The Testing of Thermal Insulators

At the turn of the 20th century the refrigeration industry in the United States was becoming a commercial reality. Mechanical refrigeration technology had achieved economic viability as a means of producing ice for cooling and was on the threshold of moving into households as an everyday appliance. Advances were underway to provide mechanical "air conditioning" for public buildings, such as theaters, department stores, and skyscrapers. In general, the early 1900s saw the evolution of a scientific approach to refrigeration through company-sponsored research and development. It was the technical progress in the area of cooling and heating for industrial processes and thermal comfort that stimulated the development of thermal insulation standards at NIST.

As described in *Measures for Progress: A History of the National Bureau of Standards,* Congress, at the request of the refrigeration industry, appropriated funding in 1913 for investigation of physical constants involved in the construction and operation of large-scale refrigeration machinery. Under Hobart C. Dickinson, D. R. Harper 3rd, and N. S. Osbourne, studies were conducted that included the investigation of insulating materials used in the construction of large-scale refrigeration structures. Of particular interest to the mechanical engineer was the development of usable data pertaining to heat transmission in thermal insulation needed for design purposes. For this purpose, Dickinson is credited with independently developing an absolute method of measurement called the guarded hot plate for homogenous slab-like materials.

In 1916, Dickinson and fellow NBS colleague Milton S. Van Dusen published *The Testing of Thermal Insulators* [1], a classic description of an NBS study to identify the causes of discordant experimental results for heat transfer through homogeneous solid materials and engineering systems. The publication contained accurate determinations of heat flow through air spaces and through 30 insulating materials; it also promoted the usage of standard terminology for thermal conductivity measurements obtained for solid materials and compound walls. Shortly after their first publication, Van Dusen published *The Thermal Conductivity of Heat Insulators* [2], which provided detailed information on the design and theory of operation of the apparatus, as well as additional thermal conductivity measurements of insulating materials. Important and insightful publications in their day, these papers are still considered recommended reading for all students of heat transfer through thermal insulation.

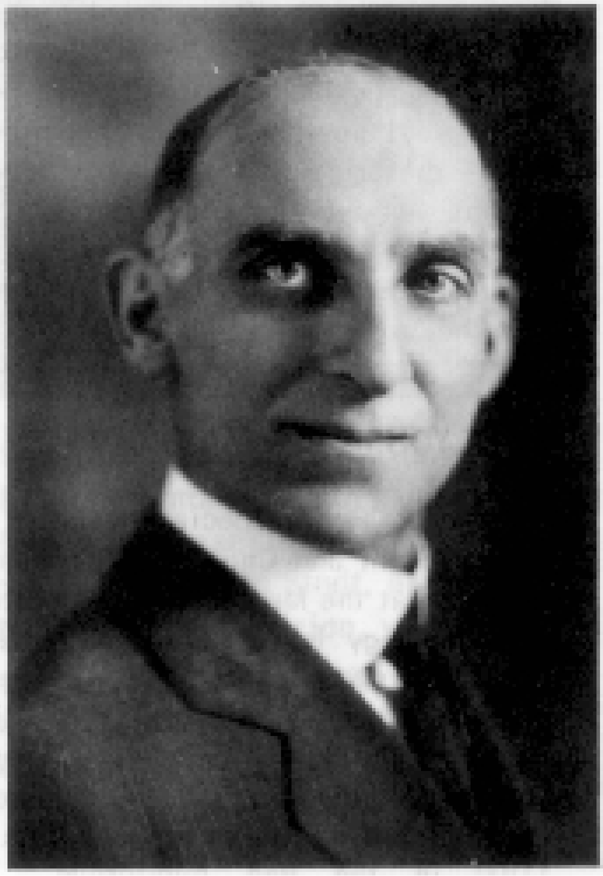

Fig. 1. Hobart C. Dickinson (1875-1949). While traveling in Europe, Dickinson learned that Richard Poensgen in Germany had independently developed and been using a guarded hot plate for thermal conductivity measurements since 1910. Thus, Poensgen is generally credited as the first to develop the guarded hot plate method.

