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An Assessment of Needs for New Thermal Reference Materials

Brian Rennex

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National Bureau of Standards
National Engineering Laboratory
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

PREFACE

This report is one of a series documenting NBS research and analysis efforts to support the Department of Energy/National Bureau of Standards' Measurements Technology Program. The work reported in this document was sponsored by Department of Energy through DOE/NBS Task Order A008 under Interagency Agreement No. DE-AI01-76PR06010.

PRODUCT DISCLAIMER

Because of the nature of this report, to assess the kinds of products that are actually in use, there is an occasional use of a trade name or a manufacturer's name. This in no way represents an endorsement of a particular product or manufacturer. The thermal parameter values for the various insulating materials were obtained from the literature or from researchers. These values were not based on experimental research at NBS.

ABSTRACT

Thermal insulation specimens are required by users to calibrate their heat transfer apparatuses. This report assesses the need for additional calibration specimens to cover a wider range of test conditions and materials. It examines two major sources of measurement error related to the use of calibration specimens. The first is due to the lack of uniformity over a specimen area and the second is due to sytematic apparatus errors which vary with the values of specimen mean temperature and thermal conductivity. Possible solutions to these problems are given, based on information obtained from users in universities, industry, and government laboratories. These include recommendations to provide calibration specimens over a wide range of values of specimen temperature and thermal conductivity.

Key Words: apparent thermal conductivity; calibration; guarded hot plate; heat flow meter; standard reference material; thermal insulation; thermal properties; thermal resistance.

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EXECUTIVE SUMMARY

Thermal insulation specimens of known thermal resistance have historically been used to calibrate heat transfer apparatuses. This report assesses the need for new calibration specimens. It examines two major sources of significant measurement error related to the use of calibration specimens. The first is due to the lack of uniformity over a specimen area, and the second is due to systematic apparatus errors which vary with the values of specimen mean temperature and thermal conductivity. The magnitude of these errors can be several percent in typical tests of building insulations, and it can be greater at more extreme test conditions. Possible solutions to these problems are given, based on information obtained from users in universities, industry, and government laboratories.

Issues related to individual calibration specimens for use in industry or research calibration programs are examined in-depth. This examination includes a discussion of the calibration procedure. A frame of reference is developed which includes the concepts of calibration curves, extrapolation errors, and material-variablity errors. In addition, there is a discussion of criteria for calibration-specimen materials.

Representatives of the various groups who use calibration specimens were interviewed to assess their needs and to search for new developments in materials. The interview information is presented along with pertinent data on insulating materials. There is considerable overlap of the needs of the different categories of users. Based on the information gathered and on technical considerations, recommendations are made for short-term and long-term solutions to the reported calibration problems.

Short-term recommendations are to (1) develop calibration-specimen materials to cover the apparent thermal conductivity ranges corresponding to loose-fill, cellulosic material and to fluorocarbon-blown foams, using existing materials and a sectored heat-flux-transducer device, (2) continue work on the first calibration-specimen material for industrial (high-temperature) insulation material, and (3) extend the temperature range of existing standard reference materials using existing National Bureau of Standards apparatuses.

Long-term recommendations are to (1) look for ways to obtain very uniform specimens in the building-insulation regime (using layered or loose-fill composite "custom-made" specimens), (2) establish two other high-temperature calibration-specimen materials (at higher and lower thermal conductivity values), (3) make available calibration specimens in the high thermal conductivity value regime depending on future demand, and (4) explore the development of materials for calibration with reference to other thermal properties.

1. INTRODUCTION

1.1 Background

Accurate measurement of the thermal resistance of insulation and building materials is a matter of national concern. Procedures to ensure such accuracy involve the use of calibration specimens, such as those provided by the National Bureau of Standards (NBS). To achieve sufficient accuracy, these specimens must be available over a wide range of test conditions. This is not the case today.

This report recognizes the valuable earlier work [1] published by an ASTM Working Group in 1978. That report identified many issues related to the use of reference materials for insulation measurement comparisons. It gave information on many candidate materials, and this information is summarized in Table 1. In addition, it recommended (1) a search for new Standard Reference Materials (SRM's), and (2) the development of a long-range priority scheme. This assessment report begins the implementation of these two recommendations.

This report addresses the question of what is necessary to maintain an effective national calibration program for thermal tests. It maintains that such a program should serve the entire user community, which includes manufacturers, commercial testing laboratories, government laboratories, and university researchers. A viable national calibration program must consist of accurate apparatuses, appropriate test methods, and calibration specimens available over a sufficient range of test and material parameters.

Often, calibration values vary with test parameters such as specimen mean temperature, apparent thermal conductivity (or thermal resistance), and thickness. For example, if a Standards Laboratory provides a calibration point at one temperature, but the user laboratory tests specimens at a very different temperature, then significant errors in calibration may result. This kind of calibration error is referred to as an extrapolation error in this report. One way to minimize extrapolation errors would be to have calibration points available over the needed range of apparent thermal conductivity and temperature.

1.2 Objectives

This report has three objectives. The first is to give a brief explanation of the calibration procedure to establish a frame of reference for subsequent discussion and to explain why calibration specimens are needed over a wide range of test parameters to reduce the extrapolation errors just mentioned. The second is to assess the need for new calibration materials which could be tested over the just-mentioned ranges of need. This assessment is based on information obtained from the heat-transfer test community. The third objective is to propose solutions in terms of new calibration materials and procedures based on this information obtained from users and based on an analysis of the calibration procedure.

1.3 Scope

The analysis and the recommendations in this report are based on experience obtained at NBS, on a survey of users, and on results reported in literature. An attempt was made to contact a sufficient number of users and potential users to achieve a good representation of the calibration needs. Some information that is important for the analyses herein is not reported in the literature, and must be documented as personal communication. Please note the product disclaimer on page iii.

This report is intended for potential users of heat-transfer calibration specimens, interested researchers, and government policy makers. This covers a wide spectrum of measurement expertise ranging from a quality control technician who just measures one kind of material to a researcher who develops state-of-the-art calibration procedures. Researchers who are very familiar with thermal resistance calibration may wish to skim section 2 for definitions, while a newcomer to the field may find it useful to read it carefully, along with the references. The users of thermal conductivity calibration specimens are categorized as manufacturers, university researchers, commercial testing laboratories, and government laboratories.

The discussion of calibration material is limited to insulating materials, as opposed to metals, in the thermal conductivity range between 0.015 to 5 W/m·K (0.10 to 35 Btu·in/ft^2·hr·°F), and to testing conditions between -200 to 1200°C (-392 to 2192°F). The emphasis, however, is on building and industrial insulation materials. Also, the emphasis is on the measurement of thermal resistance, although other thermal properties are mentioned.

This report is intended to serve as an reference document for both technical and policy issues and to provide a quick current overview of the field of insulation thermal conductivity measurement.

1.4 Organization

Section 2 provides background on the aspects of calibration procedure related to the use of calibration specimens. Section 3 discusses the needs for calibration specimens based on a survey reported in Appendices 1 and 2. Appendix 2 contains the more detailed description of this survey. Section 4 makes recommendations for new calibration specimens and procedures, and it discusses trade offs associated with the various solutions.

2. CALIBRATION PROCEDURE AND THE USE OF CALIBRATION SPECIMENS

2.1 Calibration Procedure

There are many kinds of apparatuses which measure heat transfer through insulation material. Some of these are absolute, such as the guarded hot plate [2], while others are relative, such as the heat flow meter [3].

Relative apparatuses always require calibration specimens as an integral part of the test procedure. Absolute apparatuses do not require calibration specimens, but it is often prudent to use such specimens to corroborate the absolute measurement values.

The basic idea of a calibration is the following. A calibration specimen is measured by a reference laboratory such as NBS. The important physical parameters for thermal measurements are measured and reported. Values are reported for thermal resistance (R-value), the specimen thickness, specimen mean temperature, and the apparent thermal conductivity value (λ-value). Next, this same specimen is measured in the user's apparatus. If this is an absolute apparatus, such as a guarded hot plate (GHP), the user's value is compared with the calibration value. If it is a relative device, such as a heat flow meter (HFM) apparatus, the calibration values are used to determine a calibration factor which in turn is used to determine the thermal resistance values of unknown test specimens. The calculation procedure is explained in reference [4].

2.2 Calibration Errors

Significant systematic errors are possible in many thermal measurements. Rather than undertake an extensive effort to reduce systematic errors, a user can simply calibrate it using a material which has been measured in a highly accurate apparatus. A ratio is made between data taken with the calibration specimen in place, and data taken with an unknown specimen in place. To a large extent the systematic errors cancel out, and the researcher achieves a significantly improved accuracy [4-6].

If the calibration factors were constant over the entire range of test conditions, then the calibration process would be simple. One would measure the calibration factor under the most convenient test conditions, and use that value for all test conditions and materials. However, information obtained in interviews with users and in research at NBS [7] indicates that the calibration factor often changes significantly depending on the apparatus and the test conditions. Reference [8] documents variations in calibration factors in the form of personal communications from some users. Variations of 1-4 percent were noted with a change from high-density to low-density building insulation. Changes of 2-4 percent were typical as the test thickness varied from 25 to 152 mm (1 to 6 in); however, changes as high as 8 percent were mentioned. For the subsequent discussion it is important to understand how significant measurement errors can arise when calibration values cover only a limited range of test conditions, as compared to the user's required range. The following parameters are measured in a heat-transfer test: the heat flux, the specimen thickness, and the specimen surface temperatures. There are systematic errors in these parameters due to problems such as heat leaks. These are commonly referred to as edge effects, gap or guard errors, or flanking loss. The calibration factor provides, in essence, a combined correction for all of these systematic errors.

When the test conditions change, the following two things can occur. First, the actual λ-value can change; and, second, systematic errors can change. This means that the calibration factor should be changed, which requires another set of calibration values to cover the new and different test conditions. The error that results when the calibration factor is not properly changed is referred to here as an extrapolation error.

Test parameters that cause the calibration factor to vary are referred to here as calibration-curve parameters. These include (1) the specimen mean temperature, because both the specimen λ-value and the systematic errors vary with temperature, and (2) the specimen thickness and λ-value, because the systematic errors such as edge error depend on these two properties.

Other variables may act as calibration-curve parameters for certain materials or test conditions. The most important of these are the condition of the surface (for example, the contact resistance between a specimen and an apparatus plate), the plate emittance, the pressure on the specimen surface, the atmospheric pressure and relative humidity, the specimen moisture content, the specimen age, and the anisotropy of λ-value.

One solution to the problem of extrapolation errors is to develop calibration curves. The idea would be to determine the calibration factor for several values of a calibration-curve parameter, such as the temperature. These values would be chosen to cover the range of user needs. The user could then rely on techniques of interpolation to obtain a sufficiently accurate calibration factor.

For a calibration laboratory, the picture could be very complicated, because there are usually two (temperature and λ-value) and sometimes five (also specimen thickness, atmospheric pressure, and humidity) calibration-curve parameters. Thus, it is necessary to look closely at the user's needs to develop a test scheme that does not require an inordinate number of test points.

An opinion currently held by many heat-transfer researchers is that the sources of calibration error are so poorly understood that a calibration specimen must be identical, in terms of material, with the specimens to be tested by the user. This is considered to be the safest course of action to avoid extrapolation errors that might depend on the material. The problem with this solution is that it could require an inordinate number of calibration materials, some of which would not satisfy a calibration-specimen criteria.

Consider an alternative hypothesis, that a calibration specimen with the same calibration-curve parameter values as those of a test specimen, will provide the correct calibration factor value, even though it is composed of a different type of material. Unfortunately, there has been very little experimental research to validate this hypothesis. Rather, the argument in its support is theoretical. It states that the apparatus systematic error should depend primarily on the calibration-curve parameters, and only negligibly on other material parameters, such as anisotropy of λ-value or density.

It would be desirable to pursue research on this issue for the following reason. If the just-mentioned hypothesis were true, then a few materials could be used to satisfy calibration needs for a broader grouping of test materials. The advantages to a calibration laboratory could be that fewer materials would have to be investigated or relatively more uniform or durable materials might be used for calibration specimens.

The idea of calibration curves leads to the central theme of this report. To develop such curves one must have: (1) the capability to make measurements over a wide range of temperature and λ-value, and (2) appropriate specimen materials. These two points will be addressed more fully in the course of this report.

2.3 Material-Variability Error

The other significant source of calibration error, in addition to the extrapolation error just discussed, is the material-variability error. This results from two factors: (1) most insulation material can be highly variable in thermal resistance from one part of the specimen surface to another (2 to 10 percent), and (2) the measured area of the specimen (the metered area) varies for different apparatuses. Thus, a calibration error may result because the average thermal resistance over the user's metered area may be different from that measured over the metered area of the calibration laboratory. This error can be as large as 3 percent [9]. Thus, even if the apparatus of the user and the calibration laboratory are very accurate, there may still be a significant calibration error, due to material variability. Two suggestions are made to minimize this problem. The first is to obtain or fabricate more uniform insulation material, and the second is for the calibration laboratory to develop a capability to vary the measuring area of the calibration apparatus. The latter solution would provide the user with a calibration value corresponding to the user's metered area.

2.4 Calibration-Specimen Criteria

There are a number of criteria and considerations for the choice of a calibration-specimen material. The most important of these pertain directly to the measurement of apparent thermal conductivity or thermal resistance. Characteristics (e.g. specific heat or radiative properties) which do not apply directly to the determination of the λ-value should be considered, for two reasons. First, it may be convenient to use the same specimen for calibration of several properties, such as thermal resistance, thermal diffusivity, and specific heat. Second, a calibration in a particular application could lead to unknown systematic errors if all relevant physical properties are not well understood. For example, suppose that a material is stable at building temperatures for steady-state thermal resistance measurements, but unstable at higher temperatures for specific heat measurements. Then, an application involving a transient measurement of thermal conductivity would give an incorrect result. The point is that, if the specific heat were incorrectly assumed to be constant, the user would have unwarranted confidence in the results.

Reference [1] lists the following considerations in the choice of a calibration-specimen material.

1. Range of properties for each material with respect to dimensional stability, density, and thermal properties.
2. Limits on allowable test temperatures and thermal exposures.
3. Probable reproduciblity and accuracy obtainable with general materials and what might be expected for higher-level materials.
4. Ease of handling and durability of each material since this is an expected use condition.

Table 2 gives a list of information and properties which could be of use in the choice of calibration-specimen material. This is taken from table 3 of reference [1]. The most important properties, including some from table 2, are discussed below.

STABILITY - Dimensional changes such as contraction, expansion, or warping due to temperature or humidity changes or aging must be considered. Internal structural changes due to temperature cycling, compression, or chemical reactions with the environment might change the thermal resistance even when the specimen appearance does not change. In the case of closed-cell material containing gases such as fluorocarbons, the diffusion of these gases into and out of the specimen can cause measurable differences in thermal resistance over periods of months or years. It is important to know the physical properties listed in table 2, not only as a function of temperature, but also as a function of humidity and atmospheric pressure, and possibly as a function of the history of these conditions. To achieve good repeatability, it may be necessary to define specific conditioning procedures, such as baking at a particular temperature and relative humidity to obtain a particular moisture content.

DURABILITY - This refers to the resistance to changes in a specimen due to wear, cracking, or deformation which could result in a change in thermal resistance. Also, it should be possible to achieve flat, smooth surfaces in the specimen fabrication. A goal would be for a specimen to last on the order of 20 years.

RESILIENCY - In the case of compressible specimens, resiliency is required to prevent air gaps between the specimen and the test plates. Also, a resilient specimen would be more likely to be physically stable as environmental changes occur.

There is often a trade off between durability and compressibility. Specimens which are compressible near the surface are desirable because they conform to the shape of the apparatus plates, and this prevents air gaps. On the other hand, compressible material can be less durable because the surface material can wear off. One solution might be to cover a compressible surface with a durable protective coating. But then research would be necessary to determine whether a calibration error might result.

UNIFORMITY - This refers to the λ-value, which in turn may depend on density and thickness. The uniformity can refer to several kinds of comparisons. One comparison is between different areas on the same specimen; others are among specimens within a production lot, among lots produced in the same period, and among lots produced over the years. The importance of a particular kind of uniformity depends on the strategy for production of calibration specimens. For example, if each specimen is measured, the uniformity over the specimen area would be more important than the uniformity among specimens.

THERMAL DIFFUSIVITY - This property may itself be required for calibration, or it may affect a measurement of thermal resistance when the measurement is made in a transient mode. It depends on the λ-value, the specific heat, and the density. It is important to know these properties for various test conditions.

ISOTROPY - The ratio of λ-values in the directions parallel and perpendicular to the specimen surface is important because the apparatus lateral heat flow, and hence the systematic error, depend on this. Thus, research would be required to demonstrate whether an isotropic material can be used to calibrate for anisotropic materials.

RADIATION PROPERTIES - In the case where there is a significant proportion of heat transfer via the radiative mode, it may be necessary to understand such properties as transmittance and extinction coefficients to avoid error in some applications. For example, the edge effects in an apparatus may depend on these.

Other considerations are safety, health (toxicity), and temperature limits. With respect to these limits, if an industrial insulation were to meet the calibration-specimen criteria over a wide range of temperature, then research on a single material might suffice to cover that range; whereas the alternative may require research on several materials. Finally, there are practical considerations of cost, availability, size, and demand. These criteria must be taken into consideration in both the research and the eventual choice of calibration-specimen materials.

3. AREAS OF NEED FOR CALIBRATION SPECIMENS

3.1 Introduction

The need for calibration specimens depends on: (1) the activity of the various categories of the user community, (2) the current availability of calibration specimens in that particular range of calibration-curve parameters, and (3) the self-sufficiency of that particular category of users -- in terms of their capability to make accurate absolute thermal measurements. Another consideration is that there are distinct kinds of needs. For example, in a commercial application an absolute accuracy of 2 percent might suffice, whereas a university researcher might desire an accuracy of 0.2 percent. The relative importance given to the various kinds of needs will determine the priorities for the development of new calibration specimens.

3.2 Activity

A survey was made to determine the current activity, in terms of insulation material produced and tested, by the various parts of the thermal testing community. For the most part this survey was made by telephone for expediency. An overview of the interview information is given in Appendix 1, and a more detailed account is given in Appendix 2.

There were several reasons to present a representative picture of testing activity. Good data on the activity of all parts of the thermal testing community is necessary to develop a calibration program tailored to the needs of the user community. Next, NBS sought to learn about new products or ideas, which might lend themselves to improved calibration specimens. The telephone conversations led to another benefit - of two-way communication with users who may not have thought in terms of utilizing new calibration specimens.

These same goals were pursued in a work session at NBS attended by representatives of the user groups (see Appendix 3). The ideas contained in this report were reviewed by the participants, and their comments were taken into consideration in the conclusions of this report.

An additional mechanism exists to determine user needs for calibration specimens in the form of the National Conference of Standards Laboratories (NCSL), the membership of which includes representatives from the National Bureau of Standards (NBS) and from the various user groups. Reference [10] contains preliminary information on users needs for the measurement of thermal conductivity. The information presented in appendix 2 will serve as a data resource for future NCSL activities.

The user community is categorized for this report as follows: (1) manufacturers of insulating products, (2) commercial thermal testing laboratories, (3) university researchers, and (4) federal laboratories [11]. The manufacturers are subdivided into producers of building and industrial insulation products and into producers of higher thermal conductivity materials such as plastics, rubbers, glass, wood, cement, ceramics, epoxies, and composites.

The activity in terms of thermal testing of insulation materials is presented according to categories of user-groups, to enable policy makers to arrive at their own priority scheme for the research necessary to refine their measurement capability. Here, one viewpoint will be presented as to what that priority scheme might be, along with a discussion of the trade-offs. It is entirely possible, however, that a policy maker with a different set of priority values might come up with a different priority scheme, and the information in this report is intended to aid that process.

With reference to the discussion in section 2, the areas of need will be grouped according to the most significant calibration-curve parameters, namely the λ-value and specimen temperature. The discussion will begin with building-temperature insulation material and then proceed to higher temperature and thermal conductivity ranges.

3.3 Areas of Need for Building-Temperature Insulation Materials

Table 3 presents conclusions on the λ-values where there is a clear need for calibration specimens. These conclusions are based on information summarized in Appendix 1 and detailed in Appendix 2. Referring to Table 3, there is a distinct need for calibration standards at the following λ-values: 0.016, 0.023, 0.033, 0.040, and 0.046 W/m•K (0.11, 0.16, 0.23, 0.28, and 0.32 Btu•in/ft^2•hr•F - the λ-values in English units will follow in parentheses). The generic products for these λ-values are also given in table 3. Calibration standards exist for the 0.033 W/m•K (0.23) point corresponding to high-density, glass-fiber material. These are available from the NBS Office of Standard Reference Material under the designation of 1450B. In addition, it is possible to order transfer standards of low-density, glass-fiber insulation material with a λ-value of 0.046 W/m•K (0.32), from the NBS Thermal Insulation Group [12].

