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# Long-Term Thermal Resistance of Closed-Cell Foam Insulation: Research Update from Canada

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## Abstract

*The thermal insulating efficiency of closed-cell foam insulation with a captive blowing agent changes over time during its service life in building envelope construction. Hence, the long-term thermal resistance (LTTR) value of closed-cell foam insulation has a great significance to the building envelope designers. Researchers at the National Research Council Canada – Institute for Research in Construction (NRC-IRC) have worked on various aspects of aging characteristics of closed-cell foam insulation during the past two decades. This paper will provide a comprehensive scientific outline of the research activities that have been carried out at the NRC-IRC on the aging of closed-cell foam insulation and its practical implications on the North American construction industry.*

## Introduction

Existence of life on our planet is very much dependent on insulation. The layer of air that encompasses our planet is essentially an effective insulation blanket (*Pelanne, 1978*) keeping our planet inhabitable for us. In a more day-to-day life our interaction with insulating materials and systems is a recurring theme (thermos flask, clothing, fur, window glass, building envelope etc.). Hence, the need to search for better and/or cost effective insulation materials/systems, and develop better understanding of its thermal behavior cannot be overemphasized (*Mukhopadhyaya et al. 2008*).

The use of thermal insulation in various residential, commercial and industrial applications to save energy is a common practice in the developed as well as in the

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developing world. Quite naturally, a higher thermal resistance (R-value) of insulating material is very much a desirable characteristic. Apart from instant energy savings it can also help to render better long-term durability of materials and systems, more effective moisture management, enhanced indoor comfort and improved fire protection. However, the overall insulation benefit of these materials is dependent on their long-term thermal resistance (LTTR) or aging characteristics (*Kumaran et al. 1989; Bomberg and Kumaran, 1991; Kalinger and Drouin, 2001; Mukhopadhyaya et al. 2004*). In order to understand the general behavior and LTTR of closed-cell foam insulation it is helpful to review the basic physics of heat transfer as outlined below.

### Basic Physics of Heat Transfer

There are three basic heat transfer mechanisms that control the insulating capacity of conventional thermal insulation materials and these mechanisms ([Figure 1](#)) are: (1) Conduction, (2) Convection, and (3) Radiation.

Conduction occurs when constituent particles of the insulating material are in physical contact and energy is transferred through this contact.

Convective heat transfer happens as a result of energy transfer by moving constituent particles (i.e. gas or fluid) of the insulating material.

Radiation takes place due to the emission of electromagnetic waves that transfer energy from the hot emitting object to a cold receiving surface and unlike conduction or convection this mode of heat transfer can take place when there is no contact medium (i.e. vacuum) between two objects.

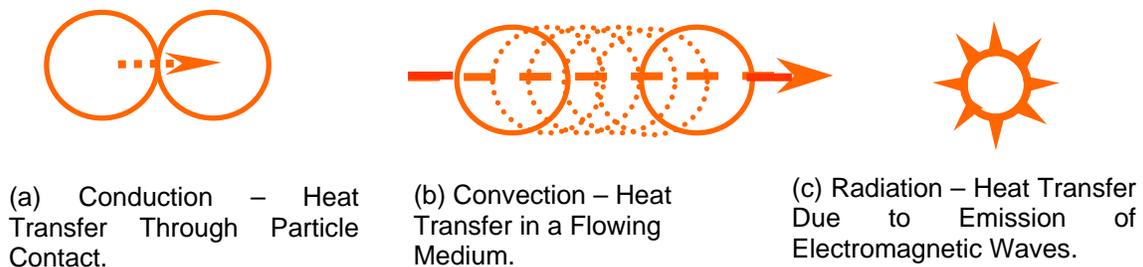


Figure 1 - Basic physics of heat transfer

## Performance of Thermal Insulation

The most basic form of thermal insulation that had been used for the construction of the built environment is the 'air space' between two layers of construction. With a better understanding of heat transfer mechanisms and the advent of advanced manufacturing technology, the development of high performance insulation has been relatively slow but steady in terms of the increased R-value of the thermal insulation.

However, even now, enormous potential still exists to develop high performance thermal insulating materials and systems for the built environment construction and the fundamentals of this development lie within the basics of heat transfer mechanisms through the air space. As shown in [Figure 2 \(Shirtliffe, 1972\)](#), heat flow through typical air space is primarily due to convection and radiation. However, the introduction of reflective surface in the airspace can reduce the radiation component of the heat flow to a minimum level. Furthermore the addition of some fibrous materials that restricts the airflow inside the air space can transform the convective heat flow phenomenon almost negligible.

