RESEARCH REPORT

PREDICTING TIME TO FOGGING OF INSULATING GLASS UNITS

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Predicting Time to Fogging of Insulating Glass Units

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RESEARCH HIGHLIGHT

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PREDICTING TIME TO FOGGING OF INSULATED GLASS UNITS

INTRODUCTION

Predicting the inevitable repair or replacement of insulating glass (IG) (Figure 1) units is a big challenge for building managers. It requires an understanding of potential service life span and the regular collection of field observations of actual performance. IG unit performance and the financial planning necessary for eventual replacement are of prime importance to condominium corporations.

Observations at many buildings with like components allow building managers to correlate visible signs of deterioration with the likely time when repairs or replacement must be undertaken. Prediction of failure times is much more difficult when there are no visible signs of deterioration. "Failure" of insulating glass units is generally considered to occur when clear vision through the unit is obscured by condensation (fogging) within the unit, but there is usually no visual sign when this might occur. This affects the ability of building owners to accumulate funds for repair or replacement at a reasonable rate.

Gerald R. Genge Building Consultants Inc. through CMHC's External Research Program conducted a research project to investigate methods for predicting the time to failure of insulating glass units and to suggest ways of improving the prediction of failure of insulated glass units.

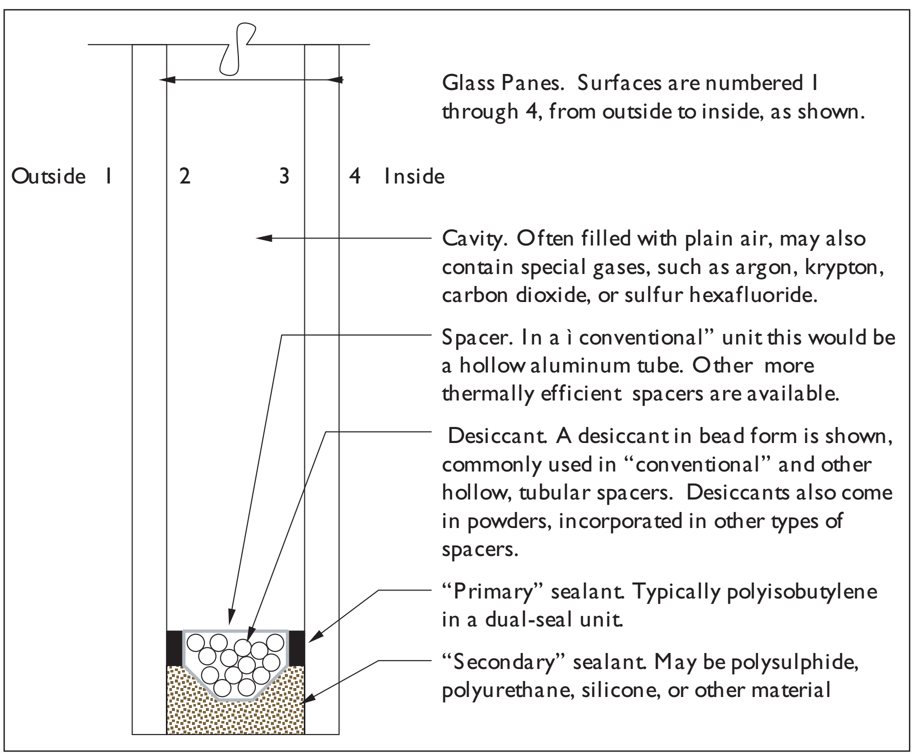

Figure 1: Cross-section through the perimeter of a typical insulating glass unit

OBJECTIVES

The intent of this research was to document common modes of failure of insulating glass units and suggest methods to help building managers predict these failures and develop replacement plans.

The work elements included the following:

- Undertake a literature search to document performance and failure modes of IG units
- Assess existing IG unit failure prediction methods
- Suggest and test new prediction tools
- Recommend next steps

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PERFORMANCE OF INSULATING GLASS UNITS

This portion of the research reviewed and summarized information about why and how insulating glass units fail. The time to fogging is directly related to:

- **Moisture content of the cavity gas fill:** During manufacturing, the desiccant is exposed to the air in the manufacturing facility and adsorbs water vapour from it. Adsorption means water vapour is attracted to and condenses on the surface of the dessicant with no chemical combination of the two. If the latter occurs, then this is defined as absorption. If significant amounts of water vapour are adsorbed, the available moisture adsorption capacity of the desiccant in service is reduced, as is the amount of water vapour required to diffuse into the unit through the perimeter sealants to cause fogging.
- **Permeability and cross-section area of the perimeter sealants:** Permeability of insulating glass unit perimeter sealants varies (Figure 2). Polyisobutylene sealants have the highest resistance compared to polysulphide, polyurethane or silicone sealants. The volume of air trapped within an insulating glass unit changes, forcing the glass panes apart or causing them to bend (Figure 3) which causes the perimeter sealants to be stretched or compressed, affecting the path length and area of the sealants and, thus, their permeance.
- **Type and quantity of desiccant:** The desiccant in the perimeter spacer must adsorb water vapour and any volatile compounds that might be present (from sealants or paints). The greater the amount of desiccant, the longer the life span and vice versa.
- **Service environment:** The difference in water vapour concentration between the cavity gas fill and the environment outside the insulating glass unit to which the perimeter seal is exposed affects service life. The rate of water vapour transmission across the perimeter sealants is greater when the units are exposed to more humid service environments, shortening the time to fogging.

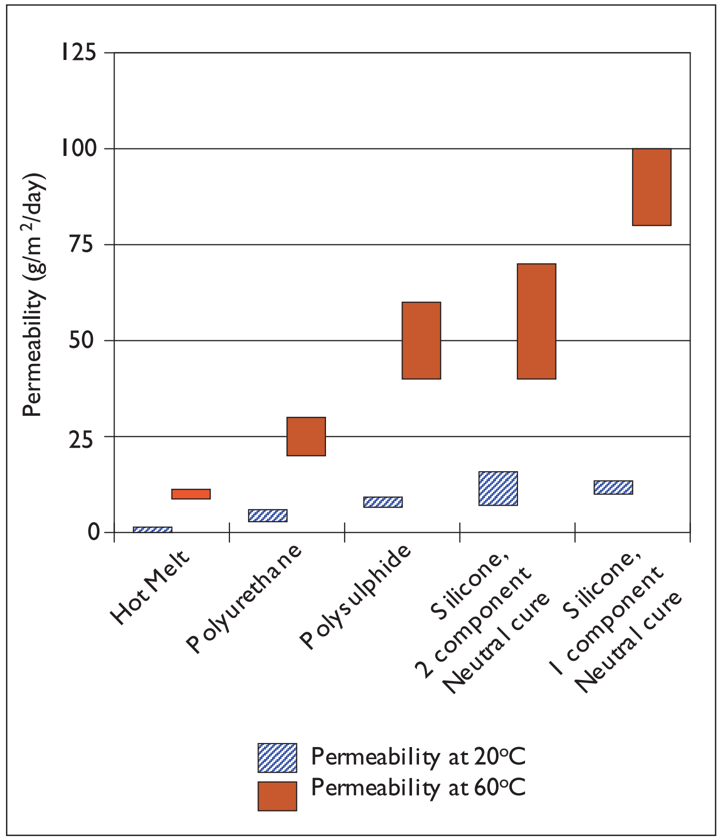

Figure 2: Water vapour transmission rates (permeability) for various insulating glass unit sealants

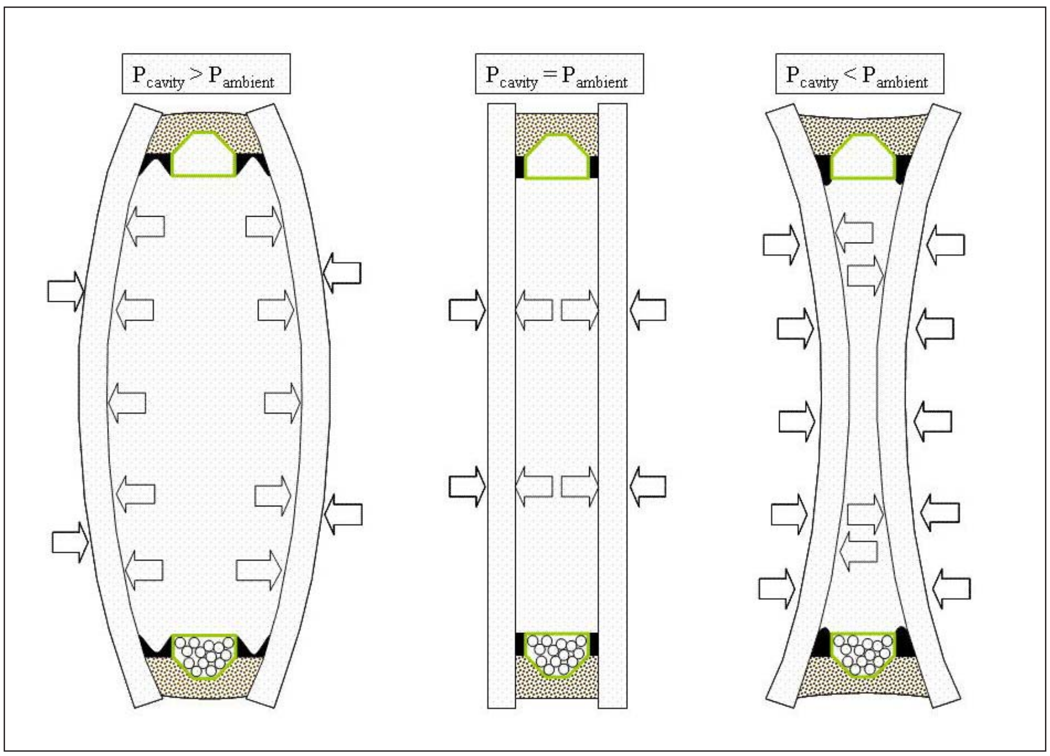

Figure 3: Effect of pane flexibility on sealant configuration

Prolonged contact with liquid water will degrade the perimeter sealants, also shortening the time to fogging (this is considered to be the most common cause for early fogging of units).

Figure 4: Field dew-point measurement apparatus: (Left) The unit is mounted on an insulating glass unit in contact with the inboard pane of glass. A digital thermometer inserted into the unit measures the temperature of unit in contact with the pane. (Right) The apparatus has been removed (except for the suction cups), revealing a circle of condensation or frost on the cavity-side surface of the pane, directly beneath the chilled contact area of the apparatus.

EXISTING METHOD FOR PREDICTING LIFE SPAN

A method to estimate time to fogging of insulating glass units installed in buildings was proposed in the 1980s (Spetz). It uses an indirect determination of the insulating glass unit cavity dew-point temperature (Figure 4) to estimate the degree of saturation of the desiccant contained in the spacer, from which a likely time to fogging can be inferred.

By relating dew-point measurements to desiccant manufacturer's technical data, it is possible to estimate desiccant moisture content (units with desiccant moisture content approaching saturation are likely to fail within a short time). This approach results in the following predictions:

- Dew-point less than -62°C (-80°F): there is almost no moisture in the IG unit cavity, thus the IG units can be expected to have a "very long expected future clear life"
- Dew-point between -62°C (-80°F) and -18°C (0°F): there is some moisture in the cavity, thus the IG unit can be expected to have a future clear life less than units with a dew-point temperature less than < -62°C (-80°F)
- Dew-point between -18°C (0°F) and 0°C (+32°F): there is "considerable" moisture in the air space, thus the IG units will have a relatively short future life. Estimation of remaining life span requires knowledge of the construction of the units, including the desiccant type and manufacturer;
- Dew-point greater than 0°C (32°F): permanent fogging of glass surfaces within the insulating glass unit (exposed to the cavity) can be expected to develop within two years.

There are two major drawbacks to this method. First, it is necessary to know the desiccant type and manufacturer—possible only if the IG unit manufacturer is still in business and cooperative. Second, only the last prediction comes with a timeframe and it is too short (two years), providing insufficient time for building owners to accumulate the substantial funds needed for replacement in modern high-rise buildings.

TESTING A MODIFIED METHOD FOR PREDICTING LIFESPAN

The testing was based on the hypothesis that it should be possible to overcome the limitations of the existing test method in the same way it was first developed—by making repeated measurements of dew-point temperature over time. The intent was to apply a performance measurement technique using accelerated laboratory testing to determine if the technique could be successfully used to predict when units would fog.

Twelve standard test-size insulated glass units were obtained from an accredited Toronto area manufacturer. The test program consisted of

- Initial examination of the units, including destruction of three units to measure desiccant moisture content.
- Repeated cycles of exposure to elevated temperature and humidity to increase the rate of water vapour transmission into the cavity and thus increasing the cavity moisture content and dew-point temperature.
- Measurement of the dew-point temperature of the units was between exposure cycles.
- Development of mathematical models, based on test measurements, to predict future dew-point temperatures and time to fogging. Subsequent dew-point temperature measurements were compared against predicted values to refine the models and the best model was selected.

The initial goal was to induce fogging through elevated temperature and humidity exposure only. However, to meet schedule and funding limitations, modifications to the test procedure were necessary to accelerate failure. Due to difficulties with mathematically predicting time to fogging of the test units during the test program, the development of the models was delayed until all the test data was available. Several prediction models were attempted using the commonly available spreadsheet program Microsoft Excel with one showing greater promise than the others.

The prediction model uses the "Forecast" function in Excel to work with existing data to predict future data. Principally, this function uses the average and standard deviation of the data for as many measurement periods as there are.

From the research, the following three distinct stages of prediction of time to fogging emerge

Stage 1: Dew-point Temperature Not Measurable – No Prediction Possible

The apparatus used for field measurement of dew-point temperature of the insulating glass unit cavity gas fill uses solidified carbon dioxide ("dry ice") to cool the cavity-side surface of one of the glass panes until condensation occurs. As long as the dew-point temperature of the cavity gas fill is lower than about –73°C, it cannot be measured and therefore, no prediction of time to fogging can be made.

Stage 2: Prediction of the Average Dew-point Temperature

Once dew-point temperatures are measurable, it is possible to begin time to fogging predictions.