Considerable interest was expressed by the manufacturers of foam products to have standards covering their range of interest, which is 0.016 W/m•K (0.11) to 0.023 W/m•K (0.16). The former point corresponds to non-aged, fluorocarbon-blown products and to an aged phenolic foam, and the latter point corresponds to aged fluorocarbon-blown foam products. Since this represents approximately a 50 percent range difference for the λ-value, two λ-value points are recommended for calibration standards. The range of thickness for testing is between 13 and 100 mm (0.5 and 4 in). It is recommended that there be specimens available at thickenesses of 25, 50, and 100 mm (1, 2, and 4 in). One reason for the recommendation of standards at the greater thickness is that the interviews revealed some evidence of a dependence of the apparent thermal conductivity on thickness for the low-density foam products.

An interest was expressed by industry for a calibration standard in the 0.040 W/m•K (0.28) range, which corresponds to the λ-value for several batt and loose-fill products (both cellulosic and mineral-fiber). A number of cellulose and mineral-fiber commercial test laboratories and manufacturing laboratories test material at this λ-value at a thickness between 100 and 150 mm (4 and 6 in). It was reported that the calibration factors for different kinds of calibration specimens did not give consistent results at the λ-value of 0.04 W/m•K (0.28) [7]. It would not be practical to interpolate between the low density calibration standard and the high-density standard points, because the high-density point uses a 25 mm (1 in) specimen. It is not recommended to stack several of these specimens to achieve the desired thicknesses -- because it would be necessary to purchase many additional calibration specimens, because the test times would be prohibitively long, because the error due to stacking is unknown, and because the error due to long-term drifts with such a relatively high-density specimen may be significant. It would be more satisfactory to have a single calibration specimen with a lower density, corresponding to that of the loose-filled material itself. The benefit would be a considerable reduction of test times.

Regarding the point at 0.065 W/m•K (0.45), there is some test activity, but not nearly as much as that in the other λ regions. There was no demand on the part of interviewed users for a calibration specimen here.

At cryogenic temperatures down to liquid nitrogen temperature no current activity on the part of manufacturers was found. In the past there was some interest, in regard to the storage of liquified gas. There has been some characterization of the low-density and high-density, glass-fiber standards available from NBS-Boulder Laboratories.

In summary, calibration points are recommended at λ-values of 0.040 W/m•K (0.28) corresponding to loose-fill products, and of 0.016 and 0.023 W/m•K (0.11 and 0.16) corresponding to the non-aged and aged fluorocarbon-blown foam products.

3.4 Areas of Need for Industrial High-Temperature Insulations

Referring to Table 4 and section 1.3 of Appendix 1, four distinct regions of λ-value were chosen to make it easier to refer to a particular area in Figure 3. Beginning with the lowest λ-value, the first region corresponds to the Min-K product which has a λ-value of about 0.043 W/m•K (0.30) over the indicated high-temperature range. A product made in England called Microtherm has λ-values comparable to Min-K. It would be useful to have calibration specimens in this region to evaluate any change in calibration factor between regions.

The second region corresponds to a class of materials which vary in λ-value from 0.058 to 0.115 W/m•K (0.4 to 0.8) over the temperature range from 24°C to 1000°C (75°F to 1832°F). This appears to be a region of considerable activity and, hence, need. A representative material from this class of insulations must be identified to serve as a calibration standard material. There is an effort underway to measure an alumina-silica fiber material (see the discussion of cera fiber in section 1.3.2 of Appendix 1), and this could satisfy the short-term needs in this region.

The third region corresponds to brick refractories. These materials have a λ-value in the vicinity of 0.14 to 0.29 W/m•K (1.0 to 2.0). This could be a third region for a calibration standard. Note that, for a particular specimen, the λ-value is fairly constant over the high-temperature range.

An additional fourth region could be that at about 2 W/m•K (14.0). This is about an order of magnitude greater in λ-value than region 3, and there might be extrapolation problems if a separate calibration standard or calibration point were not available here. That is, the existence of calibration specimens at the extremes of the ranges would aid in the estimation of extrapolation errors. On the other hand, there seems to be considerably less need at this higher λ-value range relative to that indicated at the lower ranges.

3.5 Areas of Need for Higher Thermal Conductivity Materials

In the λ-value range between 0.072 and 2.89 W/m•K (0.5 to 21.0), there are many materials that are not used primarily for thermal insulation, but which have some insulating value. With reference to figures 4 through 6 which are based primarily on the interview data, these materials include rubbers, plastics, epoxies, concrete, soils, moist insulation, wood, glass, volcanic rock, pyrex, and pyro ceram. Perhaps because these materials are not produced primarily for use as thermal insulations, the people contacted in appendix 2 did not indicate as much interest in thermal conductivity standards in this high λ-value range, as in the low λ-value range. On the other hand, various representatives from each user group did mention having made measurements of λ-value for materials in this range. In addition, information received from a manufacturer of heat-transfer apparatus (the Dynatech R & D Company mentioned in appendix 2) indicated that one out of four of the heat-transfer apparatuses sold were of a design primarily intended for high λ-value measurement.

With reference to building research in general, the following line of reasoning suggests that perhaps there should be more interest in the measurement of high λ-value materials. There are many high λ-value building components which cause thermal bridging. In almost every case, handbook values are used to estimate the λ-value for these components (several thermophysical data sources are listed in references [13-16]). The resulting errors are not well understood and could be significant. This impacts the overall quality of building research in that the modeling has become very sophisticated, but the accuracy of parameter estimation has not improved correspondingly. Moreover, even if some specimens of building components are measured, an important issue which is usually ignored is the extent to which the values for a few specimens represent the average for all of that component material in a building system. In other words, the product variability could result in large and ignored errors. Even though there is not a great deal of activity in measuring high λ-value materials, these arguments suggest that more accurate measurement in this range would be beneficial.

3.6 Areas of Need for Other Thermal Properties

In order to properly explain the heat-transfer phenomena that exist in real applications, it is necessary to know other thermal properties such as the thermal diffusivity, the surface emittance, radiation absorption and scattering cross sections, and thermal expansion. An interest was expressed in these thermal properties, primarily by representatives of the federal laboratories and by university researchers. Also, a suggestion was made to try to use the same calibration standard material for the measurement of several different thermal properties. With reference to appendix 2, there are a number of laboratories which are involved in the measurement of the radiation scattering properties of low-density insulation materials. It might be desirable to extend the temperature range of these tests to higher temperatures where radiation is the predominant heat-transfer mode.

4. DISCUSSION OF RECOMMENDED CALIBRATION-SPECIMEN MATERIALS

4.1 Introduction

In this section, candidate standard reference materials are suggested to meet the needs discussed in section 3. Issues related to the choice of a standard reference material will first be reviewed. The major sources of systematic measurement error are the extrapolation errors and the material-variability errors discussed in section 2. In order to minimize the extrapolation errors, it is necessary to have calibration points which are as close as possible to the test points for the unknown material to be measured or which bracket the range of interest.

Once the applicable λ-value and temperature ranges have been chosen, the most difficult remaining problem is the non-uniformity of specimen material. There several kinds of non-uniformity of importance to the development of calibration materials. One kind is between product lots, another is among specimens within a lot, and a third kind is between different sections of a specimen. An important conclusion of the interview work summarized in appendices 1 and 2 is that there is very little information on material uniformity. A possible reason is that it is difficult and time consuming to measure material variability. The little information that exists indicates that material-variability error may be significantly large in calibration applications [7, 9, 17]. The reason for this is that the producers' requirement for uniformity is probably quite different from a calibrator's requirement.

It is desirable for the material-variability error to be less than or of the order of the apparatus error. This would be the case, for example, if the apparatus error were 0.7 percent and the material variability error were 0.3 percent. That is, the uniformity of the material would be sufficiently good to ensure that the variation in λ-value over the specimen area would be less than 0.3 percent. Unfortunately, this kind of uniformity can not now be realized, and non-uniformity is the factor responsible for overall calibration uncertainty values of the order of 2 to 3 percent. These values could be less than 1 percent if greater uniformity were achieved [4,9].

These comments on the importance of uniformity are most pertinent where the measurement accuracy is the best. For example, in the building-temperature and in the cryogenic temperature ranges, the apparatus uncertainties are smaller than in the high-temperature and, perhaps, high λ-value ranges. For example, if the apparatus uncertainty were 0.5 percent and the material-variability uncertainty were 2 percent, then uniformity would be an important issue. But, if the apparatus error were 5 percent and the material variability were 2 percent, uniformity would not be as important an issue.

There are two approaches for the identification and acquisition of calibration specimen material. The usual approach is to locate the most uniform insulation material that is produced and to use it without modification. The major difficulty with this approach is the just-discussed problem with material non-uniformity. An alternative approach would be to fabricate a specimen which is different from the insulation material as produced, but which represents a better solution in terms of uniformity, durability, and stability over time. For example, a specimen might consist of layers of higher and lower thermal conductivity material with an intermediate effective thermal conductivity. This would be an improvement if the uniformity of the higher and lower conductivity materials were better than that of any single material at the intermediate value.

The hypothesis discussed at the end of section 2.2 is that the calibration factor will not be in error if there is a match of calibration-curve parameters between a custom-made calibration specimen and unknown test specimens. This hypothesis is implicit in the following discussion of innovative calibration specimens. There are good reasons, resulting from an analysis of the origin of systematic apparatus errors, to expect that this hypothesis will prove to be true (refer to the discussion in section 2). Even so, the hypothesis must be experimentally validated.

The idea of custom-made calibration specimens leads to innovative solutions such as layered or composite loose-fill materials or surface-sealed specimens. The basic intent in the case of a composite specimen would be to use two materials, one of higher λ-value and one of lower λ-value, to fabricate calibration specimens which cover a range of λ-values. The relative proportion of materials would then determine the resultant λ-value. This sort of a solution might have three advantages. First, the desired λ-value within the range could be achieved, and this would minimize extrapolation errors. Second, a proper mixing might significantly reduce the errors of non-uniformity. And finally, it might be possible to achieve a more economical solution, in that one composite could serve as a standard for many kinds of material. This would eliminate the time-consuming necessity of testing many different kinds of materials to satisfy the entire range of calibration needs.

The solution for the entire calibration program must take into account the various sources of error and criteria such as durability or stability in time. This means that an order of magnitude should be associated with each of these considerations. The solution will be the result of trade offs.

Another possible solution would be to develop a test method with a variable metered area. NBS is currently evaluating a sectored heat-flux transducer which is shown in figure 7. This device gives independent readouts for various sectors or metered areas which correspond to typical metered areas in use in this country. These include the following: 100 x 100 mm (4 x 4 in) square, 252 x 252 mm (10 x 10 in) square, 400 mm (16 in) diameter circular, and 457 x 457 mm (18 x 18 in) square. For a heat flux of 17.5 W/m^2 and plate temperatures of 38°C and 10°C, the outputs from the separate regions were, beginning with the smallest and proceeding to the largest, 5.1 mV, 27.5 mV, 31.3 mV, and 37.2 mV. Note that the output for each succeeding larger section does not include the area covered by the smaller sections within. The point here is that the output should be large enough in comparison with the readout precision (θ.001 mV), to determine the material variability to within a few one-hundredths of one percent.

If this device proves effective, it could be used for a second, relative measurement -- after the absolute measurement on the 400 mm (16 in) diameter circular metered area of the NBS-GHP apparatus. This second measurement would yield the λ-values of the other sectors relative to that which was absolutely determined for the NBS metered-area sector. It would be necessary to calibrate the sectored flux transducer in either a uniform heat flux or by doing a statistical study on a large number of non-uniform specimens. It would also be necessary to determine the systematic errors due to lateral heat loss effects, that would prevail in this kind of a secondary measurement. The precision of the device must be sufficient to achieve a good determination of the uniformity, but it remains to be seen whether or not systematic errors would prevent its use in calibration work. Also it would be preferable to have two such variable-meter-area devices, one on either side of the specimen, to determine the uniformity over the entire thickness of the specimen, rather than just on one side.

A screen-heater apparatus, developed at Oak Ridge National Laboratory would also lend itself to making variable meter-area measurements [18,19]. This possibility is due to the fact that the heat flux is constant over the surface area and the determination of the relative λ-values depends on the measurement of the temperature difference. This measurement of temperature difference could be accomplished by thermopiles which cover various metered areas of the specimen. That is, a system of individual section thermopiles could accomplish the desired result of a variable metered area.

A general approach implicit in the subsequent discussion of new calibration specimen material is to (1) locate the most uniform material available and (2) determine the actual λ-value over the user metered area using the sectored heat-flux-transducer device.

4.2 Recommended Calibration-Specimen Materials for Building Insulations

Short term

Short-term solutions for new calibration-specimen materials are addressed first. These involve the first approach just discussed - to use existing insulation materials for calibration specimens, since this requires less development time. The long-term recommendations use the second approach - to fabricate custom-made calibration specimens -- and this requires more time for research and development. The solutions that seem best in terms of simplicity and speed will be discussed first. Alternative solutions are also mentioned since research may demonstrate the inadvisability of an initial approach.

Referring to table 3, at a λ-value of 0.040 W/m•K (0.28) the recommended material is a glass-fiber product which has a density of about 24 kg/m^3 (1.5 lb/ft^3). This would be tested at thicknesses between 100 and 150 mm (4 and 6 in). One advantage of this material is that the density is low enough to ensure reasonably short test times even though the thickness is relatively large. That is, the time needed for a test to come to steady-state conditions depends on the total specimen mass. Also, there is a history of the use of glass-fiber material as calibration standards. The uniformity of λ-value over the specimen area is expected to be better than that of the lower-density (9 kg/m^3 or 0.6 lb/ft^3) calibration specimens that have been tested in the past by NBS. A third advantage is that durability would be somewhat better. Material of this type is available from several manufacturers.

The procedure would be to buy a quantity of specimens. After several specimens had been tested, a statistical evaluation would be made to determine the appropriate additional number of specimens to be tested. A number of ten has been found to be appropriate in the past [7]. These specimens would then be measured on the NBS-GHP apparatus, with the sectored heat-flux-transducer device, and on the NBS heat-flow-meter apparatus. In addition, ten specimens of loose-fill glass-fiber material and ten specimens of loose-fill cellulose material would be tested on the same three apparatuses. A comparison would then be made of the calibration factors calculated with data from the three different kinds of materials to determine any dependency on material type. This comparison would take into account any λ-value dependence for the calibration factor.

Another possibility is a layered specimen which would consist of a phenolic foam with a low λ-value on either side of a higher-density material. The desired average λ-value could be selected by having the appropriate thicknesses for the three layers of material. The advantages of this approach could be that the most uniform material available would be used, and the desired resultant λ-value could be closely approximated. It would be necessary to evaluate the requirements of durability, compressibility and flatness for the composite, and to find adhesives for bonding the layers that would retain their properties over time. The manufacturer of the phenolic foam indicated that the material is machinable, and therefore it should be possible to achieve a flat specimen surface where contact is made with the apparatus plates. If this layered composite were tried, then it would be necessary to compare the results of this type of calibration specimen with the results mentioned in the previous paragraph.

The next two areas of need (refer to Table 3) will be discussed together. These correspond to λ-values of 0.023 and 0.016 W/m•K (0.16 and 0.11). The materials which need to be measured in this range are primarily the fluorocarbon-blown foams. These have unusually low λ-values because the gas conductivity in the fluorocarbon gas that fills the closed cells of these materials is lower than the gas conductivity of air. When these materials are first produced, the fluorocarbon content is high and the λ-value is correspondingly low about 0.016 W/m•K (0.11); but the fluorocarbon diffuses out through the cell walls and air diffuses in over a period of months or years. The eventual λ-value depends on the equilibrium mixture of these gases. The λ-value increases to values between 0.023 and 0.029 W/m•K (0.16 and 0.20). This diffusion process is referred to as aging.

The recommended calibration-specimen material is a phenolic foam which shows promise of having a slow aging process with very little change from year to year. Refer to item #10 of section 2.1.1 in appendix 2. Although it would be preferable to use a material that does not age at all, the problem is one of finding such a material in this range of λ-value. A suitable trade off might favor a material which ages sufficiently slowly to satisfy a certain tolerance level, over a more stable material which has a significantly different λ-value.

Preliminary evidence indicated no measurable change in λ-value of phenolic foam over a period of three years. This suggests that the material might be suitable as a calibration-specimen material. The first item of research would be to investigate this question further. In the event that there is a small but non-negligible change over a period of several years, it might be acceptable to remeasure these specimens periodically. Or, specimens which have been aged for several years might be used without remeasurement.

Information from the manufacturer suggests that it would be possible to achieve a λ-value at either end of the range just mentioned, simply by controlling the amount of fluorocarbon in the blowing process. That means that this same material could be used to satisfy both λ-value calibration points, in principle. There is one difficulty, which is that the cell wall material is permeable to water vapor. There can be a variation between 0.014 and 0.019 W/m•K (0.10 and 0.13) with a change in relative humidity from a very low value to a high value of about 90 percent. A suggestion that warrants investigation is to seal the surface of a phenolic-foam specimen with a substance such as liquid applied butyl, which is not very permeable to water vapor. It would probably be advisable to seal the product in a dried state to avoid long-term drift problems due to moisture transport within a sealed specimen. A coating of butyl rubber on either side of the material would increase its thickness by about 1 mm (30 mils), and the durability of the coating needs to be researched.

The research on this candidate material would be similar to that mentioned previously. Twenty specimens, ten at each end of the λ-range, would be obtained and prepared, and the calibration results for these specimens would be compared with ten specimens of two other types of foam products at each of the two λ-value calibration points: 0.023 and 0.016 W/m•K (0.16 and 0.11). In this way the accuracy of such a calibration program would be experimentally determined. It would also be necessary to re-test the specimens over several years to look for drift due to aging.

Other possible solutions in this λ-value range include the following.

(1) Both the Min-K and the Microtherm products mentioned in items 12 and 13 of section 2.1.1 of appendix 2 have reported λ-values of 0.02 W/m•K (0.14), and this is between the two calibration points in question. This type of product has the distinct advantages that its properties do not change over time, and it has a wide range of temperature applicability. Its drawback is the λ-value dependence on atmospheric pressure. Research would be necessary to see if this dependence can be overcome with a calibration curve as a function of atmospheric pressure. The block form of this product is not very durable, but a glass-cloth covered version would be quite durable. Again, it would be necessary to ascertain that the use of different material and the use of a cover material would not result in a calibration error.

(2) An aged, extruded polystyrene might be used for the λ-value calibration point of 0.023 W/m•K (0.16).

(3) A surface-sealed, non-aged polystyrene product might be used at 0.016 W/m•K (0.11), provided that the surface sealant prevents diffusion of the fluorocarbon over time.

Long Term

The following is a suggestion for a long-term solution which is primarily aimed at solving the material and product variability contributions to calibration error These are the limiting factors in achieving an overall uncertainty of less than 1 percent for calibration specimens in the building-temperature regime. Past experience at NBS indicates that it is very time-consuming to evaluate and eliminate the material-variability contribution to calibration error, and the results have not been very satisfactory. This suggests the desirability of investigating the feasibility of fabrication of "ultra-uniform" specimen material. This kind of a solution could apply over the entire range of building insulation from λ-values of 0.014 to 0.072 W/m•K (0.10 to 0.50). An important conclusion of this report is that such a long-term solution shows promise, and is warranted in terms of its potential savings of production and testing expense on the part of the manufacturing community.

The basic idea would be to achieve good uniformity by properly mixing microspheres or micropowders which have a very small unit cell size. The range of diameters for the materials mentioned in appendix 2 varied from 0.01 to 100 μm. A potential benefit would be the capability to select any desired λ-value over a wide range with the choice of the proportions of two different microspheres - one of high λ-value and another of low λ-value.

The issue of uniform mixing is a matter for future research. There is a beginning reservoir of knowledge which has been obtained at the University of California at Berkeley, Oak Ridge National Laboratory, and the Lockheed Corporation, among others [20]. New research problems to be solved include: containment, packing and mixing with regard to uniformity, structural and λ-value stability over time, flatness and resiliency, durability, and dependence on atmospheric pressure or relative humidity.

The λ-value range of applicability depends on the low and high limits of λ-value achievable with available materials. The lowest λ-value reported was 0.020 W/m•K (0.14) for a 7 millimicron micropowder. There is an indication that a range of λ-value up to point 0.029 W/m•K (0.20) can be achieved by increasing the diameters of the millimicron powder. The λ-value of the microspheres was reported to be about 0.043 W/m•K (0.28) at much greater diameter values of approximately 50 μm. Thus, future research might show that much of the thermal conductivity range of interest to the building insulation industry could be covered with the proper choice of diameter for a single type of microsphere, without having to mix two different kinds. The interviews yielded no information as to what the resultant λ-value would be of such a composite, and they indicated that there is no experience with mixing higher λ-value microspheres to achieve a higher λ-value. In fact, it may be necessary to make cakes of loose-fill material in layers, and to combine these layers of different λ-value to achieve a desired λ-value.