At NBS the guarded hot plate quickly became the foundation for thermal conductivity measurements of heat insulators, and this encouraged the development of other apparatus for the measurement of thermal conductivity of solids, not only for building materials but also for metals, refractories, and ceramics. In fact, one might argue that either directly or indirectly the apparatus has motivated nearly eight decades of thermal conductivity work on solids at NBS/NIST. An early spin-off was the development of the guarded hot box, which was based on similar principles of operation and was utilized for heat transmission measurements of simple and compound walls. From 1915 to 1934,Van Dusen and others developed a comparative apparatus for measuring the thermal conductivity of metals up to 600 °C. Late in his career, in 1948, Dickinson developed a relatively simple steady-state method for thermal conductivity measurements of refractory solids. The apparatus employed a steam calorimeter for measuring the thermal conductivity of refractory solids from 400 °C to 1500 °C [3].

The long-term impact of the guarded hot plate technology was evident in several areas outside NBS. One of the first was the outgrowth of consensus engineering design data. The guarded hot plate originally developed by Dickinson and Van Dusen was refined over several years, and about 1928 Van Dusen [4] constructed a version of the apparatus that operated consistently until 1983. The thermal conductivity data obtained from this apparatus, along with the data from the early NBS publications [1,2], were aggregated with other data and tabulated in handbooks as design heat transmission coefficients for the engineer. These design data have served the engineering community effectively for several decades. In recent years, most of the original NBS data has been compiled in electronic format and will be available in NIST Standard Reference Database 81, *Heat Transmission Properties of Insulating and Building Materials* (Web Version 1.0).

However, the single most important impact of the guarded hot plate technology was the standardization of the test method in North America. This remarkable step has been extremely effective in reducing the differences among laboratories with respect to thermal testing. After many years of effort, NBS researcher Henry E. Robinson and others produced a tentative edition of the test method in 1942. By joint action, the American Society of Heating and Ventilating Engineers (ASHVE), American Society for Testing and Materials (ASTM), American Society for Refrigeration Engineers (ASRE), and the National Research Council (NRC) produced a *Standard Method of Test for Thermal Conductivity of Materials by Means of the Guarded Hot Plate.* In 1945, the method was formally adopted as a standard and designated ASTM Test Method C 177. The code set up the requirements for conducting tests and for construction of a guarded hot plate apparatus. It is interesting to note that the standard's adjunct still contains the design drawings for the 1929 version of the NBS guarded hot plate apparatus. ASTM Test Method C 177 became the cornerstone for all thermal insulation testing in North America. Over the decades, the standard test method has achieved international acceptance as the most accurate absolute test method for the measurement of thermal conductivity of heat insulators.

Robinson was instrumental in disseminating ASTM Test Method C 177 through laboratory intercomparison testing, development of insulation reference materials, and refinement of the measurement method. In 1947, Robinson and colleague Thomas W. Watson extended the temperature range of Van Dusen's guarded hot plate apparatus. A few years later, NBS completed one of the first published laboratory intercomparisons of thermal conductivity tests of insulation [5].

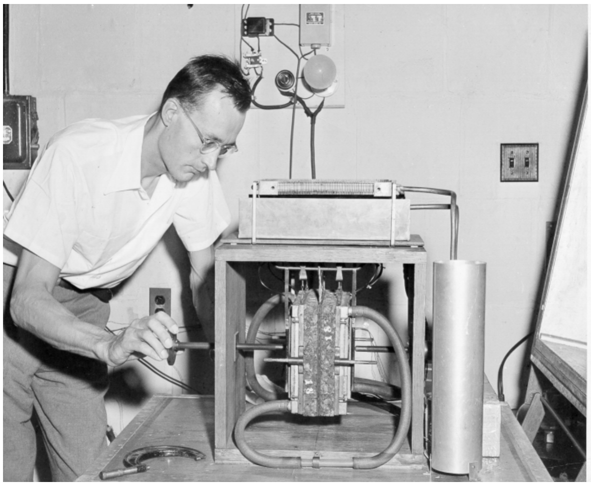

Fig. 2. Henry E. Robinson (1911-1972), installing a pair of corkboard specimens for interlaboratory testing (circa 1948).

This series of tests clearly demonstrated the need for suitable means to calibrate the apparatus at industrial and other laboratories. Shortly thereafter, a program was devised for supplying to industry measured samples of suitable insulating materials for calibration purposes. By 1977 more than 300 laboratories had been served, resulting in considerable improvement in the quality of thermal conductivity data on insulating and building materials reported in technical journals and handbooks. In 1977 the ASTM Committee C-16 on Thermal and Cryogenic Insulating Materials recommended that this program become an official part of the NBS Standard Reference Materials Program. Presently, NIST provides the thermal testing community with several thermal insulation SRMs for thermal resistance.