It is proposed that prediction of time to fogging should only be calculated when the majority of the units in the sample set have measurable dew-point temperatures. It is reasonable to expect that a more accurate prediction would be made with more data (dew-point measurements) at each measurement period. Further work is required to determine how large of a "majority" is required (such as 51 per cent, 66 per cent, and so on). From this analysis the following conclusions were drawn:

- At least three sets of measured dew-point temperatures are needed to make a prediction of time to fogging.
- The accuracy of prediction will change, and become more accurate, as more sets of dew-point temperatures become available.
- The accuracy of prediction can be increased by careful review of trends of dew-point temperature increase, comparing trends for individual units to the overall, and making repeated predictions without suspect units.

Stage 3: Broadening the Prediction

The same method used to predict future average dew-point temperatures (the "Forecast" function in MS Excel) can also be used to predict future standard deviation of dew-point temperatures from the average, and thus the future variation of dew-point temperatures. This would allow prediction of when units that have dew-points higher than the average may fog.

CONCLUSIONS

The research report reviewed the fundamentals of insulating glass unit performance, the factors affecting life span, current methods for predicting IGU lifespan, and then presented a method for field estimation of lifespan (time to fogging). A laboratory experiment to confirm the method was described, carried out, and the results presented and analyzed. It confirmed that methods of estimating life span of insulating glass units are likely to be unreliable without also obtaining *in-situ* measurement of dew-point temperatures.

Predictions of time to fogging based on the progressive results of the experiment, using embedded functions in the spreadsheet program (MS Excel) were shown to be accurate, when compared against actual laboratory data.

It can therefore reasonably be concluded that a method to predict time to fogging of insulating glass units has been identified and proven accurate.

In summary, the method consists of

- Establishment of a representative sample of the population of insulating glass units in a subject building: A review should be made to determine the likelihood that there may be sub-populations that may have different times to failure, and thus should be tracked separately. Multiple samples should be established accordingly.
- Periodic, indirect, measurements of the dew-point temperature of the cavity gas fill of sample units:

  Measurements should be made in warm weather because dew-point temperatures can be measured earlier than during cold weather. This allows more sets of dew-point measurements to be made which in turn should allow for longer-term predictions of time to fogging.
- After at least three sets of dew-point temperatures have been accumulated, preparation of predictions of time to fogging. Readily available prediction tools, such as the "Forecast" function in MS Excel, can be used. As more measurements are made, predictions should be repeated to improve the accuracy of the estimated time to fogging.

RECOMMENDATIONS

The research findings advance the prediction of time to fogging. Further work is required as follows:

- Further laboratory assessment in a timeframe that does not require intentional breach of the perimeter seal to induce failure.
- *In-situ*, field measurements and predictions of time to fogging. Subject buildings that have insulating glass units with measurable dew-point temperatures should be selected. Such a program could be lengthy, depending on the age of the units monitored and the type and severity of conditions affecting lifespan.

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PRÉVISION DU MOMENT DE L'EMBUAGE DES VITRAGES ISOLANTS

INTRODUCTION

Prévoir le moment inévitable où il faudra réparer ou remplacer les vitrages isolants (Figure 1) est un défi de taille pour les gérants d'immeubles. Ils doivent d'abord connaître la durée de vie probable des vitrages, puis recueillir régulièrement des données sur leur rendement réel. La planification du rendement des vitrages isolants et des ressources financières nécessaires à leur remplacement éventuel est de toute première importance pour les sociétés de copropriété.

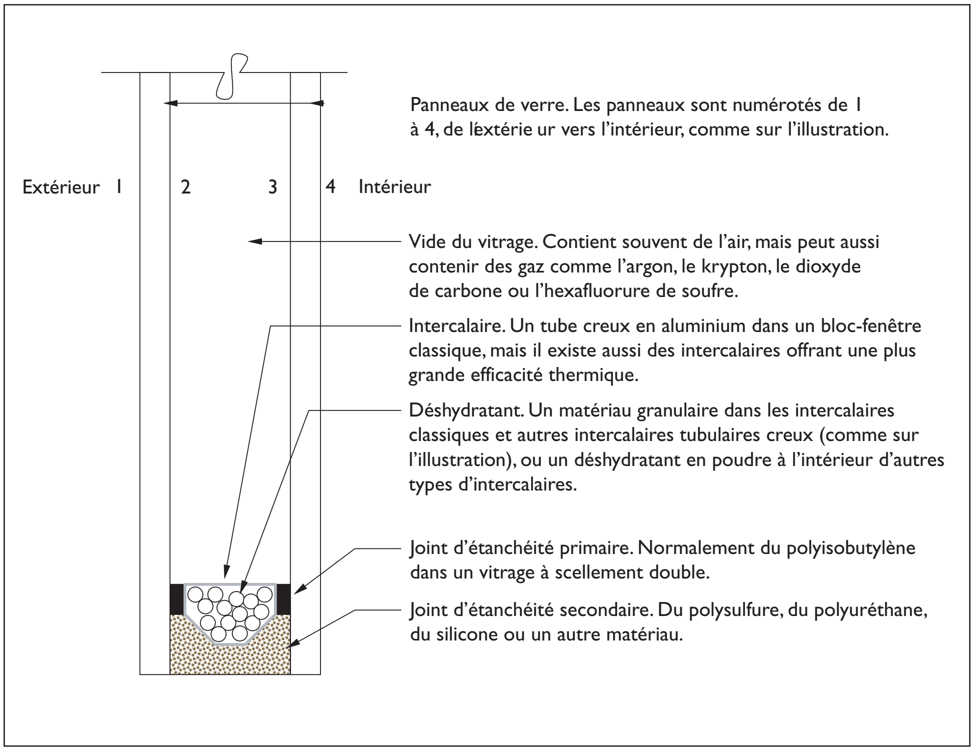

Figure 1 : Coupe transversale d'un vitrage isolant caractéristique

Grâce aux observations effectuées dans un grand nombre d'immeubles ayant des composantes semblables, les gérants d'immeubles peuvent établir des corrélations entre les signes visibles de détérioration et le moment probable où ils auront à réparer ou à remplacer les vitrages isolants. En l'absence de signes visibles de détérioration, il est beaucoup plus difficile de prévoir le moment où surviendront les défaillances. On parle généralement de « défaillance » d'un vitrage isolant quand la visibilité à travers le vitrage est réduite par de la condensation (buée) qui se forme entre les panneaux de verre. Aucun signe visible ne permet habituellement de prévoir le moment où la défaillance se produira. De ce fait, les propriétaires d'immeubles ont du mal à déterminer les sommes qu'ils doivent mettre de côté en vue d'éventuels travaux de réparation et de remplacement.

Dans le cadre du Programme de subventions de recherche de la SCHL, la firme Gerald R. Genge Building Consultants Inc. a mené des travaux de recherche visant à évaluer les méthodes permettant de prévoir le moment de la défaillance des vitrages isolants, de manière à pouvoir suggérer des moyens
de mieux anticiper le moment des défaillances.

OBJECTIFS

La recherche dont il est ici question avait pour but de consigner des données sur la façon dont se produisent habituellement les défaillances des vitrages isolants et de suggérer des moyens d'aider les gérants d'immeubles à prévoir ces défaillances et à planifier les travaux de remplacement.

Voici un aperçu des objectifs visés :

- Rechercher dans la documentation sur le sujet de l'information sur le rendement et les modes de défaillance des vitrages isolants.
- Évaluer les méthodes existantes de prévision de la défaillance des vitrages isolants.
- Suggérer et tester de nouveaux outils de prévision.
- Recommander un plan d'action.

RENDEMENT DES VITRAGES ISOLANTS

Ce volet de la recherche consistait à étudier et à résumer l'information expliquant pourquoi et comment les défaillances des vitrages isolants se produisent. Le moment de l'embuage est en lien direct avec les facteurs suivants :

- **Taux d'humidité de la lame de gaz :** Celui-ci dépend de la quantité de vapeur d'eau adsorbée par le déshydratant au moment où celui-ci est exposé à l'air de l'usine. L'adsorption est la condensation de la vapeur d'eau sur la surface du dessicant. Il n'y a pas de combinaison chimique. Si tel était le cas, il aurai de l'absorption. Si le déshydratant a adsorbé une grande quantité de vapeur d'eau pendant la fabrication du vitrage, son pouvoir d'adsorption se trouvera réduit par la suite et il suffira d'une moins grande quantité de vapeur d'eau se diffusant à l'intérieur du vitrage par les joints périmétriques pour provoquer l'embuage.
- **Perméabilité et surface transversale des joints d'étanchéité sur le pourtour du vitrage :** Les joints d'étanchéité sur le pourtour des vitrages isolants n'ont pas tous la même perméabilité (figure 2). Les joints d'étanchéité de polyisobutylène sont ceux qui offrent la résistance la plus grande lorsqu'on les compare aux joints de polysulfure, de polyuréthane ou de silicone. Le volume d'air piégé à l'intérieur des vitrages isolants subit des variations qui entraînent la flexion des panneaux de verre vers l'extérieur ou vers l'intérieur du vitrage (figure 3) et, du coup, l'étirement ou la compression des joints d'étanchéité périmétriques. Or, ces mouvements influencent la longueur et la surface des joints d'étanchéité et, par conséquent, leur perméance.

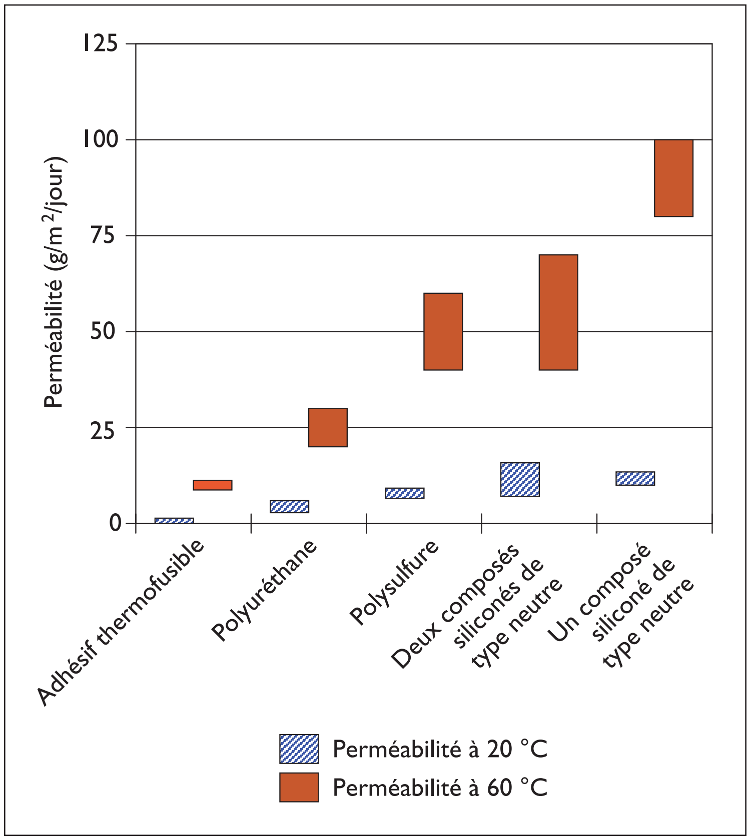

Figure 2 : Vitesse de transmission de la vapeur d'eau (perméabilité) à travers différents joints d'étanchéité de vitrages isolants

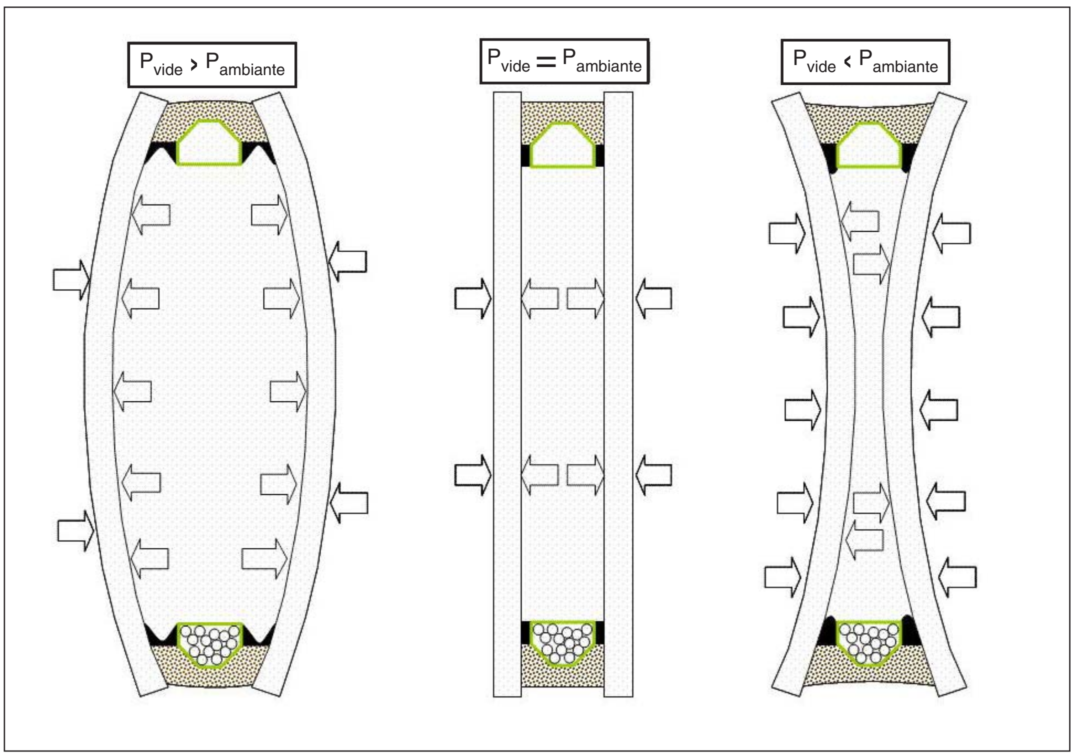

Figure 3 : Influence de la flexion des panneaux sur la configuration des joints d'étanchéité

Figure 4 : Appareil de mesure de la température du point de rosée : (À gauche) L'appareil est monté sur un vitrage isolant en contact avec le panneau de verre intérieur. Un thermomètre numérique inséré dans l'appareil mesure la température de celui-ci lorsqu'il est en contact avec le panneau. (À droite) L'appareil a été enlevé (sauf les ventouses), révélant un cercle de condensation ou de givre sur la face du panneau donnant sur le vide, directement sous la surface refroidie par le contact avec l'appareil.

