GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: April 23, 1979

Project Title: Research Initiation - Investigation of Transient Measurement Techniques for the Thermogradient Coefficient of Moist Porous Materials

Project No: E-25-621

Project Director: Dr. James G. Hartley

Sponsor: National Science Foundation

Agreement Period: From 4/15/79 Until 9/30/81 (Grant Period)

Type Agreement: Grant No. ENG-7908130, dated 4/13/79

Amount: $32,000 NSF
3,173 GIT (E-25-347)
$35,173 TOTAL

Reports Required: Annual Progress Report; Final Project Report

Sponsor Contact Person (s):

Technical Matters

NSF Program Officer

Dr. Win Aung
Division of Engineering
National Science Foundation
Washington, D. C. 20550

202/632-5787

Contractual Matters
(thru OCA)

NSF Grants Official

Ms. Mary Frances O'Connell
MPE/BBS/SE Branch
Division of Grants and Contracts
Directorate for Administration
National Science Foundation
Washington, D. C. 20550

202/632-2858

Defense Priority Rating: N/A

Assigned to: Mechanical Engineering (School/Laboratory)

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GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 1/20/82

Project Title: Research Initiation - Investigation of Transient Measurement Techniques for the Thermogradient Coefficient of Moist Porous Material

Project No: E-25-621

Project Director: Dr. James G. Hartley

Sponsor: National Science Foundation

Effective Termination Date: 9/30/81

Clearance of Accounting Charges: 9/30/81

Grant/Contract Closeout Actions Remaining:

- [ ] Final Invoice and Closing Documents
- [x] Final Fiscal Report FCTR
- [x] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______________________

Assigned to: Mechanical Engineering (School/~~Laboratory~~)

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FORM OCA 10:781

E25-621

GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

SCHOOL OF
MECHANICAL ENGINEERING

July 9, 1980

Dr. Win Aung
Division of Engineering
National Science Foundation
1800 G. St. N.W.
Washington, D.C. 20550

Dear Dr. Aung:

I have attached an annual report summarizing the work completed during the first year of my Research Initiation Grant, number ENG-7908130. A summary of the work to be completed during the second year is also included.

I believe the project is progressing very well, and I am encouraged by the results obtained thus far.

Thank you for your effort and cooperation.

Sincerely,

James G. Hartley
Assistant Professor

S. Peter Kezios, Director
School of Mechanical Engineering

Dwight L. Allen
Deputy Director
Office of Contract Administration

JGH:maw

Enclosure

ANNUAL PROGRESS REPORT
NSF Grant No. ENG-7908130

"Investigation of Transient Measurement Techniques for the Thermogradient Coefficient of Moist Porous Materials"

by

James G. Hartley
Assistant Professor
Georgia Institute of Technology
School of Mechanical Engineering
Atlanta, Georgia 30332

"Investigation of Transient Measurement Techniques
for the Thermogradient Coefficient of Moist Porous Materials"

The primary goal of the present research is to develop experimental procedures for transient measurement of the thermogradient coefficient of moist porous materials. Two laboratory set-ups have been designed and constructed to achieve this goal. The first consists of a vertical, cylindrical test section insulated on both ends. A small-diameter thermal probe is used to apply a constant heat flux along the vertical axis of the specimen. The second apparatus consists of a horizontal, cylindrical test section insulated along its length. One end of the sample is heated by a circular resistance heater. A constant heat flux or a constant surface temperature can be maintained at this end of the specimen. The opposite end is maintained at near room temperature by means of a thermoelectric cooler. Each apparatus is instrumented with thermocouples to measure the temperature distribution in the sample. In addition, the thermal probe contains a thermistor which is used to measure the thermal response of the probe.

Both proposed methods for determining the thermogradient coefficient depend on the capability to measure the moisture content distribution in the test specimen. Much of the research effort during the first year has been devoted to developing a repeatable method for moisture content measurement of a moist porous sample. This has been the most difficult problem to overcome thus far. The problems and solutions are summarized in the succeeding paragraphs.

