 19 mm (1.9 cm).

The emissivity of the beefsteak was determined with the VSWR Measurement Circuit, following the procedure given in Appendix A, Section A-2. The results were as described in Table 3-1 and the discussion that follows.

Table 3-1

PHANTOM NO. 1 VSWR DATA

Frequency	Voltage Rdg. (mv)	Power Transmission	Reference
F1 (705 MHz)	7770	0.65	Figure 2-3
F2 (768 MHz)	6946	0.72	Figure 2-4
F3 (832 MHz)	5490	0.52	Figure 2-5

The average power transmission value is 0.623. Since the emissivity of the phantom is numerically equal to the power transmission, it is also equal to 0.623. Using this value of emissivity, the apparent temperature will now be calculated and compared with the measured value.

The apparent temperature of the phantom material may be determined with the aid of the following relation:

$$T_A = \epsilon T_O + RT_R, \text{ } ^\circ\text{C} \quad (3-1)$$

where,

ϵ is the emissivity of the material, obtained from the measurement of power transmission.

T_O is the temperature of the phantom, $^\circ\text{C}$, at the instant in time when the heater was switched on, at a specified distance from the heating element.

R is the reflectivity at the antenna-phantom interface. $R = 1 - \epsilon$.

and T_R is the internal radiometer temperature, $^\circ\text{C}$, taken from the Base Load temperature reading.

In the case of Phantom Measurement No. 1, the above terms have the following values, as shown in Figure 3-2:

$$\epsilon = 0.623$$

$$T_O = 23.0^\circ\text{C}, \text{ at a distance of } 0.5 \text{ cm from the heating element}$$

$$R = 1 - \epsilon = 0.377$$

and $T_R = 38.0^\circ\text{C}.$

Substituting these quantities into Equation (3-1) gives a calculated apparent temperature of 28.7°C . This is reasonably close to the initial measured value of T_A , being only 1.3°C below it; the discrepancy is only -4.3% . This indicates that the VSWR Circuit can be a useful tool for radiometer data interpretation and for the prediction of microwave brightness temperatures of biological materials. This view is reinforced by similar results obtained in Phantom Measurements Nos. 2 and 3, described in the following Sections.

3.5 PHANTOM MEASUREMENT NO. 2

The results of Phantom Measurement No. 1 did not allow a full determination of the penetration capabilities of the radiometer. Accordingly, Phantom Measurement No. 2 was performed a few days later, using thicker layers of lean beefsteak between the heating element and antenna.

In this experiment, the Phantom Measurement Procedure, outlined in Section 3.1 and Appendix A, Section A-2, was followed exactly, including the orientation of the antenna relative to the heater, as shown in Figure 3-1. However, the YSI Model 402 thermistor sensors were used again, instead of the Model 513 needle probes.

The maximum thickness of beefsteak used in this experiment was 34 mm; this was comprised of three slices, each approximately 10 mm thick. A point worth mentioning is that, due to the time required for setting up the phantom and radiometer, the top surface of the beefsteak remained uncovered for a period of about two (2) hours. As a result, the upper portion of the meat, very likely, suffered some loss of moisture. This may have affected the readings obtained during, both, the VSWR and radiometric observations.

Figures 3-6 thru' 3-8 present the results obtained in Phantom Measurement No. 2. Unfortunately, in the first measurement, corresponding to Figure 3-6, the heater power was not applied for a sufficiently long period of time; thus, only a very slight change occurred in the apparent temperature, T_A . In Figure 3-7, T_A peaks near the maxima of the 1-cm and 1.5-cm thermistor curves; at least its peak is nearer these peaks than the maximum of the 2-cm curve. Thus, it appears that the radiometer was sensing temperatures from depths ranging from approximately (21-15) or 6 mm to (21-10) or 11 mm. In Figure 3-8, the peak of the T_A curve is nearest to the peak of the 1.5-cm thermistor curve. Thus, the radiometer is sensing temperature from a depth of approximately (34-15) or 19 mm.

It should be noted that the antenna was not positioned directly over the heater, as was the case in the first experiment, but was centered at a distance of 1.5 cm off the end of the heating element. This was done to eliminate the possibility of the antenna "seeing" the heater element during measurements. If there were any kind of a void in the intervening meat, the antenna could have received thermal radiation somewhat more directly from the heater; this would result in erroneous data.