In 1964, Robinson presented an elegant modification of the test method. The basic design of a line-heat-source guarded hot plate was presented to a thermal conductivity conference sponsored by the National Physical Laboratory in England. The design was reported in Nature [6] as follows:

> *H. E. Robinson (U.S. National Bureau of Standards) discussed forms of line heat sources that could be used as heaters in apparatus for measurements at lower temperatures on insulating materials in disk and slab form. These new configurations lend themselves more readily to mathematical analysis, they are more simple to use and would appear to be able to yield more accurate results.*

The design was novel. In contrast to a (conventional) guarded hot plate that used uniformly distributed heaters, line-heat-source guarded hot plates utilized circular line-heat sources at precisely specified locations. By proper location of the line-heat-source(s), the temperature at the edge of the meter plate can be made equal to the mean temperature of the meter plate, thereby facilitating temperature measurements and thermal guarding. The benefits offered by a line-heat-source guarded hot plate included simpler methods of construction; improved accuracy; simplified mathematical analyses for calculating the mean surface temperature of the plate as well as determining the errors resulting from heat gains or losses at the edges of the specimens; and superior operation under vacuum conditions.

After Robinson, another generation of NBS researchers continued development of the line-heat-source technology. In 1971, M. H. Hahn [7] conducted an in-depth analysis of the line-heat-source concept and investigated several design options. The design, mathematical analysis, and uncertainty analysis for a prototype line-heat-source guarded hot plate were published in 1974 by Hahn, Robinson (posthumously), and D. R. Flynn [8]. Construction of the prototype apparatus was completed in 1978 [9]. Because of the promising results from the prototype, NIST began plans for a second, larger line-heat-source guarded hot plate apparatus. In 1980, a ruling by the U.S. Federal Trade Commission concerning the labeling and advertising of home insulation dramatically accelerated the construction of this apparatus.

With the energy crisis in the 1970s, there was growing demand for thick insulation and a resulting concern from the Federal Trade Commission that the existing standards for insulation measurement, based on 25 mm thick specimens, were not protecting consumers' interests. In response to concerns from industry and the Federal Trade Commission, NBS expedited development of the one-meter line-heat-source guarded hot plate. Near the end of 1980, the second line-heat-source guarded hot plate apparatus was completed with the efforts of Hahn, B. A. Peavy, F. J. Powell, and others [10]. Industry subsequently testified to Congress [11] that the improved accuracy provided savings of $90 million per year to consumers in insulation costs alone. It is not surprising that NIST now plans to continue developing the measurement technique into the 21st century with a new design that will extend the current temperature range.

After starting at NBS in 1903, Hobart C. Dickinson was the co-author of several fundamental papers on thermometry. In 1910, he returned to Clark University for his Ph.D. His doctor's thesis was on combustion calorimetry, and his calorimeter design, with some refinements, yielded the most accurate results attainable for its time. From 1912 to 1917 he was in charge of work at the Bureau of Standards on the constants of refrigeration in a program sponsored by the American Society of Refrigeration Engineers. His contributions to this program were papers on the calorimetry of ice and on the thermal conductivity of insulating materials. At the onset of World War I, the Bureau Director, Samuel Wesley Stratton, asked him to assist in the development of aircraft engines, and he participated in the design of the Liberty Engine, which was one of the engineering triumphs of that time. After the war the activities of the section were expanded to embrace automobiles and their behavior on the road. From 1921 to 1923 he organized and directed the research department of the Society of Automotive Engineers at the headquarters in New York City, and in 1933 he was president of that society.

Dickinson was an ardent hiker and preferred to spend his vacations in the mountains. In his later years he served the Potomac Appalachian Trail Club in its program of shelter building. On his first trip to the Canadian Rocky Mountains with the Alpine Club of Canada he took only a small spare blanket and water-repellent sheet when he should have taken all his own bedding. Confronted with bleak prospects, he remembered his measurements on insulating materials, and with his usual resourcefulness gathered balsam boughs in considerable quantity to put between his blanket and his sheet. The result astonished him, and he soon learned that a relatively small thickness of balsam furnished sufficient insulation to keep him pleasantly warm even on freezing nights.

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