A research program to investigate the feasibility of a loose-fill composite calibration specimen would involve the following steps. (1) Obtain loose-fill material and fabricate specimens. (2) Measure the λ-value of these various specimens and determined the dependence on environmental parameters. (3) Develop techniques for the mixture for the most promising loose-fill materials. (4) Fabricate composite specimens and measure their λ-value. (4) Determine the material variability (the variation of λ-value over a specimen surface area) either using the sectored heat-flow-transducer device or using such techniques as moving a specimen over the apparatus metered area or cutting out specimens from one specimen of larger area and independently testing these cut-out specimens.

The calibration factors determined with the loose-fill materials would be compared with those determined from the typical insulation materials which are tested by the user community. If the loose-fill solution proves viable for a flat geometry, then it should be possible to develop it for other geometries. For example, there is a serious need of a calibration standard for industrial pipe insulation testers, which require a specimen of cylindrical geometry. It would be very desirable to use the same material for various apparatus geometries. The research problems, in addition to the ones previously mentioned, would essentially be those of achieving any desired shape. For example, molding processes might be applicable; or one could try containment solutions which would involve the fabrication of a containing structure and the pouring or packing of the loose-fill material within the structure. Finally it might be possible to fabricate a very flexible material which could be wrapped around cylindrical shapes.

4.3 Recommended Calibration-Specimen Materials at High-Temperature

Short Term

In section 3.4, four regions of λ-value were distinguished as areas of need for calibration standards. These are indicated in table 4 and figure 3. The greatest needs seem to be for the second region of λ-value between 0.058 and and 0.115 W/m•K (0.4 and 0.8). Work is in progress on a candidate material in this range. Tests have been made at the Manville Services Corporation on ten Cera-Fiber specimens. The NBS-Boulder laboratory plans to measure the same ten specimens. The NBS tests can be made at a temperature as high as 540°C (930°F). This effort represents a short-term solution in that it will provide one calibration curve in the high-temperature range.

Long Term

The following long-term work is recommended. First, it would be desirable to extend the temperature range on this candidate material to about 1000°C (1832°F) to cover the range of interest for industrial furnaces. This extension in temperature range could be accomplished either with existing or future NBS apparatuses, or with other apparatuses with proven state-of-the-art accuracies.

With regard to the issue of the extension of the temperature range to even higher temperatures, measurement activity was reported at temperatures of 1300°C (2400°F), 2000°C (3600°F) and 2800°C (5100°F). These extremely high-temperature applications were reported primarily by Federal Laboratories which deal with aerospace applications. Historically, these laboratories have received enough funding to be self-sufficient. NBS does not have measurement capability at these high temperatures but is interested in an exchange of technical information on issues related to this type of measurement.

Other long-term research applicable to regions 1,3, and 4 is indicated in table 4. The recommended priority order for future standards begins with region 3, corresponding to brick refractory insulations. It continues with region 1 corresponding to Min-K, and with region 4 corresponding to the castable refractories. The reason for this ordering is that there appears to be more activity in the brick-refractory region (3) and this region combined with the region 2 (which contains Cera Fiber), would cover the (λ,T) area that has the most activity. Region 1 corresponding to the Min-K or Microtherm products is chosen next because it permits one to bracket either side of the second region; and this would be an asset in determining the systematic errors for the various apparatuses. Region 4 (castable refractories) seems to have less activity, and is an order of magnitude higher in λ-value. Depending on the future need, a castable refractory could be a candidate for development after the other three regions have been satisfactorily addressed.

The choice of SRM for the first region would be either the Min-K or Microtherm product. This product has a strong dependence on atmospheric pressure; between sea level and an altitude of about 1.6 km (4880 ft), corresponding to Denver, Colorado, the λ-value increases by about 5 percent. There are two possible solutions to the problems resulting from this dependence. The first is to consider the atmospheric pressure as a calibration-curve parameter and to measure over a sufficient number of points to characterize the λ-value dependence on this critical parameter. Then the user would then need to measure both the atmospheric pressure and the λ-value to use the calibration standard. Even if there were a 20 percent uncertainty in the characterization of the dependence on atmospheric pressure, that would mean that the contribution to the uncertainty of the λ-value would only be 1 percent (multiplying the worst-case 5 percent by that 20 percent, for example). This error would be small compared to the systematic errors prevalent for high-temperature measurements, which could be of the order of 3 to 10 percent.

A candidate for the third region is a clay-alumina brick with a density of 960 kg/m^3 (60 lb/ft^3). This has a fairly constant λ-value of about 0.29 W/m•K (2.0) over the temperature range indicated in figure 3, and this λ-value (2) is high enough to bracket most of the activity indicated.

The candidate for region 4 is a castable refractory with a density of about 2700 kg/m^3 (170 lb/ft^3). This has a high enough λ-value to bracket the range of activity indicated in figure 3, and there is a possibility it could be used for the building temperature range where high λ-value components need to be tested.

4.4 Recommended Standards Materials at High Thermal Conductivity and at Building Temperatures

Figures 1 through 6, based on the interview data in appendix 2, indicate that measurements have been made in the higher λ-value range between 0.028 and about 2 W/m•K (0.5 and 20). In recent times, NBS has not been called upon to provide calibration specimens in this range. Users have relied primarily on a the Dynatech R & D Corporation for calibration information. Or, users have developed a capability to make absolute measurements themselves. The 1-m guarded-hot-plate apparatus of NBS could, in principle, be used at λ-values up to 2 W/m•K [4]; but there can be difficulties obtaining sufficiently large specimens, and there is not as much experience with the evaluation of errors at high λ-value measurements, such as those due to the interfacial resistance between the specimen and the plate.

If there proves to be sufficient interest, table 5 indicates some candidate materials for calibration standards. In the past, gum rubber, silicone rubber, a Pyrex 7740 product, and Pyro Ceram have been tested and used as calibration standards. NBS, Boulder currently has available Pyro Ceram as a calibration specimen material. In addition to these, reference [21] lists a number of plastic materials which cover the entire λ-value range of interest. It is possible that the manufacturing process for some of these materials could result in intrinsically uniform specimens. It is recommended that this potential source of calibration specimen material be investigated further.

4.5 Recomendations for Other Thermal Properties

Other thermal properties of interest to thermal testing groups were mentioned in section 3.6. These included the thermal diffusivity, emittance, radiation scattering coefficients, and thermal expansion. It would be desirable to have multiple characterization of calibration specimen material for these other thermal properties as well as for the λ-value.

4.6 Summary Comments on Recommendations

The intention of this section has been to identify the issues and recommended solutions related to a thermal resistance calibration program. The greatest emphasis was given to building and industrial insulation materials. Other materials, properties, and test conditions that should be a part of a comprehensive national calibration program were summarized.

The discussion of recommendations for short- and long-term research reveals complex issues and trade offs. The resolution of these issues requires substantial research. This research can best be carried out as a cooperative effort by all parts of the thermal testing community. Management of this cooperative effort will represent a significant challenge.

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CertainTeed [illegible] reported changes of 2 to 4 percent between 25 and 51 mm (1 and 6 in) and changes of 3 percent between high- and low-density glass-fiber material; and Ron Adams of Owens-Corning Fiberglas Corporation reported no noticeable change up to 152 mm (6 in) on their large HFM's of 914 and 1219 mm (36 and 48 in).

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FIGURE 1 - (λ ,T) ACTIVITY BY MATERIAL FOR BUILDING TEMPERATURE INSULATION MANUFACTURERS