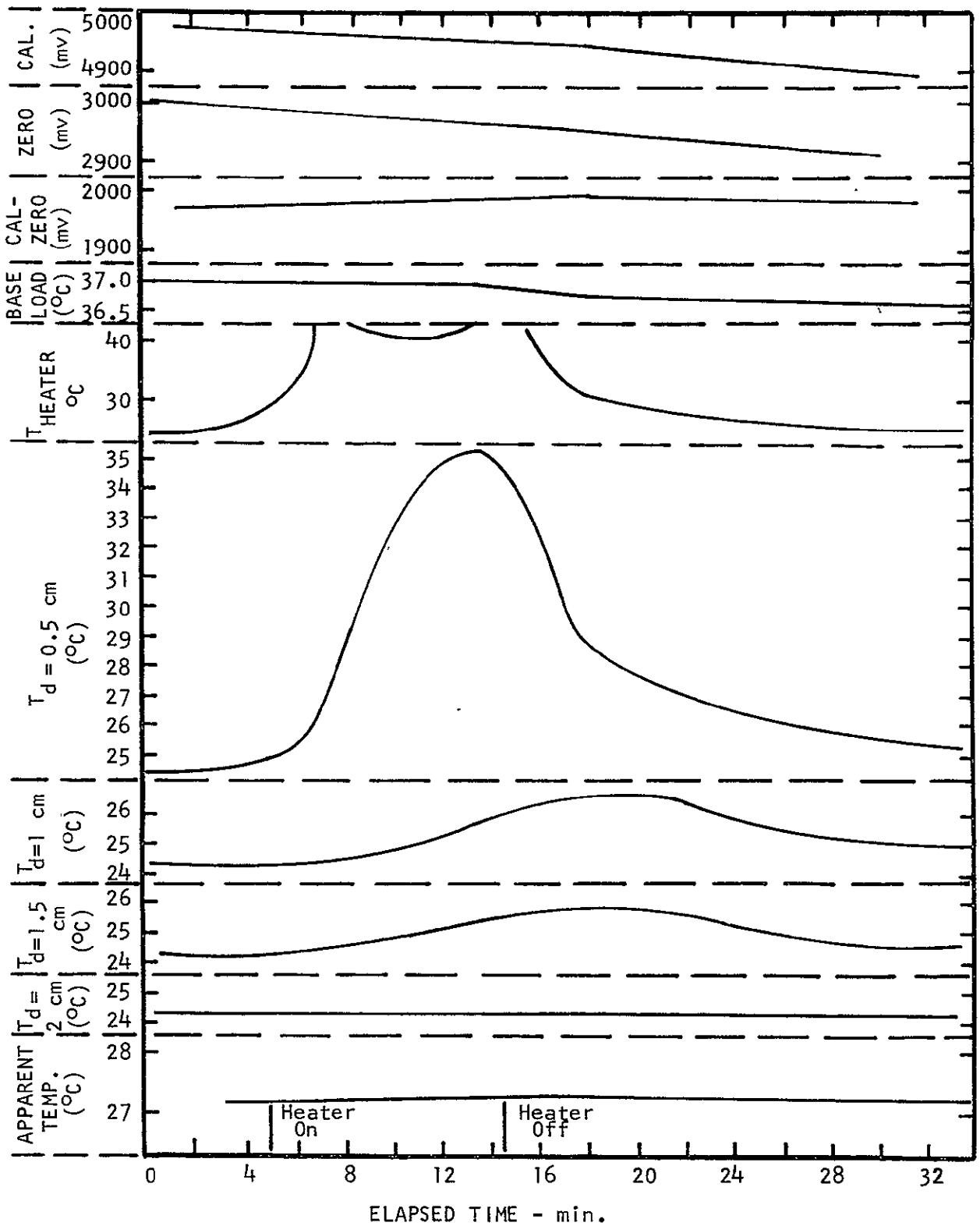


Figure 3-6 - Phantom Measurement No. 2 - Beefsteak Layer Thickness = 10 mm

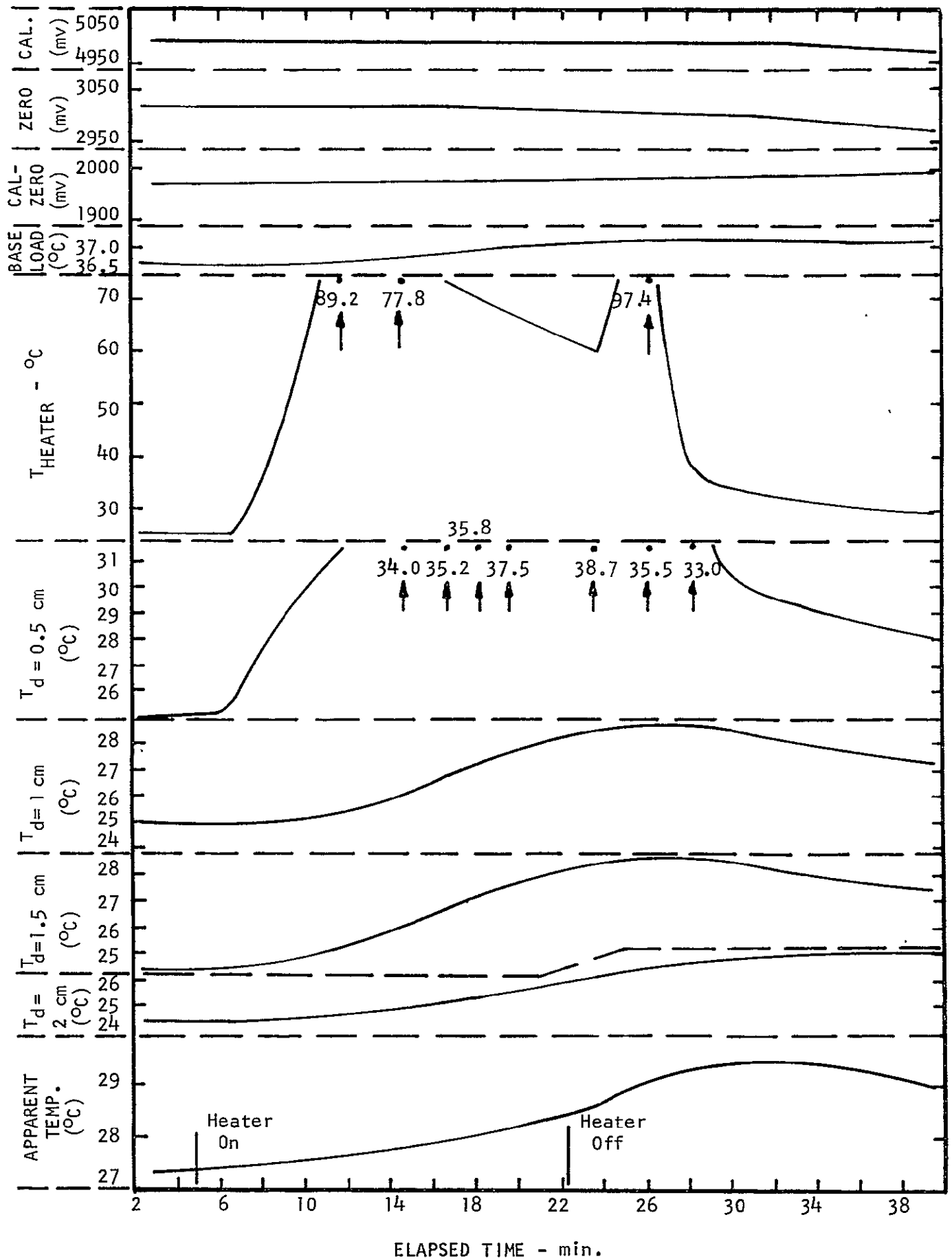


Figure 3-7 - Phantom Measurement No. 2 - Beefsteak Layer Thickness = 21 mm

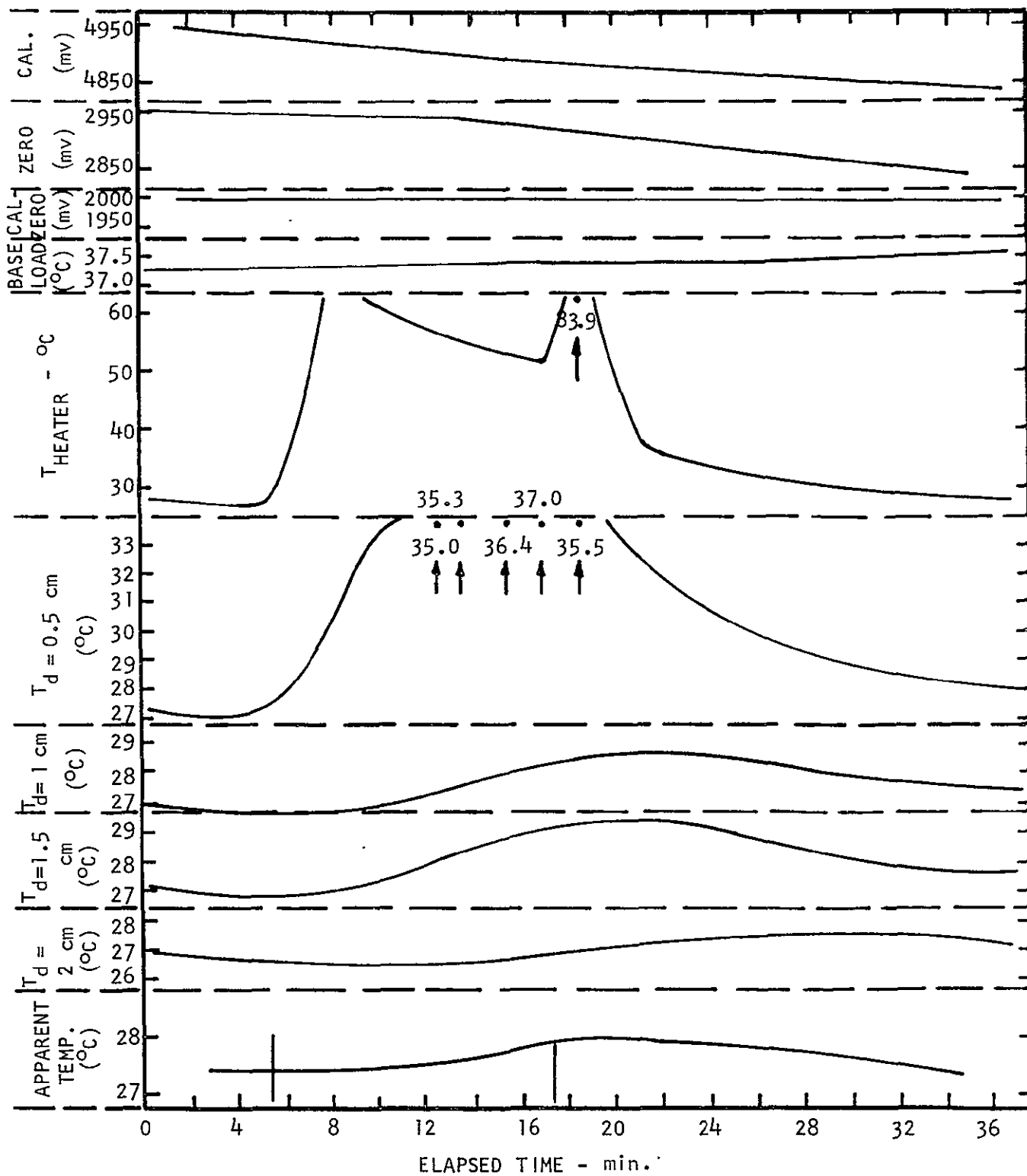


Figure 3-8 - Phantom Measurement No. 2 - Beefsteak Layer Thickness = 34 mm

The VSWR measurement was performed on the phantom shortly before the radiometric observations were initiated. It will be recalled that the beefsteak remained uncovered for approximately two (2) hours before any measurements were performed. Table 3-2 presents the results of the VSWR measurements.

Table 3-2

PHANTOM NO. 2 VSWR DATA

Frequency	Voltage Rdg. (mv)	Power Transmission	Reference
F1 (705 MHz)	8540	0.815	Figure 2-3
F2 (768 MHz)	8140	0.863	Figure 2-4
F3 (832 MHz)	6780	0.658	Figure 2-5

The average power transmission value is 0.779; thus, the emissivity of the phantom is 0.779. Referring to Equation (3-1) the quantities entering into it are as follows (see Figure 3-6):

$$\epsilon = 0.779$$

$$T_o = 24.4^{\circ}\text{C}, \text{ when the heater was switched on and at a distance of 1.5 cm from the heating element}$$

$$R = 1 - \epsilon = 0.221$$

and $T_R = 37.0^{\circ}\text{C}$, taken from the Base Load temperature reading.

These quantities give a calculated value for T_A of 27.2°C . This is exactly equal to the measured value of T_A , shown in Figure 3-6. Thus, the VSWR Circuit has permitted a very accurate prediction of the T_A obtained in this experiment.