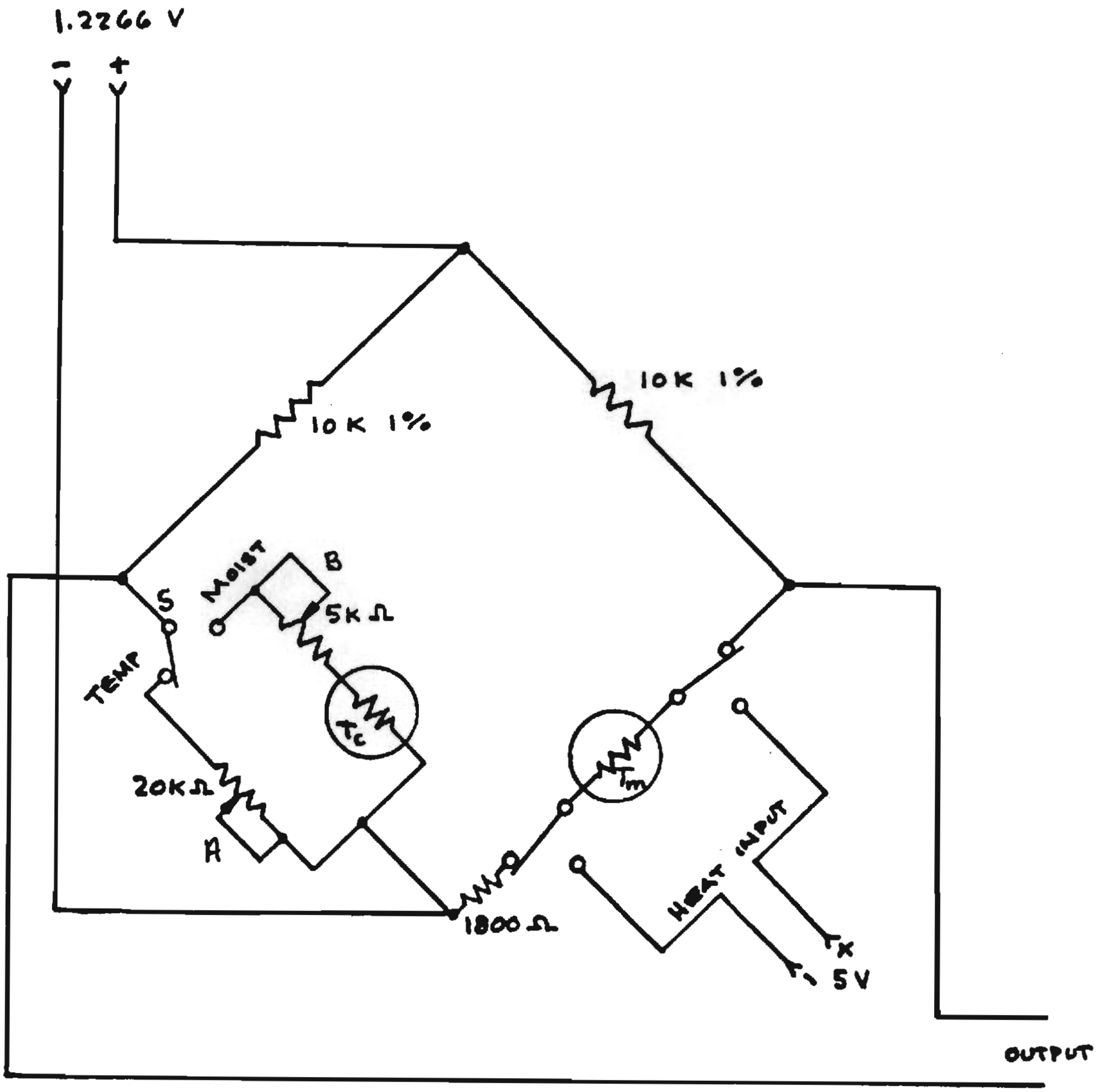
Because a "point" measurement of moisture content is desired. measurement methods based on thermal or electrical characteristics were deemed most appropriate. Electrical resistivity measurements were found to have poor repeatability, and these were abandoned. Some success with measuring moisture content using the thermal response of thermistors has been reported in the literature and this method was also evaluated.