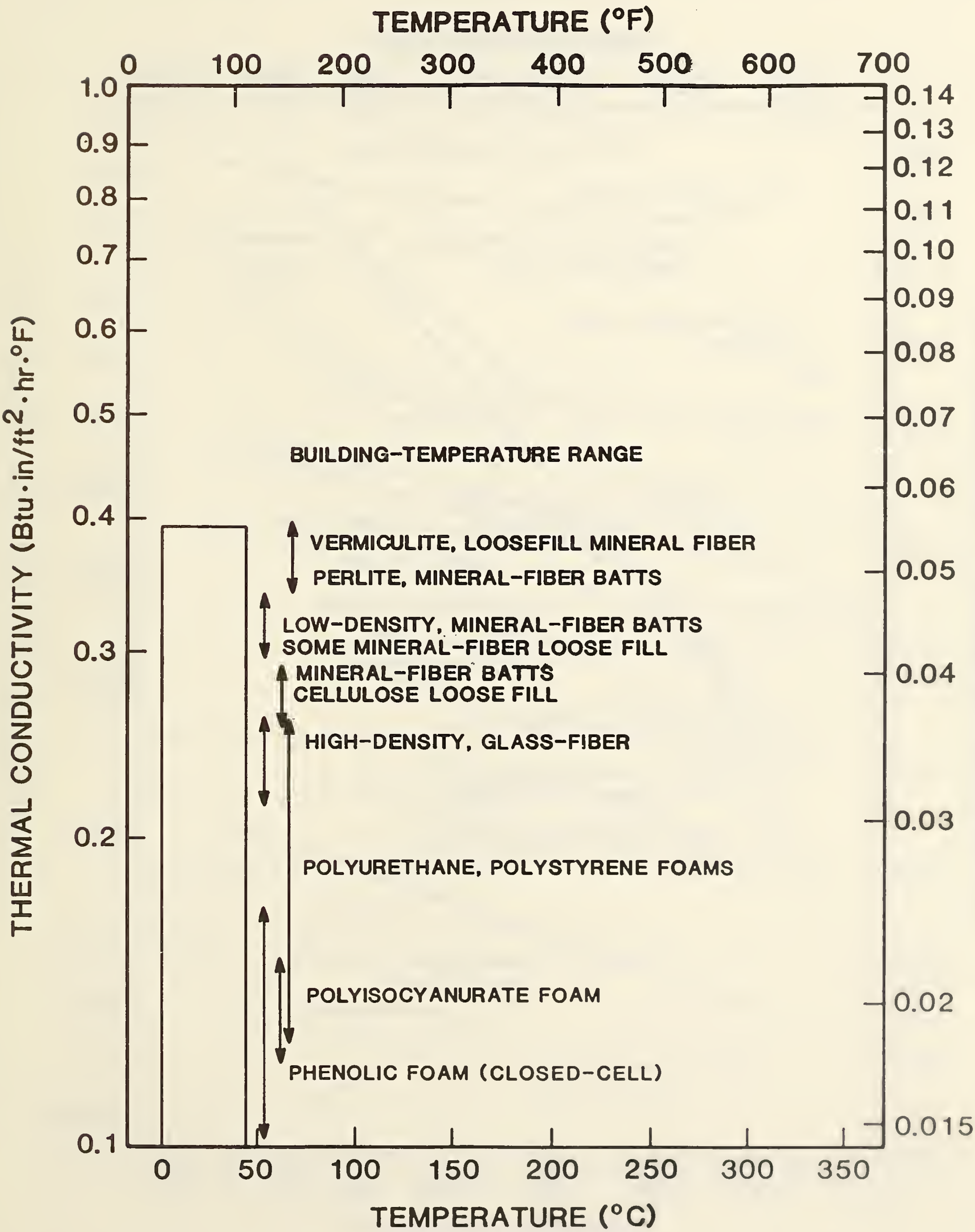


FIGURE 2 - (λ,T) ACTIVITY BY MATERIAL FOR INDUSTRIAL INSULATION MANUFACTURERS

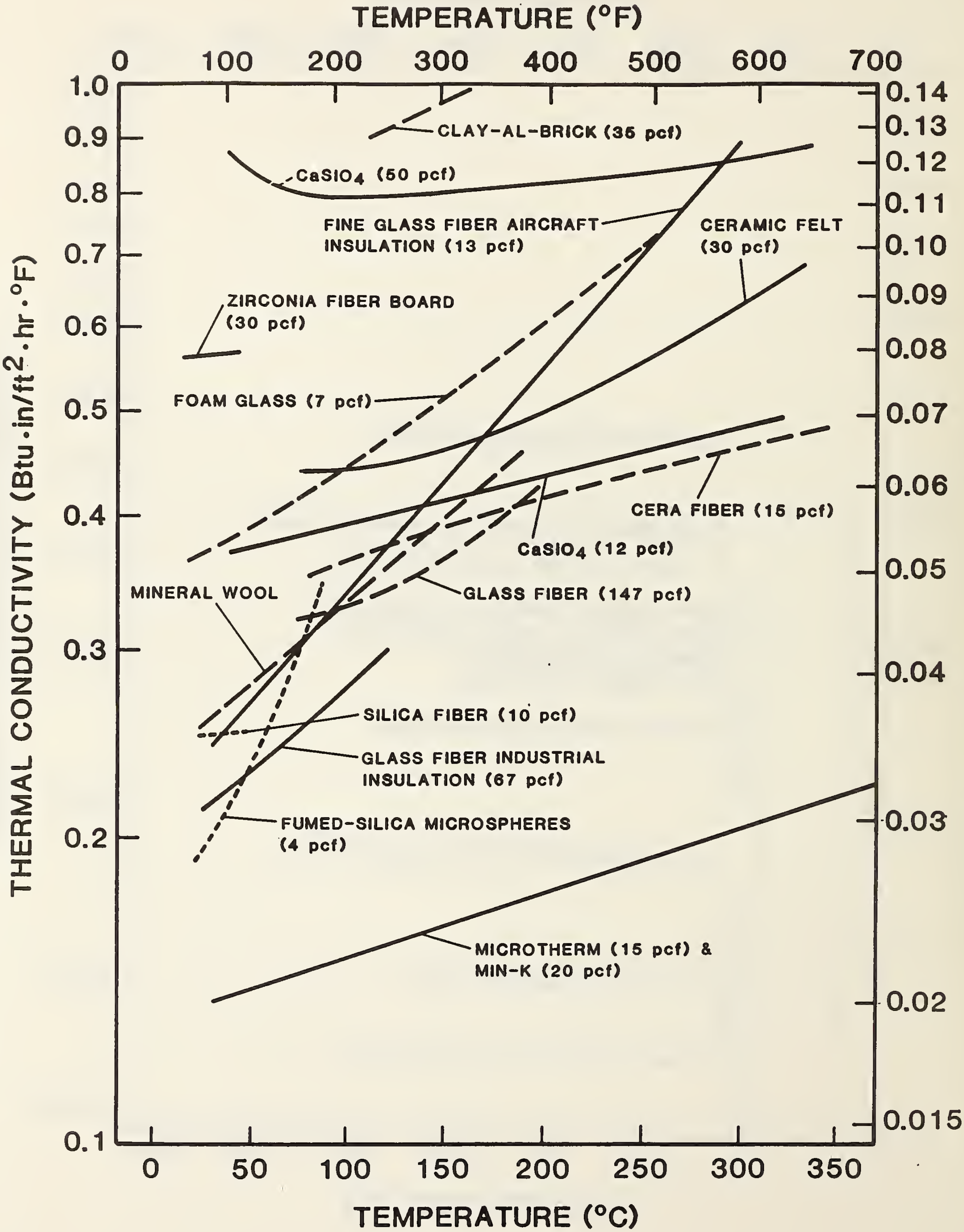


FIGURE 3 - (λ,T) ACTIVITY BY MATERIAL FOR INDUSTRIAL INSULATION MANUFACTURERS

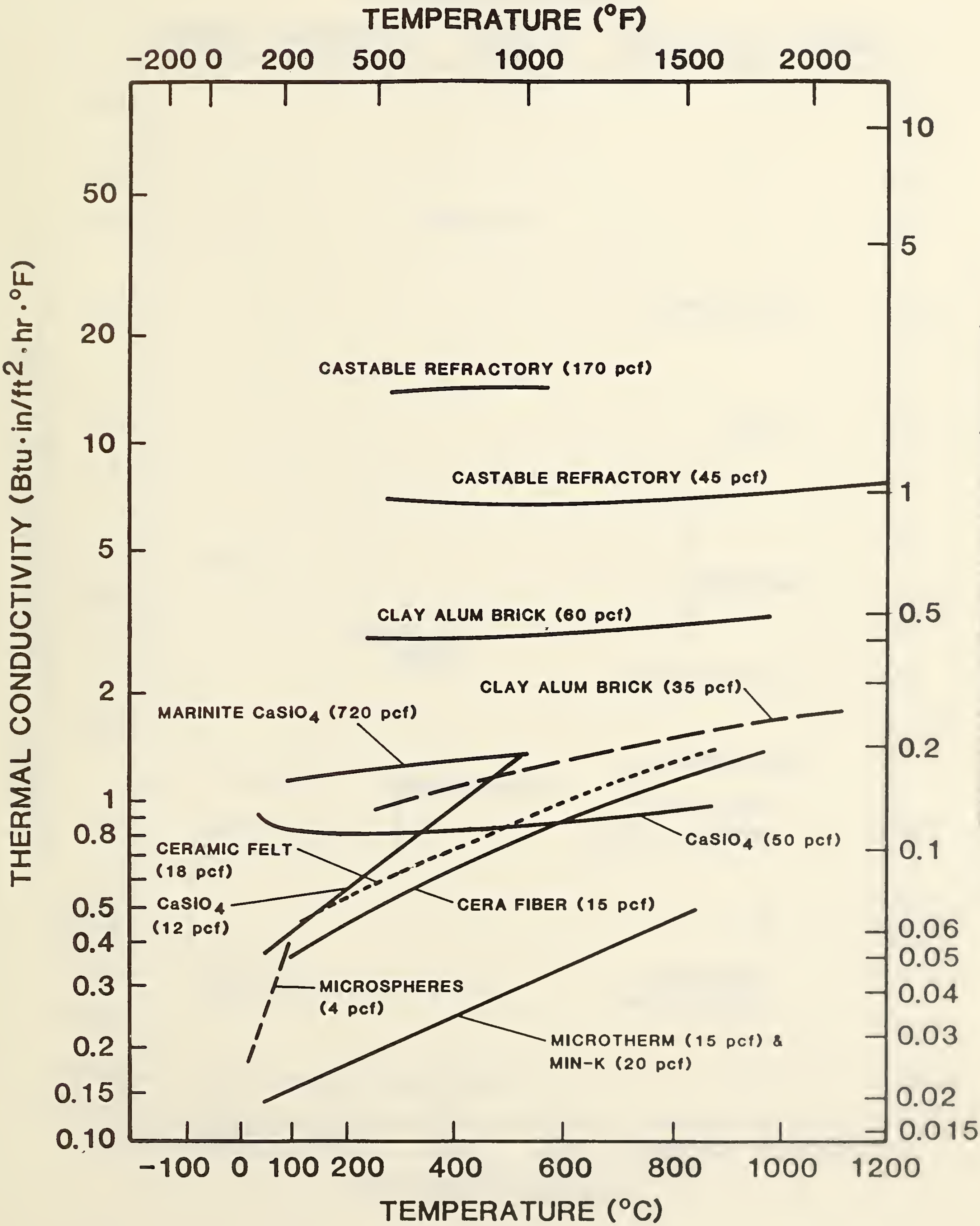


FIGURE 4 - (λ,T) ACTIVITY BY MATERIAL FOR COMMERCIAL LABORATORIES

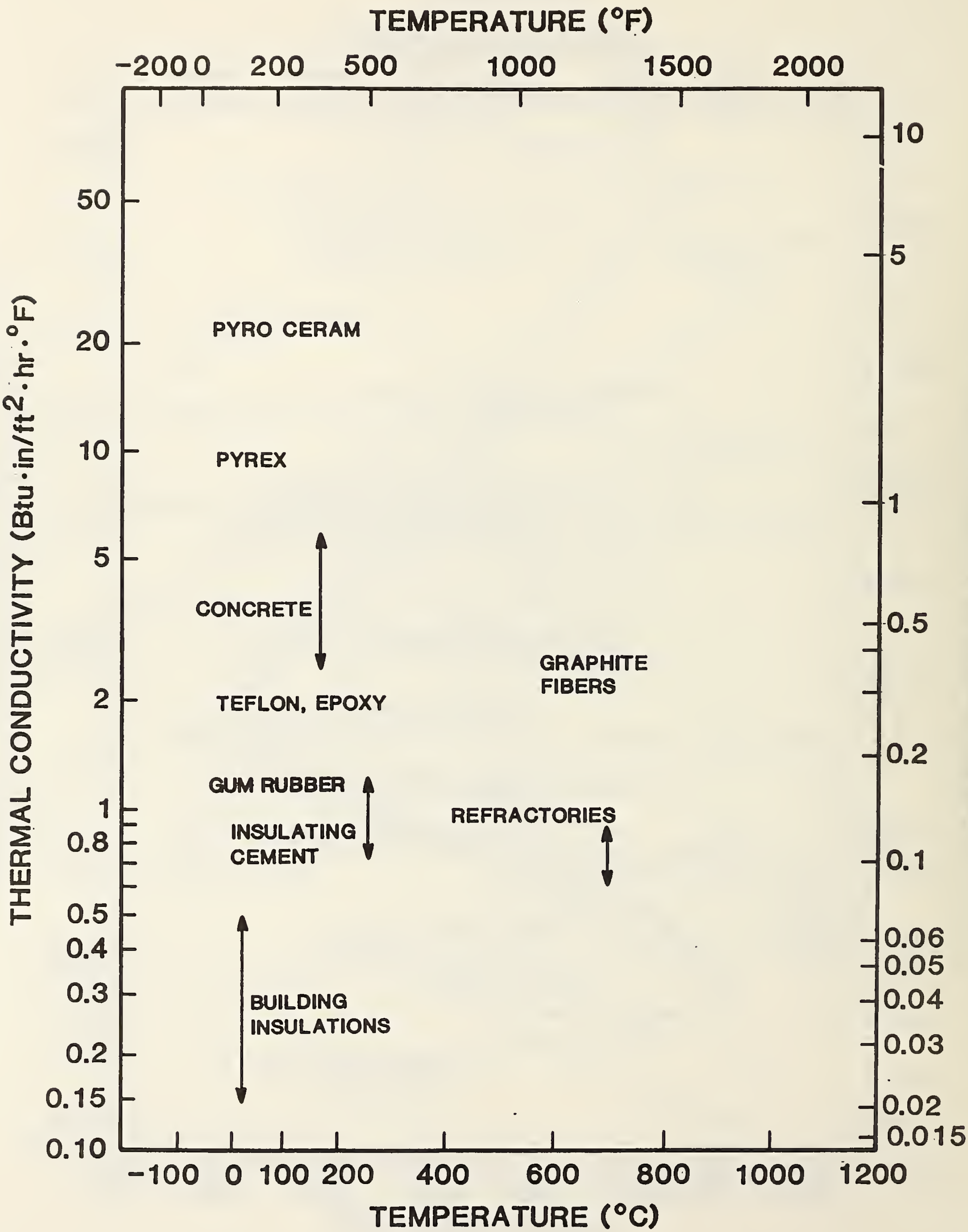


FIGURE 5 - (λ,T) ACTIVITY BY MATERIAL FOR UNIVERSITIES

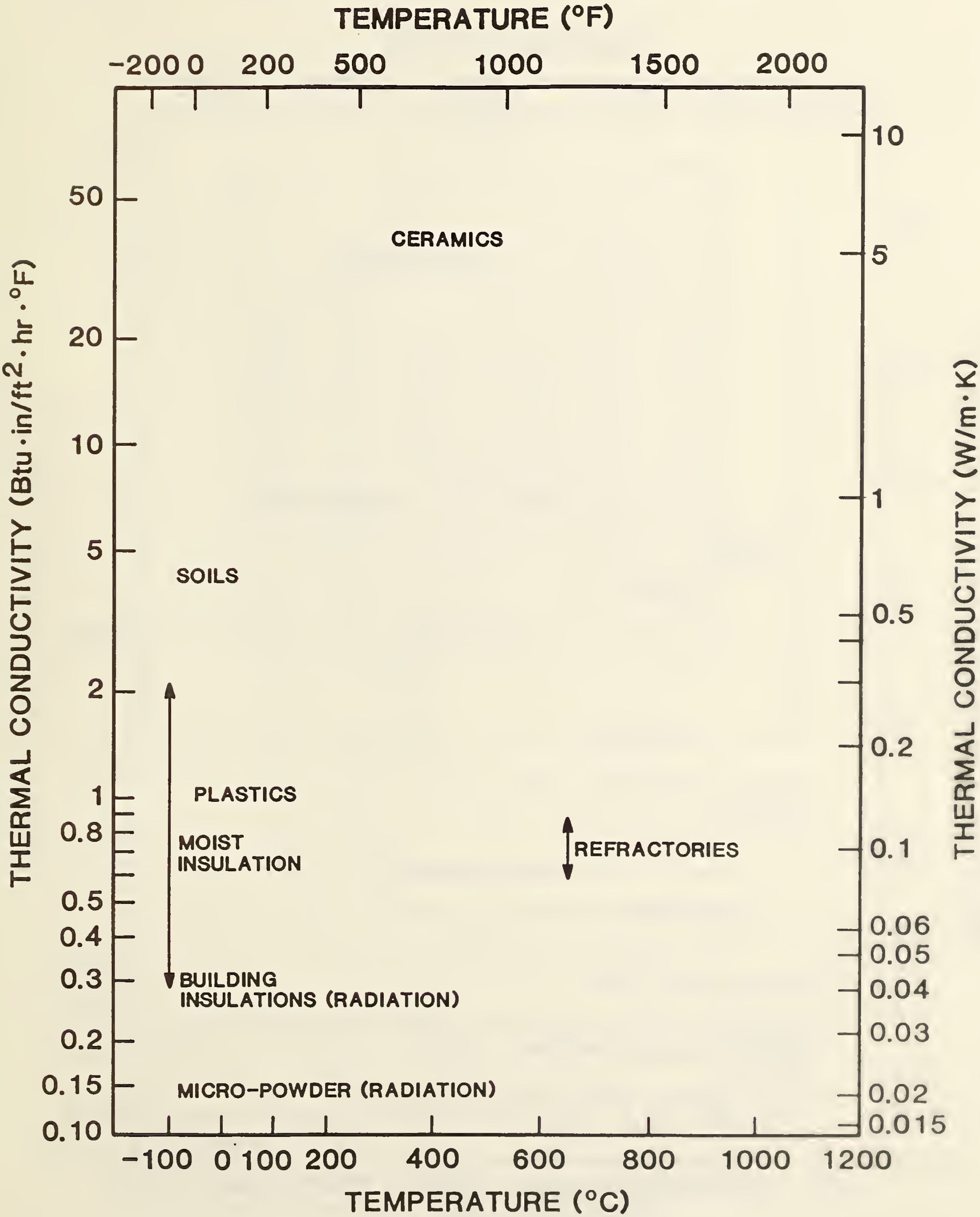


FIGURE 6 - (λ,T) ACTIVITY BY MATERIAL FOR FEDERAL LABORATORIES

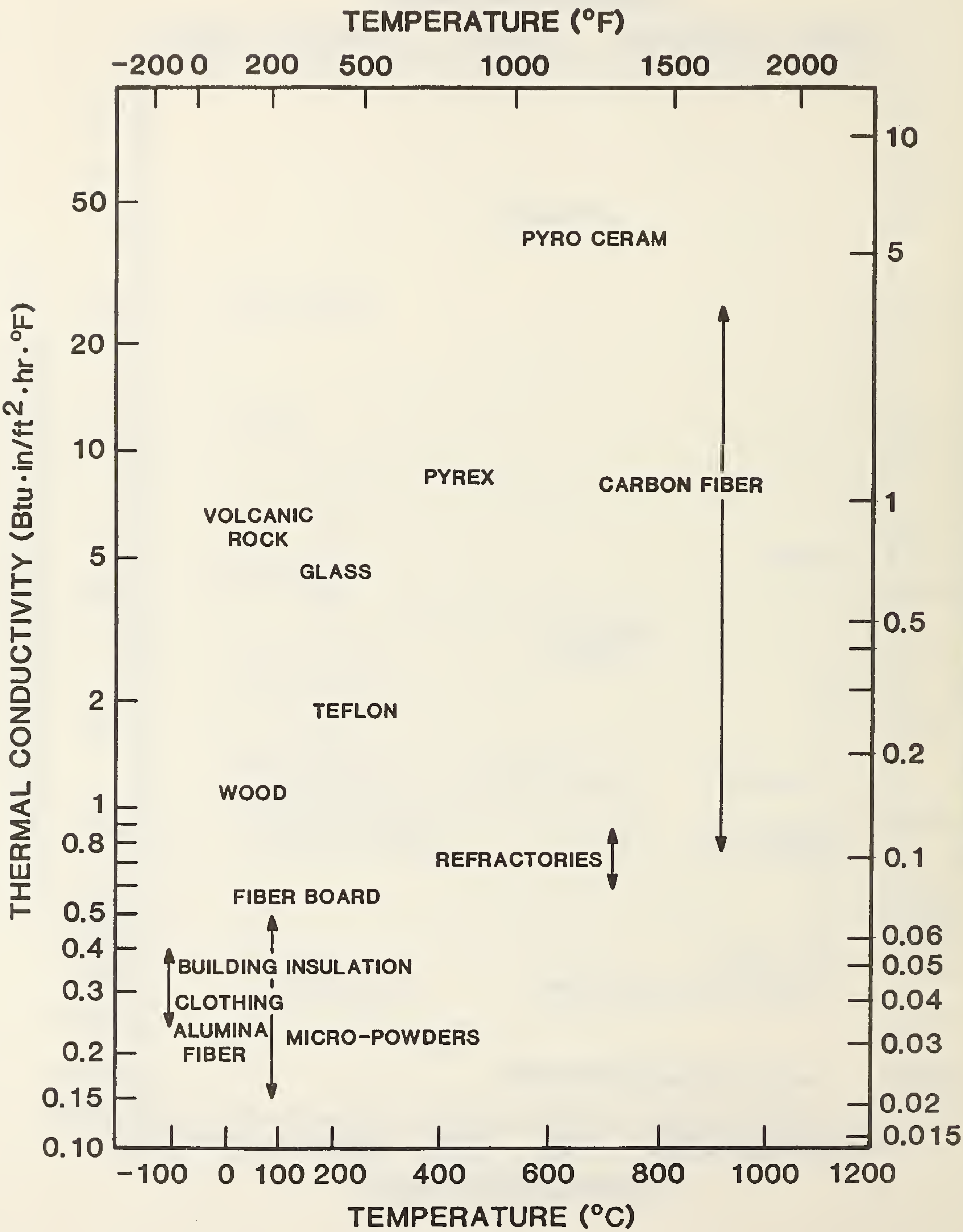
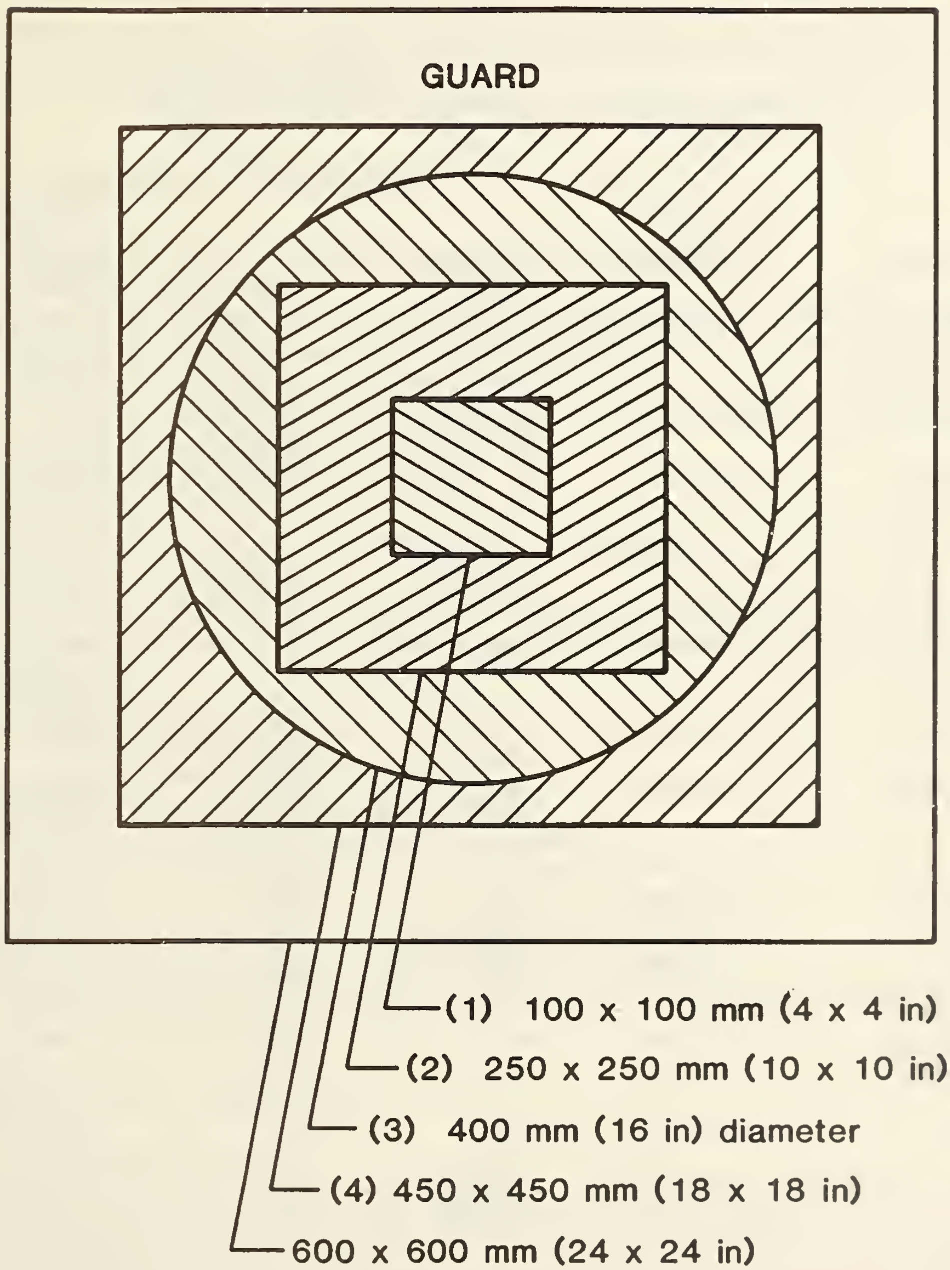


FIGURE 7 - SECTIONED HEAT-FLUX-TRANSDUCER DEVICE



- There is a separate readout from each of the four areas indicated by different shading.
- For a 1 W/m-K heat flux, the independent readout values in mV for sections 1-4 are 0.29, 1.57, 1.79, and 2.13, respectively.
- The outer unshaded area is a guard material with the same R-value as that of the central sections.

Table 1 - Candidates for Standard Reference Material recommended by 1978 ASTM study.*

Material	Probable Temperature Range of Applicability, °C	Nominal Bulk Density, kg/m³ (lb/ft³)	Thermal Resistance per Unit Thickness at 25°C, m·K/W [h ft² °F/ (Btu-in.)]	Need or Use
1. Air space	−160 to 200	. . .	. . .	procedural use, test plate emittance, and plate orientation effects
2. High-density molded fibrous glass board	−175 to 150	80 to 160 (5 to 10)	31.5 (4.5)	historical NBS material minimum radiation effect
3. AA glass fiber blanket insulation	−100 to 400	9.6 (0.6)	31.5 to 28.9 (4.5 to 4.2)	radiation effects, temperature coefficient, and geometry (thickness) effects
4. Glass fiber appliance insulation blanket	−100 to 230	11 to 32 (0.7 to 2)	20 4 to 28.9 (2.9 to 4.2)	similar to Item 3
5. Aged polystyrene foam	−180 to 75	48 (3)	21.7 to 22.4 (3.1 to 3.2)	provides useful comparison to 8.9-cm (3½ in.) fiber glass batts; stable after aging
6. Silicone rubber	glass point to 250	1280 to 1600 (80 to 100)	4.08 to 2.77 (0.59 to 0.40)	opaque material, interfacing resistance effects, and thickness edge-loss effects
7. Borosilicate glass	−175 to 800	2000 (125)	0.96 (0.14)	interfacial resistance effects, radiation effects at high temperature, and thickness effects
8. Closed-cell foam glass	−175 to 350	140 to 160 (9 to 10)	16.5 (2.38)	stable with reproducible properties
9. Silica aerogel composite block	−175 to 900	320 (20)	38.5 (5.5)	high thermal resistance per unit thickness tests and steady-state capacity temperature coefficient
10. Rigidized silica fiber tile	−175 to 1000	160 (10)	27.8 (4.00)	radiation effects and known reproducibility
11. Zirconia fiber board	−175 to 2200	480 (30)	11.55 (1.67)	very-high-temperature use, temperature coefficient, and radiation effects
12. Alumina-silicate refractory fiber insulation blanket	−175 to 1250	64 (4)	30.1 (4.34)	radiation and thickness effects, high-temperature geometry effects, and temperature coefficient
13. Mineral rock board	−175 to 650	192 (12)	23.1 (3.3)	radiation effects, temperature coefficient, and geometry effects
14. Calcium silicate	−175 to 700	190 to 220 (12 to 14)	17.3 (2.5)	generic insulation-type radiation and geometry effects and temperature coefficients
15. Powder or loose-fill insulation	. . .	. . .	. . .	specimen preparation techniques, radiation effects, isotropic nature, and temperature coefficient

*Reference: ASTM Subcommitte C16.30, "Reference Materials for Insulation Measurement Comparisons", Thermal Transmission Measurements of Insulation, ASTM STP 660, R. P. Tye, Ed., Americam Society for Testing and Materials, 1978, pp. 7 - 29.

TABLE 2 - Useful Information for Reference Materials *

GENERAL DESCRIPTIVE INFORMATION

1. Material name; ASTM designation if appropriate
2. Source or sources
3. Production process description, commercial or custom product
4. Material constituents, chemical analysis, fiber characteristics, binders used, special heat treatments
5. Product forms and densities available and prices of products
6. Typical product applications
7. Precautions on product usage

PHYSICAL PROPERTIES AS A FUNCTION OF TEMPERATURE

1. Thermal resistance or thermal resistance per unit thickness or thermal conductivity (where applicable) (method and qualifications)
2. Density
3. Specific heat
4. Thermal diffusivity
5. Thermal shock resistance
6. Thermal expansion coefficient
7. Anisotropy of any physical property
8. Emittance, transmittance, and absorptance

MECHANICAL PROPERTIES AS A FUNCTION OF TEMPERATURE

1. Compressive, tensile, and shear strengths
2. Deflection versus load for different thicknesses, density, and temperatures

OTHER PERTINENT PROPERTIES

1. Combustibility
2. Corrosive effects on materials or by various chemicals
3. Hygroscopic and moisture resistance degradation
4. Resistance to airflow
5. Clearly defined maximum-use temperature for various exposure times
6. Linear dimensional changes and other insulation property changes with aging time at temperature
7. Safety (hazard) and health (toxicity) considerations

* Reprinted from table 3 of reference [1].

TABLE 3 - SUGGESTED THERMAL CONDUCTIVITY VALUE CALIBRATION POINTS FOR BUILDING INSULATION*

APPARENT THERMAL CONDUCTIVITY		
SI UNITS (W/m·K)	ENGLISH UNITS (Btu·in/ft^2·hr·°F)	TYPICAL GENERIC MATERIAL
0.016	0.11	Non-Aged Fluorocarbon-Blown Products
0.023	0.16	Aged Fluorocarbon-Blown Products
0.033	0.23**	High-Density Glass-Fiber Product
0.040	0.28	Loose-Fill Cellulosic and Some Mineral-Fiber Batt Products
0.046	0.32**	Low-Density Glass-Fiber Batt and Some Loose-Fill Mineral-Fiber Products

* Building-Temperature Range: -35 to 65°C (-30 to 150°F)

** NBS currently provides calibration specimens in this λ-value range.

TABLE 4 - SUGGESTED MATERIALS AND THERMAL CONDUCTIVITY VALUES AT HIGH-TEMPERATURES*

REGION**	APPARENT THERMAL CONDUCTIVITY		SRM CANDIDATES
	SI UNITS (W/m·K)	ENGLISH UNITS*** (Btu·in/ft^2·hr·°F)	
1	0.043	0.3	Ceramic-Silica (Min-K or Microtherm)
2	0.057 - 0.11	0.4 - 0.8	Aluminum Silicate Fiber
3	0.14 - 0.29	1 - 2	Brick Refractory
4	2.16	15	170 lb/ft^3 Castable Refractory

* High-Temperature Range: 100 to 1200°C (200 to 2200°F).

** For convenience the thermal conductivity range was divided into four regions. See discussion in sections 3.4 and 4.3 and in section 1.3 of appendix 1.

*** Thermal parameter values for the various insulating materials were obtained from the literature or from researchers. These values were not based on research at NBS.

TABLE 5 - SUGGESTED MATERIALS AT HIGH THERMAL CONDUCTIVITY VALUES AT BUILDING-TEMPERATURES

APPARENT THERMAL CONDUCTIVITY*		
SI UNITS (W/m·K)	ENGLISH UNITS (Btu·in/ft^2·hr·°F)	CANDIDATE MATERIALS
0.16	1.1	Gum Rubber
0.29	2	Silicone Rubber
1.01	7	Pyrex 7740
3.61	25	Pyro Ceram

* Thermal parameter values for the various insulating materials were obtained from the literature or from researchers. These values were not based on research at NBS.

