PERFORMANCE TESTS OF COMPACT VACUUM INSULATION FOR REFRIGERATORS

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Development of the new compact vacuum insulation (CVI) concept has continued, with the unchanged objective of an R-value better than 10 in one-tenth inch. Early prototypes of CVI recently have been tested in full-scale refrigerators. Industry's primary interests, other than improved thermal performance, are ease of handling and the possibility of ready incorporation in the standard product of an assembly line. This report describes the configuration of the different CVI prototypes installed, analyses of thermal performance, initial tests of gross conductivity of the panel alone and later in-place efficiency tests, and observations of the process of incorporation of CVI into refrigerators.

BACKGROUND

Development of Advanced Insulations

Chlorofluorocarbon (CFC)-blown insulating foams used in refrigerators contribute to depletion of atmospheric ozone, and inefficient operation of refrigerators contributes to global warming. Therefore, the development of several vacuum insulation alternatives is of special interest and importance. The oldest of these is the vacuum powder concept (some patents were filed in the 1950s) [1]. The concept is alive today, and recently a number of domestic refrigerators containing vacuum insulation panels were made for sale [2]. A more recent approach has been the vacuum aerogel concept, based on Kistler's work in the 1930s on silica aerogels. In the current version, silica aerogels made by a lower-temperature, lower-cost process are encapsulated under partial air pressure, resulting in an insulating panel [3]. The third major vacuum insulation approach, addressed here, is compact vacuum insulation (CVI). It is expected to result in thin welded steel panels that measure R-10 in one-tenth inch and cost $1 to $4 per square foot ($0.10 to $0.40 per square foot per R-value). Such panels may be used in the sidewalls of refrigerators and in many other thermal insulation applications.

To better understand the practicality for refrigerator application of advanced insulations like CVI, which may be more expensive than the insulations they are expected to replace, a review of previous market acceptance of innovative insulation may be useful. Mass-type insulations, whose main operating mechanisms are enhanced by small air pockets and extended solid conduction paths, have been around for millennia; the straw and fur used by primal man, for example, were close at hand and effective. In more modern times, the emphasis was on inexpensive materials (on the order of $0.01 per square foot per R-value) that would also work in a wider range of temperatures and operating conditions. Fiberglass, rockwool, and cellulose mass insulations have served this requirement very well [4]. More recently, mass insulations like fiberglass have been replaced by expanded polymer foams, which can be two to three times as resistant to heat flow but at a somewhat higher price (on the order of $0.03 to $0.07 per square foot per R-value) [5].

Despite the higher cost, progression from mass insulations to foam insulations has been steady, justified in each case by the space or volume savings they achieved while they maintained or increased insulating values. The example of domestic refrigerators is well known; foam gradually replaced fiberglass in sidewalls between about 1970 and 1976. The door was the only major area not insulated with foam, and within the last two years it has also received the foam treatment. At minimally three times the cost per R-value, insulating foam has found acceptance primarily because of the volume it has conserved.

In the latest round of technical advances, new materials have been developed that could again greatly increase insulating value at a corresponding increase in cost. If the market values volume or space highly enough, the new materials may find application. If not, mass insulations or reformulated foams (without CFC blowing agents) will continue to be used. For example, note the continued excellent market acceptance of fiberglass used to insulate attics, where volume has little or no value. In any case, different types or configurations of insulations will probably be needed because of (1) the 25% decrease in energy use mandated by regulations implementing the National Appliance Energy Conservation Act (NAECA) and (2) the restrictions proposed for the manufacture and use of chlorofluorocarbon-blown insulating foams.

Initial Designs of CVI

The simple design concept of compact vacuum insulation has been generally described previously [6] and is shown schematically in Figure 1. In this section we will describe how this simple design addresses the following modes of heat transfer:

Convection. Because there is no gas within the envelope, convection is not an issue.

Gas-Phase Conductance. Similarly, because the gas pressure is very low (10^{-6} Torr), conductance is negligible. Figure 2 shows the relation of gas pressure, mean free path, and gas-phase conductance [7].