- **Nature et quantité du déshydratant :** Le déshydratant dont est rempli l'intercalaire périmétrique doit adsorber la vapeur d'eau et tout composé volatil que peuvent contenir les scellants et les peintures. Plus la quantité de déshydratant est grande, plus grande sera la durée de vie du vitrage, et vice-versa.
- **Milieu de service :** L'écart entre la concentration de vapeur d'eau qui règne dans la lame de gaz et celle qui règne dans l'environnement auquel le joint d'étanchéité périmétrique est exposé à l'extérieur du vitrage a une incidence sur la durée de vie du vitrage. La vitesse de transmission de la vapeur d'eau à travers les joints d'étanchéité est plus grande quand les vitrages sont exposés à des milieux de service plus humides, avec pour conséquence de rapprocher le moment de l'embuage. Un contact prolongé avec de l'eau à l'état liquide amène une détérioration des joints d'étanchéité périmétriques et une accélération de l'embuage à l'intérieur du vitrage (on considère qu'il s'agit là de la cause la plus fréquente de l'embuage prématuré des vitrages).

MÉTHODE EXISTANTE DE PRÉVISION DE LA DURÉE DE VIE DES VITRAGES ISOLANTS

Une méthode de prévision du moment de l'embuage des vitrages isolants installés dans des immeubles a été proposée dans les années 1980 (Spetz). Cette méthode utilise une détermination indirecte de la température du point de rosée dans le vide du vitrage isolant (figure 4) pour évaluer le degré de saturation du déshydratant que contient l'intercalaire, à partir de quoi est inféré le moment probable de l'embuage.

En établissant un rapprochement entre les mesures de la température du point de rosée et les données techniques fournies par le fabricant, il est possible d'évaluer la teneur en eau du déshydratant (les vitrages dont le déshydratant a une teneur en eau frôlant la saturation ont de fortes chances de s'embuer à court terme). Cette méthode conduit aux prévisions suivantes :

- Si la température du point de rosée est inférieure à –62 °C (–80 °F), il n'y a pratiquement pas d'humidité dans le vide du vitrage isolant, ce qui permet de prévoir que celui-ci restera clair pendant très longtemps.
- Si la température du point de rosée se situe entre –62 °C (–80 °F) et –18 °C (0 °F), le vide du vitrage renferme un peu d'humidité, ce qui laisse prévoir que le vitrage restera clair pendant moins longtemps que les vitrages pour lesquels la température du point de rosée est inférieure à –62 °C (–80 °F).
- Si la température du point de rosée se situe entre –18 °C (0 °F) et 0 °C (+32 °F), le vide du vitrage renferme beaucoup d'humidité, ce qui laisse prévoir que le vitrage isolant aura une durée de vie relativement courte. L'évaluation de la durée de vie utile restante nécessite de l'information sur la construction des vitrages, notamment sur la nature du déshydratant et son fabricant.

- Si la température du point de rosée est supérieure à 0 °C (32 °F), on peut s'attendre à ce que les surfaces vitrées exposées au vide du vitrage s'embuent de façon permanente avant deux ans.

La méthode comporte deux inconvénients importants. D'abord, elle oblige à se renseigner sur le type de déshydratant qui a été employé et sur son fabricant, si toutefois le fabricant du vitrage isolant est toujours en affaires et qu'il veut bien coopérer. Ensuite, il n'y a que la dernière prévision qui s'assortisse d'une mesure de la durée de vie restante (deux ans), ce qui ne laisse pas suffisamment de temps aux propriétaires pour accumuler la somme respectable nécessaire au remplacement des vitrages dans les gratte-ciel modernes.

MISE À L'ESSAI D'UNE MÉTHODE MODIFIÉE DE PRÉVISION DE LA DURÉE DE VIE

La mise à l'essai de la méthode modifiée reposait sur l'hypothèse qu'il devait être possible de surmonter les limites de la méthode existante en procédant de la même façon que lors de l'élaboration de la première méthode, c.-à-d. en faisant des mesures répétées de la température du point de rosée à différents moments. L'intention était d'appliquer une technique de mesure du rendement par des essais accélérés en laboratoire destinés à déterminer si la technique pouvait être utilisée avec succès pour prévoir le moment de l'embuage des vitrages.

Un fabricant accrédité de la région de Toronto a fourni à des fins d'essais 12 blocs-fenêtres à vitrage isolant de grandeur uniforme. Voici en quoi consistait le programme d'essais :

- examen initial des vitrages et destruction de trois d'entre eux pour mesurer la teneur en eau du déshydratant
- cycles répétés d'exposition à des niveaux élevés de température et d'humidité pour accroître le taux de transmission de la vapeur d'eau dans le vide du vitrage et ainsi augmenter dans celui-ci le taux d'humidité et la température du point de rosée
- mesure de la température du point de rosée dans les vitrages entre les cycles d'exposition
- élaboration de modèles mathématiques fondés sur les mesures prises lors des essais, dans le but de prévoir les températures du point de rosée futures et le moment de l'embuage. Les mesures ultérieures de la température du point de rosée ont été comparées aux valeurs prévues de manière à améliorer les modèles et à ne retenir que le meilleur.

L'objectif initial était de provoquer l'embuage uniquement par l'exposition à des niveaux élevés de température et d'humidité. Toutefois, du fait de contraintes de temps et de budget, il a fallu apporter des modifications aux méthodes d'essai de manière à accélérer la défaillance des vitrages. Comme il a été difficile de prévoir mathématiquement le moment de l'embuage des vitrages pendant le programme d'essais, l'élaboration des modèles a été repoussée jusqu'au moment où toutes les données d'essai ont été disponibles. Plusieurs modèles de prévision ont été mis à l'essai à l'aide du tableur Microsoft Excel, et l'un d'entre eux s'est révélé plus prometteur que les autres.

Le modèle de prévision utilise la fonction « Prévision » du programme Excel pour prévoir des valeurs futures à partir de données existantes. Cette fonction utilise surtout la moyenne et l'écart-type des données pour chacune des périodes de mesure.

La recherche fait ressortir les trois stades distincts de prévision du moment de l'embuage que voici :

Stade 1 : Température du point de rosée impossible à mesurer... aucune prévision possible

L'appareil utilisé pour mesurer sur place la température du point de rosée de la lame de gaz des vitrages isolants fait appel à du dioxyde de carbone à l'état solide (de la « glace sèche ») pour refroidir la surface d'un panneau vitré donnant sur le vide du vitrage jusqu'à ce que de la condensation se forme. Tant que la température du point de rosée de la lame de gaz est inférieure à environ –73 °C, elle ne peut pas être mesurée et il est par conséquent impossible de prévoir le moment de l'embuage.

Stade 2 : Prévision de la température moyenne du point de rosée

À partir du moment où les températures du point de rosée sont mesurables, il est possible de commencer à faire des prévisions quant au moment de l'embuage.

Il est proposé que la prévision du moment de l'embuage ne soit calculée qu'à partir du moment où il est possible de mesurer les températures du point de rosée pour la majorité des vitrages compris dans l'échantillon. Il est raisonnable de s'attendre à une prévision plus juste si les données (mesures des températures du point de rosée) sont plus nombreuses à chaque période de mesure. Il reste à déterminer à quel pourcentage des échantillons correspond la « majorité » nécessaire (51 %, 66 %, et le reste).

Voici les conclusions qui ont été tirées de cette analyse :

- Il faut au moins trois jeux de mesures des températures du point de rosée pour avancer une prévision du moment de l'embuage.
- L'exactitude de la prévision varie et est de plus en plus grande au fur et à mesure que s'accroît le nombre de températures du point de rosée connues.
- Il est possible d'accroître l'exactitude d'une prévision en étudiant attentivement les tendances à l'augmentation de la température du point de rosée, en comparant les tendances observées pour certains vitrages à celles qui sont observées pour l'ensemble des vitrages et en faisant des prévisions répétées sans les vitrages suspects.

Stade 3 : Extrapolation des prévisions

La même méthode qui est utilisée pour prévoir les températures moyennes du point de rosée futures (la fonction « Prévision » de MS Excel) peut aussi servir à prévoir l'écart-type futur entre les températures du point de rosée et la moyenne, et donc la variation future dans les températures du point de rosée. Cette méthode permettrait de prévoir à quel moment les vitrages qui ont des températures du point de rosée supérieures à la moyenne risquent de s'embuer.

CONCLUSIONS

Le rapport de recherche présente une méthode d'évaluation sur place de la durée de vie des vitrages isolants (moment de l'embuage) au terme d'une analyse des principes fondamentaux expliquant leur rendement, des facteurs qui agissent sur leur durée de vie et sur les méthodes actuelles de prévision de leur durée de vie. Il décrit l'expérience de laboratoire visant à confirmer la méthode qui a été utilisée, en présente les résultats et les analyse. Cette expérience a confirmé que les méthodes d'évaluation de la durée de vie des vitrages isolants risquent d'être peu fiables en l'absence de mesures faites sur place des températures du point de rosée.

Les prévisions du moment de l'embuage faites à partir des résultats de l'expérience et à l'aide des fonctions intégrées d'un tableur (MS Excel) se sont révélées précises une fois qu'elles ont été confrontées aux données réelles recueillies en laboratoire.

Il est par conséquent raisonnable de conclure qu'une méthode permettant de prévoir le moment de l'embuage des vitrages isolants a été mise au point et se révèle précise.

En bref, voici en quoi consiste la méthode :

- Établissement d'un échantillon représentatif de la population des vitrages isolants dans un immeuble donné. Vérification souhaitable visant à déterminer l'existence éventuelle de sous-populations pour lesquelles le moment de la défaillance pourrait être différent et qui nécessiteraient par conséquent un suivi distinct. Établissement d'échantillons multiples, au besoin.
- Mesures indirectes et périodiques de la température du point de rosée de la lame de gaz des vitrages faisant partie de l'échantillon :

  Ces mesures devraient être effectuées par temps doux, car les températures du point de rosée peuvent être faites avant que ne s'installe le temps froid. Ceci permet d'obtenir davantage de séries de mesures de la température du point de rosée et, éventuellement, des prévisions à plus long terme du moment de l'embuage.
- Préparation des prévisions du moment de l'embuage après qu'au moins trois séries de températures du point de rosée ont été recueillies. Il est possible d'utiliser des outils de prévision facilement accessibles, comme la fonction « Prévision » du tableur MS Excel. Dès que des mesures sont prises, les prévisions du moment de l'embuage devraient être refaites de manière à améliorer leur exactitude.

RECOMMANDATIONS

Les résultats de la recherche font progresser la prévision du moment de l'embuage. Des travaux ultérieurs devraient poursuivre les objectifs suivants :

- Lors des évaluations faites en laboratoire, trouver un moyen de provoquer la défaillance des vitrages dans un délai qui ne nécessite pas le bris intentionnel du joint d'étanchéité périmétrique.
- Recueillir des données sur place et faire des prévisions du moment de l'embuage. Il faudrait choisir, aux fins des études, des immeubles qui possèdent des vitrages isolants dont on peut mesurer les températures du point de rosée. Cet exercice risque d'être long, le temps nécessaire variant en fonction de l'âge des vitrages à l'étude, des conditions qui influent sur leur durée de vie et de la gravité de ces conditions.

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Consultants pour le projet de recherche :
Gerald R. Genge Building Consultants Inc.

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Introduction

> *The basic rules for long service life of materials are (a) to design so as to impose the least critical function upon a material, (b) to select a material that can perform the function and be durable in its service environment, or (c) to alter the environment to suit the properties of the material that must be used.*
>
> *Kirby Garden, 1969[1]*

The Basic Problem

No building material lasts forever. The late Kirby Garden, an architect and research officer with the Division of Building Research, National Research Council Canada, and the first independent building envelope consultant in Canada, succinctly captured the reasons for this in the above quote. Any material can fail to achieve promised performance if its situation is compromised by stress beyond its capabilities or a service environment that is aggressive for it. It follows that if not so stressed or exposed, building materials should perform for very long periods of time. But, for how long?

For condominium properties, the inevitability of repair or replacement of building materials and systems is recognized by Provincial legislation that requires financial reserves be established to fund such work. The amount of these funds must be calculated in a rational manner, set out in a formal plan. Assessment of remaining service life of building materials and systems requires an understanding of potential service life span, tempered by field observations of actual performance. Frequent field observations should allow building owners to track the performance of materials and systems and allow projections to be made regarding likely time to failure. If present costs for repair or replacement are known, using historic rates of inflation and standard formula for calculating future costs, appropriate rates of accumulation of funds can be calculated to ensure, as best one can, that adequate funds are available for the work when required.

Performance Tracking

Performance tracking assumes that performance can be measured in some way. For instance, although performance at the time may still be sufficient, curling of asphalt shingles on a roof, cracking, rust stains, de-lamination or spalling of reinforced concrete, or fading and chalking of acrylic baked enamel paint on aluminium window frames are indications of deterioration and an upcoming need for repair or replacement. Broad experience at many buildings with the same or similar materials in good condition, showing evidence of deterioration such as noted, and after deterioration has progressed to the point were repair or replacement is required, allows one to develop a correlation between visible signs of deterioration and the likely time when repairs or replacement must be undertaken.

But what if evidence of deterioration is not visible? “Failure” of insulating glass units is generally considered to occur when clear vision through the unit is obscured by condensation (fogging) within the unit. Until fogging occurs, there is usually no visual evidence that the unit is ageing and that replacement or repair will soon be required. This can affect the ability of building owners to accumulate funds for repair or replacement at a reasonable rate. This is of particular concern when the cost to repair or replace is significant. For example, a survey of residential condominium reserve fund plans for CMHC carried out by Gerald R. Genge Building Consultants Inc. revealed that, for high-rise residential condominium buildings in the greater Toronto area [2], for large scale, building-wide replacement programs, estimated costs for insulating glass unit replacement vary from about $50,000 to about $2,400,000 per building, depending on the size of the building and on the proportion of the building envelope incorporating insulating glass units. These cost estimates usually assume "conventional" insulating glass unit construction with clear glass, non-thermally broken aluminium spacer, and plain air in the cavity. Costs would likely be higher if the units include features such as low emissivity glass (reflective and tinted glasses are not usually used in residential construction), "warm-edge" spacer, and argon gas fill.

If the actual time to failure differs significantly from assumed time to failure, the financial impact on a condominium corporation could be severe: if less, deferral of other projects or "special assessment" to raise additional funds may be required; if more, then the residents are penalized with excessively high reserve contribution rates which can be as much as 18 – 25% of monthly maintenance fees [3]. "Special assessments" and excessively high maintenance fees would negatively affect the resale value of units, making them more costly and less marketable. Therefore, the development of a method to estimate time to failure of insulating glass units installed in a building would be of benefit to condominium unit owners.