APPENDIX 1. User Interest and Test Activity

1.1 Introduction

The discussion in the following sections is an overview based on the more detailed version given in appendix 2. It presents information obtained in conversations with many users, or potential users, of thermal conductivity calibration specimens. It is organized by user group categories, and within these categories, by increasing λ-value. The following additional appendices are provided as information resources for the reader. Appendices 4 and 5 provide lists of insulating materials ordered alphabetically and by decreasing λ-value, respectively. Appendix 6 lists members of associations of insulation manufacturers.

Because of the nature of this report, which is to assess the kinds of products that are actually in use, there will be an occasional use of a trade name or a manufacturer's name. This in no way represents an endorsement of a particular product or manufacturer.

1.2 Activity and Interests of Manufacturers of Building Insulation

The implied temperature range corresponds to building applications. Refer to figure 1. The λ-values are expressed in SI units; the English units ($Btu \cdot in/ft^2 \cdot hr \cdot °F$) are given immediately afterwards in parentheses.

1.2.1 <u>λ = 0.014 - 0.019 W/m•K (0.10 - 0.13)</u>

For the most part, the materials in this range are the fluorocarbon-blown foams: polyurethane, polystyrene, polyisocyanurate, and phenolic foam. The first three materials were reported to be in this range only when initially produced, and the last material was reported to stay in this range when aged.

1.2.2 <u>λ = 0.020 - 0.026 W/m•K (0.14 - 0.21)</u>

This range includes the aged foam products just mentioned.

1.2.3 <u>λ = 0.032 - 0.036 W/m•K (0.22 - 0.25)</u>

This range includes the high-density, glass-fiber boards, some aged polystyrene, and expanded polystyrene.

1.2.4 <u>λ = 0.039 - 0.042 W/m•K (0.27 - 0.29)</u>

This includes mineral-wool batt and blanket and loose-fill cellulose material.

1.2.5 λ = 0.045 - 0.049 W/m•K (0.31 - 0.34)

This includes low-density, glass-fiber batt and blanket insulation and some loose-fill mineral fiber material.

1.2.6 λ = 0.055 - 0.10 W/m•K (0.38 - 0.7)

This includes wood fiber board, perlite, vermiculite-aggregate concrete and insulating concrete.

1.3 Activity and Interests of Manufacturers of Industrial Insulation by Increasing Thermal Conductivity Value

Industrial insulation is produced over a wide range of thermal conductivity. In order to simplify the discussion, this range was divided into four regions - corresponding to the approximate λ-values (at 24°C or 75°F): (1) λ = 0.030 W/m•K (0.21), (2) λ = 0.060 W/m•K (0.42), (3) λ = 0.14 W/m•K (1.0), and (4) λ = 1.4 W/m•K (10). Refer to table 4.

1.3.1 Region 1

Over most of the high-temperature range, there are only two commercial materials. The first is the Min-K product (refer to Appendix 2 and to Figures 2 and 3). The mixture of a fibrous material with a radiation-blocking silica powder results in a very low λ-value. This product varies in λ-value between 0.029 W/m•K (0.20) at 94°C (200°F) to 0.068 W/m•K (0.47) at 820°C (1500°F). A lower value of 0.02 W/m•K (0.14) was reported at 24°C (75°F) based on measurements at Denver, Colorado. The second is a similar product. It is a microporous ceramic-silica material called Microtherm which also does not age and which also does vary in λ-value with atmospheric pressure. It varies in λ-value from 0.02 W/m•K (0.14) at 24°C to 0.04 W/m•K (0.28) at 500°C (932°F).

Referring to figure 2, there are also other kinds of insulation at the low temperature part of the graph. These include some high-density glass-fiber industrial insulation material, a silica-fiber product, a mineral wool product, and possibly some varieties of microspheres.

1.3.2 Region 2

Referring to figures 2 and 3, there are a number of generic products that cover temperatures up to 1000°C (1800°F) or higher. These generally have a λ-value of about 0.058 W/m•K (0.40) at 24°C (75°F) and extend up to a λ-value of about 0.22 W/m•K (1.5) at 1100°C (1600°F). These include calcium silicates ($CaSiO_4$), ceramic felts, alumina-silica-fiber insulation (Cera Fiber), a matted glass-fiber, a fine glass-fiber (aircraft insulation), and foam glass. For each generic insulation type, it is possible to have a wide range of λ-values depending on the insulation density. The higher density products have a higher λ-value in the lower temperature range and a lower λ-value in the higher temperature range, than the equivalent lower density insulation.

1.3.3 Region 3

Region 3 includes a clay-alumina brick, a marinite calcium silicate product, and zirconia fiber board.

1.3.4 Region 4

Region 4 includes a clay-alumina brick, and castable refractories. As the density of the castable material varies over its range, the entire λ-value range can be covered up to about 2 W/m·K (14).

1.4 Activity and Interests of Commercial Testing Laboratories

Referring to the interview data in section 2.2 of appendix 2 and to figure 4, the commercial testing laboratories reflect, for the most part, the manufacturers' and the federal laboratories' activity. Some testing laboratories measure, as their main activity, the usual building insulations for purposes of certification. Others concentrate more on high-temperature materials such as refractory insulation, and on composite materials such as graphite-fiber materials. Some measurements have been made on the higher conductivity materials -- such as gum rubber, plastics, epoxies, or concrete; but there is little current activity in these regions.

The majority of testing, in the higher conductivity range, corresponds to the Pyrex or Pyro Ceram materials — for high temperature work.

1.5 Activity and Interests of Universities

Referring to section 2.3 in appendix 2 and to figure 5, starting at the very low λ-value range there is some research, both experimental and theoretical, at about 0.02 W/m·K (0.14) on micropowders. The λ-value has been measured and calculations on radiation heat transfer have been made. There is research activity at about six universities on the measurement and corresponding theory of the absorption and scattering cross sections for building insulations. Between 0.043 and 0.29 W/m·K (0.3 and 2), there is a need for calibration standards to measure the λ-value of moist insulation. There is some interest at the λ-value range of about 0.14 W/m·K (1) in plastics. There is considerable activity in terms of theoretical work in the regions corresponding to refractories. However, there is not much experimental work in this region due to the high cost of high-temperature experimental apparatus. There has been some research which requires a knowledge of the λ-value of soils both for geothermal and slab-on-grade studies. Research has been carried out in the areas of natural and forced convection problems -- at cryogenic and at building temperatures. This includes work on composites such as, solids plus liquids, or solids plus solids. There has been some work on high temperature materials such as ceramics;

a problem here is that much of the data on thermophysical properties collected by the aerospace industry is proprietary. Another effort deals with thermal waves such as the ones that result from a daily change in solar radiation on the surface of the earth.

For the most part, the university researchers are interested in the understanding of the heat transfer process and physical phenomena. For this reason, they are interested in other thermophysical properties such as thermal diffusivity and surface emittance, especially at high temperatures. In the building insulation range, there is an interest in modeling heat transfer in the materials, and considerable experimental work is being conducted in this range. At high temperatures there is more theoretical activity and less experimental activity because of the high cost of the corresponding apparatus. However, there is a great deal of dependence on handbook values for physical parameters in their models. There is general agreement that this dependence leads to inaccuracy of results and that a broader range of calibration standards would be of considerable help in the validation of the researchers' models [10].

1.6 Activity and Interests of Federal Laboratories

Referring to figure 6 and to the interview data in section 2.1.2 in appendix 2, there has been some research on the micropowders both as insulation and as possible fenestration material. In the building insulation range, there has been some work on clothing material. This research requires knowledge of permeability, of radiation and convection heat transfer at the surfaces, and of conduction heat transfer through the clothing material.

There has been considerable work on building insulations and methods of installation. This includes field studies at residential installations, measurements of the entire spectrum of insulations in test labs, and lab work on building systems. There has been testing of higher conductivity materials such as wood, teflon, aluminum fiber, glass, and volcanic rock.

In the high-temperature range the major emphasis is on aerospace and fire applications. There is interest in materials which could withstand a temperature of 2800°C (5070°F) for rocket application. In the area of fire research, the temperature range of interest could be as high as 1300°C (2370°F). The work requires a knowledge of a great number of high temperature materials such as ceramic cloths, insulating foams, ablative materials, microspheres, adhesive systems, and hybrids of these. The temperature range of 800 to 1400°C (1500 to 2550°F), is of interest for aerodynamic heating; and, here, there is interest in materials such as ceramics, pyro ceram, adhesives, composites, and silicone rubber.

Thus, there is some interest in the building insulation range, and there seems to be relatively more interest in the high temperature range corresponding to aerospace materials. In addition, some interest was expressed in other thermal properties such as thermal diffusivity and surface emittance at this high-temperature range. There is also some interest in high-λ materials at room temperature.

APPENDIX 2. Interview Data

As part of the effort to identify candidate reference materials for thermal measurements, telephone inquiries were made from people involved in heat-transfer work. The interviewees were asked to give a brief statement of the nature of their work and to list the materials for which they might need to know the thermal conductivity value. The following is a list of summary statements based on the interview data from a representative sampling of these users. In most cases the respondents listed only the tested materials which they produce. In some cases the respondents listed additional materials which they have tested, but which they do not produce. It is noteworthy that, in general, the industrial researchers test a wider range of materials than what is indicated below. An overview of the information in this appendix is presented in appendix 1.

Because of the nature of this report, to assess the kinds of products that are actually in use, there is occasional use of a trade name or a manufactuar's name. This in now way represents an endorsement of a particular product or manufacturer. Also, the thermal parameter values for the various insulating materials were obtained from the literature from researchers. These values were not based on research at NBS. Reference [15] explains the various categories of insulation materials.

The λ-values are given as two numbers -- the first in SI units of W/m·K and the second (in parentheses) in English units of Btu·in/ft^2·hr·F. The temperature is given in °C (°F), and the units for density are kg/m^3 (lb/ft^3).

2.1 Manufacturers

2.1.1 Building and Industrial Manufacturers

1. American Hoechst Corporation
Contact Person: Mich Yokinen
289 North Main Street
Leominster, MA 01453
(617) 537-8131

Product Type - polystyrene [λ-value of 0.030 (0.21)]

2. Apache Building Products Inc.
Contact person: Mr. Tomasurn
2025 E. Linden Avenue
Linden, NJ 07036
(201) 486-6723

Product Type - polyurethane [λ-value of about 0.025 (0.17)]

3. Butler Manufacturing Company
   Contact Person: Charles Milburn
   13th St. & Botts Road
   Grandview, MO 64030
   (816) 763-3022

   Product Type 1 - glass-fiber [λ-value of about 0.046 (0.32)]

   Product Type 2 - polystyrene [λ-value of about 0.036 (0.25)]

   Product Type 3 - urethane type foam [λ-value of about 0.025 (0.17)]

   Heat-Transfer Apparatus - Guarded-Hot-Box, Heat-Flow-Meter

They test products at 8°C (45°F) and 24°C (75°F).

4. Cellulose Industry Standards Enforcement Program
   Contact Person: Vernon "Skip" Lowe
   610 Center City Office
   Dayton, OH 45402
   (513) 222-1024

   Product Type - loose-fill cellulose [λ-value of about 0.039 (0.27) and density of 32 to 48 kg/m^3 (2 to 3 lb/ft^3)]

This program represents about 25 percent of the cellulose production. There are about 150 companies producing cellulose. The testing for the enforcement program is done by Underwriters Laboratories, Inc.

5. CertainTeed Corporation
   Contact Person: Dave McCaa
   1400 Union Meeting Road
   Blue Bell, PA 19422
   (215) 542-0500

   Product Type 1 - a low-density glass-fiber [λ-value of ~ 0.048 to 0.049 (0.33 to 0.34) and density of ~ 10 kg/m^3 (0.6 lb/ft^3).] The test temperature is 24°C (75°F).

   Product Type 2 - loose-fill, glass fiber insulation [λ-value of about 0.045 (0.31) and density of about 14 kg/m^3 (0.9 lb/ft^3)]. The test temperature is 24°C (75°F).

   Product Type 3 - industrial glass-fiber insulation [λ-values range from 0.033 to 0.043 (0.23 to 0.30), and density ranges from 12 to 96 kg/m^3 (0.75 to 6 lb/ft^3)]. This material can be used at temperatures up to 450°C (850°F).

6. Dow Chemical
   Contact Person: Dave Greason
   P. O. Box 515
   Granville, OH 43023
   (614) 587-4362

   Product Type - extruded polystyrene foam [λ-values range at 24°C (75°F) from 0.024 to 0.032 (0.165 to 0.22). The density range is from 26 to 64 kg/m^3 (1.6 to 4 lb/ft^3), and the λ-value depends on more than just the density. The λ-value at 5°C (40°F) is 0.027 (0.185)]. Tests have been conducted at -162°C (-260°F) (the λ-value here is approximately 0.08 (0.56)), at the liquid-natural-gas temperature of approximately -40°C (-40°F), and at high temperatures. The product thickness ranges from 13 mm to 25 cm (0.5 to 10 in). The polystyrene uses a mixture of oxygen, nitrogen, and fluorocarbon as a blowing agent, and this diffuses out of the material over time, with a corresponding increase in λ-value. The λ-value of the fresh blown product is 0.016 (0.11). First, the oxygen and nitrogen diffuse out in about 60 days, at which time the λ-value is 0.017 (0.115) for a 25 mm (1 in) product. The fluorocarbon diffuses out over a longer period of time. After 5 years, typical products would have a λ-value of 0.20. Over the next 45 years this value would not be expected to change more than another 5 percent. There are not good data on exactly how uniform the material is; an estimate was that over a large 122 x 244 cm (4 x 8 ft) specimen the λ-value would not vary by more than 2 to 3 percent. Tests of products other than those produced by Dow Chemical are conducted over a wider range of λ-values.

Heat-Transfer Apparatus - Heat-Flow-Meter and a Calibrated-Hot-Box.

7. Fibrex
   Contact Person: Jane Wood
   P. O. Box 1148
   Aurora, IL 60507
   (312) 896-4800

   Product Type 1 - high-temperature mineral-wool insulations with a density range from 40 to 320 kg/m^3 (2.5 to 20 lb/ft^3). The range of temperature applicability is 24°C (75°F) to approximately 1080°C (1900°F). At a density of 128 kg/m^3 (8 lb/ft^3), the λ-value is approximately 0.045 (0.31) for a mean temperature of 95°C (200°F).

This material is used in loose form and in insulating cements

Product Type 2 - Alumina-silica fiber in block form - The density is approximately 288 kg/m^3 (18 lb/ft^3) and the temperature limit is 1260°C (2300°F). The λ-value at 538°C (1000°F) is approximately 0.088 (0.61).

8. Jim Walter Research Corporation
Contact Person: Gerry Miller
10301 9th Street N
St. Petersburg, FL 33702
(813) 576-4171

Product Type 1 - Thermax Insulation Board (a foil-faced polyisocyanurate foam). [λ-values range from approximately 0.016 to 0.020 (0.11 to 0.14) at 24°C (75°F)]. The nominal density value is 32 kg/m^3 (2.0 lb/ft^3). The thickness range is 12 to 108 mm (0.5 to 4.25 in).

Product Type 2 - Tuff-R Insulating Sheathing (a foil-faced polyisocyanurate foam). [λ-values range from approximately 0.016 to 0.020 (0.11 to 0.14) at 24°C (75°F)]. The nominal density value is 32 kg/m^3 (2.0 lb/ft^3). The thickness range is 12 to 25 mm (0.5 to 1.0 in).

Product Type 3 - Thermax Hy-Tec (Energy-LoK) Roof Insulation (a glass-fiber faced polyisocyanurate foam). [λ-values range from approximately 0.016 to 0.023 (0.11 to 0.16) at 24°C (75°F)]. The nominal density value is 32 kg/m^3 (2.0 lb/ft^3). The thickness range is 19 to 102 mm (0.75 to 4.0).

Product Type 4 - Thermax Hy-Tec Plus Roof Insulation (a composite fiberboard, glass-fiber faced polyisocyanurate foam). [λ-values range from approximately 0.023 to 0.032 (0.16 to 0.22) at 24°C (75°F)]. The thickness range is 38 to 84 mm (1.5 to 3.3 in).

Product Type 5 - Fiberboard Insulation (cellulosic fiberboard). (λ-value is approximately 0.052 (0.36) at 24°C (75°F).] The density is about 320 kg/m^3 (20.0 lb/ft^3). The thickness range is 12 to 51 mm (0.5 to 2.0 in).

Product Type 6 - CeloTherm Perlite Roof Insulation (expanded volcanic glass). [λ-value is approximately 0.052 (0.36) at 24°C (75°F).] The thickness range is 19 to 51 mm (0.75 to 2.0 in).

Heat-Transfer Apparatus - Heat-Flow-Meter, Guarded-Hot-Plate, Guarded/ Calibrated Hot Box.

Some tests are made at a mean temperatures of 40°C (110°F) and 5°C (40°F).

9. Knauf Fiber Glass
Contact Person: David Anewalt
240 Elizabeth Street
Shelbyville, IN 46176
(317) 398-4434

Product Type 1 - low-density, glass-fiber insulation [λ-value of 0.046 (0.32); density of about 9 kg/m^3 (0.6 lb/ft^3).]

Product Type 2 - glass-fiber insulation in the form of rolls, batts, and pipe covering [λ-values range from 0.033 to 0.043 (0.23 to 0.30) and density values range from 12 to 96 kg/m^3 (0.75 to 6 lb/ft^3). The temperature range of use of this material is from 24°C (75°F) to 454°C (850°F).]

10. Koppers Company
Contact Person: Rod Shapard
440 College Park Drive
Monroeville, PA 15146
(412) 227-2270

Product Type - phenolic foam (closed-cell) [λ-value ranges from about 0.014 to 0.022 (0.10 to 0.15); the density is 42 kg/m^3 (2.6 lb/ft^3).] The thickness varies from 13 to 90 mm (0.5 to 3.6 in). The range of temperature applicability is 27 to 177°C (80 to 350°F). The λ-value can vary by as much as 30 percent with relative humidity. It was reported that over a period of 3 years there was no measurable change in λ-value. Thus, there must have been only a negligible amount of diffusion of the fluorocarbon blowing agent out of the specimens. That is, the cell-wall material seems to be unusually impermeable to the fluorocarbon. The reported estimate of the amount of variation of the λ-value over the specimen area was 1 percent. Since the material is machinable, it should be possible to improve on the manufactured flatness of 1.3 mm (50 mils). There may be a problem with breakage of large specimens.

11. Lockheed Palo Alto Research Laboratories
Contact Person: George Cunnington
D52-32, B205
3251 Hanover Street
Palo Alto, CA 94304
(415) 424-2426

This is a partial list of the materials that they test.

Product Type 1 - silica fiber insulation- The density ranges between 96 and 720 kg/m^3 (6 and 45 lb/ft^3); the λ-value at 24°C (75°F) is about 0.058 (0.4) and at 1000°C (1831°F) it is 0.29 (2.0). The estimate of uniformity in λ-value was 2 percent. This material is used in the space-shuttle tile, and it can be metalized for high-temperature applications.

Product Type 2 - carbon and graphite-fiber materials [The λ-value is the order of 1 (7) and it is tested at temperatures up to 1000°C (1800°F).]

Product Type 3 - Approximately ten years experience in testing a variety of loose-fill micro-powders has been gained.

12. Manville Services Corporation
Contact Person: Dick Troyer
P. O. Box 5108
Denver, CO 80217
(303) 978-5312

Product Type 1 - low-density glass-fiber insulation [The λ-value at 24°C (75°F) is 0.049 (0.34); the density range is 8 to 11 kg/m^3 (0.5 to 0.7 lb/ft^3).]

Product Type 2 - medium-density glass-fiber insulation [λ-value of 0.032 (0.22); density of 40 kg/m^3 (2.5 lb/ft^3).]

Product Type 3 - a glass-fiber board [λ-value of 0.036 (0.25); density of 80 kg/m^3 (5 lb/ft^3).]

Product Type 4 - a polyurethane foam product for use at building temperature. [Six month λ-value ranges from 0.023 (0.16) at a thickness of 33 mm (1.3 in) to 0.019 (0.135) at a thickness of 69 mm (2.7 in); density of about 32 kg/m^3 (2 lb/ft^3).]

Product Type 5 - polyisocyanurate foam [Six-month-age λ-value of about 0.023 (0.16) at 24°C (75°F); density of about 32 kg/m^3 (2 lb/ft^3).]

