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Phalguni Mukhopadhyaya¹, Bas Baskaran², Nicole Normandin³, John Lackey³ and Sebastian Evoniak³

Critical Evaluation of Existing Specifications for Polyisocyanurate (ISO) Foam Insulation Boards in Roofing Applications

ABSTRACT: In North America, more than 50% of low slope roofing applications use faced rigid cellular polyisocyanurate (hereafter abbreviated as ISO) board as thermal insulation. Long-term performance of a roof assembly is critically depended on the ISO characteristics during the service period in various environmental conditions. For this reason, the ASTM C 1289-02, Standard Specification for Rigid Cellular Polyisocyanurate Thermal Insulation Board, outlines the physical and thermal property requirements for the ISO boards. However, these requirements are based on the available knowledge, information and consensus at the time of drafting and balloting of the ASTM standard. Nevertheless, the standard gets updated and revised when more credible data are available that solicits revisions of the current standard. This paper presents experimental results from an ongoing pilot research study that critically evaluates the ASTM C1289-02 specification requirements for the ISO on three engineering properties: (1) dimensional stability, (2) thermal resistance and (3) compressive strength. Preliminary results from this study reveal many unknown phenomena, particularly regarding the dimensional stability and compressive strength of ISO boards.

KEYWORDS: Polyisocyanurate (ISO) foam, dimensional stability, thermal resistance, compressive strength, roofing assembly.

¹ Research Officer, Institute for Research in Construction, NRC Canada, Ottawa, Ontario, Canada.

² Group Leader, Senior Research Officer, Institute for Research in Construction, NRC Canada, Ottawa, Ontario, Canada.

³ Technical Officer, Institute for Research in Construction, NRC Canada, Ottawa, Ontario, Canada.

Introduction and Research Background

According to the ASTM Standard C1289-02 [1], Standard Specification for Faced Rigid Cellular Polyisocyanurate Thermal Insulation Board, length and width dimensional stability requirement is $\pm 2\%$ for the ISO board (Type II) and it is normally based on the tests conducted on specimens of specific size (e.g. 12 in. $\times$ 12 in. or 300 mm $\times$ 300 mm). However, the dimensional stability relationships between small-scale specimens and full size boards such as 4 ft. $\times$ 8 ft. (1.2 m $\times$ 2.4 m) or 4 ft. $\times$ 4 ft. (1.2 m $\times$ 1.2 m) are not clearly established. Assuming linearity, it is numerically obvious that 2% shrinkage or expansion in a full size ISO board can lead to a significant absolute physical change (i.e. length, width and thickness) of the ISO board. For example the allowable $\pm 2\%$ on 12 in. $\times$ 12 in., specimen is 0.24 in. (6 mm) whereas the same on a 4 ft. $\times$ 8 ft. full board can be as high as 1.92 in. (48 mm). The effect of this change can be significant or otherwise and needs to be investigated further. However, before doing that, it is necessary to find out whether such linear or nonlinear relationship really exists between the small-scale and full size ISO boards.

The thermal resistance value of the ISO board is normally determined from the test results obtained from the specimens conditioned to room temperature ($23 \pm 2^\circ\text{C}$) and relative humidity or RH ($50 \pm 5\%$) condition (see ASTM C 1289-02). The long-term thermal resistance (LTTR) value of the ISO is also determined from thin-slicing experiments on specimens exposed to laboratory temperature ($23 \pm 2^\circ\text{C}$) and RH ($50 \pm 10\%$) [2,3]. However, in roofing applications there could be situations when the ISO board would be exposed to an extreme temperature and/or high humidity condition [4-6]. This change in exposure condition can adversely alter the thermal resistance property. The real thermal resistance value of the ISO board in such a situation is not known or available to the end users. Nevertheless this value of the ISO is required

for the realistic determination of the thermal performance of the roofing assembly and the whole building envelope.

Very much like the thermal properties, the mechanical properties of the ISO board (see ASTM C 1289-02) are also determined based on the test results obtained from the specimens conditioned at room temperature ($23 \pm 2^{\circ}\text{C}$) and RH ($50 \pm 5\%$). However, insulation can get wet and/or exposure to a higher temperature level [4], and this may affect the mechanical properties of the ISO board. In roofing applications, the mechanical strength and stability of the insulation board is very critical for the overall integrity of the roofing structures. For example, in a mechanically attached roofing system, the fastener plate holding capacity primarily depends on the compressive strength of ISO board. Hence, it is very important for the overall integrity of the roofing structure that ISO board maintains its compressive strength under fatigue loading during the service life.