Research Need

The purpose of this External Research Program project was to attempt to confirm a method to predict time to fogging. A proposed method is described in detail in this report. It was evaluated by accelerated ageing of a set of insulating glass units to induce fogging. Ageing was tracked by measuring the moisture content of the cavity gas fill. Calculation methodologies were developed to estimate time to fogging, the most promising of which is described in detail. Conclusions are drawn regarding the proposed method of prediction, limitations are discussed, and recommendations for further research are made.

Financial assistance for the research program was provided by CMHC through its External Research Program. Assistance in the development of a viable method to estimate when insulating glass units would fog is consistent with past CMHC involvement in developing performance standards for insulating glass units. As will be discussed later in this report, at the request of CMHC[1] in the late 1950s through the 1960s the Division of Building Research of the National Research Council of Canada developed a performance test method to identify insulating glass units likely to fail within the then industry standard five-year warranty period [4, 5, 6]. The performance test method that was developed became CGSB[2]12-GP-8, and eventually CGSB 12.8-97[3] (last version). Implementation of the performance test standard was successful in improving performance of insulating glass units [6] so that today, insulating glass unit

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1 At the time, CMHC was the Central Mortgage and Housing Corporation. The name has since been changed to Canada Mortgage and Housing Corporation.

2 At the time, CGSB was the Canadian Government Specifications Board. The name has since been changed to the Canadian General Specifications Board.

3 CGSB-12.8-97, *Insulating Glass Units*, Canadian General Specifications Board, Ottawa, Ontario, 1997.

replacement is usually no longer a short-term operating budget item but instead, a long-term capital replacement reserve item. Unfortunately, a method to determine the length of the "long-term" has not been developed. Given that CMHC spurred the development of performance tests to improve short-term durability that, indirectly gave rise to uncertainties of long-term durability, it is appropriate that CMHC fund research into a method to determine long-term life span.

It should be noted that it is not an objective of the field test method described in this report, and not an objective of the laboratory test program undertaken to verify the field test method, to measure time to fogging of insulating glass units such that a rating scheme of different insulating glass unit sealant materials and construction methods could be established. As will be described in this report, the rate of moisture gain in the cavity of a gas filled insulating glass unit is dependent upon many factors, some of which are under the control of the unit manufacturer (materials, workmanship), some of which are under the control of the window manufacturer (resistance to rain water penetration, resistance to condensation and condensate accumulation, venting and drainage of the glazing pocket), and some of which are under control of the building occupants (indoor air relative humidity, installation of window coverings). Weather and, potentially, changing climate conditions also affect performance (UV breakdown of sealants, etc.). Thus the results of monitoring of insulating glass unit performance at a given building should be considered specific to the building and not necessarily an indication of performance of specific sealants, spacers, or window framing in general.

Performance of Insulating Glass Units

Fundamentals

Insulating glass units will not last forever. Eventually, repair[4] or replacement will be required. An understanding of the factors contributing to fogging of insulating glass units is essential to understanding how time to fogging may be estimated.

Most insulating glass units consist of:

- two panes of glass,
- a perimeter spacer to separate the glass panes,
- one or two sealants / adhesives to bind the spacer and glass panes together and to restrict the diffusion of water vapour into the cavity between the glass panes,
- one or more desiccants are included in the perimeter spacer, usually concealed from view,
- plain air (usually) filling the cavity within the glass panes and perimeter spacer, or one or more inert gasses (except for a very limited number of experimental units, there is not a vacuum inside an insulating glass unit, as some people believe).

The function of the desiccants (generally, a blend of different desiccants is used) is to remove water vapour from the cavity gas fill. This is necessary because in general, insulating glass units are used to separate indoor and outdoor environments that at times have considerably different ambient air temperatures. The cavity gas fill contains water vapour. If the cavity gas fill is cooled sufficiently, such as by exposure of one face of the unit to cold outdoor temperatures, condensation of water vapour may occur, obscuring vision. This is explained further in the following text and accompanying diagrams.

In Canada, Part 9 of the model National Building Code of Canada (NBCC) requires that residential buildings intended for use in winter months shall be equipped with heating facilities capable of maintaining an indoor air temperature of 22ºC, at local outdoor ambient air design temperatures. Most provincial building codes are based on the NBCC and would contain similar requirements, sometimes also for high-rise residential buildings.[5] A cursory review of climatic information in Appendix C of the 1995 NBCC reveals that the January 2 1/2% design temperature (used, in combination with the required indoor air temperature, to size heating systems) varies from a high of -2ºC in Tofino, British Columbia (on the west coast of Vancouver

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[4] Typically, insulating glass units are replaced when fogging becomes objectionable. Recently, a method to modify insulating glass units in the field to remove fog and prevent the recurrence of fog has been commercialized by Crystal Clear Window Works Inc., from Ottawa, Canada. The method is reported to be successful although we understand there are limitations on successful application. Without offering endorsement, we therefore note that fogged units may be repaired (field modified to remove fog) or replaced (the existing unit removed and disposed of and a new unit installed in its place).

[5] Part 9 of the 1995 NBCC applies to housing and small buildings, 3 storeys or less in building height and not exceed $600m^2$ in building area. For larger buildings such as high-rise residential apartment buildings, the NBCC does not include such prescriptive requirements. However, it is not unreasonable to expect to maintain the interior design temperature in a high-rise residential apartment at the same temperature as in a house. This is recognized by the 1997 Ontario Building Code which includes a prescriptive requirement in Part 6, Sentence 6.1.2.1, for buildings of residential occupancy to be inhabited during winter months to be insulated and equipped with heating facilities to maintain an indoor air temperature of 22°C.

Island) to a low of -50ºC in Dawson, Yukon Territory.[6] As noted, for insulating glass units with plain air in the cavity, the air is simply what is in the manufacturing plant at the time of assembly. The NBCC does not prescribe required temperatures or levels of indoor relative humidity for factories but based on Health Canada and American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) recommendations, it would be reasonable to assume indoor conditions of 22ºC and 45%RH.[7] By reference to a psychrometric chart the dew point temperature would be about 9.5°C (Figure 1).

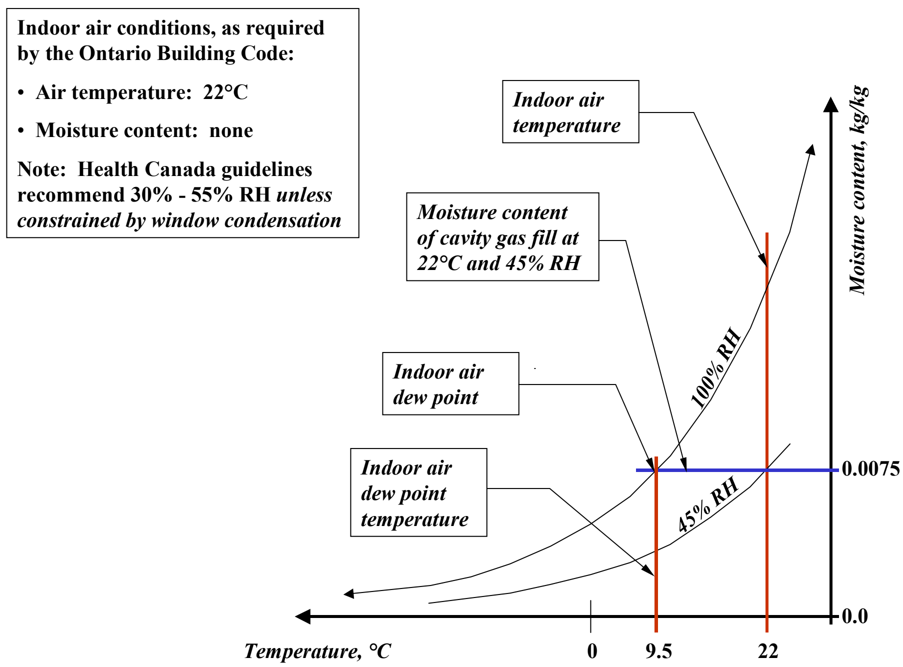

Figure 1: Psychrometric chart showing the dew point temperature of the cavity gas fill within an insulating glass unit. Gas fill is assumed to be plain air, captured at 22ºC at 45% RH.

A simple thermal gradient calculated through the centre-of-glass region of an insulating glass unit with 4mm clear glass, no coatings, and a 13mm cavity filled with plain air[8] reveals that the cavity-side surface temperature of the outer pane of glass would be +2ºC for Tofino and -40ºC for

6 The January 2 1/2% design temperature is a severe measure of winter temperature conditions. However, it quickly shows that service temperatures can be considerably below assembly temperatures, so the potential for condensation of water vapour in the cavity gas fill must be considered even in mild climate areas.

7 A relative humidity of 45% is assumed, based on the 2001 ASHRAE *Handbook of Fundamentals*, Figure 5, ASHRAE Summer and Winter Climate Zones, p. 8.12.[7] This value also coincides with the mid-range of indoor relative humidity for houses and office buildings recommended by Health Canada (there is no Health Canada guideline for factories).[8,9]

8 For high-rise residential condominium buildings in the Toronto area, it is common for windows to be designed to accept insulating glass units with an overall depth of about 22 mm (7/8 in.). For air filled cavities, a 13 mm (12 in.) cavity width is optimum for thermal performance (air filling is still common, to reduce initial capital cost). The thickness of the glass panes was assumed at 4 mm, approx. 3/16 in.) to accommodate these dimensions.

Dawson at the indoor and outdoor design temperatures noted (Figure 2).[9] This is less than the dew point temperature of the cavity gas fill at about 9.5ºC and thus, there is a potential for condensation to form within the unit in winter conditions throughout Canada.

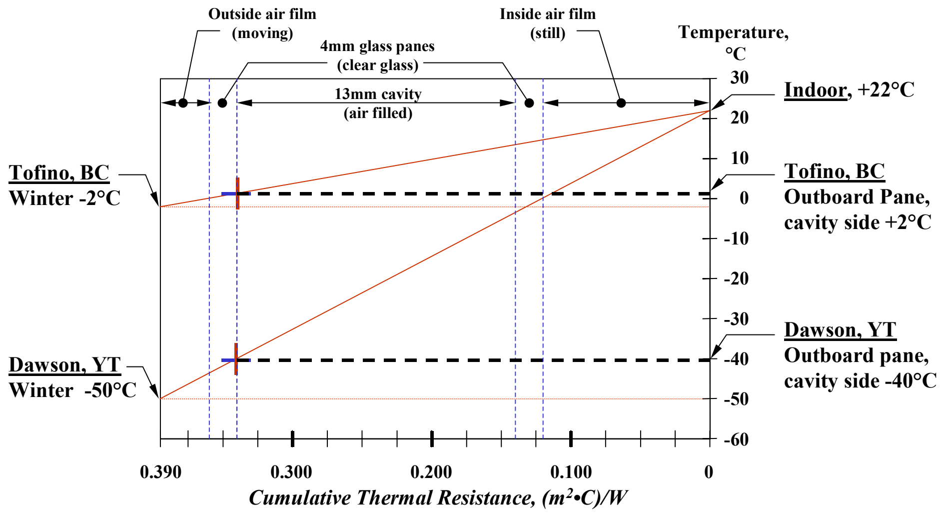

Figure 2. Simple thermal gradient through centre-of-glass region of an insulating glass unit with 4mm glass, 13mm air-filled cavity, exposed to room temperature conditions and the warmest (Tofino, BC) and coldest (Dawson, YT) outdoor January 2 1/2% design temperature in Canada.

To prevent condensation from forming, one or more desiccants are included in the perimeter spacer of insulating glass units. The desiccant(s) adsorb[10] water vapour in the cavity gas fill. This reduces the moisture content of the gas fill, reducing its dew point temperature to below the wintertime cavity-side temperature of the outer glass pane[11] so that the possibility of condensation (fogging) within the unit is reduced (Figure 3).

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9 The method of determining thermal gradients is described in Canadian Building Digest No. 36. Material thermal properties are listed in the ASHRAE *Handbook of Fundamentals*. Ambient outdoor air temperatures are used for the thermal gradient in Figure 3 (solar heating effects are not included) so that the outboard pane cavity-side surface temperatures are not elevation specific. There are more precise methods of calculating thermal performance of insulating glass units (such as FramePlus from NRCan) but for the simple units used in this study, the simple graphical method used is accurate and provides a better visual image of thermal performance.

10 The term "adsorb" indicates that a desiccant does not chemically combine with the water vapour. Instead, the water vapour is attracted to and held on the surface of the desiccant by relatively weak inter-molecular forces (van der Waahls forces). Therefore, it is said that water vapour condenses onto the surface of a desiccant. If chemical combination occurred, the water vapour would be ab̲sorbed.

11 Generally, it is assumed in this report that when condensation occurs within an insulating glass unit, it occurs on the cavity side of the outer pane of glass. This follows from the example of winter design temperatures for Tofino and Dawson: in the winter, it is the outer pane that is likely to be sufficient cold that it is below the dew point temperature of the cavity gas fill. However, in warmer climates, air conditioning (cooling) may reduce indoor air temperatures sufficiently that condensation could occur on the cavity side of the inner panel of glass. This would

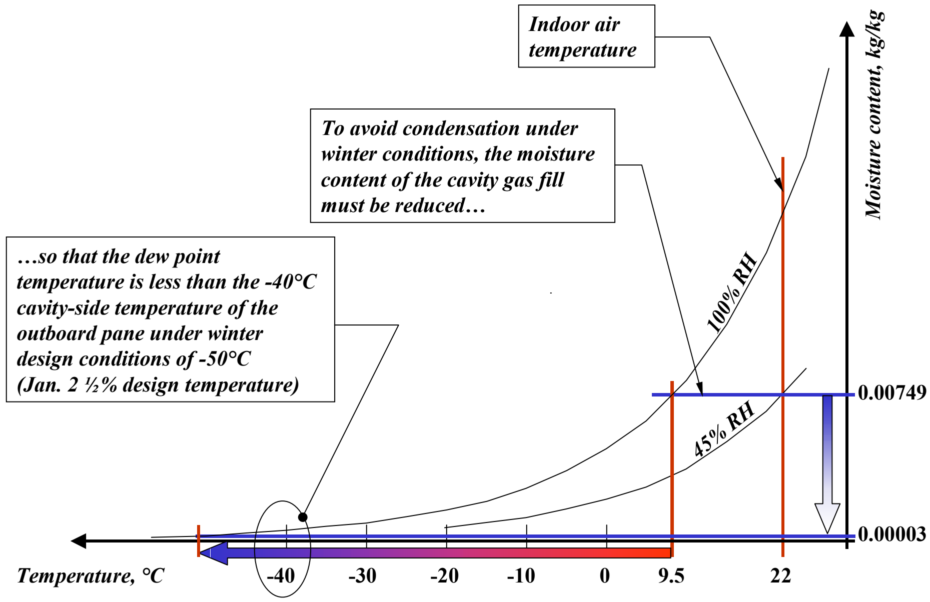

Figure 3: Psychrometric chart showing how the moisture content of the cavity gas fill, and therefore its dew point temperature, must be reduced to avoid condensation under winter design conditions for Dawson, YT.