Product Type 6 - Min-K (made for use at high-temperature and vacuum conditions, although it can be used at a low-temperature and/or an atmospheric-pressure condition.) This material is formed from fibrous material mixed with heat resistant silica powder as an opacifier. The product brochure indicates a λ-value (at atmospheric pressure) of 0.029 (0.20) at 94°C (200°F), of 0.043 (0.30) at 650°C (1200°F), and of 0.068 (0.47) at 820°C (1500°F), for a density of 320 kg/m^3 (20 lb/ft^3). A personal communication from Mark Albers of Manville stated that a measurement at Denver, Colorado gave the λ-value at 24°C (75°F) of 0.02 W/m•K (0.14), which is lower than what the product curves would indicate. At higher altitudes the λ-value is smaller; for example, at an altitude of 10 miles it can decrease by as much as 50 percent. The λ-value depends significantly on the atmospheric pressure. There is about a 5 percent decrease in λ-value at Denver, Colorado from the value at sea level. On the other hand there is only a small dependence of λ-value on relative humidity. Min-K is produced in a blanket form at a thickness of 25 mm (1 in), and it is produced as a molded product in all shapes. Flatness is indicated to be as good as ±2 mils, and an estimate of λ-value variability over a specimen area is perhaps 2 to 3 percent. Depending on the product the maximum temperature of use varies from about 700°C (1300°F) to 1100°C (2000°F).

Product Type 7 - calcium silicate -- This is used at temperature range between 40 to 540°C (100 and 1000°F). [The curve for the λ-value as a function of temperature depends on the density; for a density of 190 kg/m^3 (12 lb/ft^3) the λ-value at 40°C (100°F) is 0.053 (0.37), and at a temperature of 540°C (1000°F) the λ-value is 0.127 (0.88). At a higher density of about 800 kg/m^3 (50 lb/ft^3), the λ-value at 24°C (75°F) is 0.13 (0.88), at 260°C (500°F) the λ-value is 0.115 (0.80), and at about 540°C (1000°F) the λ-value is 0.12 (0.86).] The estimate of the λ uniformity is about 1 percent.

Product Type 8 - alumina-silica fiber (Cera Fiber). This material is a candidate for a Standard Reference Material (SRM). It has been tested by Manville Service Corporation and they will provide ten specimens to NBS (Boulder) for further testing. This material has a density of 240 kg/m^3 (15 lb/ft^3). The entire range in density is between 192 and 416 kg/m^3 (12 to 26 lb/ft^3). For the 240 kg/m^3 (15 lb/ft^3) density, the λ-value at

94°C (200°F) is 0.050 (0.35), at 540°C (1000°F) it is 0.11 (0.75), and at 980°C (1800°F) its value is 0.18 (1.25). The variation of λ over area is estimated to be less than 3 percent.

Product Type 9 - alumina-silica fiber - the generic material described above is available over a wide range of density, from 48 to 384 kg/m^3 (3 to 24 lb/ft^3). Temperature limits for application range between 870 to 1538°C (1540 to 2800°F). At the low end of the temperature range [260 to 540°C (500 to 1000°F)], the following statement holds. The λ-value for the lower density products is lower than the λ-value for the higher density products. At the higher temperatures such as 800 to 1100°C (1500 to 2000°F), the λ-value is higher than in the case of the higher density material.

Product Type 10 - clay-alumina brick refractory insulation - [density ranges from 540 to 1500 kg/m^3 (34 to 95 lb/ft^3). At the density value of 560 kg/m^3 (35 lb/ft^3), and at the temperature of 260°C (500°F), the λ-value is 0.13 (0.90); at 540°C (1000°F), λ is 0.16 (1.1); at 816°C (1500°F), λ is 0.20 (1.4); and at 1100°C (2000°F), λ is 0.23 (1.6). For a density value of 960 kg/m^3 (60 lb/ft^3) and a temperature of 260°C (500°F), the λ-value is 0.36 (2.5); at 540°C (1000°F), λ is 0.375 (2.6); at 816°C (1500°F), λ is 0.40 (2.8); and at 1100°C (2000°F), λ is 0.43 (3.0).] This material is particularly resistent to chemical degradation.

Product Type 11 - castable refractory insulation made of clay, calcium, aluminate, and cement - [density ranges from 720 to 2700 kg/m^3 (45 to 170 lb/ft^3).] At the low end of the density range, the λ-value behaves very similarly to the 960 kg/m^3 (60 lb/ft^3) clay alumina brick described above, at the high end of the density range its λ-value is about 2 (13). This material is chemically stable in a reducing atmosphere, such as a hydrogen atmosphere.

Product Type 12 - marinite-calcium-silicate board - This material contains molten metal and is machinable. [The density ranges from 560 to 960 kg/m^3 (35 to 60 lb/ft^3).] At a temperature of 94°C (200°F), its λ-value is 0.16 (1.1); at 320°C (600°F), λ is 0.17 (1.2), and at 540°C (1000°F), λ is 0.18 (1.24)]. Thus, the λ-value is fairly constant over the density range. This material is used at temperatures below 980°C (1800°F).

With regard to the high-temperature refractory insulations just discussed, the manufacturer recommended a number of SRM's at various densities. These were 96, 270, 640, 1300, 1900, 2600 kg/m^3 (6, 17, 40, 80, 120, and 160 lb/ft^3). The reason given was that the λ-value curve as a function of temperature depends of the density, and it would be useful to have more interpolation points.

13. Micropore International Limited
    Contact Person: John Hughes, Marketing Manager
    Hadzor Hall, Hadzor
    Droitwich, Worcs., WR9-7DJ, England
    (0905 774211)

This firm produces a product called Microtherm which shows promise as a calibration material over a wide range of temperature. There is no reason that it could not be used down to cryogenic temperatures, although there was no experience here, and it could be used at temperatures up to 1000°C (1832°F). The material consists of a microporous mixture of silica and ceramic powders. It contains titanium dioxide for opacification and ceramic fiber for reinforcement. This material is produced over a density range of 192 to 384 kg/m^3 (16 to 24 lb/ft^3), although it is usually produced at 240 kg/m^3 (15 lb/ft^3). The λ-value varies only a few percent over this density range. For this reason, the λ-value is expected to be extremely uniform over the area of a specimen, between specimens in a lot (better than 1 percent), and between lots (better than 5 percent). It comes in thicknesses between 3 and 51 mm (0.125 and 2 in). This material is similar to the Min-K product just discussed in item 12 (produced by the Manville Services Corporation), and its dependence on atmospheric pressure was estimated to be comparable. The λ-value at 24°C (75°F) is 0.02 W/m•K (0.14) and at 500°C (932°F) is 0.032 W/m•K (0.22). The latter point is measured with a temperature difference of approximately 800°C (1440°F). The ratio of λ-value in the direction across the specimens to that in the direction parallel to the surface is 0.88. The material is produced in a block form, in which case the surface is chalky and not very durable. It is also produced in panel form, covered with glass cloth, in which case it is very durable. There are flexible and quilted versions of the panel form.

Microtherm is used in industry for the insulaton of ovens, furnaces, pipework, aircraft and nuclear power installations as well as in domestic equipment such as ranges and microwave ovens. The thickness of Microtherm required is generally one-third the thickness needed using alternative insulation materials.

14. Owens-Corning Fiberglass Corporation (OCF)
Contact Person: Ron Adams
Box 415
Granville, OH 43023
(614) 587-7048

<u>OCF produces and tests the following materials:</u>

Product Type	Thickness cm	Thickness in	Density kg/m^3	Density lb/ft^3	T_m °C	T_m °F	Apparent Thermal Conductivity W/m·K	Apparent Thermal Conductivity $Btu \cdot in/ft^2 \cdot hr \cdot F$
Calcium Silicate	3.8	1.5	208	13.0	66	150	0.063	0.44
					138	280	0.055	0.38
					233	450	0.061	0.42
					333	630	0.074	0.51
	4.1	1.6	141	8.8	71	160	0.046	0.32
					94	200	0.046	0.32
					121	250	0.049	0.34
					158	315	0.055	0.38
					266	510	0.072	0.50
					360	680	0.089	0.62
Air Craft Insulation (fine glass-fiber)	3.8	1.5	13	8.8	99	210	0.048	0.33
					205	400	0.078	0.54
					310	590	0.113	0.91
			16	1.0	24	75	0.032	0.22
					99	210	0.043	0.30
					216	420	0.069	0.48
					327	620	0.113	0.78
(Excellent homogeneity. Very hygroscopic.)								
Wood Fiber Sheathing	1.3	0.5	288	18	24	75	0.055	0.38
					52	125	0.056	0.39
Duct Board	2.54	1.0	66	4.1	24	75	0.033	0.23
					55	130	0.036	0.25
Glass-Fiber for Industrial Insulation	2.54	1.0	67	4.2	24	75	0.030	0.21
					49	120	0.033	0.23
					94	200	0.039	0.27
					121	250	0.043	0.30
TIW	5.1	2.0	35	2.2	24	75	0.033	0.23
Aercor-Black	1.9	0.75	24	1.5	24	75	0.033	0.23
Navy Board	5.1	2.0	43	2.7	24	75	0.032	0.22

Product Type	Thickness cm	in	Density kg/m^3	lb/ft^3	T_m °C	°F	Apparent Thermal Conductivity W/m·K	Btu·in/ft^2·hr·F
Aercor Aircraft Ins.	2.54	1.0	10	0.6	24	75	0.035	0.24
	1.9	0.75	24	1.5	24	75	0.030	0.21
Polyisocyanurate Foam	1.3-10.2 -	.5-4.0	30	1.9	24	75	0.020	0.14
P 80 Molded			80	5.0	24	75	0.033	0.23
			208	13.0	24	75	0.036	0.25
			272	17.0	24	75	0.039	0.27
			336	21.0	24	75	0.046	0.32
(Very stable and homogeneous.)								
Roof Insulation	5.1	2.0	117	7.3	24	75	0.035	0.24
	3.2	1.25	125	7.8	24	75	0.033	0.23
	3.2	1.25	93	5.8	24	75	0.033	0.23
	3.3	1.3	122	7.6	24	75	0.036	0.25
MBI	10.2	4.2	16	1.0	24	75	0.040	0.28
	8.9	3.5	18	1.1	24	75	0.039	0.27
	7.6	3.0	21	1.3	24	75	0.038	0.26
	7.6	3.0	9	0.6	24	75	0.048	0.33
	7.6	3.0	12	0.7	24	75	0.043	0.30
	7.6	3.0	8	0.5	24	75	0.049	0.34

OCF has tested, but does not produce the following other materials:

Product Type	Thickness cm	in	Density kg/m^3	lb/ft^3	T_m °C	°F	Apparent Thermal Conductivity W/m·K	Btu·in/ft^2·hr·F
Matted Glass Fibers	2.54	1.0	147	9.2	83	180	0.045	0.31
					133	270	0.051	0.35
					183	360	0.058	0.40
					199	390	0.061	0.42
(Candidate for high-temperature SRM.)								
Microspheres (Fumed Silica)	3.8	1.5	62	3.9	21	70	0.027	0.19
					49	120	0.033	0.23
					77	170	0.045	0.31
					88	190	0.049	0.34
					96	204	0.055	0.38

Product Type	Thickness		Density		T_m		Apparent Thermal Conductivity	
	cm	in	kg/m^3	lb/ft^3	°C	°F	W/m·K	Btu·in/ft^2·hr·F
Open-Cell Phenolic Foam	3.6	1.4	34	2.1	24	75	0.035	0.24
Rockwool Mineral Fiber	2.54	1.0	67	4.2	26	78	0.035	0.24
					127	260	0.052	0.36
			141	8.8	24	74	0.036	0.25
					121	250	0.050	0.35
					196	385	0.066	0.46
Mineral Fiber	7.6	3.0	26	1.6	24	75	0.040	0.28
Fibair Filter Media	7.6	3.0	3.2	0.2	24	75	0.125	0.87
	6.4	2.5	3.8	0.24	24	75	0.113	0.78
	5.1	2.0	5	0.31	24	75	0.097	0.67
	3.8	1.5	6.6	0.41	24	75	0.081	0.56
expanded polystyrene	7.4	2.9	-	-	24	75	0.038	0.26
							0.039	0.27
Truck Decking	2.8	1.1	880	55.0	23	73	0.173	1.20
Vinyl Flooring Material	-	-	-	-	24	75	0.100	0.69
							0.082	0.57
Down	2.54	1.0	-	-	24	75	0.040	0.28
Thinsulate 200	1.4	0.55	-	-	24	75	0.036	0.25
Felted Ceramic Fiber	1.3-10.2	0.4-4.0	288	18	94	200	0.062	0.43
					205	400	0.075	0.52
					323	600	0.086	0.60
					427	800	0.107	0.74
					538	1000	0.121	0.84
					649	1200	0.141	0.98
					760	1400	0.166	1.15
					871	1600	0.188	1.30

(Possible candidate for a high-temperature standard.)

15. Rmax, Inc.
Contact Person: Amy Ely
13524 Welch Road
Dallas, TX 75234
(214) 387-4500

Product Type - Polyisocyanurate [λ-value is approximately 0.021 (0.145).

16. Rockwool Industries, Inc.
Contact Person: Jesse Bridwell
7400 South Alton Court
Englewood, CO 80112
(303) 733-6200

Product Type 1 - blown mineral wool [λ-value at a temperature of 24°C (75°F) and a density of 27 kg/m^3 (1.7 lb/ft^3) is 0.048 (0.33).]

Product Type 2 - mineral wool blanket [λ-value ranges from 0.036 to 0.049 (0.25 to 0.34) at a temperature of 24°C (75°F) and a density range from 19 to 40 kg/m^3 (1.2 to 2.5 pcf).]

17. Texaco Chemical
Contact Person: David McCoy
P.O. Box 15730
Austin, TX 78761
(512) 459-6543

Product Type - polyurethane foam [λ-value ranges from about 0.023 to 0.025 (0.16 to 0.17).]

18. The Upjohn Company, CPR Division
Contact Person: Robert Pilmer
555 Alaska Avenue
Torrance, CA 90503
(213) 320-3550

Product Type - polyurethane, polyisocyanurate, and polycarbanilide foamed plastics [λ-value of about 0.023 (0.16) for the first two and 0.039 (0.27) for the latter.]

19. W. R. Grace
Contact Person: Robert Orlandi
62 Whittemore Ave.
Cambridge, MA 02140
(617) 876-1400

Product Type 1 - polystyrene (expanded) [At 5°C (40°F) the λ-value is about 0.036 (0.25); density 16 kg/m^3 (1.0 lb/ft^3).] It is produced in 25 to 200 mm (1 to 8 in) thicknesses.

Product Type 2 - insulating cement [The λ-value is 0.097 (0.67) at 24°C (75°F); the density ranges between 350 and 450 kg/m^3 (22 to 28 lb/ft^3).]

Product Type 3 - vermiculite [At a temperature of 24°C (75°F) the λ-value is about 0.056 (0.39) for the density value of 95 kg/m^3 (5.9 lb/ft^3).]

20. Whirlpool Corporation
    Contact Person: David Valentine
    850 Arcade Street
    St. Paul, MN 55164
    (612) 778-2372

    Product Type 1 - polyurethane foam [λ-value of about 0.025 (0.17).]

    Product Type 2 - glass-fiber [λ-value of approximately 0.049 (0.34).]

2.1.2. Microsphere Manufacturers

1. Degussa Corporation
   Contact Person: Pat Linard
   P. O. Box 2004
   Teterboro, NJ 07608
   (201) 288-6500

A fumed silicon-dioxide micro-powder material called aerosil is produced over a size of 7-50 milli-microns. Information from the University of California, Berkeley, indicated that the λ-value of a "cake layer" of 7 milli-micron material was 0.020 W/m·K (0.14). In addition to the fumed silicon-dioxide material, an amorphous silicon-dioxide material and a precipitated silica material are produced. It is possible to make the powders hydrophobic by a chemical treatment.

2. P. Q. Corporation
   Contact Person: John Peters
   P. O. Box 258
   Lafayette Hill, PA 19444
   (215) 825-5000

This company produces microspheres of various materials, such as silica, borosilicate glass, and alumina-silicate glass. These microspheres are hollow and have wall diameters from 1 to 2 μm. The range of diameters is 10 to 180 μm; a λ-value range from 0.043 to 0.089 W/m·K (0.30 to 0.62) was reported. The material can be produced to be hygroscopic or hydrophobic.

2.2 Testing Laboratories

1. Cal-Coast Laboratories
   Contact Person: Mike Fairley
   P. O. Box 2044
   Berkeley, CA 94702
   (415) 540-7837

They plan to test a layered industrial insulation between temperatures of 0 to 300°C (32 and 570°F). They are not certain of the λ-value for this proposed project.

2. Dynatech R & D Company
   Contact Person: Andre Desjarlais
   99 Erie St.
   Cambridge, MA 02139
   (617) 868-8050

This testing laboratory makes thermal measurements over almost the entire range of materials, λ-values and temperatures. The following is a sample of the products they have tested.

Product Type 1 - high-temperature glass fiber - At a temperature of 24°C (75°F), this 50 kg/m^3 (3 lb/ft^3) material has a λ-value of about 0.040 (0.28); at 94°C (200°F) it is 0.052 (0.36); and at 200°C (400°F) it is 0.072 (0.50).

Product Type 2 - mineral fiber - At a temperature of 24°C (75°F) this mineral fiber has a λ-value of 0.036 (0.25); at 94°C (200°F) a 96 kg/m^3 (6 lb/ft^3) product has a λ-value of 0.046 (0.32); and a 192 kg/m^3 (12 lb/ft^3) product has a λ-value of 0.048 (0.33).

Product Type 3 - refractory insulation - At a temperature of 430°C (800°F), it has a λ-value of about 0.115 (0.80).

Product Type 4 - ceramic fiber - This product has a λ-value of 0.039 (0.27).

Product Type 5 - non-woven glass fiber - At a density value of about 160 kg/m^3 (10 lb/ft^3) and a temperature of 150°C (300°F), this material has a λ-value of 0.079 (0.55) and at 370°C (700°F) a λ-value of 0.108 (0.75).

Product Type 6 - zirconia fiber - This material can be used at temperatures up to 1650°C (3000°F). It has a density range between 96 to 1600 kg/m^3 (6 to 100 lb/ft^3). Its λ-value at room temperature is about 0.087 (0.60).

Product Type 7 - insulating cement (filled with vermiculite or perlite) - This material is produced over a density range of 320 to 2200 kg/m^3 (20 to 140 lb/ft^3). At the low end of the density range it acts like a fiber board material in terms of its λ-value curve as a function of temperature; and at the higher densities it acts as a ceramic insulating material. At 24°C (75°F) the λ-value varies from 0.098 to 0.159 (0.68 to 1.1).

Product Type 8 - calcium silicate [λ-value of about 0.058 (0.40).]

Product Type 9 - polyurethane [λ-values range between 0.023 and 0.025 (0.16 to 0.17).]

Product Type 10 - phenolic foam - This foam material has a λ-value of about 0.025 (0.17) at a temperature of 24°C (75°F).

Product Type 11 - microsphere and epoxy foam [λ-value of 0.3 (2).]

Product Type 12 - gum rubber [λ-value of 0.16 (1.1).]

Product Type 13 - glass fiber - This type glass fiber has been tested up to 450°C (850°F). [λ-value of 0.3 (0.042) at 24°C (75°F).]

Product Type 14 - mineral fiber - This type mineral fiber has been tested up to 1040°C (1900°F). [λ-value of 0.042 (0.29) at 24°C (75°F).]

Product Type 15 - Pyrex 7740 is a glass material of 13 mm (0.5 in) thickness having a λ-value of approximately 1.0 (7.0). This product was produced by Corning.

Product Type 16 - polycrystalline ceramic (Pyro Ceram) - This material is produced in 25 mm (1 in) diameter rods and 13 mm (0.5 in) thick plates. At a temperature of 24°C (75°F) the λ-value is approximately 2.88 (20); and at 150°C (300°F) it is about 2 (15).

Product Type 17 - foam glass - This material can be used at temperatures up to 480°C (900°F). At a temperature of 24°C (75°F) the λ-value is approximately 0.05 (0.35); at 260°C (500°F) it is 0.1 (0.7), for a density of approximately 112 kg/m^3 (7 lb/ft^3).

Product Type 18 - Teflon, Rayon and Epoxies - These materials all have a λ-value at a temperature of 24°C (75°F) of about 0.22 (1.5).

3. Dynatherm Engineering
Contact Person: James B. Funkhouser
595 Marshan Lane
Lino Lakes, MN 55014
(612) 786-1853

Product Type 1 - Thermax board - [λ-value 0.022 (0.15) at temperatures between -17 to 74°C (0 to 165°F).]

Product Type 2 - extruded polystyrene - [λ-value of about 0.026 (0.18) at temperatures between -17 to 74°C (0 to 165°F).]

Product Type 3 - expanded polystyrene - [λ-value about 0.036 (0.25).]

Product Type 4 - expanded urethane - [λ-value about 0.022 (0.15).]

Product Type 5 - wood fiber board - [λ-value about 0.072 (0.5).]