This paper presents the results from a pilot experimental study, conducted at the Institute for Research in Construction (IRC) of the National Research Council (NRC) Canada, that critically evaluates the effects of environmental exposure on the dimensional stability, thermal resistance and compressive strength of the ISO board and these can lead to further investigation and/or modifications in the existing ASTM C 1289-02 specifications for the use of ISO board in roofing construction.

Experimental Program

In order to critically evaluate the *dimensional stability*, *thermal resistance* and *compressive strength*, a series of experiments were conducted on the ISO boards before and after exposing them to aggressive temperature and/or humidity conditions, as outlined in Table 1. The 4ft. $\times$ 8 ft. $\times$ 2 in. (1.2 m. $\times$ 2.4 m. $\times$ 50 mm.) ISO boards (classified as Type II, Class 1, Grade 3

in ASTM C1289-02) were stored in the laboratory storage condition (uncontrolled indoor environment) for more than six (6) months before they were cut to smaller boards of three different sizes (12 in. $\times$ 12 in. or 300 mm. $\times$ 300 mm.; 18 in. $\times$ 18 in. or 450 mm. $\times$ 450 mm. and 24 in. $\times$ 24 in. or 600 mm. $\times$ 600 mm.) for dimensional stability and thermal resistance tests and the specimens (4 in. $\times$ 4 in. $\times$ 2 in. or 100 mm. $\times$ 100 mm. $\times$ 50 mm.) for compressive strength tests were cut out from these boards (Figure 1) after the measurements for dimensional stability and thermal resistance had been completed. These specimens were aged sufficiently to show subsequently about 3% reduction (less than the limit of experimental tolerance) in the thermal resistance in a period of twelve (12) months while exposed to controlled laboratory condition ($23\pm 2^{\circ}\text{C}$ and $50\pm 5\%$ RH).

Table 1- Test program and exposure conditions

Specimen size	Number of specimens	Test Parameters		
		Dimensional Stability	Thermal Resistance ⁴	Compressive Strength ⁵
12 in. $\times$ 12 in. (300 mm $\times$ 300 mm)	3	Initial ⁶ length, width and thickness measurements.	Initial measurement of thermal resistance.	Initial measurement of compressive strength.
18 in. $\times$ 18 in. (450 mm $\times$ 450 mm)	3			
24 in. $\times$ 24 in. (600 mm $\times$ 600 mm)	3			
12 in. $\times$ 12 in. (300 mm $\times$ 300 mm)	3	Length, width and thickness measurements taken initially and after 28 days exposure to $70\pm 2^{\circ}\text{C}$ and $75\pm 3\%$ RH.	Thermal resistance values are determined.	Compressive strength values are determined.
18 in. $\times$ 18 in. (450 mm $\times$ 450 mm)	3			
24 in. $\times$ 24 in. (600 mm $\times$ 600 mm)	3			
12 in. $\times$ 12 in. (300 mm $\times$ 300 mm)	3	Length, width and thickness measurements taken initially and after 90 days of exposure to $60\pm 2^{\circ}\text{C}$.	Thermal resistance values are determined.	Compressive strength values are determined.
18 in. $\times$ 18 in. (450 mm $\times$ 450 mm)	3			
24 in. $\times$ 24 in. (600 mm $\times$ 600 mm)	3			

⁴ Thermal resistance will be measured following the ASTM Standard C518-02 at $24\pm 2^{\circ}\text{C}$ with temperature gradient $22\pm 2^{\circ}\text{C}$

⁵ Compressive strength will be measured following the ASTM Standard D1621-04a.

⁶ Initial measurements will be taken after conditioning the full size boards for 4 days at 23°C and 50% RH.

FIG. 1 – Specimens for dimensional stability, thermal resistance and compressive strength tests.