3.6 PHANTOM MEASUREMENT NO. 3

Since the second phantom experiment did not demonstrate the full penetration capabilities of the radiometer, Phantom Measurement No. 3 was performed a few days later, using thicker layers of beefsteak between the heating element and antenna.

The phantom setup and measurement procedure was identical to that observed in the case of the second phantom; however, the VSWR and radiometer measurements were initiated immediately after the meat was unwrapped and placed under the antenna.

Figures 3-9 thru' 3-11 present the results obtained with Phantom Measurement No. 3. It will be noted, in Figure 3-9, that the apparent temperature curve shows an increase of 1.6°C between t = 5.5 min. and t = 24 min. The 1-cm and 1.5-cm thermistor temperature curves both show increases of 5.2°C, over the same interval of time. It is clear, from the similar shapes of these three curves, that the T_A curve followed the 1-cm and 1.5-cm thermistor curves quite faithfully. Thus, it can be concluded that the radiometer sensed temperatures through a meat thickness of approximately (40-10) mm or 30 mm (3.0 cm).

Figures 3-10 and 3-11, representing beefsteak layer thicknesses of 50 and 60 mm, respectively, show no increase in apparent temperature during the 40-minute measurement. Thus, it is likely that the full penetration capability of the radiometer was reached in the 40-mm-thick layer of beefsteak, discussed above in connection with Figure 3-9.