Product Type 6 - perlite [λ-value ranges between 0.039 and 0.058 (0.27 and 0.40) for loose-fill perlite and between 0.072 and 0.134 (0.50 and 0.93) for concrete perlite.]

Product Type 7 - vermiculite [λ-value ranges between 0.048 and 0.059 (0.33 and 0.41) for loose-fill vermiculite and between 0.085 and 0.139 (0.59 and 0.96) for concrete vermiculite.]

Product Type 8 - fiber-glass blanket and board material [λ-value ranges between 0.035 and 0.050 (0.24 and 0.35) at 24°C (75°F).]

Heat-Transfer Apparatus - Guarded-Hot-Box.

4. Energy Materials Testing Laboratory (EMTL)
Contact Person: Mr. Lagedrost
Bidderford Industrial Park
Bidderford, ME 04005
(207) 282-5911

Product Type 1 - carbon fiber [λ-value ranges between 0.1 and 4 (0.7 and 28) at 24°C (75°F).]

Product Type 2 - graphite [λ-value about 2 (14) at a temperature of 24°C (75°F) and 0.3 (2) at high temperatures.]

Product Type 3 - ceramics [λ-value of about 4.3 (30).]

Heat-Transfer Apparatus - a Guarded-Hot-Plate and comparative measurements equipment.

EMTL measures all thermal properties on nearly all classes of solids, over the temperature range from below room temperature to 2760°C (5000°F). In the specific area of thermal conductivity, they have worked with materials having λ-values between 0.10 (0.7) and 300 (2080). The lower part of this range is usually evaluated with a steady-state technique (absolute or comparative) in the range up to about 1000°C (1832°F). For most materials and for most classes of solids with moderate to high λ-values and at the higher temperatures, they use a transient technique (laser pulse) to measure thermal diffusivity, from which thermal conductivity can, in most cases, be calculated.

For reference standards, they use those materials currently available. However, they feel a real need for standards in the moderate to low λ-value range, which can be used up to higher temperatures (1600°C or 2912°F). Their apparatus can operate at these temperatures, but the large mis-matches in λ-values of the specimens and the existing standards result in a potential for large errors.

5. Hauser Laboratories
   Contact Person: Rod McKeever
   5680 Central Ave.
   P. O. Box G
   Boulder, CO 80306
   (303) 443-4662

   Product Type 1 - glass fiber [λ-value of 0.049 (0.34) for low-density glass fiber and between 0.032 and 0.036 (0.22 and 0.25) for high-density glass fiber.]

   Product Type 2 - loose-fill [λ-value of about 0.046 (0.32).]

   Product Type 3 - cellulose products [λ-value ranges between 0.039 and 0.045 (0.27 and 0.31).]

   Heat-Transfer Apparatus - Heat-Flow-Meter (tests at room temperature)
   Hauser Laboratories would like to have transfer standards available at different temperatures for building applications.

6. Law Engineering Testing Company
   Contact Person: Mr. John Lynch
   P. O. Box 13260
   Atlanta, GA 30324
   (404) 873-4761

   Product Type - concrete [λ-value of approximately 0.35 (2.4) for cinder concrete, and of 1.21 (8.4) for stone concrete.]

7. Multi-Tech Corporation
   Contact Person: Dr. Ralph Goldman
   1 Strathmore Road
   Natick, MA 01760
   (617) 651-1030

   Product Type 1 - materials for insulating and clothing applications are tested using a heated flat plate to determine their R-value or clo-value.

Product Type 2 - materials, films and membranes for clothing applications are tested for their moisture permeability using a heated, sweating flat plate.

Product Type 3 - clothing items are tested for their insulation and permeability using a heated, sweating life-size manikin which can be operated still or walking.

Product types tested include: conventional and reflective insulations, PVC, PTFE, and similar waterproof but vapor permeable membranes, protective uniforms, sports clothing, raincoats, blankets, sleeping bags, etc.

8. National Association of Home Builders
Contact Person: Hugh Angleton
627 Southlawn Lane
Rockville, MD 20850
(301) 762-4200

Product Type 1 - low-density glass-fiber [λ-value ranges between 0.043 and 0.053 (0.30 to 0.37) for density range from 6 to 16 kg/m^3 (0.4 to 1.0 lb/ft^3).]

Product Type 2 - mineral wool fiber [λ-value ranges between 0.039 and 0.043 (0.27 to 0.30) for density of about 26 kg/m^3 (1.7 lb/ft^3).]

Product Type 3 - foil covered polyisocyanurate [λ-value ranges between 0.014 and 0.023 (0.10 and 0.16) as the density ranges from 24 to 32 kg/m^3 (1.5 to 2.0 lb/ft^3).]

Product Type 4 - expanded polystyrene [λ-value of about 0.040 (0.28) for a density of approximately 16 kg/m^3 (1 lb/ft^3).]

Product Type 5 - extruded polystyrene [λ-value of about 0.029 (0.20) for a density of approximately 26 kg/m^3 (1.6 lb/ft^3).]

Product Type 6 - blown mineral wool [λ-value ranges between 0.046 to 0.065 (0.32 to 0.45) as the density ranges from 10 to 26 kg/m^3 (0.6 to 1.6 lb/ft^3).]

Product Type 7 - wood fiber board [λ-value of about 0.055 (0.38); density of about 352 kg/m^3 (22 lb/ft^3).]

9. Technical Microns Control, Inc.
Contact Person: Mrs. Kathy Clayton
P. O. Box 1330
210 Synn Drive
Huntsville, AL 35805
(205) 837-4430

Product Type - loose-fill cellulose [λ-value of about 0.040 (0.28); density of 46 kg/m^3 (2.9 lb/ft^3).]

10. Underwriters Laboratories, Inc.
Contact Person: Bob Kingsbury
333 Pfingsten Road
Northbrook, IL 60062
(312) 272-8800

Product Type 1 - loose-fill cellulose [λ-value ranges between 0.039 and 0.042 (0.27 and 0.29), density ranges between 32 and 48 kg/m^3 (2 and 3 lb/ft^3).]

Product Type 2 - high-density polystyrene [λ-values range from 0.024 to 0.037 (0.17 to 0.26) at a nominal thickness of 25.4 mm (1 in) and over a density range from 32 to 56 kg/m^3 (2.0 to 3.5 lb/ft^3).]

Heat-Transfer Apparatus - Heat-Flow-Meter

UL is interested in having a standard at their conductivity and thickness test conditions.

11. United States Testing Co., Inc.
Contact Person: Bob Manno
1415 Park Avenue
Hoboken, NJ 07030
(201) 792-2400

Product Type 1 - loose-fill cellulose [λ-value ranges from 0.039 to 0.046 (0.27 to 0.32).]

Product Type 2 - glass-fiber blanket insulation [λ-value ranges between 0.035 and 0.050 (0.24 to 0.35) at 24°C (75°F).]

Product Type 3 - polyurethane [λ-value of approximately 0.026 (0.18).]

Product Type 4 - polystyrene [λ-value of approximately 0.033 (0.23).]

2.3 Universities [22]

1. Carnegie-Mellon University
   Pittsburgh, PA 15213
   Contact Person: Dr. Yao
   (412) 578-2508

Carnegie-Mellon does research on multi-phase heat transfer in connection with boiling phenomena. Work is conducted on droplet and spray combustion which could have an application in coal slurry work, and interest was expressed in λ-values of various metal alloys at very high temperatures and of fluorocarbons near critical temperatures. Another issue is the determination of the surface emittance at these test conditions. An area of research dealing with combustion requires the use of estimated thermal conductivity values of various mixtures of fuel from handbook sources, and these do not have the desired accuracy.

2. Clemson University
   Clemson, SC 29631
   Contact Person: Dr. Bishop
   (803) 656-3201

Dr. Bishop conducts research in the area of natural convection in horizontal cylindrical annuli at low-temperature (down to liquid nitrogen temperature). The medium is helium gas and the annulus pressure can be varied from low vacuum to 1724 kPa (250 psi). A maximum Rayleigh number of about 10^{12} can be achieved in the apparatus. The apparatus can also operate at high values of the temperature difference ratio, and thus, the effects of variable transport properties can be studied. Accurate values of the thermal conductivity of helium over a temperature range of 77 K to 280 K are required. Additional researchers are working on droplet evaporation and fluidized-bed heat transfer.

3. Cornell University
   Ithaca, NY 14853
   Contact Person: Dr. Torrance
   (607) 256-6253

Cornell University conducts research on the thermal properties of composites, such as solids/liquids or two solids (e.g. glass beads in water or in air). Another interest is geothermal studies. An apparatus was fabricated to measure thermal diffusivity, and this device uses a glass product from Corning-Glass for calibration purposes.

In the Chemical Engineering Department at Cornell University, Paul Steen does theoretical work on convection in porous materials.

4. Iowa State University
Ames, IA 50011
Contact Person: Dr. Martin
(515) 294-3344

Dr. Martin conducts research on plane periodic thermal waves; for example, the sun's radiation onto the earth creates a daily variation that can be sensed within a depth of 1 m below the earth's surface and a yearly variation which can be sensed within a depth of about 16 m into the earth. Experiments are carried out on bricks, and Fourier analysis results have shown that the drop off of intensity for higher harmonic is very rapid. For example, the first harmonic is only 0.4 percent of the fundamental frequency intensity. This university has also done research on refractories at temperatures as high as 1650°C (3000°F), but more typical temperatures lie in the 870°C (1600°F) range.

5. Massachussetts Institute of Technology (MIT)
Cambridge, MA 02139
Contact Person: Dr. Glicksman
(617) 253-2233

MIT has investigated polyurethane and phenolic foams in terms of coupled conduction and radiation heat transport. Research is oriented to the measurement of radiation scattering and the modeling of heat transfer on a microscopic level -- taking into account the actual structure of the insulation material. Studies were conducted on moisture phenomena in expanded polystyrene in terms of water vapor diffusion and condensate spreading. This research showed an increase of about 10 percent in λ-value with moisture. Measurements were made of the λ-value of the solid polymers used in insulation foams. That is, the crushed material which actually forms the cell structure, such as polyisocyanurate or polyurethane, was measured. The λ-values varied between 0.17 and 0.26 (1.2 and 1.8).

6. Purdue University
School of Mechanical Engineering
West Lafayette, IN 47906
Contact Person: D.P. DeWitt
(317) 494-5629

Purdue University researchers have done extensive work on high-temperature radiation heat transfer and thermophysical properties. Present activities include measurement of spectral emissivity from 600 to 1200 K and 0.6 to 12 μm. Simultaneous heat and moisture transport processes in the normal environmental temperature range are being experimentally studied using a calibrated, ASTM-hot-box apparatus. Purdue maintains a close association with the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) which is a data base resource for thermophysical properties of materials.

7. Rutgers University
New Brunswick, NJ 08903
Contact Person: Dr. Yaluria
(201) 932-3652

Rutgers University researchers are interested in natural and forced convection flow in air or water. The researchers have collaborated with NBS and with the Solar Energy Research Institute (SERI) in such studies. They are particularly interested in knowing the temperature dependence of the λ-value for materials such as polystyrene or masonite in the temperature range associated with building materials.

8. University of California
Berkeley, CA 94720
Contact Person: Professor Tien
(415) 642-7540

Professor Tien is paricularly interested in radiation contributions. For example, his group does calculations for radiation shielding in furnace chimneys for a temperature range between 540 and 1100°C (1000 and 2000°F). A practical application of this work is the reduction of the refractory wall temperature by about 40°C (100°F). In addition, his group does first principle calculations of radiation transport in ambient temperature fiber-glass for high and low temperatures. They have done some research on the 70 to 80 Å diameter microspheres from the Degussa Corporation and found the λ-value to be approximately 0.020 (0.14).

9. University of Delaware
Newark, DE 19711
Contact Person: Prof. Frank Kulacki
(302) 451-2421

Professor Kulacki conducts research on convection in porous medium. For example, he looks at borosilicate glass beads in liquids, and needs to know the λ-value of glass and of metals. In addition, he investigates composites, such as glass or carbon fibers and epoxies, and it is necessary to know the thermophysical properties up to temperatures of 260°C (500°F). In the case of aluminum fiber or boron ceramics, the high temperature limit is about 800°C (1500°F). Dr. Kulacki indicated that there is very little data for such thermophysical properties at high temperatures. The aerospace industry has collected data, but this is usually considered proprietary. Additional data are needed on the thermophysical properties at high temperatures. He is designing a test facility to do high-temperature work, so that such data will be available in the public domain.

10. University of Illinois
1206 W. Green, Rm168-MEB
Urbana, IL 61801
Contact Person: Dr. Richard Buckius
(217) 333-1079

Dr. Buckius is interested in radiation heat transfer and the combustion process, solar applications, and fluidized bed studies. Previously, he has done work on radiation transfer in gas and particulate mixtures, in fibrous materials and in microspheres. Experimental infra-red research provided data on radiation scattering properties in a pure particulate medium. He has also modeled coal-air mixtures used in coal combustion.

11. University of Massachusetts
    Amherst, MA 01003
    Contact: Dr. William P. Goss
    (413) 545-2037/2505

The Thermal Measurements Laboratory has a calibrated hot box and a guarded hot plate (now being fabricated). The calibrated hot box has recently been used to measure the thermal transmittances of reflective building insulation systems and window treatment products. The present calibration samples used are high density, glass-fiber boards (2 and 4 inches) and expanded polystyrene board (2 and 4 inches). There is an interest in obtaining low to high thermal conductance standards in the range of thicknesses of 0.5 to 4 inches for use in calibration of the hot box and of the window mask walls in the temperature range -17.8 to 65.6°C (0 to 150°F).

12. University of Mississippi
    University, MS 38677
    Contact Person: Dr. Alley Smith, Dr. Jeff Roux
    (601) 232-7407
    (601) 232-5375

The University of Mississippi research includes both work on radiation transfer through fibrous insulation material and the measurement of reflectance using integrating spheres. They have been modeling this transport process using a discreet ordinate technique and assuming a plane-parallel layer for the binder. They have also been studing innovative layered materials.

13. University of Oklahoma
    Norman, OK 73019
    Contact Persons: Tom Love and Will Sutton
    (405) 325-5011

Dr. Love's research deals with the experimental determination of the extinction coefficient and the albedo for fiber insulations. He uses integrating spheres to determine the diffuse transmittance and reflectance. He is interested in looking at foam insulation and insulations in vacuum as well. He has done some other work on multi-dimensional radiation scattering for high-temperature ceramic materials.

14. University of Pennsylvania
    Philadelphia, PA 19104
    Contact Person: Dr. Bau
    (215) 898-8363

The University of Pennsylvania conducts research on multi-phase porous medium, such as glass beads and liquids. This simulates physical phenomena in soils. They are also interested in natural convection in porous and non-porous media.

15. University of Washington
    Seattle, WA 98195
    Contact Person: Dr. Corlett
    (206) 543-8590

Dr. Corlett conducts research on underground coal gasification, and would like to know the λ-value for materials at all stages in this process.

Contact Person: Dr. Emery
(206) 543-5338

Dr. Emery has done studies involving radiation heat transport in high-temperature materials such as the space shuttle tile and ceramics. The temperatures of interest include 0 to 310 K (-460 to 100°F) and, for applications such as re-entry of space vehicles into the Earth atmosphere, 1300°C (2370°F). In the area of building insulation there is an interest in the problem of moisture phenomena in reflective foils, as well as in problems of slab-on-grade heat transfer, and this requires knowledge of the λ-value of soil. They are particularly interested in knowing the thermal diffusivities of the materials involved in their research.

16. Virginia Polytechnical Institute
    Blacksburg, VA 24061
    Contact Person: William Thomas
    (703) 961-7464

VPI research has investigated the use of a transient thermal technique using a thermistor probe to determine moisture content by measuring the λ-value of moist glass-fiber insulation specimens. An interest was expressed in calibration points between 0.045 to 0.30 (0.31 and 2.1).

2.4 Federal Laboratories [11]

1. Naval Oceanographic Research & Development Agency
   Contact Person: James Elkins
   Bay St. Louis, MS 39529
   (601) 688-4702

The agency is interested in λ-values of titanium steel, glass fiber, epoxies, thinsulite (diving suit), and teflon and neoprene rubber for temperatures ranging between -56 and 1100°C (-70 and 2000°F), depending on the application.

2. Naval Weapons Center
   Contact Persons: Dr. Jim Baldwin, Mr. J.P. Newhouse
   China Lake, CA 93555
   (619) 939-7392

The Naval Weapons Center has a high-temperature calorimeter apparatus to measure the heat flux of flames. They are interested in a new insulation system for rocket ramjet applications. The temperature is estimated to be about 2800°C (5000°F).

They have investigated a material called DC93104, produced by Dow Corning. This is a silica reinforced rubber with a carbon fiber in it. The high-temperature exposure converts the rubber to a carbon-fiber filled char. The λ-value at 40°C (100°F) is about 0.039 (0.27), and at 820°C (1500°F) it is about 0.043 (0.30).

Contact Person: Charles Beach
(619) 939-7392

Research is conducted on materials such as epoxy and special cork insulators at temperatures up to 200°C (400°F). They are interested in using these materials to protect electronics in aerospace applications. The hot- and cold-side temperatures might be 370°C (700°F) and 74°C (165°F). They also look at ablated coatings as a way to keep the temperatures of the electronic equipment low.

Contact Person: Kent Farmer
(619) 939-7225

Mr. Farmer is doing research on fire in airplanes. He is interested in materials that provide thermal protection. A deck fire can involve temperatures up to 1300°C (2300°F). An extensive study is beginning on the following types of materials. This study will include the characterization of these materials according to their thermophysical properties, such as λ-value.

(1) ceramic clothes
(2) insulating foams
(3) intumescent paints
(4) high-temperature silicone based corks
(5) honey-comb materials such as fiber-phenolic for high-temperature applications and hybrids of these with other types of materials.
(6) ablative (phase-change) materials such as tar coating
(7) selective emissivity materials which would irradiate heat selectively for the temperature range of use
(8) microspheres, both by themselves and in hybrid with other materials such as rubber
(9) adhesive systems
(10) thermal barrier, such as high-temperature polystyropolodeens or silicon carbide.

Contact Person: Dick Compton
(619) 939-2866

The research includes aerodynamic heating of missiles in flight. It is done with a propane torch and a wind tunnel. The λ-value is a parameter in their studies, and for the most part they use the data resources listed in references [13, 14, and 15]. They consider materials such as ceramics, various composites, pyro ceram, explosives and propellants, adhesives (they are specially interested in the λ-value of these materials), and silicone rubber. They are very interested in radiation properties, such as emissivity, of materials in the temperature range between 800 and 1400°C (1500 to 2500°F).

3. Clothing and Textile Research Facility (Navy)
   Contact Person: Joe Gible
   Natick, MA 01760
   (617) 651-4740

The Navy has a guarded-hot-plate with a sweating feature to determine vapor permeability. Measurements are made of the λ-value and the permeability for a wide range of clothing.

4. Natick R & D Laboratory
   Contact Person: Deirdre Rapacz
   Natick, MA 01760
   (617) 651-4273

Measurements are made of the thermal transport properties of materials utilized in cold weather clothing applications, including various denier polyester and polyolefin fibrous battings, down, needled felts, foams, fleeces and apparel fabrics. The λ-values range from 0.032 to 0.110 (0.13 to 0.77), and the density ranges from 4.8 to 292 kg/m^3 (0.30 to 18 lb/ft^3). A guarded-hot-plate and a heat-flow-meter apparatus are utilized with the hot-plate temperature maintained at 33°C (92°F). Also, a bi-guarded hot plate with a sweating feature is used to determine the moisture vapor permeability index of textiles.

5. U.S.A. Cold Regions Laboratory (Army)
   Contact Person: Steve Flanders
   72 Lyme Road
   Hanover, NH 03755
   (603) 646-4302

The Cold Region Laboratory conducts building-system investigations using a calibrated hot box; thus they need to know the λ-value for standard building materials, such as insulation and wood. They have a guarded hot plate and two heat flow meters. Their soils research requires the use of these apparatus for thermal measurements. They have also done some work on moist solids.

2.5 Department of Energy

1. Lawrence Berkeley Laboratory (LBL)
   Contact Person: Michael Rubin
   University of California
   Berkeley, CA 96720
   (415) 486-7124

Dr. Rubin has conducted research on silica aerogel, which is the 100 Å material produced by the Degussa Corporation. LBL has made it into cakes using a gel and extracting the solvent super-critically. The λ-value is about 0.020 (0.14); also, this material can be used at high temperatures. It can also be used for window insulation because there is very little scattering of the visible radiation, and, hence, the material is transparent. There is a need to measure the λ-value of thin films on plastic, for application as an infra-red reflecting heat mirror.