Solid-Phase Conductance. Thermal transfer in the middle of the sheet is mostly through the spacer array. Edge effects are a concern in CVI as in all high-performance insulation. The heat conducted through the perimeter, metal-to-metal weld must be limited by use of a "thermal break" of some kind. In a refrigerator/freezer, the CVI can be used as a composite with foam polymer insulation, which provides the thermal break. CVI panels may also be overlapped so that one provides the necessary thermal break at the edge of the next. Calculations indicate that edge effect losses can be kept in the range of 10% to 20% by use of such composite designs.

The amount of heat transferred through the edges and the spacers of the bare panel is related to the thermal conductivity of the envelope material; a performance premium is gained by the use of an envelope material like stainless steel, which has lower thermal conductivity than most other metals. For applications other than refrigerators, in which corrosion resistance and other characteristics may not be issues, other metals could be used. Some, like titanium, are more expensive but have outstanding thermal and corrosion-resistance performance. Others, like tin-plated sheet steel, could be cheaper by a factor of six or more, but have three times the thermal conductivity and less resistance to corrosion [8].

Radiation. Infrared transfer across the vacuum space is reduced by using a low-emissivity metal. Mill-finish stainless steel has an emissivity of 0.09; tinplate, with an emissivity of 0.05, could reduce the radiative component of heat transfer by about half.

Key Materials and Process Issues

Making CVI practical depends on developing a design which uses materials and manufacturing processes that will result in the desired combination of performance and cost. The key material characteristics identified to date in laboratory tests and in discussions with manufacturing industry supporters are (1) cost and availability, (2) relative impermeability of the envelope material, (3) the ability to achieve a hermetic weld of that material, (4) cleanliness of the material from a demanding vacuum perspective, and (5) longevity under the temperature and corrosion conditions anticipated. The key process characteristics appear to be reliability and speed of the hermetic joining process, materials handling, and the evacuation process.

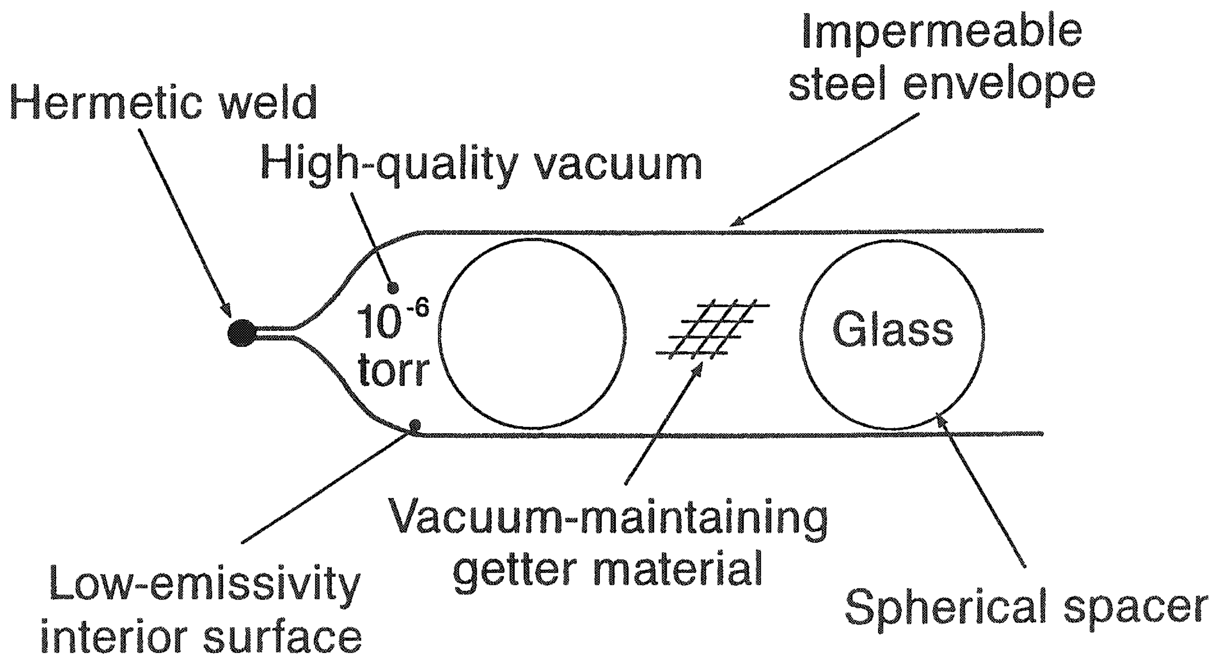

Figure 1. Schematic Cross Section Through Compact Vacuum Insulation. The insulation has all of the elements of a vacuum Dewar plus a periodic array of spherical glass spacers to support the steel envelope against atmospheric pressure.