In this experiment, the VSWR measurement was made just before the radiometric observations were initiated and immediately after they were completed approximately two (2) hours later. Both sets of results are presented in Table 3-3.

Table 3-3

PHANTOM NO. 3 VSWR DATA

Frequency	Voltage Rdg. (mv)	Power Transmission	Reference
<u>Before Radiometric Measurements</u>			
F1 (705 MHz)	8235	0.752	Figure 2-3
F2 (768 MHz)	7735	0.813	Figure 2-4
F3 (832 MHz)	6170	0.590	Figure 2-5
<u>After Radiometric Measurements</u>			
F1 (705 MHz)	8560	0.823	Figure 2-3
F2 (768 MHz)	8185	0.868	Figure 2-4
F3 (832 MHz)	6630	0.642	Figure 2-5

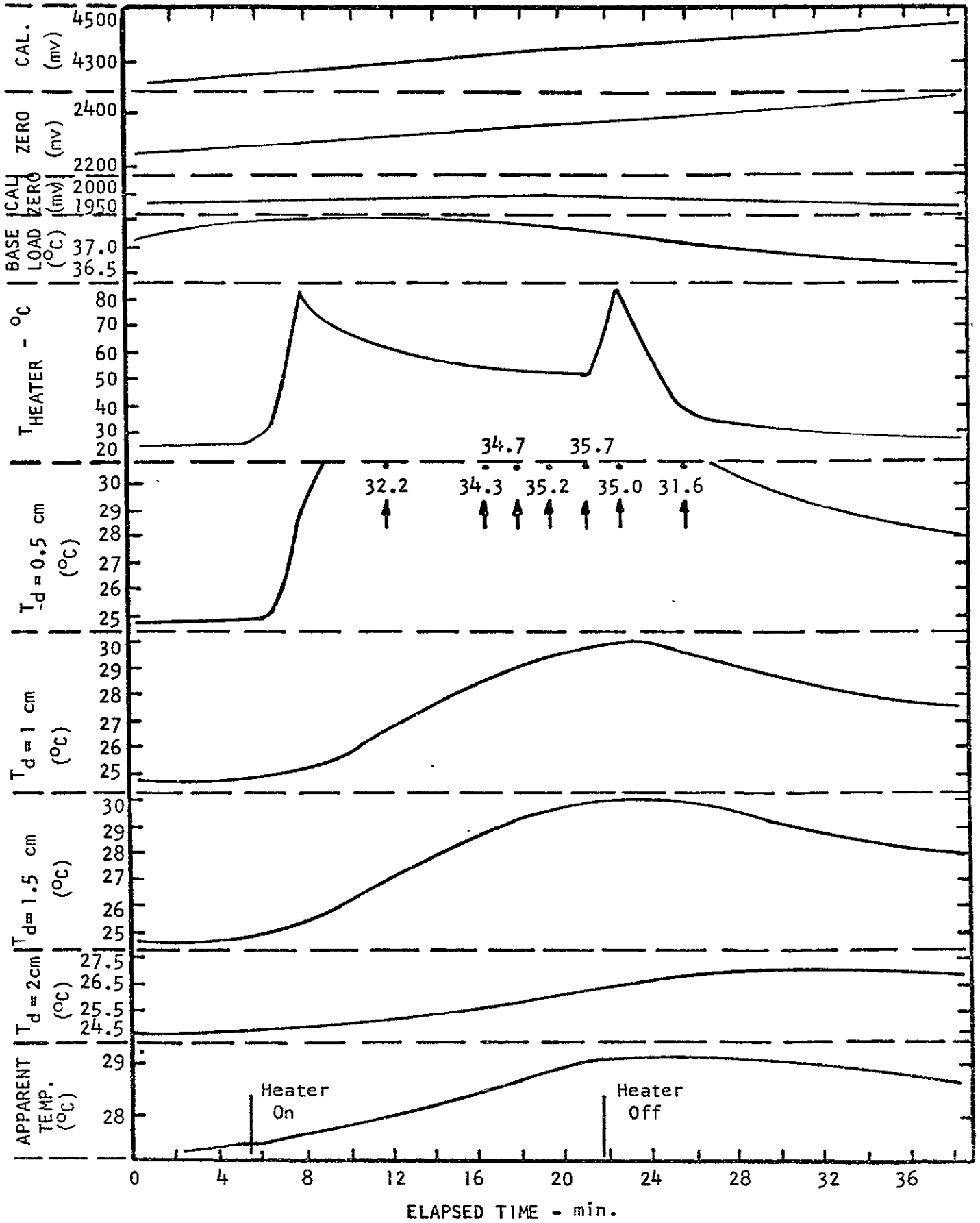


Figure 3-9 - Phantom Measurement No. 3 - Beefsteak Layer Thickness = 40 mm

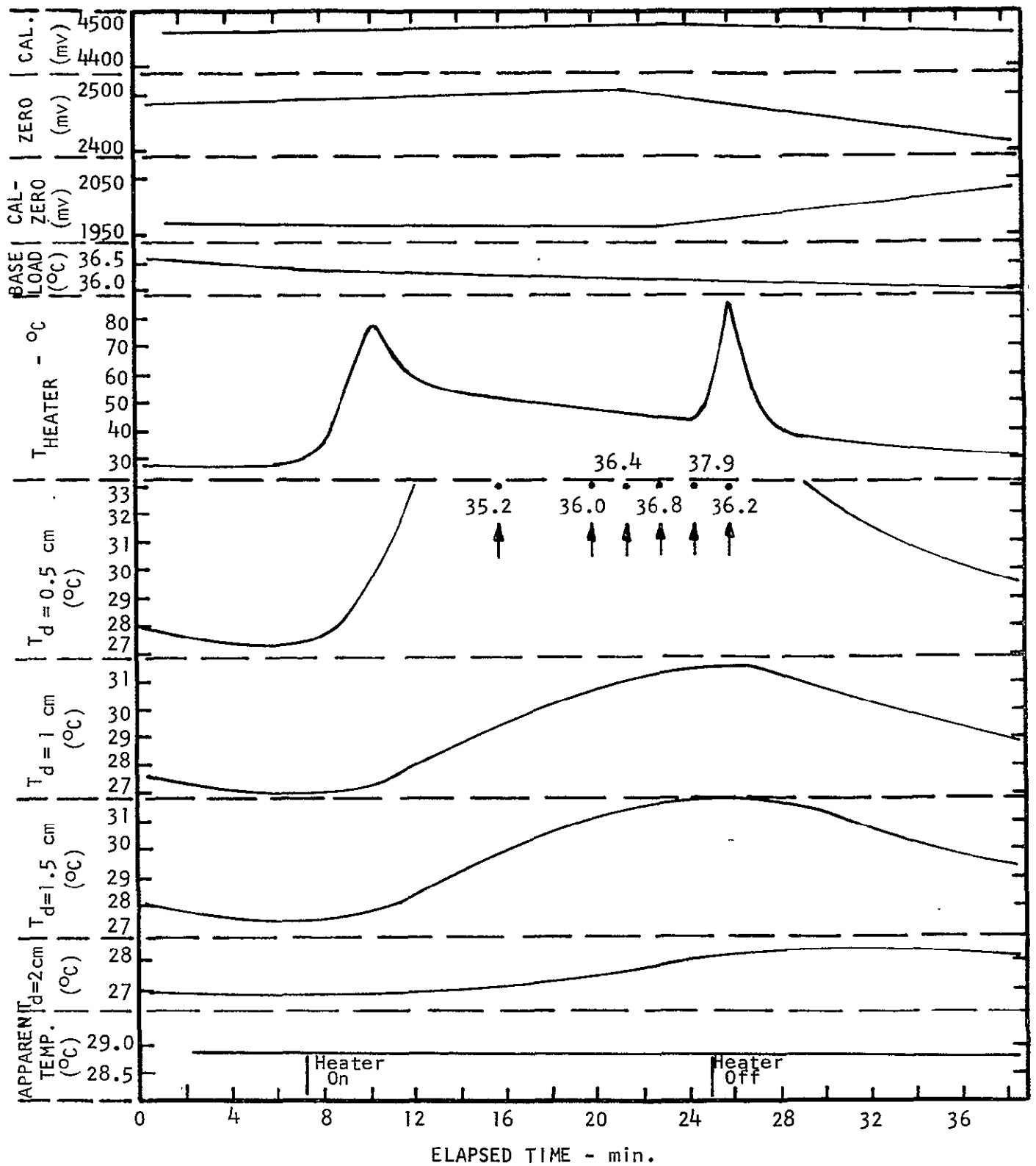


Figure 3-10 - Phantom Measurement No. 3 - Beefsteak Layer Thickness = 50 mm

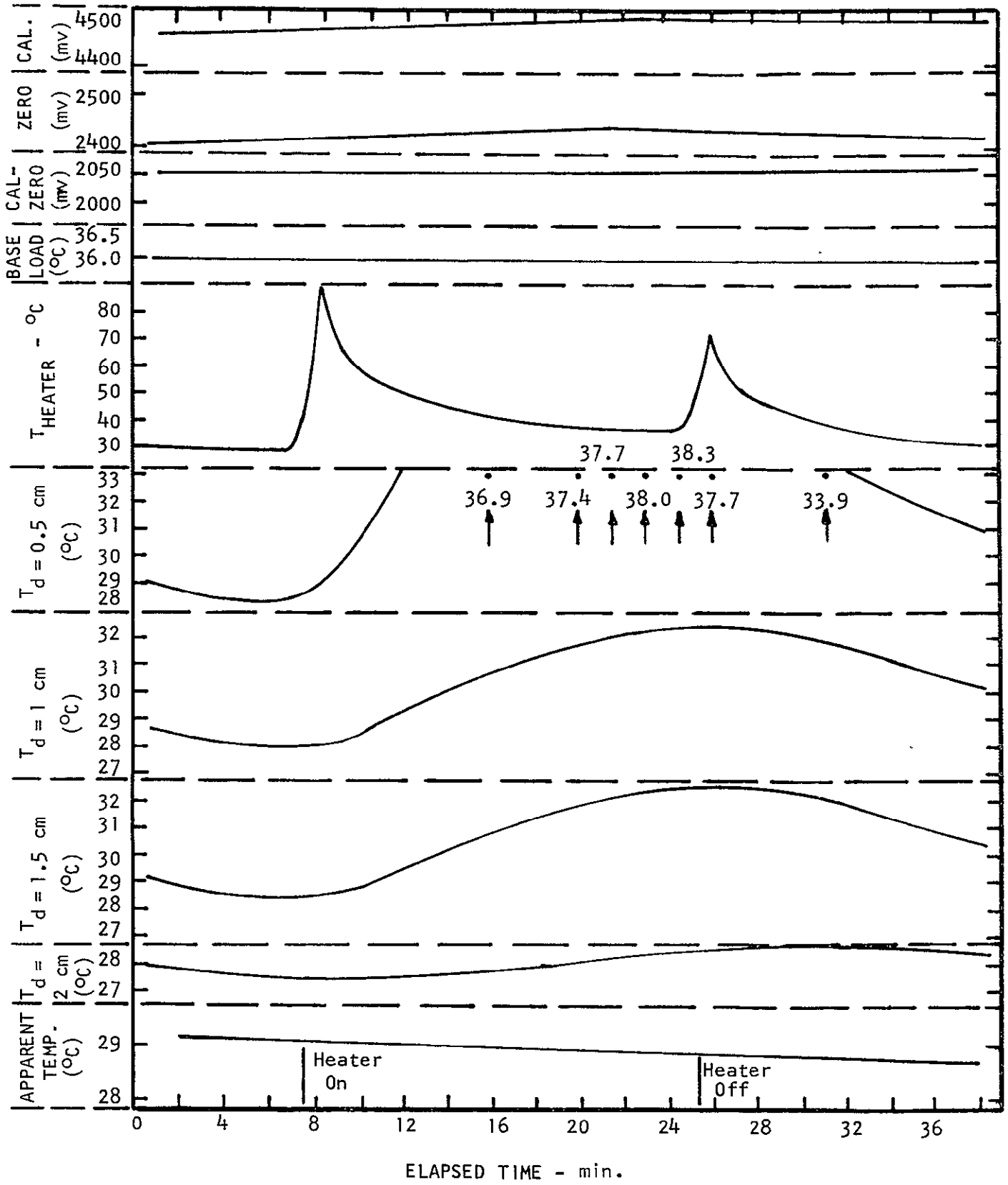


Figure 3-11 - Phantom Measurement No. 3 - Beefsteak Layer Thickness = 60 mm

The average power transmission values are 0.718 and 0.778, respectively. Thus, the emissivity of the phantom was 0.718 before the radiometric measurements and 0.778 after the measurements.