Drying of the cavity gas fill creates the conundrum of insulating glass units. To avoid condensation within the unit, one or more desiccants are included to dry the cavity gas fill. However, in drying the cavity gas fill, a differential in water vapour concentration is created between the cavity gas fill and the air in the environment surrounding the unit. This creates a driving force for water vapour to diffuse into the cavity, through the perimeter sealants.[12] Generally, in recognition of this, additional desiccant is included in the perimeter spacer to adsorb water vapour that has diffused into the cavity. However, desiccants have a finite capacity for adsorption of water vapour. Eventually, the desiccant cannot adsorb further water vapour and the water vapour content of the cavity gas fill begins to increase.[13] When the water vapour content is

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require a much higher water vapour content of the cavity gas fill than would be required for condensation on the cavity side of the outer pane in the winter, so it is rarely seen. Thus we refer to condensation formation on the cavity side of the outer pane only.

[12] Generally, the panes of glass of insulating glass units are sealed together with organic sealants. Non-organic sealant methods, such as fused glass edges or lead spacers soldered to copper strips fused to the cavity-side faces of the glass panes, can prevent diffusion of water vapour into the cavity gas fill. However, generally these methods are not sufficiently flexible to allow for deflection of the glass panes resulting from wind pressure on the glass, and cavity gas fill volume changes resulting from temperature change, etc. The rigid seals or the glass panes usually break (although the author is aware of one building in Newmarket, Ontario in which many original units with soldered lead spacers are still performing, fog-free, after 40 years of service). Organic sealants allow for deflection of the panes, but the trade-off is that they provide a resistance, not an absolute barrier, to water vapour diffusion. The net result is a more durable unit, but with a finite, rather than indefinite, life span.

[13] This assumes that the desiccant(s) act as a reservoir, adsorbing all water vapour until maximum capacity is reached, during which time the cavity gas fill remains dry. Desiccant behaviour is somewhat more complex, as will be discussed later in this report.

sufficiently high so that its dew point temperature is no longer below the cavity-side temperature of the outer glass pane, condensation occurs (Figure 4). Thus in preventing condensation within a newly manufactured insulating glass unit, we ensure that condensation will occur, albeit (ideally) far in the future. It is for this reason that condensation within insulating glass units should not be considered a "failure" but instead, an expected, almost natural occurrence. Some experts in the industry refer to this as "natural age death"[10].

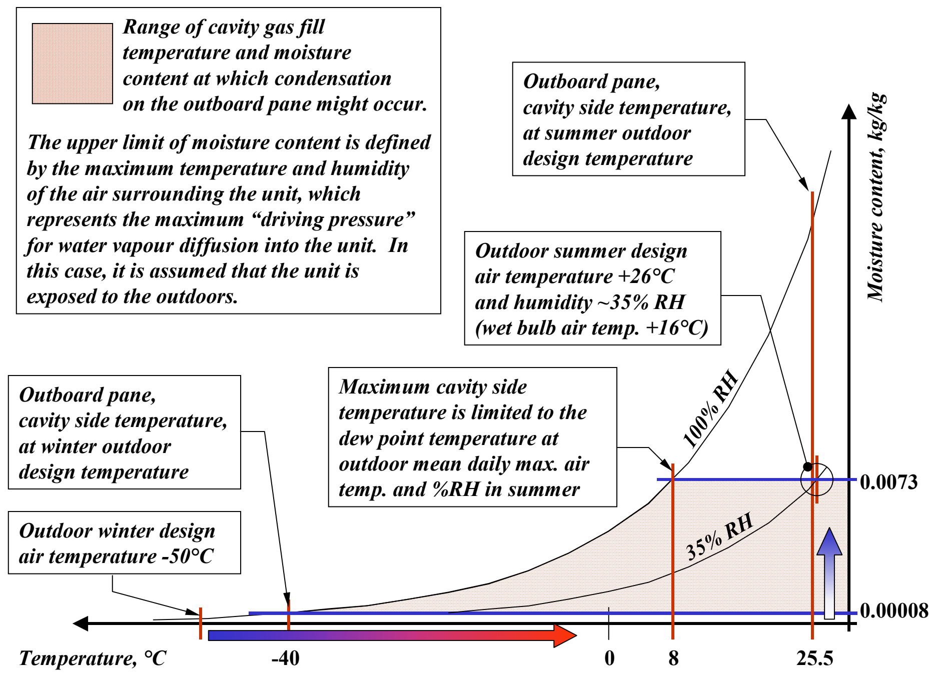

Figure 4: **Psychrometric chart showing the moisture content range in which condensation of the cavity gas fill might occur, for an insulating glass unit installed in Dawson, YT. The upper and lower temperatures are defined by the summer and winter design temperatures, and the upper limit of moisture content is defined by the environment to which the perimeter seal of the unit is exposed.**

Estimating Life Span of Insulating Glass Units

It is clear, then, that condensation within insulating glass units is inevitable. But what is the expected life span of an insulating glass unit? There is no definitive answer. Usually, a combination of experience, reference to published estimates of life span, and reliance on successful performance to laboratory test methods are relied upon to give some indication of potential life span. Such methods must be used with caution to estimate the life span of insulating glass units.

Estimates Based on Experience

Various experience-based estimates have been reported in glazing publications and in technical papers, generally 20 to 25 years or more [10, 11, 12, 13]. What are such generalizations based on? Experience with one particular construction of insulating glass unit in many types of buildings? Or many types of insulating glass unit construction in many buildings? A review of the noted references does not reveal such information. The authors have examined insulating glass units with internal condensation within a few months of installation, and has examined many others still free of condensation older than 20 to 25 years, including a thirty-four year old high-rise residential building in Toronto in which the vast majority of units are original and reportedly free of condensation, and a smaller building with insulating glass units imported from Belgium that were 46 years old.[14] Clearly, there is a considerable possible range for the life span of insulating glass units.

The weakness of relying on experience is be illustrated by the following example. In the Greater Toronto Area (GTA), beginning in the late 1980s and continuing through the early 1990s, there was a common problem with premature fogging of insulating glass units in high-rise residential condominium ownership apartment buildings. Most units were made with Swiggle Strip®, a pre-manufactured sealant / spacer product; as a result, this product developed a reputation for poor durability. To this day, in the GTA, it is common for window manufacturers, glaziers and consultants, to assume that insulating glass units with this sealant / spacer product will fog prematurely and to assume very short life spans. Yet many insulating glass units of the same vintage that were made with this same product continue to perform successfully. Indeed, the product is reported, by the current manufacturer, TruSeal Technologies[15], to have a good international reputation for durability.

Cases of premature fogging with this sealant / spacer products have been examined by the product manufacturer, and independently by the lead author of this study. In some cases the sealant / spacer material appears to have degraded physically (cracks and bubbles observed), although the manufacturer insists that such conditions would not adversely affect product performance. Other factors contributing to premature fogging include:

- "Face-sealed" window frames with un-drained glazing cavities into which the insulating glass units were installed.[16]
- Plastic flow of the preformed, butyl mastic tape ("glazing tape") between the exterior face of insulating glass units and the surrounding window frames.
- High relative humidity of indoor air and chronic wintertime condensation on window glass and sometimes adjacent framing.
- Window framing that did not prevent condensation water from draining into and accumulating in the glazing cavity.
- Frame components on which condensate can drain and be held against the perimeter seal of the units.
- Incorrect application of the pre-manufactured sealant / spacer during assembly of the insulating glass units, and other poor unit assembly practices.[17]

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[14] Sadly, the forty-six year old units were destroyed as part of a window replacement program. However, the thirty-four year old units remain in service.

[15] TruSeal Technologies manufactures the product under the name of Swiggle® Seal.

[16] It should be noted that National Standard of Canada CSA (Canadian Standards Association)-A440-M84 and M90, in effect at the time, required drainage of the glazing cavity only for windows in which insulating glass units are sealed at the exterior face with preformed elastomeric gaskets. Such units were also required to have an seal at the interior face to control water leakage. Insulating glass units sealed at the exterior face with "wet" sealants, such as preformed butyl mastic tapes ("glazing tape"), a common approach in the GTA, were allowed to escape the requirement for a drained glazing cavity.

In addition,

- Throughout the late 1980s and early 1990s, four window manufacturers dominated the high-rise residential apartment building market, all of whom manufactured their own insulating glass units with this particular sealant / spacer material. Generally, there was little difference in design and materials of the window frames made by these different manufacturers. Fundamentally, window design had not changed significantly in about 20 years (and it has changed little in the 15 years since).
- The majority of high-rise residential apartments constructed throughout this period was speculative condominium development, and thus very capital cost sensitive.
- Changes to the provincial building code in the mid 1980s required, for the first time, inclusion of an air barrier in the exterior walls of the building.[18]
- Absence of mandatory condensation resistance testing from the governing window performance standard.[19]

A careful consideration of these factors leads to a realization that there were many contributing factors leading to the premature fogging of units made with this particular sealant / spacer product:

- The requirement for an air barrier in the exterior walls reduced inward air leakage (driven by stack effect and wind pressure) that in winter months would normally reduce humidity generated by occupants. As a result, indoor air relative humidity levels increased.
- Window design had not changed significantly since before the requirement for air barriers was imposed. Although generally adequate in relatively poorly sealed buildings, under more humid conditions the window design, faced-sealed at the exterior, without drainage of the glazing cavity, and sometimes with details that collected and held water directly against the perimeter of the insulating glass units, became inadequate.

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17 Soap film was detected on some units examined by the authors, by an informal, destructive test known as the "Rinse and Froth" test. This involves removal of a prematurely fogged unit, punching an opening through the perimeter spacer, and injecting distilled water. When the unit is shaken, a "head" of bubbles appears; if the head persists after shaking is stopped and the water allowed to settle, it is considered to be an indication that soap was present on glass surfaces facing the unit cavity. Soap film can be detrimental to unit performance if the perimeter seal becomes wet during service, for instance, if rain water or condensate collects in the glazing cavity. Soap, being a wetting agent, will draw water between the sealant and glass, resulting in loss of adhesion and breaching of the perimeter hermetic seal. Normal insulating glass unit cavity pressure variations will expel and draw in air through such breaches, leading to rapid water vapour gain by the desiccant and fogging, at a rate far greater than would occur only by diffusion of water vapour through the sealants.

18 The 1986 Ontario Building Code. This change mirrored requirements in the model 1985 National Building Code of Canada, which in turn was based on research and practice the demonstrated that the leakage of warm, humid air contributed to the deterioration of the building envelope.

19 National Standard of Canada CSA (Canadian Standards Association) A440-M84 (Metric, 1984 edition) and M90 (Metric, 1990 edition). A condensation resistance test is included as a voluntary test. Testing is performed in a climate chamber with the window installed in a wall separating a nominally room temperature indoor environment from a cold outdoor environment. There are two important conditions of the test method which contributed to this failure. Firstly, the indoor environment humidity is controlled to prevent condensation on the test window. Secondly, temperature readings are not made in the "edge of glass" area of fixed, insulating glass units. From the test results, by reference to a psychrometric chart (for example), it is possible to determine indoor room air temperature and humidity conditions at which condensation on window frame and glazing is likely to occur. However, in the "edge of glass" area, room-side surface temperatures will be lower and thus, the temperature and / or humidity conditions necessary for condensation formation will be different. Preventing condensation during the test does not allow observation of control of condensation formation, drainage, and possible accumulation.

- Plastic flow of the exterior sealant between insulating glass units which in some cases allowed rain water penetration into un-drained glazing cavities, and also opened joints between insulating glass units and interior, removable "stops" that retained the units in place, allowing condensation drainage into the un-drained glazing cavities.
- Poor quality control during insulating glass unit manufacture, incorrect placement of the sealant / spacer product, and other poor unit assembly practices, compromised the ability of the sealant / spacer of the units to maintain a hermetic seal.

This combination of factors and their combinations are rarely taken into account. Instead, as noted, the sealant / spacer material is widely considered to be solely at fault and is considered to have poor durability. This emphasizes then need for considerable caution when using experience to estimate the longevity of insulating glass units installed in buildings.

Estimates Based on Laboratory Testing

Existing North American IG unit laboratory test methods, and indeed many of the insulating glass unit laboratory test methods world wide, are based on research at the Division of Building Research (DBR), National Research Council Canada and other similar organizations in the late 1950s and early 1960s [14]. As noted in the introduction, the research by DBR was carried out for CMHC to evaluate the suitability of insulating glass units promoted by manufacturers for installation in new housing funded under the Canadian National Housing Act (NHA) and administered by CMHC [4, 5, 6]. The test program that was developed, included the following laboratory tests:

- Accelerated weather exposure (repeated cycles of heating, water spray, drying and cooling) primarily to test mechanical strength of the perimeter seal),
- High humidity exposure (repeated cycles of heating and cooling while maintaining 100% relative humidity) primarily to test the water vapour resistance of the perimeter sealants.
- UV radiation exposure (Volatile Fog Test)

The program also included outdoor testing:

- Exposure to "natural" weather cycling, to provide some correlation to "real" life including exposure to UV radiation.

The test program became a CMHC qualification standard in 1961, although without outdoor exposure testing. Further changes were made, and in 1965 the test program was adopted by the Canadian General Specifications Board (CGSB) standard 12-GP-8. The last version of this standard was CGSB-12.8-97, amended in 2001

In the 1960s, the Sealed Insulating Glass Manufacturers Association (SIGMA) in the USA developed similar standard test method, 65-7-2, also without outdoor exposure testing but including exposure to UV radiation (from "blacklight" florescent bulbs) in the accelerated weather exposure apparatus. This test standard eventually became American Society for Testing and Materials (ASTM) standards E 773[20] and E 774[21].