Two thermistors, each of which formed an arm of a Wheatstone bridge (Figure 1), were placed in soil about an inch apart. One thermistor, T_m, was used for temperature compensation. A voltage was applied to T_m for a fixed period of time and the corresponding bridge out-of-balance was recorded. The results of several such tests are shown in Figure 2 as voltage out-of-balance vs. soil moisture content. The repeatability of the method was poor and could be attributed to several possible causes, including: manual switching and timing for the heating mode, inability to accurately record the maximum bridge out-of-balance, slight variations in the applied voltage, etc. A number of improvements and modifications were incorporated in an effort to improve repeatability, including microprocessor-controlled switching and instrumentation, without much success.

The bridge circuit was abandoned, and an attempt was made to correlate resistance change of the thermistor during heating directly with moisture content as shown in Figure 3. This too, was found to be inadequate.

A decision was finally made to abandon the idea of using the self-heating mode of the thermistor. Instead, glass bead thermistors were wrapped with several turns of Nichrome wire. In this way, power applied to heat the thermistor could be maintained constant, and the heated thermistor could be modeled as a continuous spherical source in an infinite medium. The results of a number of such tests with three different thermistors are shown in Figure 4.

As can be seen, the repeatability is much improved. Although the response values are slightly different for the three thermistors



5KΩ = 10 TURN (BALANCE MOISTURE)
20 KΩ = 10 TURN (BALANCE TEMPERATURE)

Figure 1. Bridge Circuit for Temperature and Moisture Content Measurements.