In addition to the aforementioned experimental program, a separate accelerated aging study was conducted few years ago that investigated dimensional changes in ISO boards of three different thicknesses (1 in., 2 in. and 3 in. or 25 mm., 50 mm. and 75 mm.) and two different sizes, small (12 in. $\times$ 12 in. or 300 mm. $\times$ 300 mm) and full size (4 ft. $\times$ 8 ft. or 1200 mm. $\times$ 2400 mm.). Selected results from these tests are also presented in this paper.

Exposure Conditions

Two primary exposure conditions were used for accelerated aging. These conditions were:

- (i) *Exposure A* - 28 days exposure to $70\pm 2^{\circ}\text{C}$ and $75\pm 3\%$ RH, and
- (ii) *Exposure B* - 90 days of exposure to $60\pm 2^{\circ}\text{C}$. The controlled environment chambers available at Insulation and Building Materials Laboratory of the NRC-IRC were used to carry out these tests.

A comparison between the environmental conditions outlined in the ASTM C 1289 – 02 and CAN/ULC-S704-01 [7] for the dimensional stability tests and the exposure conditions adopted in this study are shown in Table 2. The temperature and humidity conditions chosen in

this study were not as severe as the prescribed extremes in the ASTM or CAN/ULC standard; however, the extreme exposure duration was higher in this study. Considering this is a pilot study, these deviations in the environmental exposure conditions were allowed to accommodate some practical arrangements in the laboratory and expedite the test program.

Table 2 – Exposure conditions

Temperature		Relative Humidity (RH)	Exposure Time (days)	Remarks
°F	°C			
+200 ± 4	+93 ± 2	Ambient	7	ASTM C 1289 – 02
– 40 ± 6	– 40 ± 3	Ambient	7	ASTM C 1289 – 02
+158 ± 4	+70 ± 2	97 ± 3 %	7	ASTM C 1289 – 02
<i>+158 ± 4</i>	<i>+70 ± 2</i>	<i>75 ± 3 %</i>	<i>28</i>	<i>This study – Exposure A</i>
<i>+140 ± 4</i>	<i>+60 ± 2</i>	<i>Ambient</i>	<i>90</i>	<i>This study – Exposure B</i>
– 20 ± 6	– 29 ± 3	Ambient	7	CAN/ULC-S704-01
+176 ± 4	+80 ± 2	Ambient	28	CAN/ULC-S704-01
+158 ± 4	+70 ± 2	97 ± 3 %	28	CAN/ULC-S704-01

In addition to exposure conditions outlined in Table 2, a separate study was conducted, as mentioned in the previous section, where small and full size ISO specimens were exposed to 70°C (158°F) and 77% RH for 7 days.

Test Methods and Measurements

The test procedures to determine dimensional stability, thermal resistance and compressive strength of the ISO board specimens are outlined in the following paragraphs. After exposure, the specimens were conditioned at the room temperature for at least 24 hours before conducting tests and taking measurements.

Dimensional Stability

For the dimensional stability tests the length, width and thickness of the specimens were measured before and after the environmental exposure at the same specific locations ([Figure 2](#)),

using a thickness-measuring gauge⁷ (Digimatic Indicator, Mitutoyo) with a precision 0.01mm.

The averaged values of length, width and thickness were used for analysis purpose.

FIG. 2 – Locations for dimensional measurements

Thermal Resistance

The thermal resistances of the specimens before and after the environmental exposure were measured following the ASTM standard C518-02 [8], Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus (Figure 3). Two heat flow meters (12 in. × 12 in. or 300 mm. × 300 mm. and 24 in. × 24 in. or 300 mm. × 300 mm.) were used for this purpose. The tests were run at a mean temperature $24 \pm 5^\circ\text{C}$ and with a temperature differential $22 \pm 5^\circ\text{C}$.

⁷ Calibrated for various thicknesses using transfer standard which in turn are certified by the National Research Council, Canada-Institute for National Measurement Standards.

FIG. 3 – Heat flow meter apparatus

Compressive Strength

The compressive strength of the 4 in. $\times$ 4 in. $\times$ 2 in. or 100 mm. $\times$ 100 mm. $\times$ 50 mm. (thickness) specimens, before and after the exposure, were determined in an *Instron 5566* machine with a 10kN load cell (Figure 4). The testing was carried out according to the ASTM standard D1621-04a [9], Standard Test Method for Compressive Properties of Rigid Cellular Plastics. As per the Standard, the crosshead speed was 5.0 mm/min since the sample thickness was ~50 mm (2 in.). The samples were compressed to approximately 15% deformation. The compressive strength (kPa) was then determined at the 10% deformation point as outlined in the standard.