PERFORMANCE OF FIRST CVI PROTOTYPES

The prototypes we have made of simple CVI designs to demonstrate operation of the concept have typically been small because of the limitations of our current facilities. We have tested them in the laboratory and inside full-scale refrigerators. In this section we will discuss their thermal performance and life expectancy.

Laboratory Tests

Figure 3 shows measurements of the thermal resistance at the center of small test panels of CVI as a function of temperature. Results from SERI's laboratory tests and from tests of two major insulation manufacturers are shown. The temperature parameter is the parameter that is predicted to be proportional to radiative component of heat transfer in CVI. The other modes of heat transfer are not sensitive to the temperature of operation, only to the temperature difference between hot and cold sides of the panel. As expected, the measured data follow a linear trend and agree quite well with our finite-difference one-dimensional heat-transfer model.

More complex heat flow patterns occur near the perimeters of CVI panels and in the interior of more complex panel designs now being developed. These heat flows will be modeled in more detail using finite-element-analysis computer codes as part of our design optimization efforts aimed at the development of composite panels that minimize degradation of center-of-panel performance from thermal shorts.

Accelerated Life Tests. Besides the thermal performance of the CVI panels, an important aspect of their practicality is their service life expectancy. The only absolutely certain way to assure maintenance of the vacuum over a life of a panel is to wait for 20 years and measure it. However, industry has developed methods for making much more rapid determinations for leakage failure, and extensive data exist to

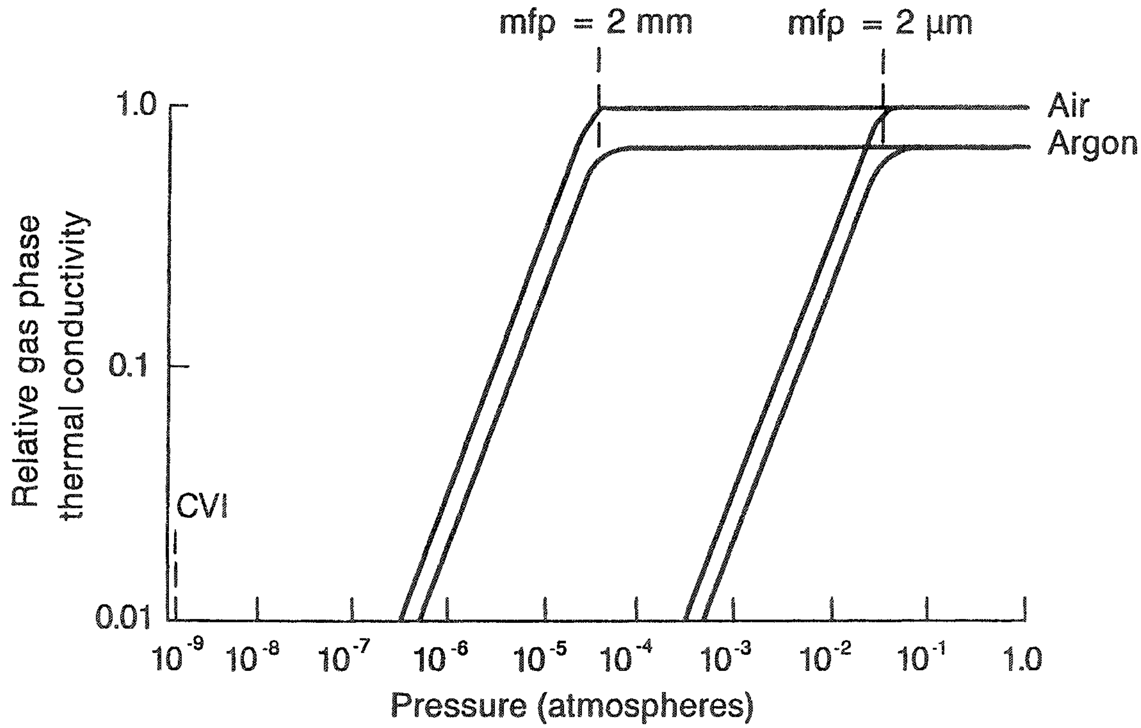

Figure 2. The Thermal Conductivity of Air and Argon as a Function of Pressure. The decrease in conductivity begins at a higher pressure in powder insulations because the gas molecule mean-free-path (mfp) length is limited to about 2 microns by the fine particle spacing, unlike in CVI which provides about 2 mm of free path length.