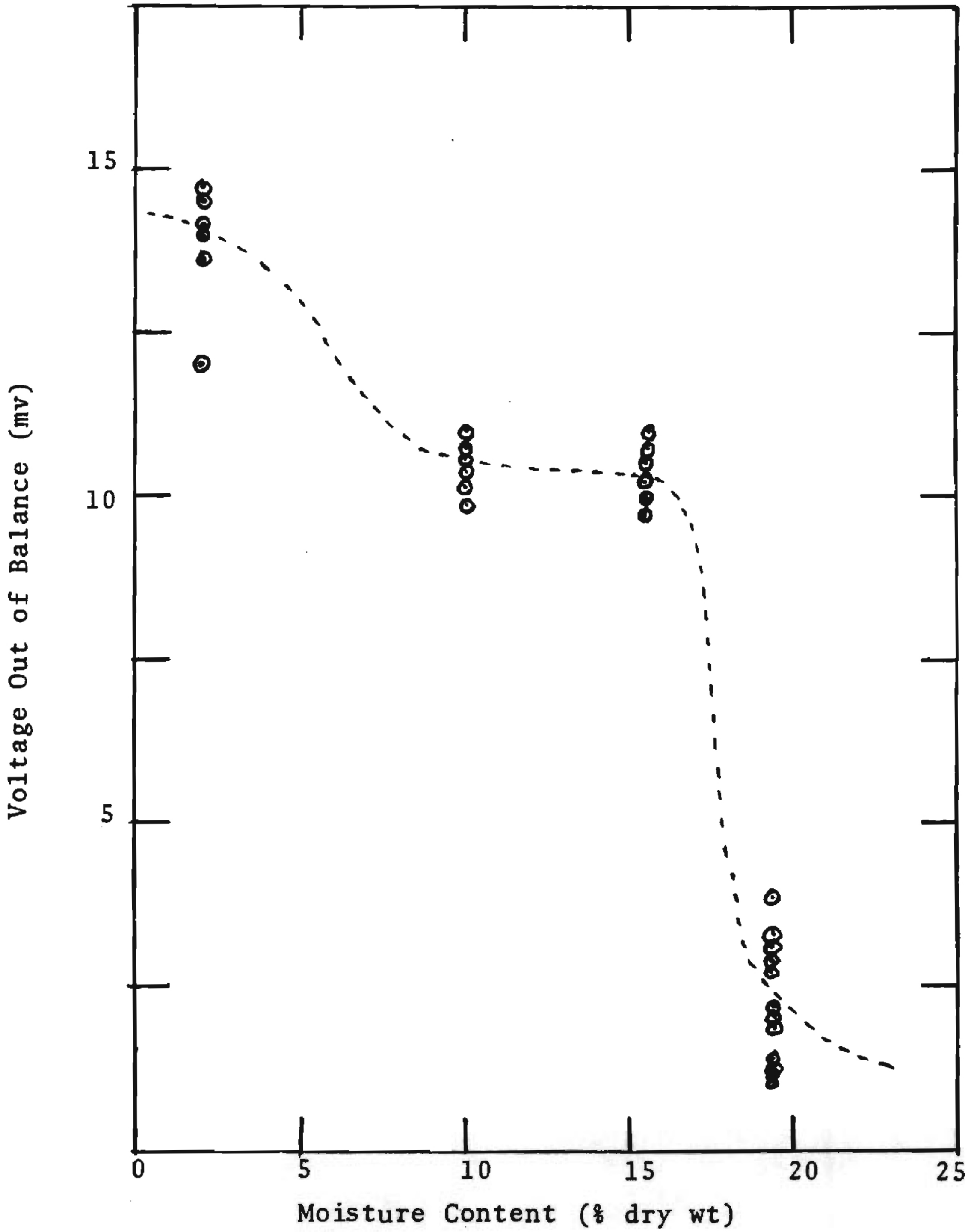


Figure 2. Voltage Out-of-Balance vs. Moisture Content

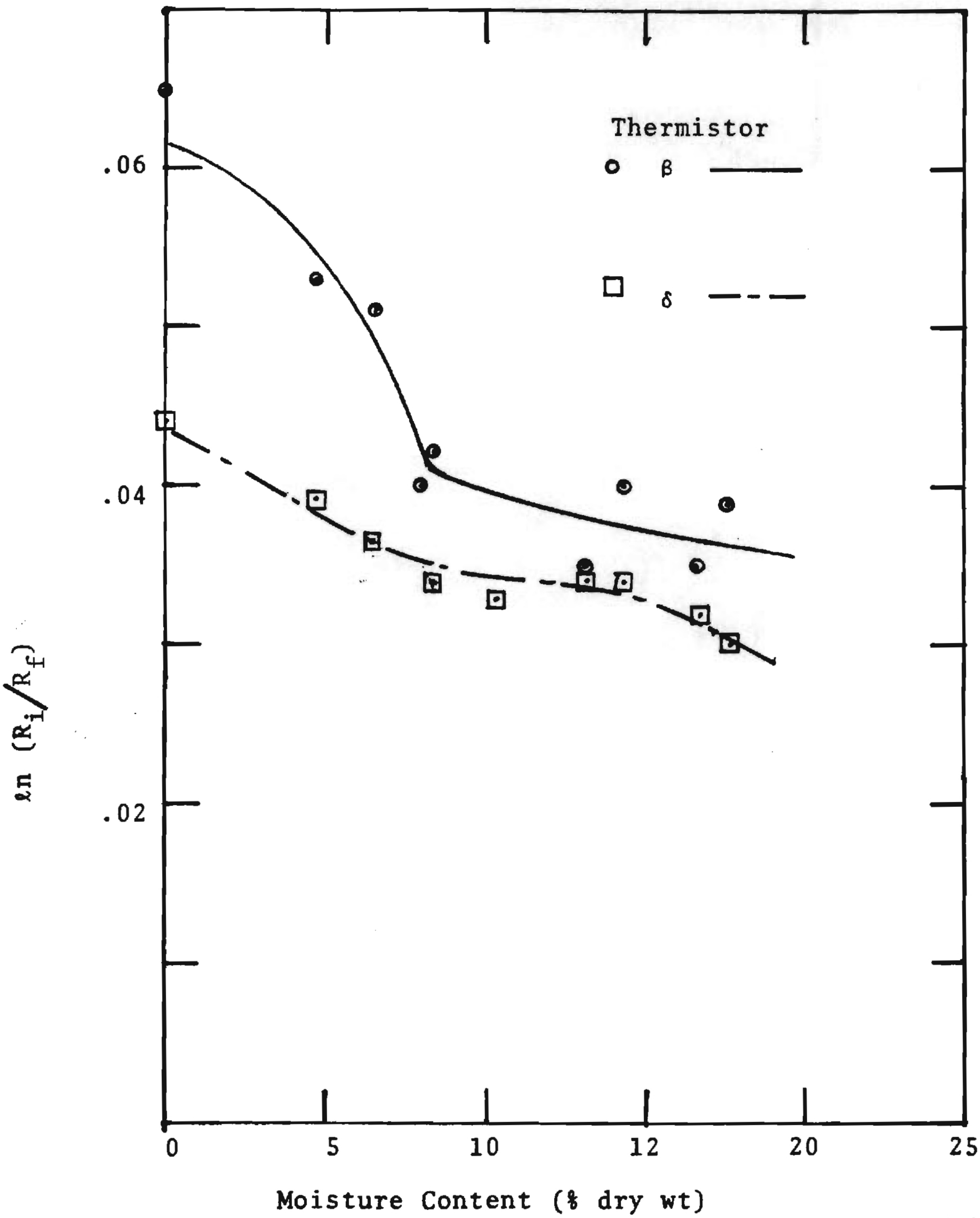


Figure 3. Dissipation Function vs. Moisture Content

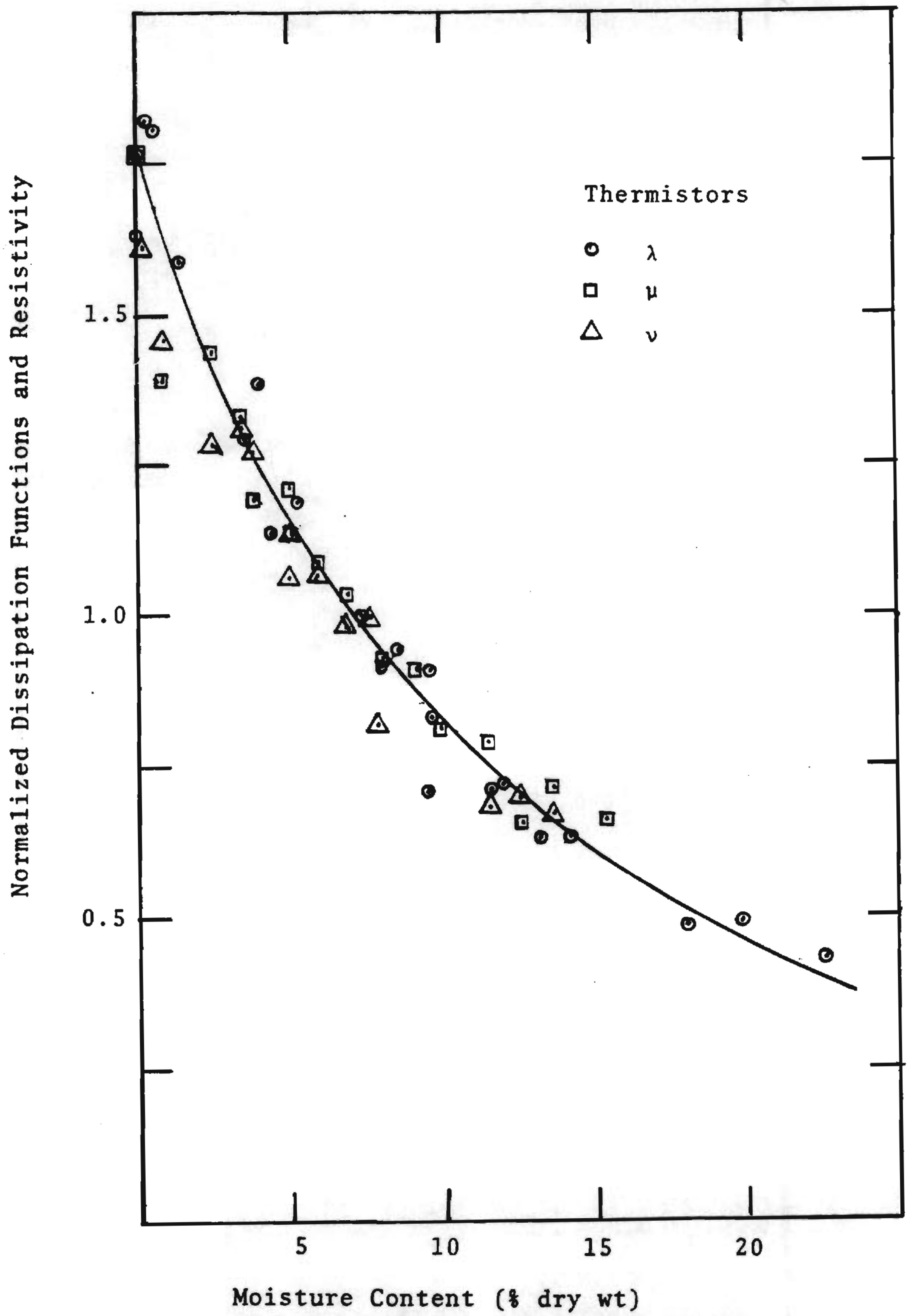


Figure 4. Normalized Dissipation Functions vs. Moisture Content

(due to slightly different thermistor characteristics) the general shape of the response curve is the same for each. This allows the response curves to be normalized as in Figure 4.

This method, called the constant-power method, holds considerable promise for repeatable, "point" measurements of moisture content of moist porous samples and represents a significant development which allows the present research to continue on schedule.

An interesting, and potentially significant, result of the present developmental work on the new moisture content measurement scheme has been obtained. The normalized dissipation function shown in Figure 4 correlates very well with the thermal resistivity (reciprocal of thermal conductivity) at zero moisture content and at moisture contents above about seven or eight percent for the soil being investigated. However, at intermediate moisture contents the normalized dissipation function would indicate lower values of thermal resistivity (higher thermal conductivity) than are obtained using standard measurement techniques, e.g. the thermal probe method. The analytical model shows that, for the values of the Fourier number encountered experimentally, the normalized dissipation function should correlate with the thermal resistivity even at the intermediate moisture contents.