2. Lawrence Livermore National Laboratory
Contact Person: Bob Trusty
P.O. Box 808 L-145
Livermore, CA 94550
(415) 422-7401

This laboratory has tested specimens over a λ-value range of 0.030 to 4.76 (0.21 to 33). This includes polyurethane, foams, plastics, composites, aluminum-honeycomb material, ebonite, metals, and graphite. The tests are carried out on a 4-inch guarded hot plate, a thermal comparator (for higher λ-values), and a 1.06 μm laser, flash diffusivity device (for the metals). The thermal comparator requires calibration specimens over a wide range of λ-value. A concern was expressed over calibration-standard, material variability errors caused by forming the standard material into the sizes and shapes required by different testing stations. In addition to making thermal diffusity measurements, they make thermal expansion, specific heat, and density measurements on many materials.

3. Oak Ridge National Laboratory
Contact Person: Dave McElroy
P. O. Box X
Oak Ridge, TN 37830
(615) 574-4193

Testing is done over a wide range of λ-value and temperature with a number of apparatuses. In addition to testing typical building insulation such as glass-fiber at high and low densities, mineral-fiber, expanded polystyrene and blown-wool, there is a current effort to study evacuated panels which have an effective λ-value of 0.009 (0.06) at a thickness of 50 mm (2 in). They have tested a fiber-board material with a λ-value of about 0.072 (0.5) and a density of 320 kg/m^3 (20 lb/ft^3). They have tested about 20 loose-fill powders. At 24°C (75°F), a 7 milli-micron micro-powder was found to have a λ-value of 0.021 (0.146), and a 12 milli-micron one had a λ-value of 0.020 (0.139). An amorphous silica microsphere with a diameter of about 1 μm had a λ-value of about 0.03 (0.21), and a coarse alumina loose-fill material had a λ-value of 0.28 (1.94). They have tested a high-temperature carbon-fiber insulation. The λ-value ranges between 0.1 and 4 (0.7 and 28) at 24°C (75°F); and, it can be used at temperatures up to 930°C (1700°F). They plan to test an alumina fiber (λ-value of about 0.033 (0.23) for temperatures between 24 and 930°C (75 and 1700°F).

The following areas of need for standards were emphasized: thermal diffusivity (including specific heat and density data), thermal expansion, and radiation transport properties such as the emissivity, the extinction coefficient, and the absorption and scattering coefficients. These were considered to be necessary for an adequate description of real or practical applications.

4. Sandia National Laboratory
Albuquerque, NM 87185
Contact Person: Ron Hadley
(505) 844-3449

Tuff volcanic rock has been examined as a candidate medium for nuclear waste storage. The dry material has a λ-value of approximately 1 (7) at 60°C (140°F). The λ-value as a function of moisture content is of interest.

Contact Person: Marvin Moss
(505) 844-7307

Sandia has a number of instruments for the measurement of the apparent thermal conductivity of materials ranging from good insulators to pure metals. Three of these instruments were supplied by Dynatech R/D Company: the Model TCFCM comparator, the Model TCFGM guarded hot plate, Colora Thermoconductometer.

The comparator covers the range λ = 0.1 to 100 (0.69 to 690) over temperatures from - 196 to 850°C (320 to 1560°F). The comparator measurements are accurate within 5-10 percent, and these rely on known conductivities of one of four reference materials, depending on the λ range covered: Pyrex 7740, Pyroceram 9606, Inconel 718, and a pure grade of iron. The first two products are made by Corning Glass Works.

The guarded hot plate operates in the range of λ of 0.02 to 2 (0.14 to 14) over temperatures from -196 to 850°C (-320 to 1560°F). Measurements are absolute and are considered accurate within 2-5 percent.

The Colora Thermoconductometer allows relatively rapid measurement of small samples at 33°C (90°F), 94°C (200°F), 120°C (250°F), and 170°C (340°F). The conductivity range is λ = 0.1 to 100 (0.69 to 690). The measurement involves the evaporation of a liquid of known heat of vaporization by means of heat passing through the sample. The time required to distill a given quantity of the liquid is used to calculate λ. The accuracy is 5-10 percent, and it is used for materials such as glass, adhesives and metals.

Contact person: Dr. William D. Drotning
(505) 844-7934

A Sandia-developed thermal conductivity probe is available for measurement of the λ-value of liquids, powders, porous solids and other low-conductivity materials. The instrument is useful to 1000°C (1833°F) and works best for $\lambda \leq 0.1$ (0.69).

Contact Person: Dr. E. Peter Roth
(505) 844-7934

A Sandia-developed laser-flash system can measure the thermal diffusivity of solid materials in the temperature range 50-3000°C (122-5430°F).

APPENDIX 3. Attendees at the Assessment Issues Work-session held at the National Bureau of Standards on July 13, 1984.

Ron Adams	Owens-Corning Fiberglas
Bill Gerken	Department of Energy
David M. Greason	Dow Chemical
Lee Kieffer	Office of Standard Reference Materials
Edward Kifer	Koppers Corporation
Dave McCaa	CertainTeed Corporation
David McElroy	Oak Ridge National Laboratory
Richard L. Troyer	Manville Services Corporation
Ron Tye	Testing Services Dynatech
Brian Rennex	Center for Building Technology, NBS
Tom Faison	" "
Frank Powell	" "

APPENDIX 4. Alphabetical List of Insulating Materials in Appendix 2

	APPARENT THERMAL CONDUCTIVITY*	
PRODUCT NAME OR TYPE	SI UNITS W/m•K	ENGLISH UNITS Btu•in/ft^2•hr•°F
Aercor Aircraft Insulation	0.030 - 0.036	0.21 - 0.25
Aercor-Black	0.033	0.23
Air Craft Insulation (fine glass-fiber)	0.035	0.24
Aluminum-Silicate Refractory Fiber Insulation Blanket	0.033	0.23
Blowing Wool	0.046 - 0.065	0.32 - 0.45
Borosilicate Glass	1.042	7.14
Calcium Silicate	0.058	0.40
Cellulose	0.039 - 0.045	0.27 - 0.31
Closed-Cell Foam Glass	0.061	0.42
Concrete: cinder	0.35	2.4
stone	1.21	8.4
Down	0.040	0.28
Duct Board	0.033	0.23
Felted Ceramic Fiber	0.062	0.43
Fibair Filter Media	0.081 - 0.125	0.56 - 0.87
Foil Face Insulation	0.020	0.14

*Because of the nature of this report to assess the kinds of products that are actually in use, there will be an occasional use of a trade name or a manufacturer's name. This in no way represents an endorsement of a particular product or manufacturer. The thermal parameter values for the various insulating materials were obtained from the literature or from researchers. These values were not based on experimental research at NBS.

PRODUCT NAME OR TYPE	APPARENT THERMAL CONDUCTIVITY SI UNITS W/m•K	APPARENT THERMAL CONDUCTIVITY ENGLISH UNITS $Btu \cdot in/ft^2 \cdot hr \cdot °F$
Glass-Fiber: low-density	0.049	0.34
Glass-Fiber: high-density	0.032 - 0.036	0.22 - 0.25
Glass-Fiber Appliance Insulation Blanket	0.035 - 0.049	0.24 - 0.35
Glass-Fiber for Industrial Insulation	0.030	0.21
Glass-Foam	0.056	0.39
High-Density Molded Fibrous Glass Board	0.032	0.22
Insulation Cement	0.097	0.67
Loose-Fill Mineral Fiber	0.045	0.32
Loose-Fill Cellulose	0.040	0.28
Low-Density Blanket	0.047 - 0.049	0.33 - 0.34
MBI: low-density	0.049	0.34
MBI: high-density	0.038	0.26
Matted Glass Fibers	0.045	0.31
Microspheres (Fumed Silica)	0.027	0.19
Mineral Fiber	0.040	0.28
Mineral Rock Board	0.043	0.30
Navy Board	0.032	0.22
Open-Cell Phenolic Foam	0.035	0.24
P 80 Molded: low-density	0.033	0.23
P 80 Molded: high-density	0.046	0.32

PRODUCT NAME OR TYPE	APPARENT THERMAL CONDUCTIVITY SI UNITS W/m•K	APPARENT THERMAL CONDUCTIVITY ENGLISH UNITS Btu•in/ft^2•hr•°F
Perlite: loose-fill	0.039 - 0.058	0.27 - 0.40
concrete	0.072 - 0.134	0.50 - 0.93
Phenolic Foam (closed-cell)	0.032 - 0.136	0.22 - 0.94
Polyisocyanurate Foam	0.020	0.14
Polystyrene: extruded	0.029	0.20
molded	0.033 - 0.038	0.23 - 0.26
expanded	0.040	0.28
Polyurethane	0.023 - 0.025	0.16 - 0.17
Rayon	0.216	1.5
Rigidized Silica Fibertile	0.036	0.25
Rock & Slag Wool: batts	0.039 - 0.045	0.27 - 0.31
loose-fill	0.049	0.34
Rockwool Mineral Fiber	0.036	0.25
Silica Aerogel Composite Block	0.026	0.18
Silicone Rubber	0.245 - 0.361	1.70 - 2.50
Teflon	0.216	1.5
Thermax	0.016 - 0.020	0.11 - 0.14
Thinsulate 200	0.036	0.25
TIW	0.033	0.23
Truck Decking	0.173	1.20
Urea-Formaldehyde Foam	0.035	0.24
Vermiculite: loose-fill	0.048 - 0.059	0.33 - 0.41
concrete	0.085 - 0.139	0.59 - 0.96

	APPARENT THERMAL CONDUCTIVITY	
PRODUCT NAME OR TYPE	SI UNITS $W/m \cdot K$	ENGLISH UNITS $Btu \cdot in/ft^2 \cdot hr \cdot °F$
Vinyl Flooring Material	0.082 - 0.100	0.57 - 0.69
Wood Fiber Board	0.056	0.39
Wood Fiber Sheating	0.055	0.38
Zirconia Fiber Board	0.087	0.60

APPENDIX 5. List of Insulating Materials in Appendix 2 by Decreasing Thermal Conductivity Value.

APPARENT THERMAL CONDUCTIVITY* SI UNITS W/m•K	ENGLISH UNITS Btu•in/ft^2•hr•°F	MATERIAL OR PRODUCT NAME
1.21	8.4	Concrete (stone)
1.042	7.14	Borosilicate Glass
0.35	2.4	Concrete (cinder)
0.245 - 0.361	1.70 - 2.50	Silicone Rubber
0.216	1.5	Rayon
0.216	1.5	Teflon
0.173	1.2	Truck Decking
0.097	0.67	Insulation Cement
0.087	0.60	Zirconia Fiber Board
0.085 - 0.139	0.59 - 0.96	Vermiculite (concrete)
0.082 - 0.100	0.57 - 0.69	Vinyl Flooring Material
0.081 - 0.125	0.56 - 0.87	Fibair Filter Media
0.072 - 0.134	0.50 - 0.93	Perlite (concrete)
0.062	0.43	Felted Ceramic Fiber
0.061	0.42	Closed-Cell Foam Glass
0.058	0.40	Calcium Silicate
0.056	0.39	Wood Fiber Board
0.056	0.39	Glass-Foam
0.055	0.38	Wood Fiber Sheathing

*Because of the nature of this report to assess the kinds of products that are actually in use, there will be an occasional use of a trade name or a manufacturer's name. This in no way represents an endorsement of a particular product or manufacturer. The thermal parameter values for the various insulating materials were obtained from the literature or from researchers. These values were not based on experimental research at NBS.

SI UNITS W/m•K	ENGLISH UNITS Btu•in/ft^2•hr•°F	MATERIAL OR PRODUCT NAME
0.049	0.34	Glass-Fiber (low-density)
0.049	0.34	MBI (low-density)
0.049	0.34	Rock & Slag Wool (loose-fill)
0.048 - 0.059	0.33 - 0.41	Vermiculite (loose-fill)
0.047 - 0.049	0.33 - 0.34	Low-Density Blanket
0.046 - 0.065	0.32 - 0.45	Blowing Wool
0.046	0.32	P 80 Molded (high-density)
0.046	0.32	Loose-Fill Mineral Fiber
0.045	0.31	Matted Glass Fibers
0.043	0.30	Mineral Rock Board
0.040	0.28	Down
0.040	0.28	Polystyrene (expanded)
0.040	0.28	Mineral Fiber
0.040	0.28	Loose-Fill Cellulose
0.039 - 0.058	0.27 - 0.40	Perlite (loose-fill)
0.039 - 0.045	0.27 - 0.31	Cellulose
0.039 - 0.045	0.27 - 0.31	Rock & Slag Wool (batts)
0.038	0.26	MBI (high-density)
0.038	0.26	Polystyrene Beadboard
0.036	0.25	Thinsulate 200
0.036	0.25	Rigidized Silica Fibertile
0.036	0.25	Rockwool Mineral Fiber
0.035 - 0.049	0.24 - 0.35	Glass-Fiber Appliance Insulation
0.035	0.24	Urea-Formaldehyde Foam

APPARENT THERMAL CONDUCTIVITY SI UNITS W/m•K	ENGLISH UNITS Btu•in/ft^2•h •°F	MATERIAL OR PRODUCT NAME
0.035	0.24	Air Craft Insulation (fine glass-fiber)
0.035	0.24	Open-Cell Phenolic Foam
0.033 - 0.038	0.23 - 0.26	Polystyrene (molded)
0.033	0.23	TIW
0.033	0.23	Aluminum-Silicate Refractory Fiber Insulation Blanket
0.033	0.23	P 80 Molded (low-density)
0.033	0.23	Aercor-Black
0.033	0.23	Duct Board
0.032 - 0.036	0.22 - 0.25	Glass-Fiber (high-density)
0.032	0.22	High-Density Molded Fibrous Glass Board
0.030 - 0.036	0.21 - 0.25	Aercor Aircraft Insulation
0.030	0.21	Glass-Fiber for Industrial Insulation
0.029	0.20	Polystyrene (extruded)
0.027	0.19	Microspheres (Fumed Silica)
0.026	0.18	Silica Aerogel Composite Block
0.023 - 0.025	0.16 - 0.17	Polyurethane
0.020	0.14	Foil Face Insulation
0.020	0.14	Polyisocyanurate Foam
0.016 - 0.020	0.11 - 0.14	Thermax
0.010 - 0.13	0.07 - 0.09	Phenolic Foam (closed-cell)

APPENDIX 6. Insulation Manufacturers' Associations

6.1. Mineral Insulation Manufacturers' Association, Inc. (MIMA)
Summit, NJ 07901
(201) 277-1550

6.1.1. Member Companies

a. L. C. Cassidy & Son, Inc. 1918 So. High School Road Indianapolis, IN 46241	Don Cassidy, Sr. Chairman of the Board (317) 241-6391
b. Certain-Teed Corporation P. O. Box 860 Valley Forge, PA 19482	G. A. Hoffmann Vice-President Residential Marketing (215) 687-5000
c. Guardian Industries Corp. 1000 E. North Street Albion, MI 49224	Richard T. Galloway Vice-President Sales & Marketing (517) 629-9464
d. Knauf Fiber Glass 240 Elizabeth Street Shelbyville, IN 46176	Jeffrey R. Brisley Market Manager Residential Manufactured Housing (317) 398-4434
e. Manville Building Materials Corp. P. O. Box 5108 Denver, CO 80217	D. W. Korte Vice-President General Merchandising Manager Fiberglass Building Insulation Div. (303) 978-2809
f. Owens-Corning Fiberglas Corp. 4 Fiberglas Tower Toledo, OH 43659	B. G. Woodham, Jr. Manger Technical Services Department Insulation Operating Division (419) 248-8513
g. Rock Wool Manufacturing Co. P. O. Box 506 Leeds, AL 35094	E. F. Cusick, Jr. Vice-President Sales (205) 699-6121
h. Rockwool Industries, Inc. P. O. Box 5170 Denver, CO 80217	S. L. Matthews Vice-President Technical Services & Government Affairs (303) 773-6200
i. United States Mineral Products Co. Stanhope, NJ 07874	J. P. Verhalen President (201) 347-1200

6.1.2. Mailing List of Non-Member Companies

a.	Bethlehem Steel Corp. Stone & Slag Division Bethlehem, PA 18016	Harry Campbell
b.	Carney Insulation Corp. 1009 W. 80th Street Bloomington, MN 55420	R. L. Wallentine (612) 881-3837
c.	Fiberfine P. O. Box 3055 901 Mitchell Road Memphis, TN 38109	Bruce Graybeal
d.	Forty-Eight Insulations, Inc. P. O. Box 1148 Aurora, IL 60507	Victor Von Schlagel
e.	Masa 1402 Dunlavy Houston, TX 77019	R. Bertrams (713) 521-1451
f.	Spring Hope Rockwool, Inc. Box 880, Spring Hope, NC 27856	Barton W. Bromley (919) 478-5111
g.	Sun Insulation Company 1474 Valley Industrial Park Blvd. Casa Grande, AZ 85222	Charles W. Miller
h.	U. S. Pipe & Foundry Company 3300 First Avenue, North Birmingham, AL 35202	Harold Hall
i.	United States Gypsum Company 101 S. Wacker Drive Chicago, IL 60606	Bruce Wittrup

6.2. Thermal Insulation Manufacturers' Association (TIMA)
7 Kirby Plaza
Mt. Kisco, NY 19549
(914) 241-2284

6.2.1. Member Companies

a.	Apache Building Products Company 2025 E. Linden Avenue Linden, NJ 07036	W. H. Hill (201) 486-6723

b.	Babcock & Wilcox P. O. Box 923 Augusta, GA 39093	M. A. Pereyo (404) 798-8000
c.	Benoit Industries, Inc. 36-26 Binz-Engleman Road San Antonio, TX 78219	J. Willing (800) 531-1078
d.	Carborundum Company P. O. Box 337 Niagara Falls, NY 14302	W. J. Breitsman (716) 278-6349
e.	Celotex Corporation 1500 North Dale Mabry Tampa, FL 33607	E. F. Levin (813) 871-4545
f.	C-E Refractories P. O. Box 828 Valley Forge, PA 19482	P. J. Longua (215) 337-1100
g.	CertainTeed Corporation P. O. Box 860 Valley Forge, PA 19482	L. J. Law (215) 341-7134
h.	GAF Corporation 1361 Alps Road Wayne, NJ 07470	W. C. Schwingen (201) 628-4130
i.	Homasote Company P. O. Box 7240 West Trenton, NJ 08628	P. D. Petrino (609) 883-3300
j.	International Permalite, Inc. 300 N. Haven Avenue Ontario, Canada 91761	J. Carcich (714) 983-9591
k.	Knauf Fiber Glass 240 Elizabeth Street Shelbyville, IN 46176	D. G. Anewalt (317) 398-4434
l.	Koppers Company, Inc. 700 Koppers Building Pittsburgh, PA 15219	W. Spencer (412) 227-2272
m.	Manville Products Corporation Ken-Caryl Ranch Denver, CO 80217	W. R. Browne (303) 978-2000

n.	NRG Barriers, Inc. 61 Emery Street Sanford, ME 04073	W. S. Jelin (207) 324-7745
o.	Owens-Corning Fiberglas Corp. Fiberglas Tower Toledo, OH 43659	L. T. Solari (419) 248-8753
p.	Pabco Insulation Division P. O. Box 1328 Ruston, LA 71270	K. P. Cachill (318) 251-2920
q.	Pittsburgh-Corning Corp. 800 Presque Isle Drive Pittsburgh, PA 15239	C. P. Smolenski (412) 327-6100
r.	Rmax, Inc. 13524 Welch Road Dallas, TX 75234	R. W. Griner (214) 387-4500
s.	Rock Wool Manufacturing Company P. O. Box 506 Leeds, AL 35094	E. F. Cusick, Jr. (205) 699-6121
t.	Temple-Eastex, Inc. P. O. Box Drawer N Diboll, TX 75941	A. Tillery (409) 829-1219
u.	Thermal Systems, Inc. 2250 S. Redwood Road, Suite 2 Salt Lake City, UT 84119	H. L. Woodcock (801) 972-6650
v.	U. S. Gypsum Company 101 South Wacker Drive Chicago, IL 60606	W. B. McManus (312) 312-4000

6.3. Rubber Manufacturers' Association
1400 K Street, NW
Washington, DC 20005
(202) 682-4818

6.4. Society of Plastic Industries
355 Lexington Avenue
New York, NY 10017
(212) 573-9400

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Thermal insulation specimens are required by users to calibrate their heat transfer apparatuses. This report assesses the need for additional calibration specimens to cover a wider range of test conditions and materials. It examines two major sources of measurement error related to the use of calibration specimens. The first is due to the lack of uniformity over a specimen area and the second is due to systematic apparatus errors which vary with the values of specimen mean temperature and thermal conductivity. Possible solutions to these problems are given, based on information obtained from users in universities, industry, and government laboratories. These include recommendations to provide calibration specimens over a wide range of values of specimen temperature and thermal conductivity.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

apparent thermal conductivity; calibration; guarded hot plate; heat flow meter; standard reference material; thermal insulation; thermal properties; thermal resistance.

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