back up the estimates. One common method is to expose the vacuum envelope to a helium environment and measure its performance. In a thermally insulating envelope like the CVI panel, the leakage of helium into the envelope causes a more rapid change in the thermal resistance (than the same leakage in air over a much longer period of time) for three reasons: (1) The passage of gas through the leak is dependent on the mass of the gas molecule. The helium molecule, only about one-seventh the mass of nitrogen, flows through a small leak about 2.6 times faster than air. (2) The reactive metal getter inside the CVI panel (used to chemically scavenge gas molecules desorbing from the metal over the panel's life) traps the reactive gas components of air leaking into the panel. Only about 1% of air (mostly argon) is inert; the other 99% would be trapped until the getter becomes saturated. Because 100% of a helium environment is inert, the internal pressure in the accelerated test increases 100 times faster than in an air environment. The pressure with air leakage will not increase until the getter becomes saturated. (3) The thermal conductivity of a low-pressure gas is greater for a smaller, lower-mass gas molecule; for helium this translates to about eight times greater conductivity than that of argon at the same pressure.

Figure 4 shows these relationships schematically and demonstrates that the accelerated leak test in a helium environment speeds up determination of leaks in air by a factor of about 2000 (one day of accelerated testing would be about equal to four years of life in air). If the thermal performance of the same panel in the same testing apparatus before and after exposure to the helium environment can be determined with an accuracy of 2% to 5%, this will provide an additional significant acceleration factor. A continuing technical challenge will be to shorten this or some similar test dramatically, so

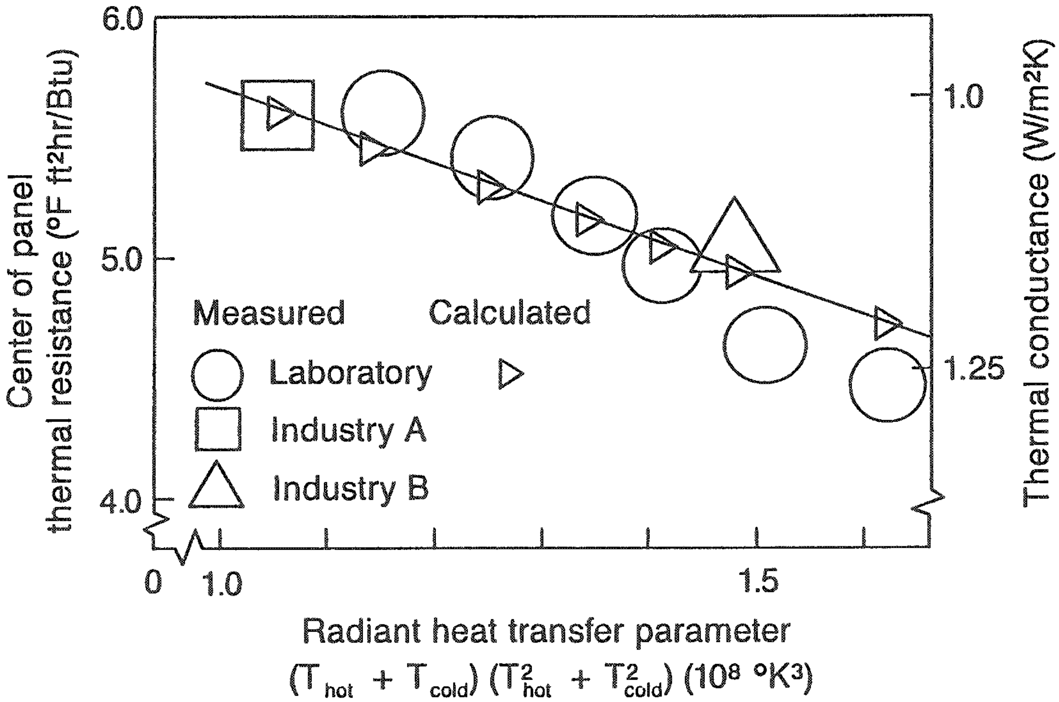

Figure 3. Measurements of the Thermal Resistance of CVI Test Panels at Our Laboratory and at Two Different Industry Laboratories Agree Well with Finite-Difference Model Predictions

that industry is not required to maintain a stock of panels undergoing accelerated-life tests. It is probable that some statistical techniques will find use here.