Related research in the area of soil thermal stability has shown that this soil is thermally unstable at the intermediate moisture contents. Therefore, even at very low heat fluxes it might be impossible to obtain accurate measurements of thermal conductivity using the probe method with these moisture contents because moisture migration becomes significant before the initial probe transients have disappeared. Under such circumstances the probe method would give a thermal conductivity which is too low. This could explain the disparity between probe measurements and the results shown in Figure 4 at the intermediate moisture contents. These results are presently being investigated in further detail since they indicate that the constant-power thermistor method could be used for more accurate thermal conductivity measurements at moisture contents which result in unstable behavior.

Summary of Proposed Work - Second Year

Calibration tests for thermistor response vs. moisture content using the constant-power method are continuing. During the second year these tests will be completed. The results will be used to confirm the applicability of the normalized response curve for the heated thermistor design. With this confirmation, succeeding calibration curves can be obtained with only a few calibration points.

A sufficient number of these specially constructed thermistors will be made so that the test sections described earlier can be fully instrumented for moisture content measurements.

Next, temperature distributions and moisture content distributions will be measured in a series of experiments on the samples in the test sections. With this data, the thermogradient coefficient can be determined. The reliability of the two different experimental methods will be evaluated by comparing the results with a steady-state method of measurement.

APPENDIX VI

E25-621

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Georgia Institute of Technology Atlanta, Georgia 30332	Heat Transfer	ENG 79-08130