Hence, in any conventional insulation material, the three major components of heat flow are: (1) air conduction, (2) radiation and (3) solid conduction ([Figure 3](#)). The solid conduction and radiation components are functionally related to the bulk density of the insulation materials. However, for practical purposes the air conduction is treated as an independent component and offers a significant opportunity to develop high-performance insulation materials by effectively reducing this component and this is the basic principle that leads to the development of closed-cell foam insulation.

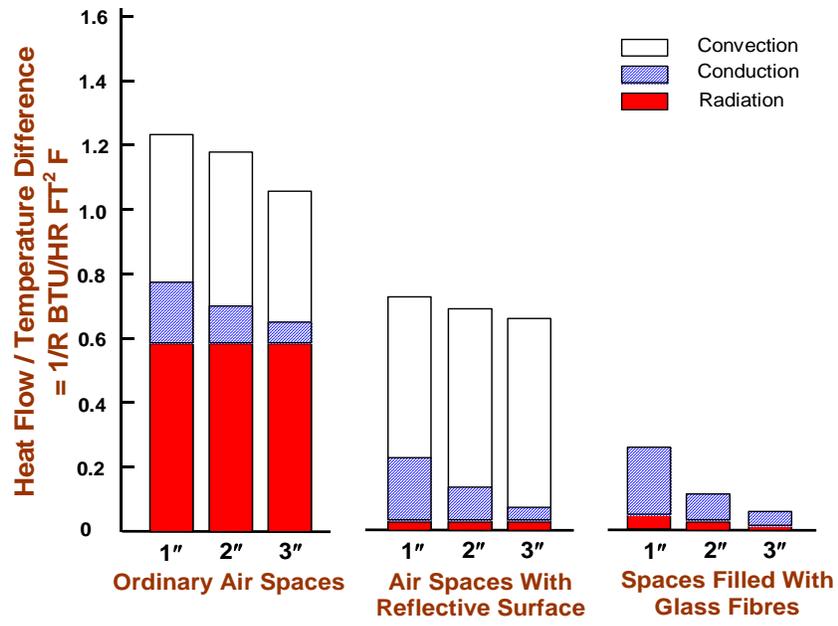


Figure 2 - Heat transfer across air spaces

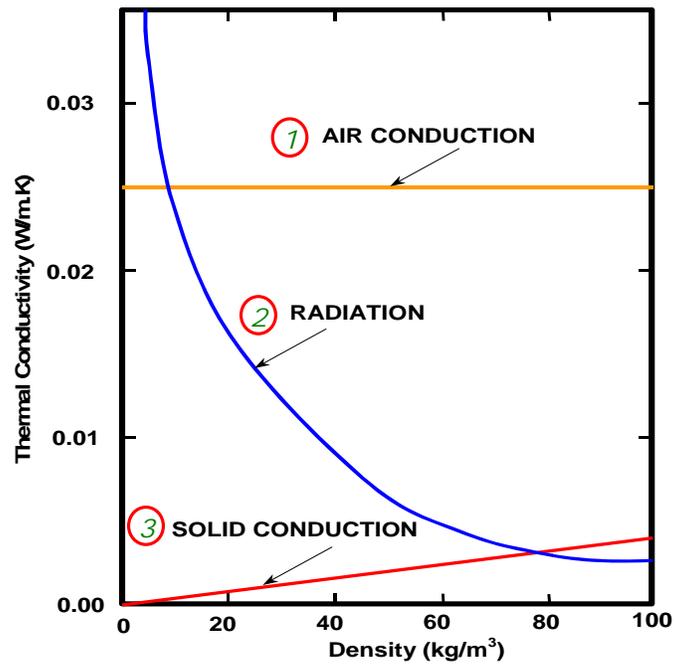


Figure 3 - Heat transfer mechanisms in conventional insulation

## What is Closed-Cell Foam Insulation?

The basic structure of closed-cell foam insulation consists of two major components (1) polymer matrix, and (2) gas-filled closed cell ([Figure 4](#)). The captive gaseous blowing agent(s) fills up the closed-cells, surrounded by polymer matrix, during the manufacturing process of the foam. The thermal conductivity of blowing agent is usually lower than air. In effect, the presence of blowing agents inside the closed-cell reduces the air conduction component of thermal conductivity significantly depending on the type of blowing agent used in the closed-cell foam insulation, as shown in [Table 1](#) ([Wu and Eury, 2002](#)). The thermal conductivity of most of the commonly used blowing agents is lower than half of the thermal conductivity of air.