Figure 5 displays the accelerated-life test data. The thermal resistance of a test panel was measured repeatedly over a 67-day period of exposure to a helium atmosphere. The measurements indicate little or no change in the thermal resistance--certainly less than a 5% decrease. The lower set of curves in Figure 5 indicates the predicted time in years required for the panel's thermal resistance to degrade by 20% in air if it had a leak. The 2% line indicates the predicted lifetime in air if the panel shows a 2% degradation during the helium-accelerated leak test. The 5% line shows the predicted lifetime in air if the panel shows a 5% degradation in helium. Because the measurements indicate less than 5% degradation in helium during the 67-day test, the predicted lifetime in air is greater than 60 years.

In Situ Tests

Single-Layer Application to an Entire Refrigerator. In a first test of CVI in the sidewalls of a standard refrigerator, we fabricated the panels to sizes specified by an industry collaborator and applied them to the inner surfaces of a steel refrigerator case drawn at random from the assembly line. Nine CVI panels of different sizes were made, two for each vertical side and one for the top. The bottom was not insulated because the manufacturer thought that the CVI could not be bent into the shape needed for coverage. They were held in place temporarily by hot-melt glue and tape and were then foamed in place with the conventional facilities, chemicals, procedures and staff used at the factory. After assembly, the refrigerator was tested by the accepted procedures to determine compliance with energy-efficiency standards. In this case results after several weeks of repeated measurements showed little or no improvement in energy