Referring to Equation (3-1) the quantities entering into it are as follows, for the case before radiometric observations were initiated (see Figure 3-9):

$$\begin{aligned}\epsilon &= 0.718 \\ T_O &= 24.8^{\circ}\text{C}, \text{ when the heater was switched on and at all distances} \\ &\quad \text{from the heating element} \\ R &= 1-\epsilon = 0.282 \\ \text{and } T_R &= 37.5^{\circ}\text{C}.\end{aligned}$$

These quantities give a calculated value for T_A of 28.4°C . This is 1.9°C above the value of T_A , at heater switch-on, in Figure 3-9.

For the case after radiometric observations were completed we have, from Figure 3-11,

$$\begin{aligned}\epsilon &= 0.778 \\ T_O &= 28.0^{\circ}\text{C}, \text{ at time } \approx 43 \text{ minutes, at a distance of 2 cm from the} \\ &\quad \text{heating element} \\ R &= 1-\epsilon = 0.222 \\ \text{and } T_R &= 35.9^{\circ}\text{C}.\end{aligned}$$

These quantities give a calculated value of T_A of 29.8°C . This is 1.1°C higher than the final value of the observed T_A , shown at time ≈ 43 minutes in Figure 3-11, representing a discrepancy of + 3.8%. It is worth noting that the above emissivity of 0.778, obtained after the beefsteak had been uncovered under the antenna for about two hours, is almost identical to the 0.779 value obtained at the beginning of Phantom Measurement No. 2, when the beefsteak had also been left uncovered for a similar period of time. In other words, there is good repeatability in the data, furnished by the VSWR Circuit.

Section 4

CONCLUSIONS

Several important conclusions may be drawn from the results of this project. These are as follows:

1. A useful voltage standing-wave ratio (VSWR) circuit has been developed and incorporated in the UHF radiometer RF head. The circuit, operating over the radiometer RF band, provides convenient and rapid readings of power transmission, at the antenna-material interface, which are numerically equal to the emissivity of the material. The accuracy of the VSWR circuit is within $\pm 5\%$, referred to a standard laboratory slotted line. The precision, with which the circuit measures VSWR, is estimated to be within $\pm 0.5\%$.
2. The temperature stability of the radiometer RF head has been improved to the point where its internal temperature remains steady within $\pm 0.2^{\circ}\text{C}$, over a period of 30 minutes.
3. The stability of the internal RF calibration circuit has also been improved. During extensive performance tests, the calibration signal level shifted by only $\pm 0.1^{\circ}\text{C}$ within a period of 30 minutes.
4. The signal stability of the radiometric system, as a whole, has been improved such that the zero-signal output voltage drift is equivalent to an apparent temperature change of less than 0.15°C , over a period of 30 minutes.
5. Power transmission measurements, performed on three (3) separate phantom models, consisting of lean beefsteak, showed that the emissivity of this material ranges from 0.623 to 0.779, at the radiometer operating frequency (800 MHz) depending on its moisture content. As expected, the emissivity increases with decreasing moisture content.
6. Radiometric measurements, performed on the above phantom models, showed that the radiometer could sense small temperature changes occurring at depths in the range, 19 to 30 mm. Although this is not as great as the 38 mm depth, determined in the original measurements¹, it is sufficient to justify a measure of optimism relative to the utility of microwave radiometric techniques for subsurface temperature sensing in biological tissue.

Section 5

RECOMMENDATIONS

The favorable results, obtained during the course of this project, justify serious consideration of certain areas of investigation, for proper development of the radiometric subsurface temperature sensing technique. Most of these were discussed in the recommendations presented at the completion of the previous project¹. For purposes of convenience, appropriate recommendations, given in that report, will be included in the current recommendations, which are presented below.

5.1 RADIOMETRIC OBSERVATIONS ON PHANTOM MODELS OF BIOLOGICAL TISSUE

Additional radiometric observations should be made on phantoms, at NASA-Ames, for the following purposes:

1. To permit NASA personnel to gain experience in the operation of the equipment and in data reduction and analysis. These observations and studies should be conducted under the supervision of personnel from Radiometric Technology, Inc.
2. To assess the capabilities of the UHF radiometer in observations on phantoms representing various areas in the human body i.e., phantoms constructed with different types of animal tissue, with suitable layers of fat representing the top layer.

To eliminate externally generated electromagnetic interference, all radiometric observations should be conducted in a radio-frequency (RF) screen room. If such a facility is not available, radiometer signal stability should be checked with all nearby fluorescent lights switched off, including those on the floors above and below the room in which the radiometer is located. These tests should be conducted with the radiometer antenna resting on a slab of lean beefsteak at least 5 cm thick. If the radiometer output signal is stable, within the limits cited in Section 2 of this report, over a 1-hour period of time, serious phantom measurements may be performed under similar operating conditions.

5.2 MEASUREMENT OF BLOOD FLOW IN ANIMALS

Once the subsurface temperature sensing capabilities of the radiometer are determined from phantom measurements, it is recommended that suitable observations be performed on animals. The thigh of a large dog is considered to be a worthwhile area for initial investigations of blood flow in living tissue. The heating and cooling techniques, described in Section 4 of the previous report¹, coupled with careful monitoring of surface and subsurface temperatures with thermistor sensors, should provide a good indication of the depth to which the radiometer can sense small changes in temperature.

If possible, additional correlative measurements should be performed with the aid of radio-isotope techniques or an impedance plethysmograph.

5.3 MEASUREMENT OF BLOOD FLOW IN THE HUMAN BODY.

Following successful completion of radiometric observations on animals, the knowledge gained from them should be applied in an extensive investigation aimed at developing a technique for indirect measurement of blood flow in the human body. The radiometer could be employed in measuring apparent temperatures of the head and other parts of the body, under stresses imposed by heat and exercise. Of particular interest are heat losses from various parts of the body, under specified conditions.