FIG. 4 – Instron machine used for compressive strength test

Results and Discussion

The major observations on the results obtained from the dimensional stability, thermal resistance and compressive strength tests are presented and discussed in the following paragraphs.

Dimensional Stability

The dimensional changes of specimens of three different sizes due to two exposure conditions are shown in [Table 3](#). [Figures 5a and 5b](#) show the relation between the size of the specimens and dimensional changes due to environmental exposures. These results clearly indicate that exposure condition A (28 days at 70°C and 78% RH) caused higher dimensional changes than the exposure condition B (90 days at 60°C). While exposure A caused expansion in all specimens, exposure B inflicted a small amount of shrinkage in a few specimens ([See Figure 5b](#)). It also appears that exposure to high humidity and temperature caused higher dimensional change in the perpendicular direction of the knit-line⁸ [\[10\]](#) and this dimensional change seems to

⁸Knit-line is the linear impression left on the ISO foam insulation board during the manufacturing process. This is a high-density layer of foam indicating the joint between two adjacent pours of foam that did not flow together until

be linearly increasing with the size of the insulation board. It is to be referred here that ASTM C 1289-02 specifies a maximum allowable 2% dimensional change. In this case both along and perpendicular to the knit-line direction the maximum observed dimensional changes were less than 1% (expansion). Similar trends, i.e. less than 2% dimensional change and maximum dimensional changes in the direction perpendicular to the knit-line, were also observed in the test results obtained from the small scale and full size ISO specimens as shown in Figures 6a and 6b. However, probably more important for the structural integrity of the roofing systems, the absolute physical dimensional change seems to linearly increase with the size of the ISO insulation board. Further investigation is needed to find out the effect of this dimensional change, in the perpendicular direction of the knit-line, on the mechanically or otherwise attached components with the ISO boards and interfaces.

Table 3 – Results from dimensional stability tests

Specimen Size	Linear Dimensional Change (mm)					
	Exposure A – 28 days at 70°C and 78% RH			Exposure B - 90 days at 60°C		
	Length ^A	Width ^B	Thickness	Length ^A	Width ^B	Thickness
12 in.×12 in. (300 mm × 300 mm)	1.48	3.08	0.56	0.17	-0.23	0.14
	1.39	2.78	0.47	0.05	0.11	0.12
	0.28	2.96	0.65	0.09	0.16	0.36
<i>Average</i>	<i>1.05</i>	<i>2.94</i>	<i>0.56</i>	<i>0.10</i>	<i>0.01</i>	<i>0.21</i>
18 in.×18 in. (450 mm × 450 mm)	1.34	3.78	0.73	0.02	-0.04	0.08
	1.99	2.99	0.75	-0.02	0.05	0.13
	1.99	3.45	0.84	-0.01	0.06	0.26
<i>Average</i>	<i>1.77</i>	<i>3.41</i>	<i>0.77</i>	<i>0.003</i>	<i>0.02</i>	<i>0.16</i>
24 in.×24 in. (600 mm × 600 mm)	0.65	3.95	0.66	-0.03	-0.21	0.12
	1.72	3.84	0.68	0.09	0.13	0.16
	1.57	4.35	0.80	-0.11	-0.23	0.32
<i>Average</i>	<i>1.31</i>	<i>4.05</i>	<i>0.72</i>	<i>-0.02</i>	<i>-0.10</i>	<i>0.20</i>

^A: Along the knit-line.

^B: Perpendicular to the knit-line.

after skins were formed [10]. Under ideal conditions the various parts of a pour should flow together while still liquid, thus avoiding the formation of knit-lines. This is a common occurrence with all rigid foam insulation boards.