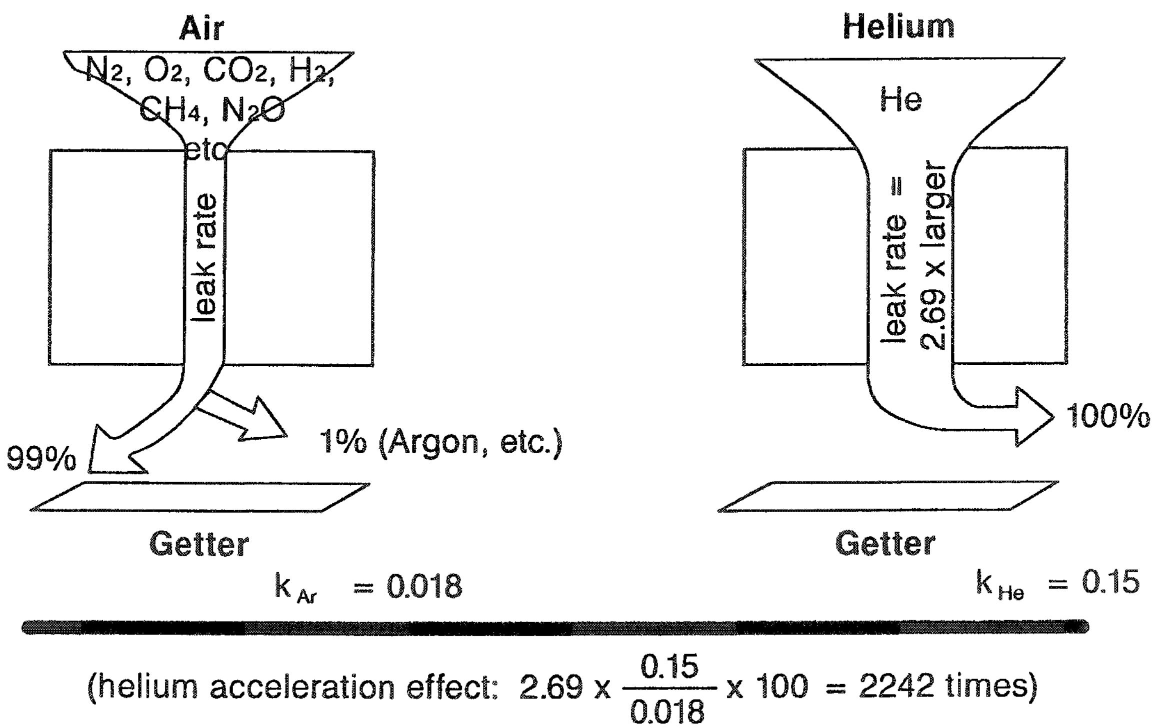

Figure 4. *Exposure of a Vacuum Insulation Panel to Helium Greatly Accelerates Its Loss of Thermal Resistance if it has a Leak. The smaller helium molecule penetrates a leak more readily, is not absorbed by the getter, and conducts heat better. The change in thermal resistance is expected to be more than 2000 times faster in helium than in air.*

performance. Examination of a panel from the same fabrication series that was maintained in our laboratory as a control revealed a failure in the gas-tight integrity of the steel envelope at the location of a series of spot welds to the getter material. We determined that the spot weld procedure had been faulty, and had introduced microscopic leaks to the CVI envelope. No other problems were discovered with this prototype, and the only change required for future panel preparation was the modification of the getter placement procedure.

The other major objective of this in situ exercise was to observe the installation of CVI in a refrigerator in an assembly-line procedure. This objective was more successfully met; to all appearances, the installation of the CVI went smoothly, and the custom-sized panels reasonably covered the areas for which they were intended. The only objection encountered had to do with the lack of knowledge (by SERI and by the collaborator) concerning the ability to form the CVI panels after welding to shapes compatible with irregularities in the refrigerator walls. This topic is scheduled for coverage in work under way now, and later field installation tests will benefit from this new knowledge.

Double Layer Application Around Freezer Compartment. A second industry collaborator requested test CVI panels for increasing the insulating performance of only the freezer compartment of a standard refrigerator/freezer. Initial calculations at the laboratory showed maximum energy savings of no more than 5% if only a single layer of CVI was used in this application. Because the limited energy savings could be lost in the measurement "noise," we agreed with our collaborator to put together doubled CVI panels of the requested sizes. The doubled panels, about 0.25 in. thick, were installed as the previous ones had been against the inner surface of the steel refrigerator case (consisting of