During the previous project, it was found that the radiometer is capable of sensing subsurface temperatures, in living tissue, to a depth of about 1.5 cm. Since a significant portion of the blood volume is in this region, measurements at different points on the body should yield a good indication of blood distribution and heat flow.

5.4 CORRELATIVE MEASUREMENTS OF BLOOD FLOW

It has been difficult to obtain accurate correlative data on blood flow in dogs, during temperature and radiometric measurements. Even when square-wave electromagnetic flowmeters perform satisfactorily, their use is limited to a single blood vessel; thus, no indication is given of the amount of collateral flow. The other disadvantage of these instruments is that a surgical operation is required to permit their use. This precludes their application in humans.

In view of the above problems, it is recommended that correlative data on blood flow be obtained by, either, a radio-isotope method, an impedance plethysmograph, the ultrasonic method, a cold mass or a heat pulse whichever is most appropriate for a given experiment. If the necessary equipment is not readily available, consideration should be given to performing the experiment at a facility that can furnish it temporarily, on a rental basis.

5.5 LOWER FREQUENCY RADIOMETER

The operating RF center frequency of the radiometer, delivered to NASA-Ames, is near 800 MHz. This is about 75 MHz higher than was originally intended and was caused by the need for a bandpass filter for elimination of certain UHF TV frequencies.

Since the depth from which the radiometer can sense temperatures, in living tissue, appears to be limited to about 1.5 cm, it would be worthwhile furnishing an additional RF head to operate at a lower frequency and, hence, provide a means for sensing temperatures at greater depths. Figure 2-8, in the previous report¹ shows that operation in the vicinity of 500 MHz should be optimum. The tendency of the antenna aperture to increase to objectionable proportions could be avoided by raising the dielectric constant of the loading material to a value that would compensate for the increase in aperture. It has been discovered that loading materials, with dielectric constants above 30, are available on the market.

Operation at a lower frequency would permit temperature measurements on organs located at some depth in the body. An ideal approach would involve a 3-frequency radiometer. Since each frequency would be limited to a particular depth, such an instrument could measure three temperatures simultaneously, in profile, to a maximum depth dictated by the lowest frequency. This approach would permit a better understanding of heat flow from the body.

Section 6

REFERENCES

1. Porter, R.A. and F.J. Wentz, "Study of Blood Flow Sensing with Microwave Radiometry", NASA-Ames Contract NAS 2-7087, Radiometric Technology, Inc., October 1973.

APPENDIX A

RADIOMETER SETTING UP
AND
PHANTOM MEASUREMENT PROCEDURE

Section A-1

RADIOMETER SETTING UP PROCEDURE

1. AC Connections

- 1.1 The isolator transformer, attached to the equipment stand base, plugs into a 115 VAC wall outlet.
- 1.2 AC cords, from Lock-In Amplifier and RDS, plug into 115 VAC outlet strip mounted at rear of equipment stand.

2. Radiometer Connections

- 2.1 The Radiometer is hung onto its yoke by means of the two securing knobs.
- 2.2 The four (4) cables attached to the radiometer support arm, labeled J1, J2, 1 KHZ and RAD OUT, plug into their respective sockets on the radiometer.

3. Lock-In Amplifier and RDS Connections

- 3.1 Set Lock-In Amplifier on top of the cushioning material and slide it carefully into the wooden frame on the equipment stand table. Avoid subjecting the Amplifier to any jolts.
- 3.2 Place RDS on top of the wooden frame containing the Lock-In Amplifier.
- 3.3 Grounding braids of, both, RDS and Lock-In Amplifier are to be firmly attached to ground screw on equipment stand table. This is important.
- 3.4 Plug BNC cable, labeled 1 KHZ, into back of Lock-In Amplifier.
- 3.5 Plug Amphenol connector, J3, into back of RDS.
- 3.6 Plug BNC cable, labeled RAD OUT, into INPUT on front of Lock-In Amplifier.

- 3.7 Connect BNC cable between MONITOR, on front of Lock-In Amplifier, to connector at rear of RDS.
- 3.8 Plug Radiometer temperature probes 13, 14 and 15 into RT2, RT3 and RT4, respectively, on back of RDS.
- 3.9 Plug remaining temperature probes, except the Model 513 probes, into RT5 through RT9, in any desired order.

See Section A-2 for Model 513 probe plug-in instructions.

4. Radiometer Operation

4.1 Applying Power to Equipment

- a) Turn power on.
- b) Plug isolator in 115 AC, 60 cycle outlet.
- c) Operate outlet strip switch to ON.
- d) Operate Lock-In Amplifier power switch to ON.
- e) Push on RDS POWER button.
- f) Operate radiometer heater switch to ON and, after 30 minutes, switch to OFF. This is important.
- g) Allow at least 45 minutes for equipment warm-up.

4.2 Adjustment of Lock-In Amplifier

- a) Switch mode to INT.
- b) Switch time constant to 1 SEC.
- c) Switch sensitivity to 1 mV.
- d) Switch Meter/Monitor to OUT X 1.
- e) Turn the radiometer control switch on the RDS to ZERO.
- f) Set meter to red mark by adjusting zero knob.
- g) Turn radiometer control switch to CAL.

- h) Adjust phase controls for maximum positive deflection of meter. Refer to Lock-In Amplifier manual for further information, if needed.
- i) Switch time constant to 10 SEC.

4.3 Operation of RDS

- a) Turn recorder switch to REC.
- b) Load clean tape cassette, making certain that the full reel is on right side. The Write Protect light should be on, indicating that the protect tabs on cassette are closed.
- c) Engage tape head by pushing downward on top bar.
- d) Set four X-Y thumbwheels to any operator-determined data identification number, such as time of day.
- e) Set two R thumbwheels to number of samples to be recorded, from 30 to 100.
- f) Set two EX NO thumbwheels to desired experiment number (excluding 99).
- g) Set Transmission Circuit Frequency Selector switch to F2, and leave it in this position whenever data is being recorded.
- h) Perform radiometer calibration initially and every 15 minutes thereafter.
 - 1) Set three white toggle switches to T, \bar{S} , C.
 - 2) Turn radiometer control switch to ZERO.
 - 3) Wait one minute.
 - 4) Set data I.D. thumbwheels to time of day.
 - 5) Press START button.
 - 6) When READY switch light comes on, turn radiometer control switch to CAL.
 - 7) Wait one minute.
 - 8) Set time thumbwheels.
 - 9) Press START button.
 - 10) Calibration is completed when READY light comes on again.