	4. Award Period From 4/15/79 To 9/30/81	5. Cumulative Award Amount $32,000

6. Project Title
Investigation of Transient Measurement Techniques for the Thermogradient Coefficient of Moist Porous Materials.

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

The primary goal of this research was to investigate the feasibility of transient measurement techniques for determining the property which describes the relative importance of moisture flow due to temperature gradients and to moisture content gradients. Two methods were considered, both of which are based on the thermal response of moist soil subjected to a heat source which dissipates heat at a constant rate. Method A employs a planar heat source while Method B employs a cylindrical heat source.

Due to difficulties associated with making local measurements of moisture content, Method A was not found to be a feasible alternative. However, using indirect measurements of moisture content, Method B was developed to the extent that the thermogradient coefficient can be measured accurately for low moisture contents. This transient method is much faster and more reliable than the steady-state methods currently available.

In conjunction with this work a sensor was devised for moisture content measurements in the absence of thermal gradients. It has also been determined that this sensor can be used to provide more accurate measurements of thermal conductivity than can be obtained with the traditional thermal probe at low moisture contents. Further research is necessary to refine the sensor so that moisture content measurements can be made under the transient conditions which prevail with Method B described above. Furthermore, additional developmental work is required to extend the transient measurement technique for use at higher moisture contents.