FIG. 5 – Dimensional changes due to accelerated aging exposures

FIG. 6 – Dimensional changes in small and full size ISO boards

Thermal Resistance

The comparisons between initial and final (i.e. after exposure) thermal resistance (R-value) values of three different size specimens are shown in [Figures 7a and 7b](#). Without any exception, the thermal resistance of the ISO specimens reduced between 0.08% and 5.30%. Exposure B resulted in a slightly higher (average 3.6%) reduction in the thermal resistance than the same with exposure A (average 2.5%). However, even after this reduction, the reduced R-

values are still higher than the value specified in the ASTM standard C 1289-02 (i.e. 5.3 per inch.). Nevertheless further investigation with prolonged exposure period would be necessary to see if this trend of thermal resistance reduction is a continuous process or otherwise. It is also to be remembered here that polyiso boards do age (i.e. reduction in thermal resistance) naturally [11-13] due to outward diffusion of blowing agent and intrusion of air into the closed foam cells. The aging of the ISO board is very rapid immediately after the manufacturing and tends to slow down rapidly within a few weeks or months afterwards⁹. However, the aging rate depends on a multitude of factors such as the foam characteristics, blowing agent properties, manufacturing process etc. It is believed that aggressive environmental condition, particularly elevated temperature, can accelerate and further this aging process.

FIG. 7 – Thermal resistance changes due to accelerated aging exposures

⁹ The ISO specimens were exposed to uncontrolled laboratory indoor environment for at least six months before they were considered in this study and subsequent measurements demonstrated that the specimens reached to a thermally stable condition (see section 'Experimental Program' for details) before the initiation of accelerated environmental aging tests.

The effects of size on the aging (i.e. reduction of thermal resistance) of the ISO boards are shown in Figure 8. These results are in no way conclusive to establish a relationship between aging and the size of the specimens, primarily because of two reasons:

- (1) The aging effect (i.e. reduction of thermal resistance) is small and almost within the limit of expected experimental uncertainties.
- (2) The variation of results within the same set of specimens is more than the variation among specimens of different sizes.

Hence, these experiments show that reduction of thermal resistance does occur in the ISO boards exposed to the aggressive high temperature and/or humidity conditions but in this case these reductions are not very large and statistically almost within the limit of experimental uncertainty.

FIG. 8 – Effects of size on thermal resistance change of ISO specimens due to accelerated environmental aging exposures

Compressive Strength

The compressive strengths of the ISO board specimens (4 in. × 4 in. × 2 in or 100 mm. × 100 mm. × 50 mm.) before and after the exposure are shown in Figures 9a, 9b and 9c. The initial

thermal resistance values (Figure 9a) indicate that there are some specimens (4 out of 15) that do not live up to the ASTM C 1289-02 (Type II, Class 1, Grade 3) specification (Compressive strength = 172 kPa). However, the average compressive strength of fifteen (15) specimens is above (173.3 kPa) the ASTM C 1289 specification. The effect of exposure condition A (28 days at 70°C and 78% RH) has a definite negative influence on the compressive strength of ISO board (Figure 9b). The average and individual compressive strengths of most (10 out of 18) of the exposed specimens do not satisfy the ASTM C 1289 specification. On the other hand, the positive effect of exposure condition B (90 days at 60°C) on the compressive strength of ISO specimens is very much evident in Figure 9c. The compressive strength of each of the eighteen (18) specimens is found to be higher than the ASTM C 1289 specification. Hence, it appears that while combined high humidity and temperature softens the ISO board, the prolonged exposure to elevated temperature makes the ISO specimens harder to compress. Obviously, these particular characteristics of the ISO boards would have implications on: (1) the structural integrity and stability of the mechanically attached roofing systems, and (2) performance of fastener.

Further investigation needs to be carried out to quantify these phenomena.