Section A-2

PHANTOM MEASUREMENT PROCEDURE

This Section describes the procedure to be observed in positioning the heater element, thermistor sensors and radiometer antenna on the phantom. The electrical connections, heater current adjustment, transmission measurement and radiometric measurement procedures are also described.

1. Phantom Setting Up Procedure

- 1.1 Tape together the leads from the surface-type thermistor and the 15-ohm heating strip with masking tape so that the temperature-sensing surface of the thermistor lies against one side of the heating element.
- 1.2 Place the heater-thermistor unit on the surface of the beefsteak, as shown in Figure 3-1.
- 1.3 Position the four YSI Model 513 thermistor needle probes on the meat surface, as shown in Figure 3-1. Distances are measured from the thermistor beads to the heater edges. If preferred, the YSI Model 402, white vinyl thermistor probes may be used, in place of the 513's; however, care must be taken to plug these into the proper jacks at the back of the RDS.
- 1.4 The leads for all the thermistors and the heater should be taped down to the table surface, to prevent the thermistors and heater from being shifted out of position. The positions of the thermistor beads and heater on the meat surface can be noted by marking on the surrounding table top the X-Y coordinates corresponding to these points.
- 1.5 The Model 513 thermistor probe plugs must be inserted only into their corresponding jacks on the back of the RDS. These are clearly labelled.

<u>Probe No.</u>	<u>RDS Input Jack No.</u>
3034	RT10
3035	RT11
3036	RT12
3037	RT13

The data reduction computer programs are set up to convert the individual Model 513 probe millivolt outputs to degrees Centigrade and require that the probes be plugged into the RDS according to the above table.

- 1.6 Connect any standard laboratory multi-test meter, with a milliampere scale, to the terminals of the furnished 6 VDC heater power supply. With the meter set to read 500 ma full scale, the 15-ohm heater operating at maximum power will draw about 390 ma. Do not turn on the heater when it is first positioned on the meat sample; wait until it is time to actually use it during the phantom measurement, to generate a local temperature elevation.
- 1.7 Once the thermistor probes and heater are in position, place a layer of lean beefsteak over them, taking care not to disturb their arrangement. Do not use any plastic wrapping between meat layers.
- 1.8 Position the antenna over the top beefsteak layer, relative to the now-covered thermistor/heater arrangement, as shown in Figure 3-1. Lower the antenna perpendicularly onto the top surface of the meat so that it makes a slight depression, thus ensuring that firm contact between the antenna and meat surface is maintained at all points. Do not touch or move the antenna again until the measurement with the chosen beefsteak layer is completed.

2. Power Transmission Measurement Procedure

The measurement of power transmission at the antenna-phantom interface may be performed after the radiometer is set up, as described in Section A-1. The power transmission, at the antenna-material interface, may be measured at three (3) frequencies, designated F1, F2 and F3. These are the lowest, center and highest frequencies in the radiometer operating pass band, respectively. The power transmission reading is numerically equivalent to the emissivity of the material to be measured by the radiometer. The following procedure must be observed when measuring power transmission at any of the above frequencies:

- 2.1 Set the "SENSITIVITY" switch on the Lock-In Amplifier to the "5 mv" position.
- 2.2 Set the "TIME CONSTANT" switch on the Lock-In Amplifier to the "1 Second" position.
- 2.3 Set the "MODE" selector switch on the RDS to its full clockwise position, labeled "CAL" i.e., transmission calibration.
- 2.4 Set the "FREQUENCY" selector switch on the RDS to the desired frequency.
- 2.5 Set the gain control on the RDS so that the voltage readout indicates $\pm 10,000 \text{ mv} \pm 40 \text{ mv}$.
- 2.6 Set the "MODE" selector switch to "TRANS" position and note the voltage readout on the RDS.
- 2.7 There may be some drift in the TRANS/CAL voltage readout; therefore, as soon as the $\pm 10,000 \text{ mv} \pm 40 \text{ mv}$ range is achieved, switch to TRANS position, wait at least 5 seconds, and note the voltage readout. This value may soon drift also; only the initial voltage value is to be considered.
- 2.8 The power transmission, at the antenna-material interface, may now be read on the appropriate graph, shown in Figures 2-3, 2-4 and 2-5 and referring to the voltage determined in Step 2.6.

Note: The estimated measurement accuracy of the Transmission Measurement Circuit, in the radiometer RF Head, is $\pm 5\%$.

3. Radiometric Measurement Procedure

This procedure is to be followed after the Setting Up Procedure, given in Section A-1 has been completed.

- a) Set three white toggle switches on the RDS to T, \bar{S} , \bar{C} .
- b) Place antenna on subject, being careful to make a firm, even contact.
- c) Turn radiometer control switch, on RDS, to OPER.
- d) Wait one minute.
- e) Press START button on RDS.
- f) When RDS READY light comes on, another measurement may be made, or a calibration performed.

3.1 Use of Visual Display When Not Recording i.e., READY Light On.

- a) The TEST button light is normally off, indicating that the radiometer signal output is being displayed in millivolts.
- b) To display the temperature probe outputs, in millivolts, push TEST button. The initial push will display probe RT1. A second push will display RT2, and so on through RT13. The 14th, 15th, and 16th pushes will display the zero, probe voltage source, and full-scale readings of the RDS, respectively. A 17th push will end the test cycle, extinguishing the test light, and the radiometer signal output will again be displayed.
- c) The START button should not be pushed while in a test sequence, i.e., TEST light on. To end a test sequence, all 16 positions must be cycled through, or the recorder switch may be switched to OFF and then back to REC in the middle of the cycle, or the left-hand toggle switch may be flipped up momentarily to \bar{T} , then back down to T.

3.2 Concluding Experiment

- a) Set EXP. NO. thumbwheels to 99.
- b) Press START button.
- c) When READY light comes on, push cassette release lever.
- d) Remove cassette.
- e) Rewind cassette by loading it again. Upon loading, cassette will automatically rewind.
- f) Remove cassette.
- g) Turn off all power.