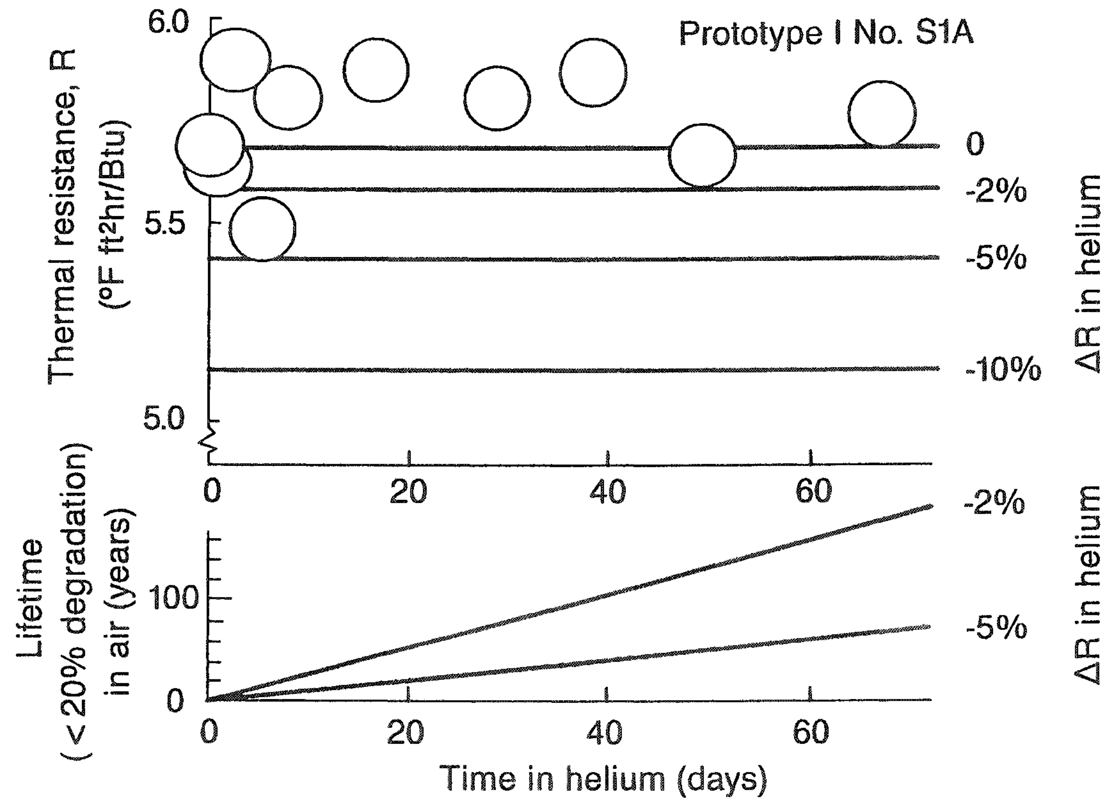

Figure 5. A Sample Exposed to Helium for 67 Days Showed Little or No Change in Thermal Resistance, Indicating That Whatever Leak May Exist in it Would not Cause Significant Loss of Thermal Resistance in Air for at Least 50 Years

about 70% coverage of the five exterior walls of the freezer compartment only) before foaming between the inner and outer shells of the cabinet.

Standard AHAM (Association of Home Appliance Manufacturers) tests were made by the industry collaborator comparing this unit to the one without CVI that was made next in the assembly line sequence. Results of this one-to-one comparison showed an energy saving of 6.3% in the CVI experimental model. Such a result is useful only as a gross indicator of performance and should not be used to make generalizations about other insulation configurations or other refrigerators. In this case the control panel kept at the laboratory has maintained its performance and is in fact the panel on which the accelerated leak tests were successfully performed.

Again the observation of the experimental assembly process supported the initial conclusion by researchers that the CVI panels could be used without major refrigerator/freezer industry retooling as a "drop-in" improvement to sidewall thermal performance.

Anticipated Near-Term Progress

As part of our continued experiments with full-scale refrigerators, we have planned two further "make-and-test" experiments. We are now evaluating different designs for spacer arrangements and several new materials for the envelope. We anticipate that the third and fourth refrigerators will be ready for testing by the end of 1990.

One current emphasis of our work is to improve performance through design and material modification of the original simple prototypes. The other emphasis is to use lower-cost materials to improve the benefit:cost ratio, though this may reduce thermal performance or increase panel thickness or both. These tradeoffs properly reflect a range of broader industry and market demands, and they will be resolved in different ways for different applications identified for this technology. Finally, the more competitive CVI is with foam and mass insulations based on cost per R-value, the more likely the market is to accept it on a broad basis. Laboratory, application, and manufacturing studies will continue to investigate and broaden this challenging possibility.

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REFERENCES

1. Brooks, F. P., et al. *Heat Insulating Panels*. Patent no. 2,989,156 issued June 20, 1961.

2. U.S. Department of Energy. January 12, 1989. Proceedings of Public Hearings on Regulations Implementing the National Appliance Energy Conservation Act, Testimony of General Electric Appliances.

3. Fricke, J. 1988. "Aerogels." *Scientific American*, May, Volume 258, pp. 92-97.

4. U.S. Department of Energy. Undated. *Insulation Fact Sheet*. Publication No. DOE/CE-0180.

5. Ibid.

6. Potter, T. F., D. K. Benson, and L. K. Smith. 1988. "Impacts of Advanced Refrigerator Insulation." In *Proceedings of the ACEEE 1988 Summer Study on Energy Efficient Buildings: Appliances and Equipment*. Washington, D.C.

7. Touloukian, Y. S., P. E. Liley, and S. C. Saxena. 1970. *Thermophysical Properties of Matter, Vol. 3: Thermal Conductivity, Nonmetallic Liquids and Gases*. Plenum, New York.

8. Touloukian, Y. S., P. E. Liley, and S. C. Saxena. 1970. *Thermophysical Properties of Matter, Vol. 1: Thermal Conductivity, Metallic Solids*. Plenum, New York.