FIG. 9 – Compressive strength of ISO specimens: (a) Initial, (b) Exposure A, and (c) Exposure B

Summary of Observations

It is to be noted here that the results and discussion presented in this paper are from a pilot study that has critically analyzed the existing selected ASTM C 1289-02 specifications for ISO foam insulation boards, particularly for roofing applications. Thus the observations and discussion are solely for the purpose of stimulating and finding direction for the further research and development. Keeping this in perspective, following conclusions can be derived from this study:

- (1) The dimensional changes in the ISO boards exposed to aggressive environment appear to be more in the direction perpendicular to the knit-line on the foam board surface and linearly related with the size of the specimens.
- (2) Results from this study show that the reduction of thermal resistance due to aggressive environmental exposures (condition A: 28 days at 70°C, and 78% RH; condition B: 90 days at 60°C) does occur in the ISO boards but in this case these reductions are not very large and statistically almost within the limit of experimental uncertainty.
- (3) The exposure to simultaneous high humidity (78% RH) and temperature (70°C) reduces the compressive strength of the ISO board but the prolonged exposure to elevated temperature increases the compressive strength of the ISO specimens.
- (4) As stated above, the dimensional changes in the direction perpendicular to the knit-line and reduction in compressive strength of the ISO boards due to aggressive environmental exposure are the two major concerns that need to be investigated further for the effective use of ISO boards in roofing applications.

References

- [1] ASTM Standard C1289-02, “Standard Specification for Faced Rigid Cellular Polyisocyanurate Thermal Insulation Board”, *ASTM International*, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.
- [2] CAN/ULC-S770-03, “Standard Test Method for Determination of Long-Term Thermal Resistance of Closed-Cell Thermal Insulating Foams”, *Underwriters' Laboratories of Canada*, 7 Underwriters Road, Toronto, Ontario M1R 3B4T, Canada.

- [3] Kumaran, M. K. and Bomberg, M. T., “Thermal Performance of Sprayed Polyurethane Foam Insulation with Alternative Blowing Agents”, *Journal of Thermal Insulation*, Vol 14, July 1990, P. 43.
- [4] Leonard, J. and Leonard, T., “Beyond ‘Cool’ to ‘Sustainable’ Reflective Roof Coatings”, Proceedings Cool Roofing... Cutting Through The Glare, *Roof Consultants Institute Foundation*, May, 2005, Atlanta, GA, USA, pp. 1-13.
- [5] Handegord, G.O., “Moisture Considerations in Roof Design” CBD-73, Institute for Research in Construction, National Research Council, 1966, Ottawa, Canada.
- [6] Desjarlais, A.O. and N. Byars. 1997., “Moisture Design to Improve the Durability of Low-Slope Roofing Systems”, *Proceedings of the Sustainable Roofing Workshop* (ORNL CONF-9610200), Oak Ridge, TN: Oak Ridge National Laboratory.
- [7] CAN/ULC-S704-01, “Standard for Thermal Insulation, Polyurethane and Polyisocyanurate Boards, Faced”, *Underwriters' Laboratories of Canada*, 7 Underwriters Road, Toronto, Ontario M1R 3B4T, Canada.
- [8] ASTM standard C 518-04, “Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus”, *ASTM International*, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959 USA, www.astm.org.
- [9] ASTM standard D1621-04a, “Standard Test Method for Compressive Properties of Rigid Cellular Plastics”, *ASTM International*, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428-2959, USA, www.astm.org.
- [10] A Glossary of Polyurethane Industry Terms, *The Edge Sweets Company*, 2887 Three Mile Road NW, Grand Rapids, MI 49544-1386, USA, www.edge-sweets.com.

- [11] Kumaran, M.K. "Cellular plastic insulation research continues," *Building Performance News*, (6), pp. 2, April, 1990 (Aussi disponible en français: Recherche sur les plastiques cellulaires isolants), (NRCC-35465) (IRC-P-3098).
- [12] Bomberg, M.T. and Kumaran, M.K. "Laboratory and roofing exposures of cellular plastic insulation to verify a model of aging," *ASTM Special Technical Publication*, 1224, Roofing Research and Standards Development : 3rd Volume (Montreal, Que., Canada, June 19, 1994), pp. 151-167, May, 1994 (ISBN: 080311883X), (NRCC-37928) (IRC-P-3775 ASTM-STP-1224).
- [13] Mukhopadhyaya, P., Bomberg, M.T., Kumaran, M.K., Drouin, M., Lackey, J.C., van Reenen, D. and Normandin, N. "Long-term thermal resistance of polyisocyanurate foam insulation with gas barrier," *IX International Conference on Performance of Exterior Envelopes of Whole Buildings* (Clearwater Beach, Florida, December 05, 2004), pp. 1-10, December 01, 2004, (NRCC-46881), URL: <http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc46881/>.