Table 1 – Thermal conductivity of blowing agents

Blowing Agent	Thermal Conductivity [k <sub>gas</sub> @ 25 (°C) mW/m.K]	Blowing Agent	Thermal Conductivity [k <sub>gas</sub> @ 25 (°C) mW/m.K]
CFC-11	8.7	Hydrocarbon n-C <sub>5</sub>	15
HCFC-141b	9.7	HFC-134a	13.6
HCFC-142b	11.5	HFC-245fa	12.2
HCFC-22	11.0	HFC-365mfc	10.6
Hydrocarbon c-C <sub>5</sub>	12.0	Air	26

In general closed-cell foam insulation has many desirable properties as insulation and a construction material such as:

1. High r-value per unit thickness
2. Fire resistance
3. Moisture resistance and water repelling characteristics
4. Dimensional stability
5. Efficient filler for cavities, and
6. Resistance to solvents commonly found in construction adhesives.

However, it is also true that the thermal conductivity of the closed-cell foam insulation, due to the presence of captive blowing agents inside the closed-cell, increases over time as air diffuses into and blowing agent(s) diffuses out of the closed-cells ([Figure 5](#)). The rate at which this diffusion (also called aging) occurs depends on a number of parameters such as properties of foam matrix, geometry and structure of the cells, exposure

conditions, density of material, manufacturing process, thickness of the insulation, chemical composition and permeability of the surfaces etc. This aging process of the foam insulation is very rapid just after the manufacturing and slows down with the time and almost reaches to an equilibrium state after a certain time. Hence, for the thermal design purposes, unlike traditional fibrous insulation materials, the long-term thermal resistance (LTTR) value is to be considered as the effective thermal resistance of the closed-cell foam insulation. The researchers at the National Research Council (NRC) Canada, Institute for Research in Construction (IRC) have been researching on the various aspects of the LTTR characteristics of the closed-cell foam insulation for more than 20 years now. A brief summary of these research activities and the technical challenges are presented in the following paragraphs.

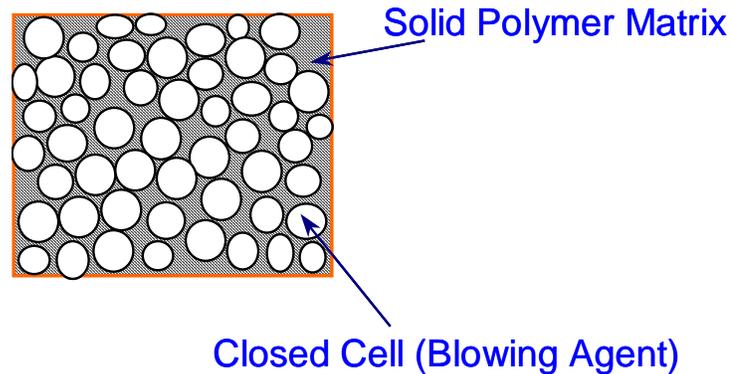


Figure 4 – Basic structure of closed-cell foam insulation

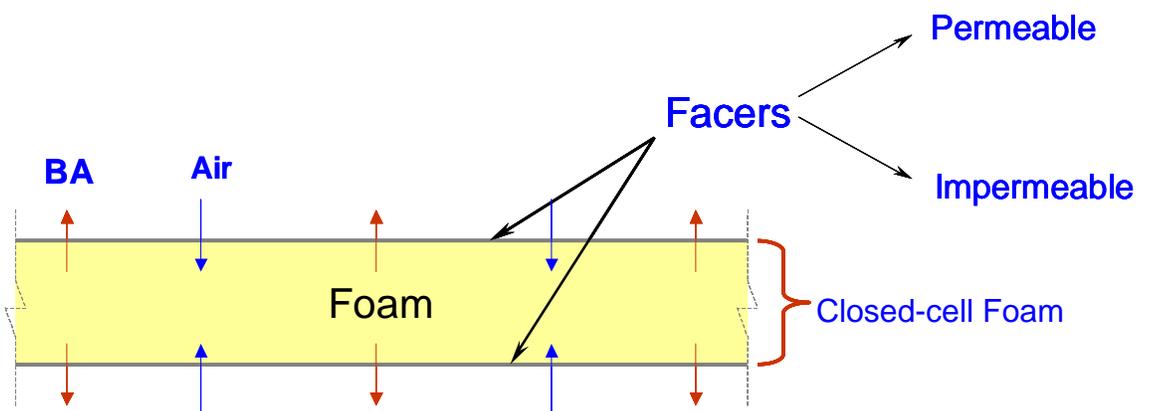


Figure 5 – Aging of closed-cell foam insulation

## **Research on Closed-cell Foam Insulation at NRC-IRC: A Success Story**

In the late 1980s a very timely action by the NRC-IRC helped the plastic foam insulation industry deal with a technical crisis stemming from environmental concerns.