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[20] ASTM E 773, *Standard Test Methods for Seal Durability of Sealed Insulating Glass Units,* ASTM International, West Conshohocken, Pennsylvania, 1995.

[21] ASTM E 774, *Standard Specification for Sealed Insulating Glass Units*, ASTM International, West Conshohocken, Pennsylvania, 1995.

Recently, the ASTM and CGSB test protocols were "harmonized" to form new ASTM standards E 2190[22], E 2188[23] and others.[24] These most recent standards retain the accelerated weather exposure and high humidity exposure tests from the previous ASTM and CGSB test methods, although generally, the tests are closer to the earlier ASTM E 773 and E 774 than to those in the CGSB-12.8 standard with the one significant exception that there is only one performance level.[25]

Correlation of the DBR / CMHC / CGSB test method and the ASTM E 773 and E 774 test methods with "real time" service exposure is limited. A "rough correspondence" was found between failures of units subject to laboratory testing and outdoor exposure testing [5]. Other studies examining the CGSB, ASTM and other test methods generally found no direct correlation to in-building performance (in the sense that passing the standard did not correlate to a given number of years of successful in-building performance). However, it was reported that there was an improvement in performance of units subjected to the DBR / CMHC / CGSB test method [6]. Although not reported in papers reviewed, it is probably safe to assume that there was also a corresponding increase in successful in-building performance, within the industry standard five-year warranty period. It may be that from this coincidence that the notion of an equivalency of the DBR / CMHC / CGSB and ASTM test programs to five years of in-field exposure, and the industry standard five-year warranty period, was developed.

Estimates Based on the SIGMA "Field Correlation Study"

In the late 1970s, the Sealed Insulating Glass Unit Manufacturers Association (SIGMA) in the USA embarked on a "Field Correlation Study" to confirm the apparent correlation between the ASTM E 773 and E 774 test methods and field service life.[15, 16, 17] By that time, it was generally understood that insulating glass unit constructions tested successfully in the laboratory were capable of much longer service lives than five years. Advances in materials (new desiccants, sealants, etc.) and methods of assembly had improved the durability of insulating glass units. Field studies began in 1980 and were terminated fifteen years later. The study has its limitations: it is a comparison of field exposure of units made to perform successfully under the ASTM E773 and E774 test methods; 2,400 IG units of a population of 40,000 in 40 buildings in 14 cities in the continental USA were studied, most of which faced south or southwest; about 450 (19%) of the original units were "lost" during the test period because of demolition, renovation or subsequent denial of access; and the units studied were made with available sealant products, desiccants, etc., and installed in accordance with practices of the day. Thus the results are, perhaps, unique to the USA, to units of that vintage, to units with those orientations.

Within these limitations, the SIGMA "Field Correlation Study" revealed that failure of IG units made to the highest performance level of the ASTM E774 specification ("CBA"), installed so that

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[22] ASTM E 2190, *Standard Specification for Insulating Glass Unit Performance and Evaluation*, ASTM International, West Conshohocken, Pennsylvania, 2002.

[23] ASTM E 2188, *Standard Test Method for Insulating Glass Performance* ASTM International, West Conshohocken, Pennsylvania, 2002.

[24] In Canada, the CGSB-12.8 standard remains in effect until adopted by the model National Building Code of Canada (NBCC) and by provincial building codes, which typically are revised to follow improvements to the NBCC. As of the date of this report, the NBCC has not yet adopted ASTM E2190, 2188 and other related standards.

[25] The ASTM E 773 test program allowed testing to three performance levels: C, CB, and CBA. CBA was the highest level, roughly equivalent to the single performance level allowed under the original CGSB 12-GP-8 and later 12.8 standards. The new ASTM E 2190 and E 2188 standards include only one performance level, roughly equivalent to the ASTM E 773 CBA and CGSB-12.8 performance levels.

the perimeter seals were not subject to prolonged wetting, was about 2.9% after 15 years [17].[26] This clearly indicated that insulating glass units were capable of much longer life spans than when the test method was first developed in the 1950s and 1960s, but it still did not answer the question of the potential life span of insulating glass units in "real life" conditions.

Conditions Affecting Life Span

FICK'S LAW

The discussion of the limitations of experience, results of laboratory testing, and correlation studies of laboratory test methods to real life performance, reveal that many factors affect the life span of insulating glass units. A convenient way to relate these factors is through Fick's Law, which defines the rate of moisture (water vapour) transmitted through a barrier separating one material from another, in terms of the permeability of the barrier to water vapour, dimensions of the barrier (area and thickness), and the difference in water vapour concentration on both sides of the barrier (usually expressed as water vapour pressure). If the equation is re-arranged slightly by dividing by time, then we have an equation defining the water vapour content of the material on side of the barrier in terms of the permeability of the barrier to water vapour, the dimensions of the barrier (area and thickness), the difference in water vapour content on both sides of the barrier (vapour pressure), and time. This relationship is expressed mathematically as follows:

$$\mathbf{W} = \mathbf{M} \bullet \mathbf{A} \bullet \theta \bullet \Delta\mathbf{P}$$

Where **W** = cavity gas fill water vapour content

M = μ / l, μ = permeability
l = path length (depth of seal)

A = area of seal (width of seal x perimeter of seal)

θ = time

Δ**P** = water vapour pressure (concentration) differential across the seal

[26] It was recently reported in an industry newsletter [18] that The Insulating Glass Manufacturers Alliance (IGMA), the successor to SIGMA, has resumed the study. Formal results have yet to be issued, but results are reported to indicate that 4.8% of the original units had fogged by year 25. A second set of units, entered into the program in about 1990 and including some newer sealants and spacers, are reported to have a fogging rate of 1.3% after 15 years (in 2005), about half the rate of the original set of units at their 15th year (1995).

This equation may be rearranged to show a simple relationship of the time required for fogging to occur, as follows:

$$\theta = \frac{\mathbf{W} \bullet l}{\mu \bullet \mathbf{A} \bullet \Delta \mathbf{P}}$$

Thus it can be seen that time to fogging is directly related to the moisture content of the cavity gas fill, the depth of the perimeter sealants, the permeability and cross-section area of the perimeter sealants, and the difference in water vapour concentration between the cavity gas fill and the environment outside of the insulating glass unit to which the perimeter seal is exposed. It should also be noted that although each these factors is individually significant, they also act in combination, such that weakness in one or more may result in either extended, or shortened, time to fogging. The example given previously, of the pre-manufacturer spacer / sealant material, demonstrates synergistic effect well.

The factors affecting time to failure are discussed in more detail as follows:

MOISTURE CONTENT OF THE CAVITY GAS FILL (W)

TYPE, ACTIVITY, AND QUANTITY OF DESICCANT

The desiccant(s) in the perimeter spacer must be suitable for its purpose. It must adsorb water vapour and any volatile compounds expected to be present in the cavity gas fill, such as might be released by sealants, paints used to touch up muntin bars within the cavity, etc.[27]

During manufacture of insulating glass units, the desiccant is exposed to the air within the manufacturing facility and adsorbs water vapour from it. If the exposure time is excessive, significant amounts of water vapour can be adsorbed (the desiccant is said to be less "active"), reducing the available moisture adsorption capacity of the desiccant in service, and thus reducing the amount of water vapour required to diffuse into the unit through the perimeter sealants to cause fogging (Figure 5).

The amount of desiccant included within an insulating glass unit is not fixed. In a "conventional" rectangular unit with hollow spacers, often only two (2) sides of the spacer may be filled with desiccant (this was the case for the units in the test program. Pre-formed spacers with desiccant integral within the spacer (such as Swiggle® Seal, Super Spacer®, TPS) and spacers with desiccant applied in a carrier medium (desiccated matrix) within the spacer (Intercept™) have a fixed amount of desiccant per unit length of spacer or quantity of applied carrier, which varies with unit size and therefore, length of perimeter. The quantity of desiccant within a unit will directly affect the life span, since more desiccant provides more vapour storage capacity.

27 If not, a "chemical fog" may be deposited on the glass, clouding vision in the same way as condensation of water vapour.

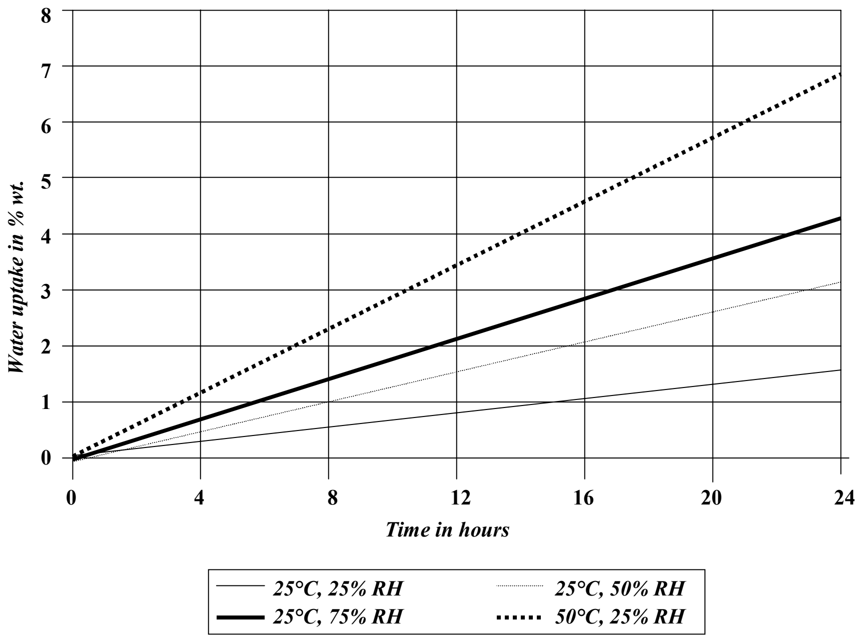

Figure 5 **The relationship between "hang time" and water vapour content of the desiccant, redrawn from Thamm, 2003 [19]. Water vapour content of the desiccant is given as a percent of dry weight (water content divided by dry weight of desiccant). The lower three bars show that for a given temperature, over the same period of time, the water vapour content of the desiccant increases with humidity of the environment to which it is exposed. The lower and upper bars show that for the same relative humidity, water vapour content increases as the environment temperature increases.**

SERVICE ENVIRONMENT

Fogging within an insulating glass unit is determined by the moisture content of the cavity gas fill and the cavity-side temperature of the outboard pane. The cavity-side temperature of the outboard pane is determined by the thermal resistance of the unit, the indoor air temperature, and the outdoor air temperature. The effect of outdoor air temperature is shown in Figure 2, where for the same unit construction and the same interior temperature, the cavity-side temperature is colder in Dawson, YT, than in Tofino, BC, a direct result of the outdoor temperature.

It would be reasonable to expect that for the same construction of insulating glass unit, for the same indoor temperature, fogging should occur earlier in locations with colder climates. However, the water vapour adsorption capacity of the desiccant(s) included in insulating glass units increases with decreasing temperature. Thus as the cavity-side temperature of the outboard pane of glass falls, there is a coincident increased adsorption of water vapour from the cavity gas fill, reducing its moisture content and its dew point temperature (Figure 6). This will be examined further in the test program described later in this report.

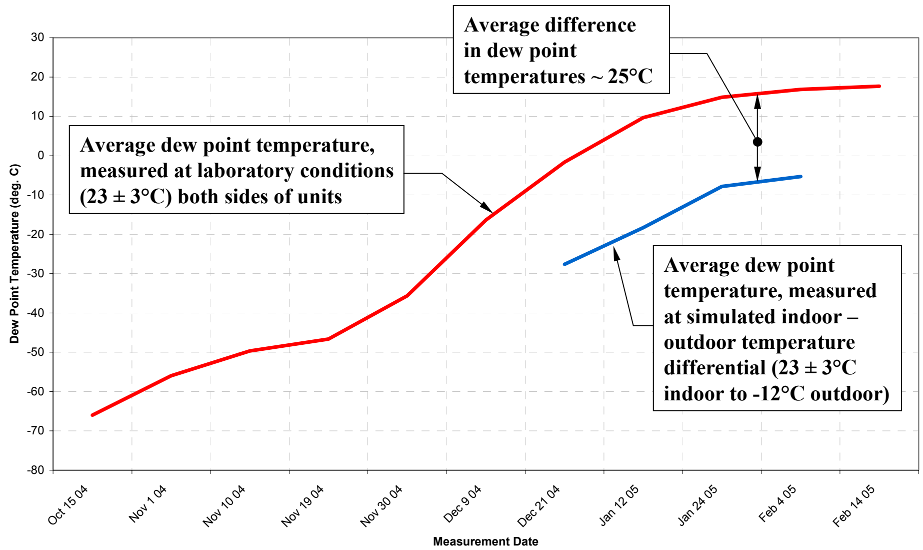

Figure 6: **Graph from the test program, showing dew point temperature measurements for insulating glass units. The upper red line shows dew point temperatures measured with both sides of the units exposed to standard laboratory conditions of 23 ± 3°C. The lower blue line shows dew point temperatures for the same units with one face exposed to standard laboratory conditions of 23 ± 3°C and the other to a cold chamber at -12°C. The difference in dew point temperature is about 25°C.**

SEALANT PROPERTIES (μ, l & A)

PERMEABILITY (μ)

Available sealants for insulating glass units include polyisobutylene, polysulphide, polyurethane, silicone, and “hot melt” sealants of various compositions. Polyisobutylene sealants have the highest resistance to water vapour diffusion (Figure 7) but low structural strength. For this reason, they are often applied in combination with polysulphide, polyurethane or silicone sealants which have much lower resistances to water vapour diffusion but much higher structural strength. In such “dual seal” units the water vapour resistance is considered to be almost entirely due to the polyisobutylene primary sealant because of its relatively much greater water vapour resistance [11, 12, 20], whereas structural strength is considered to be due to the secondary sealant.