The results of this work provide a means of rapidly determining properties which are used to describe the movement of moisture in porous materials which are subjected to temperature gradients. The application of these results extends to a variety of engineering areas including thermal insulation systems, underground construction, underground power transmission systems, and agriculture.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (√)	Approx. Date
a. Abstracts of Theses	X				
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions	X				
e. Technical Description of Project and Results		X			
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
James G. Hartley, Assistant Professor		12/26/81

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Form Approved OMB No. 99R0013

PUBLICATIONS

A. The following publication is based on the information/findings generated by this project.

1. Hartley, J. G., "A Transient Measurement Technique for the Thermogradient Coefficient of Moist Porous Materials", in preparation, to be submitted for presentation at 1982 ASME Winter Annual Meeting.

B. The following publications by the principal investigator relating to heat transfer in soils and soil thermal behavior were also written during the period of this report.

1. Hartley, J. G. and Black, W. Z., "Predicting Thermal Stability and Transient Response of Soils Adjacent to Underground Power Cables", published in the Proceedings and Presented at the 7th IEEE/PES Conference and Exposition on Transmission and Distribution, Atlanta, Georgia, April, 1979.

2. Saleeby, K. E., Black, W. Z. and Hartley, J. G., "Effective Thermal Resistivity for Power Cables Buried in Thermal Backfill", <u>IEEE Trans. on Power Apparatus and Systems</u>, VOL. PAS-98, No. 6, November/December 1979.

3. Martin, M. A., Black, W. Z., Bush, R. A. and Hartley, J. G., "Practical Aspects of Applying Soil Thermal Stability Measurements to the Rating of Underground Power Cables", <u>IEEE Trans. on Power Apparatus and Systems</u>, Vol. PAS-100, No. 9, pp. 4236-4249, Sept. 1981; also precented at IEEE/PES Winter Meeting, Atlanta, February 1981.

4. Hartley, J. G. and Black, W. Z., "Transient Simultaneous Heat and Mass Transfer in Moist, Unsaturated Soils", <u>ASME J. Heat Transfer</u>, (103), pp. 376-382, 1981; presented at 20th ASME/AIChE Heat Transfer Conference, August 1981.

5. Hartley, J. G., Black, W. Z., Bush, R. A. and Martin, M. A., "Measurements, Correlations and Limitations of Soils Thermal Stability", Symposium on Underground Cable Thermal Back-Fill, Toronto, Canada, September, 1981.

6. Drew, B. C. and Hartley, J. G., "An Experimental Investigation of the Thermal Stability of Soils Subjected to a Constant Heat Transfer Rate", presented at 1981 ASME Winter Annual Meeting, November, 1981.

7. Black, W. Z., Hartley, J. G. and Manson, J. M., "Energy Conservation in Underground Buildings by Means of Exterior Insulation", presented at 1981 ASME Winter Annual Meeting, November, 1981.

SCIENTIFIC COLLABORATORS

1. J. G. Hartley, Assistant Professor, Principal Investigator, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia.

2. F. Raji, Graduate Student, M.S. Candidate, currently Mechanical Engineer, Hewlett-Packard Co., Fort Collins, Colorado. (Mr. Raji worked on the development of sensors for moisture content measurement.)

TECHNICAL SUMMARY

The primary goal of this research was to investigate the development of two experimental procedures for transient measurement of the thermogradient coefficient of moist porous materials. In method A, which employs a planar heat source, temperature would be measured at two different positions at various time intervals throughout the duration of each experiment. In method B, however, the moisture content and temperature at a single point (the surface of a cylindrical heat source) would be measured as a function of time. Two laboratory set-ups have been designed and constructed to achieve this goal. The first consists of a vertical, cylindrical test section insulated on both ends. A small-diameter thermal probe is used to apply a constant heat flux along the vertical axis of the specimen. The second apparatus consists of a horizontal, cylindrical test section insulated along its length. One end of the sample is heated by a circular resistance heater. A constant heat flux or a constant surface temperature can be maintained at this end of the specimen. The opposite end is maintained at near room temperature by means of a thermoelectric cooler. Each apparatus is instrumented with thermocouples to measure the temperature distribution in the sample. In addition, the thermal probe contains a thermistor which is used to measure the thermal response of the probe. Both proposed methods require a knowledge of the moisture content at a specific location in the test specimen. Therefore, much of the research effort during the first year was devoted to developing a repeatable method for moisture content measurement of a porous sample.