Up until that time, closed-cell foams, such as polyurethane foam, polyisocyanurate foam and phenolic foam used chlorofluorocarbons (CFCs) as a captive blowing agent to impart excellent thermal resistance for insulation applications in buildings, exceeding that provided by traditional insulating materials such as glass and mineral fibre. Non-toxic, non-flammable and non-corrosive, CFCs were thought to be stable gases and were considered ideal blowing agents. The foam industry thus maintained a strong share of the multi-billion dollar North American insulation market.

This rosy financial picture faded abruptly with the discovery that CFCs escaping into the atmosphere pose a long-term danger to the environment. Free radicals resulting from the occasional breakdown of the compounds eat away the ozone layer. When the extent of the problem became apparent, an international agreement known as the Montreal Protocol was signed by 24 nations in 1987 to restrict the use of CFCs in manufacturing technologies. In Canada this included a ban on the use of CFCs in foam insulation.

With very little time to respond, the foam industry was in desperate need of a solution to enable it to hold onto its market advantage. That solution would be found in a research project between the Society of Plastic Industries (SPI) and NRC-IRC.

The project began in 1988 and immediately it became evident that there was more to this work than simply replacing blowing agent A with blowing agent B. It was more a case of a radical change in technology because so many aspects of the foam cellular morphology had to be changed to obtain comparable thermal performance of foams using blowing agents with probably lower thermal effectiveness. The research challenge was to develop accelerated techniques to evaluate new materials and link them to the development of new foam products. An even greater challenge was to develop a methodology that substantiated the long-term performance of viable products, using data from short-term laboratory experiments and field-testing.

To build on the incremental knowledge that was acquired over 20 years and to set the linkage between the material and the test methodology development, the researchers first developed a generic and homogeneous foam product. Called Base 88, it represented the

industrial technology of sprayed polyurethane foams that existed in 1988. This generic product was manufactured by three industry participants in the project. Improved control of application variables generated in a sub-project permitted Base 88 to become highly reproducible and suitable for drawing the "baseline" to compare any innovation. Hydrochloro-fluorocarbon (HCFC)-based blowing agents, such as HCFC-123, HCFC-141b, combinations of HCFCs with and without water, all alternatives to CFC-11, were then introduced. A new generation of alternative foam products resulted. A satellite project between one of the partners and NRC-IRC focused on identifying desirable properties of new blowing agents. Principles and measurement methods from classical thermodynamics, heat and mass transport, equations of state and even biology found their way into the research activities. The research team delivered solutions to the Canadian foam industry well within the time limit imposed by the Montreal Protocol. At that time the industry was globally ahead of any other competition.

Following on the heels of the successful project, the researchers at NRC-IRC, jointly with the cellular plastic industry, developed a new Canadian National Standard called [CAN/ULC-S770](#) to "measure" the long-term performance of any innovative foam product. What is more, working with researchers from the Oak Ridge National Laboratory in the U.S., NRC-IRC researchers introduced various aspects of their research findings into the corresponding ASTM (American Society for Testing and Materials) International Standard ([ASTM C1303](#)) for polyurethane, polyisocyanurate, extruded polystyrene and sprayed polyurethane foam products. This has furthered North American innovation and helped produce the modern generation of cellular plastic insulation materials. The innovation continues and interestingly enough innovations also bring new challenges as outlined in the following paragraphs.

### **Today's Challenges**

Though there is a standard test method now to determine the LTTR of closed-cell foam insulation based on the scaling relationship ([equation \[1\]](#)) there are also many challenges today arising primarily from variations in constituent materials, manufacturing processes, product thickness etc.

$$\frac{t_1}{t_2} = \left( \frac{L_1}{L_2} \right)^2 \quad [1]$$

Where,

$t_1$  &  $t_2$ : Two different times, and

$L_1$  &  $L_2$ : Two different slice thickness.

A significant amount of closed-cell foam insulation products are made with or without facers in the form of a rigid board. Facers can be permeable or impermeable (Figure 5). It has been experimentally established that presence of permeable facer on both surfaces does not have any measurable effect on the LTTR value of closed-cell foam insulation. However, the introduction of impermeable facers on the surface is aimed at enhancing the LTTR properties of the closed-cell foam insulation.