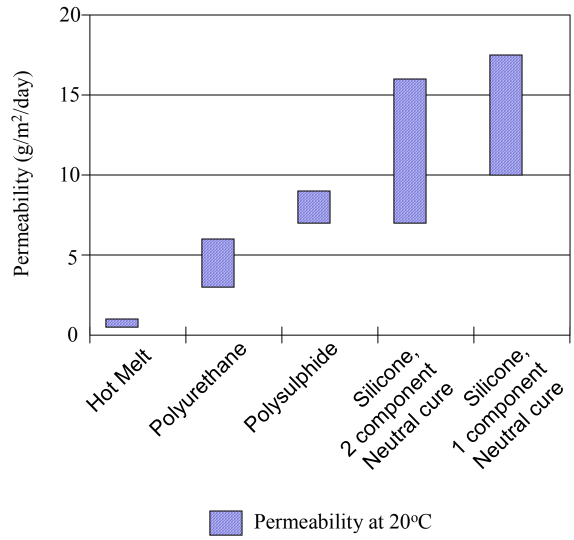

Figure 7: Chart showing water vapour transmission rates (permeability) for various insulating glass unit sealants, from data reported in Wolf 1992 [11]. The measurement test procedure was not reported. Note the wide range in permeability for the different types of sealant materials shown.

The rate of water vapour diffusion through some materials is also known to be affected by relative humidity of the service environment [21]. This is detected by comparison of results of diffusion testing by the "dry cup" and "wet cup" methods, as described in ASTM standard E 96[28]. In the "dry cup" method, a sample of material is sealed to an impervious cup containing a desiccant that is placed into a chamber with the environment controlled at 23°C and 50% relative humidity. In the "wet cup" test, a sample of material is sealed to an impervious cup containing water and placed into a chamber, also at 23°C and 50% relative humidity. The "dry cup" test determines the diffusion rate, or permeability[29] under water vapour pressure differential of 0% - 50%, and the "wet cup" test determines permeability at a water vapour pressure differential of

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28 ASTM E 96, *Standard Test Methods for Water Vapor Transmission of Materials,* ASTM International, West Conshohocken, Pennsylvania, 2000.

29 Although longevity of insulating glass units is dependent on the resistance to water vapour diffusion through the perimeter sealants, the insulating glass unit industry refers instead to the inverse of resistance, permeance, and specifically to the permeance through a standard thickness of sealant, thus permeability. This is usually termed the MVTR, or Moisture Vapour Transmission Rate, where moisture refers to water vapour. When comparing reported permeability values of different sealants, one must take care that the reported values are for the same unit thickness and as discussed in this section, that permeability was determined by the same test method.

50% - 100% (Figure 8). Measurements of "dry cup" and "wet cup" permeability shows that for some materials, permeability is higher when tested by the "wet cup" method.[30]

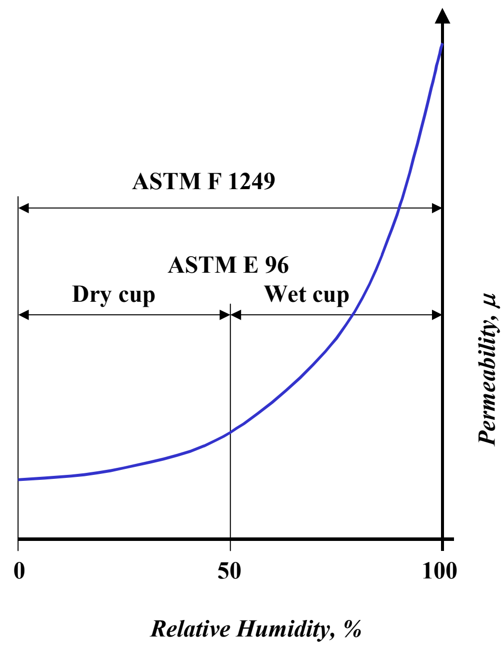

Figure 8: Relationship of permeability to relative humidity of the measurement environment, noted for some materials by comparative measurements made with the "dry cup" and "wet cup" methods of ASTM E 96. The diagram is based figure 5.10 from Hutcheon and Handegord, 1983 [21]. The range of relative humidity between the cup and sensor chamber for ASTM F 1249 is added, for reference.

The permeability of insulating glass unit sealants may also be measured in accordance with ASTM standard F 1249[31]. In this test, the apparatus is similar to that used for the "wet cup" test although the cup is sealed to a chamber that is swept with dry air, so that the sealant sample is subjected to a 100% relative humidity water vapour concentration differential. With this test alone (or with only the "dry cup" or "wet cup" tests), one cannot tell if the permeability of sealants changes with lower water vapour concentration differentials.

Permeability measurements in accordance with ASTM E 96 or F 1249 are made at certain temperatures. However, it is known that permeability of insulating glass unit perimeter sealants increases with temperature, more for some sealants than for others (Figure 9) [11, 12, 20].

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30 The curve of permeability vs. relative humidity shown in Figure 8 can be determined experimentally by measuring permeability at intermediate relative humidities, by controlling the humidity of the environment within the cup or within the test chamber.

31 ASTM F 1249, *Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor,* ASTM International, West Conshohocken, Pennsylvania, 2001.

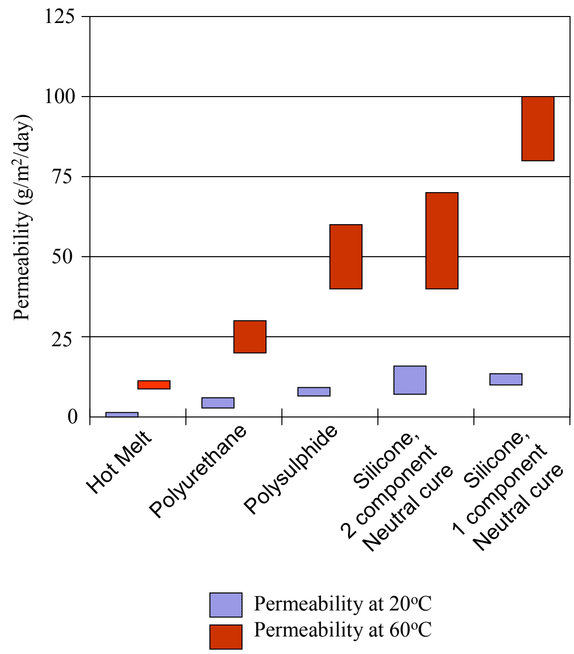


Figure 9: **Chart showing water vapour transmission rates (permeability) for various insulating glass unit sealants, from data reported in Wolf 1992 [11]. The measurement test procedure was not reported. The red bars indicate permeability at 60°C and the blue bars show permeability at 20°C (from Figure 6) for reference. Note that generally, permeability increases with temperature, and that the increase is considerably greater for some materials than for others.**

Monitoring of windows confirms that the relative humidity and temperature of the frame cavity into which insulating glass units are installed, and to which the perimeter sealants are exposed, varies with changes in outdoor air temperature, outdoor air humidity, and rainwater penetration for windows in which the frame cavity surrounding the insulating glass units are drained and nominally vented to the exterior (Figure 10) [23]. For windows in which insulating glass units sealed at the exterior face and the perimeter seal is exposed to the indoor environment (a common arrangement in high-rise residential apartment buildings), water accumulation in the framing, from rainwater penetration or from room-side condensation run-off, would increase the water vapour content of the air within the framing surrounding the insulating glass unit [10, 23]. It is reasonable to expect that the relative humidity of the air in the frame cavity surrounding the perimeter seal of the insulating glass units would be elevated.

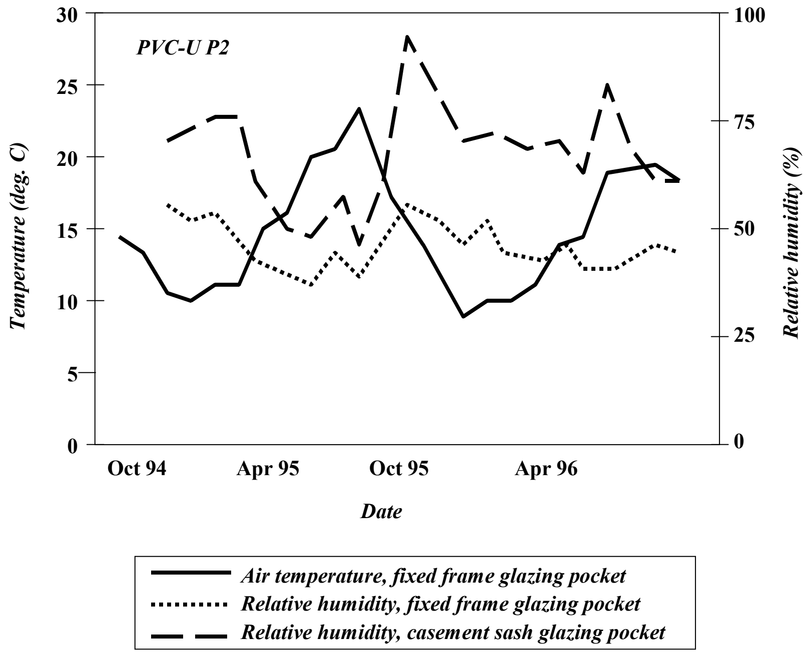


Figure 10: Measurements of mean monthly temperature and relative humidity within frame cavities of a PVC window exposed to outdoor conditions, redrawn taken from Garvin & Wilson, 1998 [23]. The window was a composite type, with a full-height casement sash and a full-height fixed portion, both glazed with insulating glass units. Frame cavities were drained (and thus nominally vented) to the outdoors. Note that temperature and relative humidity vary throughout the year.

An example of the effect of temperature on insulating glass unit longevity was previously reported by the authors [24]. In this case, field measurements of insulating glass unit dew point temperatures in a municipal building in Toronto revealed that the dew point temperature of units in the south elevation of the building were distinctly higher (less likely to condense) than units in the north elevation (Figure 11). The units were the same construction, exposed to the same indoor space (an atrium), and installed in curtain walls of identical construction. There were no apparent differences in the units, the curtain wall framing, or the service environment that were different, other than the exposure.

The practical effect of relative humidity dependence (possibly) and temperature dependence (verified by experiment) of permeability of insulating glass unit sealants is that permeability cannot be considered constant. Permeability will change over the life span of an insulating glass unit. Permeability will vary with the service environment, which could change with exterior orientation, interior relative humidity and / or condensation and run-off, etc. Thus, there may be variations in insulating glass unit life span within a given building, and between buildings with the same insulating glass unit and window frame construction. This must be taken into account when evaluating the potential remaining life span of insulating glass units.

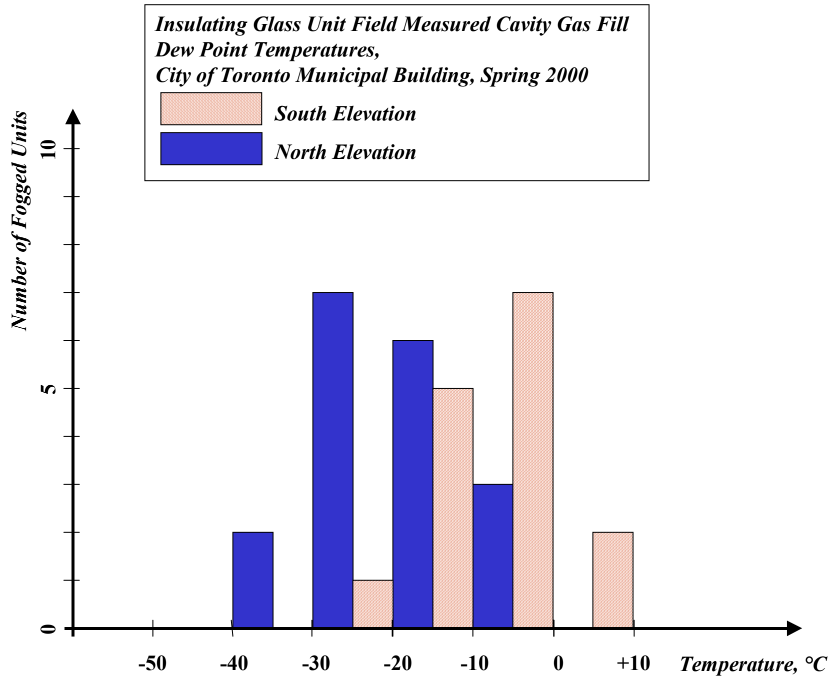
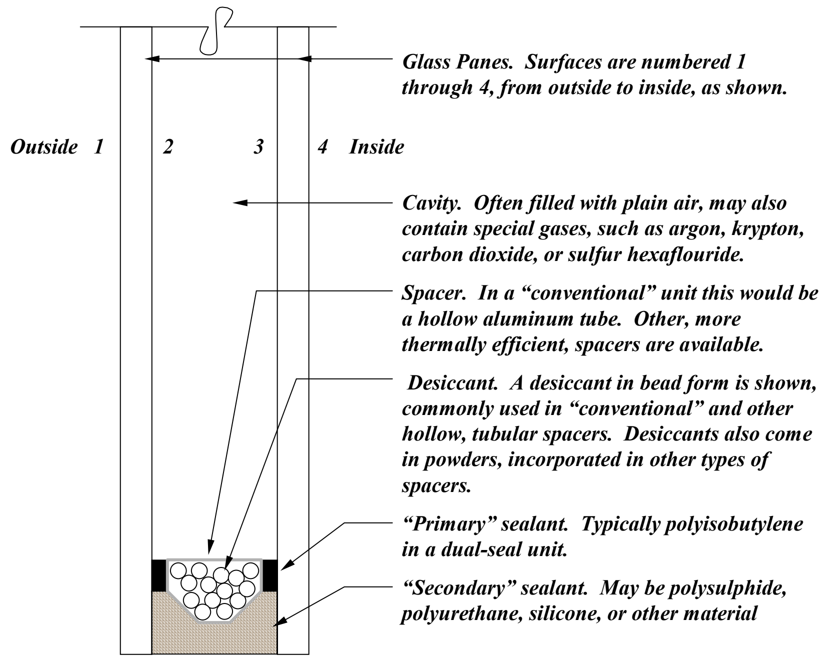
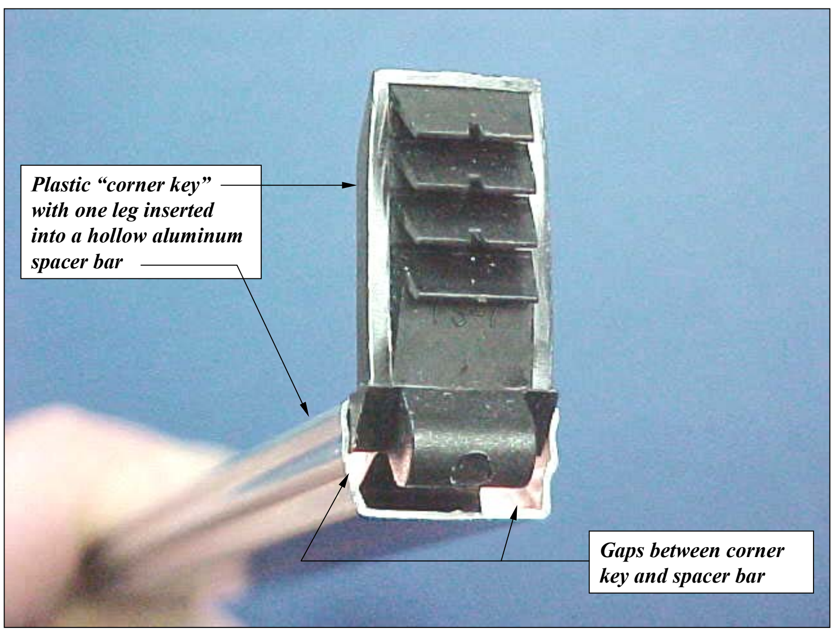


Figure 11: Field dew point measurements of the cavity gas fill of insulating glass units in a municipal building in Toronto, Ontario. The units were installed in identical curtain walls, in the south elevation and north elevation of the building. The curtain walls were exposed to the same atrium space within the building. Cavity gas fill temperatures were distinctly warmer in units in the south elevation, indicating a shorter time to fogging.