Because a point measurement of moisture content was desired, measurement methods based on thermal or electrical characteristics were deemed most appropriate. Electrical resistivity measurements were found to have poor repeatability, and these were abandoned. Self-heated thermistors were not entirely suitable, and a constant-power thermistor element was developed instead. Glass bead thermistors were wrapped with several turns of Nichrome wire and a constant power was applied to heat the thermistor and surrounding soil. A normalized dissipation function was defined which provides repeatable, indirect measurements of moisture content in the range from zero moisture to moderate moisture contents only. This method, however, has not been perfected to the point that moisture content measurements can be made on samples which have an imposed temperature gradient as would occur in the measurement methods being investigated in this work. While research associated with the moisture measurement problem continues under a separate contract, it was decided that indirect techniques should be pursued for the present work.

The indirect technique of determining the moisture content consists of relating the instantaneous thermal response of the heat source to the apparent thermal conductivity of the soil adjacent to the surface of the heat source. This precluded the further investigation of method A using a planar heat source. Method B, however, is based on a well known test for thermal conductivity and further research was limited to the development of this method.

Thermal conductivity measurements were first made on the soil under investigation in order to characterize the relationship between thermal conductivity and moisture content for the entire range of moisture contents of interest. Next, the cylindrical heat source was energized in soil samples of various initial moisture contents using a number of different values for the power input per unit length. The transient thermal response of the probe was used to determine the moisture content history of the soil adjacent to the heat source from instantaneous thermal conductivity determinations. Finally, the thermogradient coefficient, δ, was estimated from the relationship

$$\delta = - \frac{\Delta\theta}{\Delta T}$$

where θ and T are instantaneous values of moisture content and temperatures, respectively, at the surface of the heat source.

The validity of this procedure was analyzed by comparing experimentally determined values with values of the thermogradient coefficient calculated from numerical solutions of the transient, simultaneous partial differential equations which govern the transport of heat and moisture in the porous medium. The results indicate that the experimental procedure outlined above provides reasonably accurate values for the thermogradient coefficient for moisture contents up to the value where the thermogradient coefficient achieves a maximum. At higher moisture contents the method is not as accurate but could possibly be refined with further research.

An interesting, and potentially significant, result of the developmental work on the moisture content measurement scheme has been obtained. The normalized dissipation function correlates very well with the thermal resistivity (reciprocal of thermal conductivity) at zero moisture content and at moisture contents above about seven or eight percent for the soil being investigated. However, at intermediate moisture contents the normalized dissipation function would indicate lower values of thermal resistivity (higher thermal conductivity) than are obtained using standard measurement techniques, e.g. the thermal probe method. The analytical model shows that, for the values of the Fourier number encountered experimentally, the normalized dissipation function should correlate with the thermal resistivity even at the intermediate moisture contents.

Related research in the area of soil thermal stability has shown that this soil is thermally unstable at the intermediate moisture contents. Therefore, even at very low heat fluxes it might be impossible to obtain accurate measurements of thermal conductivity using the probe method with these moisture contents because moisture migration becomes significant before the initial probe transients have disappeared. Under such circumstances the probe method would give a thermal conductivity which is too low. This could explain the disparity between probe measurements and the present experimental results at the intermediate moisture contents. These results indicate that the constant-power thermistor method could be used for more accurate thermal conductivity measurements at moisture contents which result in unstable behavior.

In summary, this work has produced a moisture content measurement system which is suitable for a wide range of moisture contents and a transient method for determining the thermogradient coefficient for moisture contents below that at which the coefficient achieves its maximum value. The moisture content measurement system often provides more accurate measurements for thermal conductivity of moist soils at low moisture contents then can be obtained with the traditional thermal probe. Further work is needed to extend the transient thermogradient coefficient measurement technique for use at higher moisture contents, but the method, in its present form, is a substantial improvement over the usual, often inaccurate, steady-state methods. This work is being extended in a separate contract with funding provided by the Electric Power Research Institute.