### *Research Significance and Objectives*

The current research at the NRC-IRC focuses on the development of a comprehensive test procedure that can be used to predict the LTTR of closed-cell foam insulation products with impermeable facers.

More specifically, there are two major tasks involved in this project:

1. Laboratory and field tests on specimens, and
2. Analysis of the test observations/data with a numerical modeling tool (DIPAC-2D) (*Bomberg and Kumaran, 1995*).

It is envisaged that by combining the output from the above two tasks, a methodology could be developed that can be applied to estimate the LTTR characteristics of closed-cell foam insulation boards with impermeable facers.

## Research Findings To Date

In general this research project established the fact that aging process of impermeably faced closed-cell foam insulation boards can be explained with the concept of combined lateral and normal diffusion processes (Figure 6).

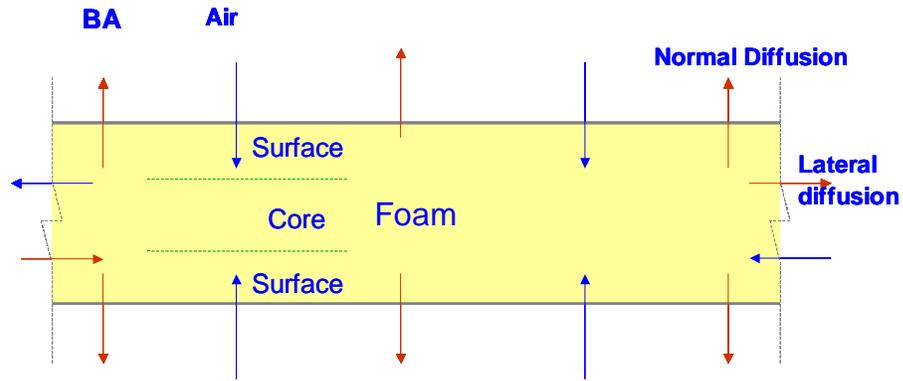


Figure 6 – Diffusion processes in closed-cell foam insulation

More specifically the following observations could be made from analyses of the results obtained from the numerical model (DIPAC-2D) and examining experimental and field test data.

Firstly, while the laboratory measurements, field observations and numerical calculations appear to agree well (Figure 7), there is an inconsistency with the lateral diffusion coefficient. The lateral diffusion coefficient determined for different specimens (i.e. full thickness and thin slices with facer) are significantly different. It is an important issue that needs further research.

Secondly, a considerable amount of aging occurred in thin slice specimens despite having untouched impermeable facers, as well as a glass plate at the bottom of the specimens and edges sealed completely with epoxy coating. This may be due to imperfections of the gas barrier system.

Further investigation on these issues would be imperative for the future progress towards the development of a methodology to predict the LTTR of closed-cell foam insulation board with impermeable facer.

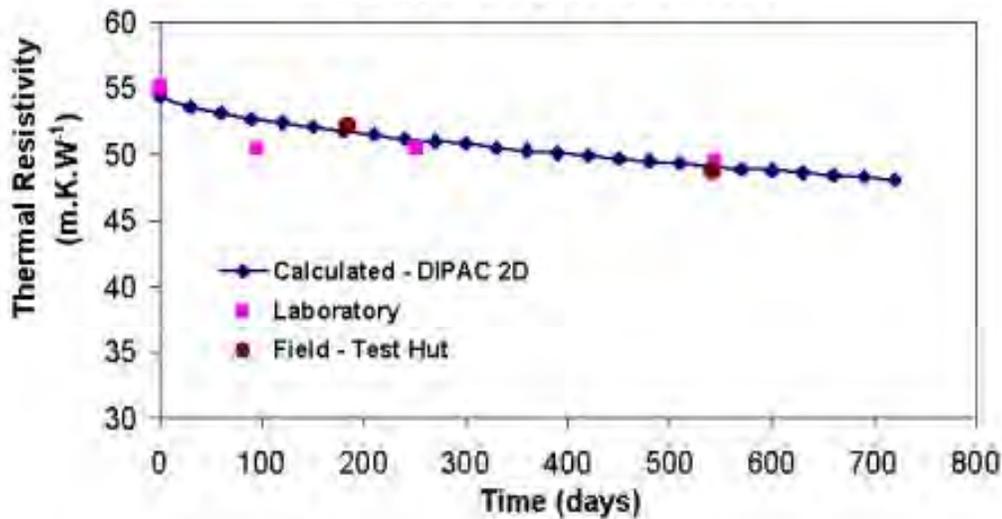


Figure 7 – Comparison of numerical, laboratory and field study results

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