SEALANT DIMENSIONS (l & A)

Water vapour resistance of the perimeter sealant(s) depends on width and depth of the sealant, and consistency and continuity of application. In units that include two perimeter sealants, a “primary” sealant between the sides of the spacer and the glass panes and a “secondary” sealant between the glass panes across the bottom of the spacer, it is the primary sealant that provides most of the resistance to water vapour diffusion (Figure 12) [11, 12, 20]. At corners of units in which the spacer is jointed and connected with a mechanical connector or ‘key’, the primary sealant must also seal the joint to maintain continuity. This seal is not always provided (Figure 13).





Figures 12 and 13: Cross-section through the perimeter of a "conventional" insulating glass unit, of the type used in the test program. Aluminium spacers are cut from stock lengths to the size needed, and cut ends are secured together with metal or plastic "corner keys". Note the gaps between the key and the spacer that, if not filled with primary sealant (in a dual-sealed unit), would allow water vapour diffusion directly into the spacer bar and to the desiccant, bypassing the primary sealant.

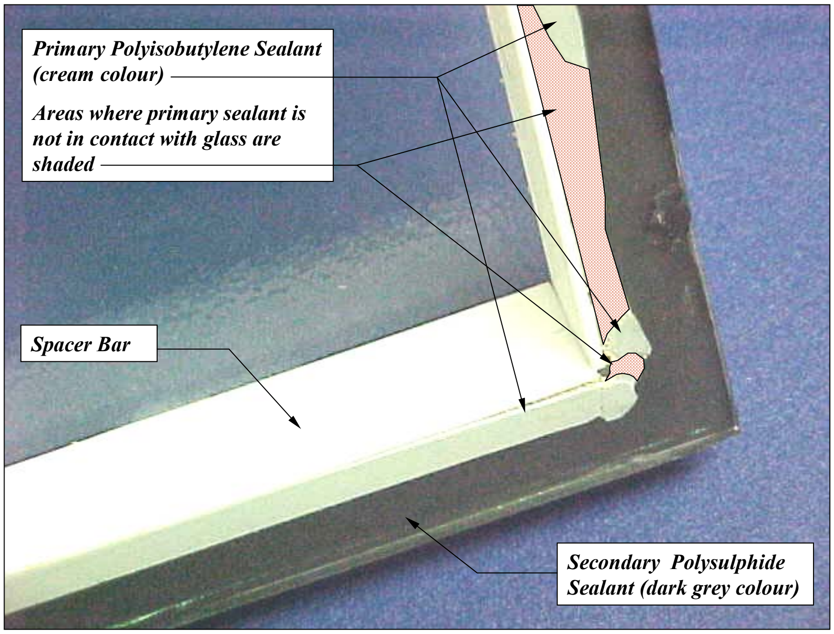


Figure 14: Corner of an assembled insulating glass unit with polyisobutylene primary sealant and polysulphide secondary sealants. Shaded areas show where the primary sealant is not in contact with the cavity-side surface of the nearest pane of glass.

Insulating glass units, like any manufactured product, are subject to variations in quality of assembly. Workmanship errors include improper washing of glass, contamination of glass at the sealant bond line by cutting oils, dirty fingers, etc., incomplete and poor application of sealants (Figure 14).

Insulating glass units are dynamic assemblies. The cavity gas fill is sealed into the unit at the ambient conditions with manufacturing plant. With exposure to solar gain, different air temperatures and atmospheric (barometric) pressure than in the manufacturing plant,[32] the cavity gas fill will expand or contract. Depending on the size and shape of the units and on the thickness of the glass panes, the glass panes may move inwards or outwards as flat plates or they may bend inwards or outwards to follow the change in the volume of the cavity gas fill. Such movements cause dimensional change in the sealants (Figure 15), which affects their permeance.[33] Units subject to more frequent cavity volume change and variation of sealant permeance can be expected to fog earlier than units that are less stressed. Sealant dimensional change, as a result of solar gain, is likely one factor contributing to the higher (warmer) dew point temperatures of the insulating glass units in the south elevation of the municipal building previously discussed (Figure 11).

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[32] Barometic pressure not only changes with the passage of weather systems but also with changes in elevation.

[33] In this case, we speak of permeance because movement of the glass panes does not affect permeability - μ - (which is determined on the basis of a unit thickness) but instead, the applied thickness and area of the sealant.

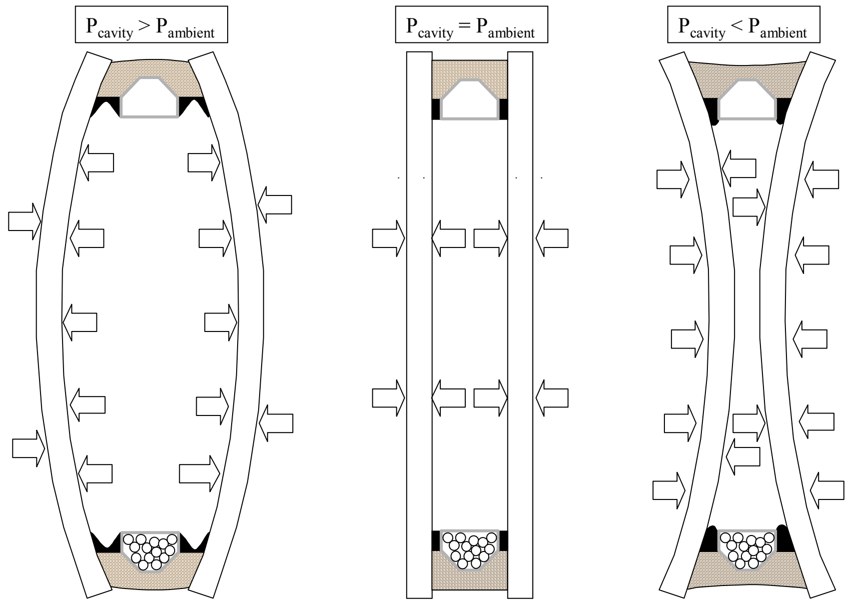

Figure 15: The cavity gas fill within an insulating glass unit will change in response to solar gain and changes in ambient air temperature and pressure. If the glass panes are flexible, as shown above, they will bend, hinging on the spacer and causing sealants to be stretched or compressed, affecting the path length and area of the sealants and, thus, the permeance of the sealants (the amount of deflection of glass panes and dimensional changes in sealants has been exaggerated).

SEALANT DEGRADATION

Prolonged wetting of the perimeter of insulating glass units will lead to failure of the perimeter seal. There are several possible modes of failure. Some of the metallic reflective and low-emissivity ("low-e") coatings may be susceptible to corrosion when wetted. Poor workmanship may leave soap residue from glass washing operations on glass surfaces. If wetted, corrosion of metallic coatings and wetting of soap film may destroy the bond between perimeter sealants and the glass panes. Sealants will also absorb water and swell, some more than others (generally, silicone sealants exhibit the least swelling when wet) [11, 12, 20]. In dual-seal systems, in which there are two sealants, a "primary" sealant between the sides of the spacer and the glass panes and a "secondary" sealant between the glass panes across the bottom of the spacer, wetting and swelling of the secondary sealant forces apart the glass panes and stretches the primary sealant, reducing its thickness, which in turn reduces its resistance to diffusion of water vapour into the unit cavity (Figure 16).

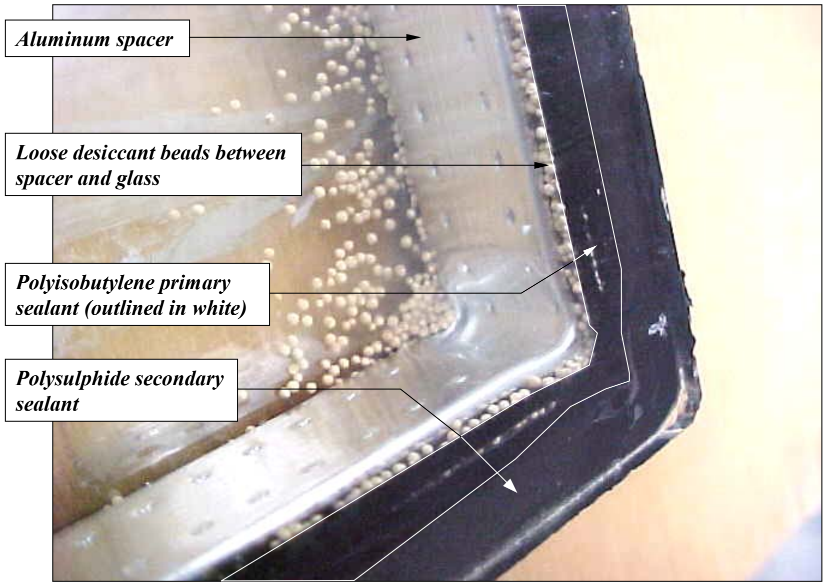

Figure 16: Corner of an insulating glass unit following prolonged high humidity exposure (one of the units from the test program). Loose desiccant beads are trapped between the glass panes and the aluminium spacer, indicating that the panes have moved apart during exposure. The photograph was made following conditioning at standard laboratory conditions. Subsequent destruction of the unit revealed that the width of the primary sealant (from outside the unit to the cavity) had been reduced by 50%.

Wetting of perimeter sealants may also cause chemical breakdown affecting adhesion of the sealants to the glass panes (Figure 17). Prolonged wetting of the perimeter sealants is understood to be the most common cause of premature fogging of insulating glass units[34] [10, 11, 12, 13, 15, 17, 20, 23, 24, 25]. Fogging may occur quickly or it may take many years to develop if wetting is not continuous, as in residences with excessive levels of indoor relative humidity and resulting wintertime condensation on window glass and framing. This is a significant mode of premature fogging that is often overlooked, especially in residential high-rise apartment buildings, as in the situation involving Swiggle Strip®.

[34] For example, in 60% of all observed cases of fogged units in the SIGMA "Field Correlation Study", the window frames were found to retain water, causing prolonged wetting of the perimeter seal.

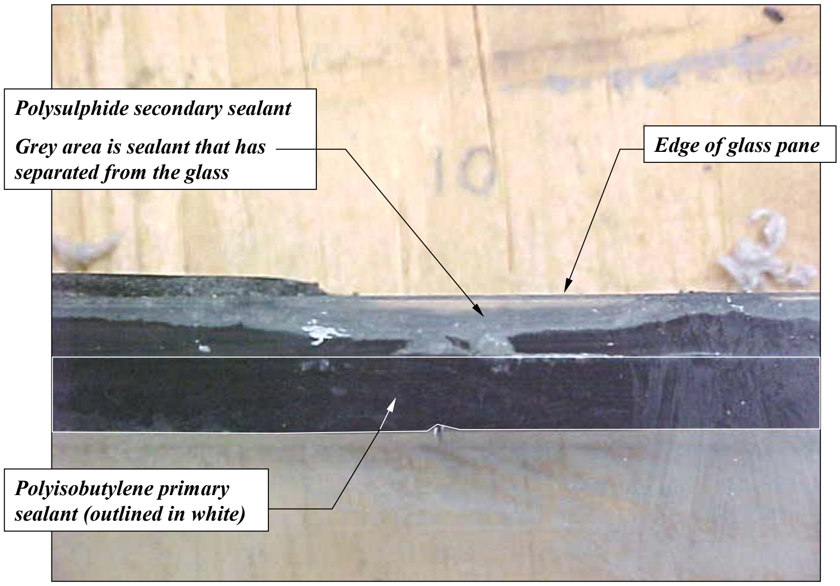

Figure 17 Top edge of an insulating glass unit following prolonged high humidity exposure (unit 10 from the test program). The sealant has deteriorated and adhesion of the secondary sealant to the glass panes has begun to fail. In the area shown, adhesion loss has progressed to the primary sealant.

MOISTURE CONTENT DIFFERENTIAL (ΔP)

The re-arrangement of Fick's Law shows that water vapour diffusion through sealant(s) is proportional to the difference in water vapour concentration between the cavity gas fill and the air surrounding the unit. The formula implies a constant differential in water vapour content across the barrier. However, from the discussion thus far, it should be apparent that the differential is not constant. The differential is greatest when the unit is new and the air in the cavity is driest (Figure 3). It decreases with time as water vapour diffuses into the cavity, the desiccant moisture content increases, and as a result, the moisture content of the cavity gas fill increases (Figure 4). Since time to fogging is inversely proportional to the differential in water vapour content across the perimeter seal, as the differential decreases, the time to fogging increases. Thus as the moisture content of the cavity gas fill approaches the moisture content of the surrounding environment to which the seal is exposed, the rate of increase in the cavity gas fill moisture content will decrease. One would expect, then, that as a unit approaches "natural age death" (ie. increase in the cavity gas fill moisture content by water vapour diffusion through the perimeter sealants) incidences of fogging would at first occur, infrequently, from time to time during colder weather then with greater frequency during progressively warmer weather. This fits well with anecdotal reports of fogging of insulating glass units reported to the lead author by various clients, and will be examined further in the discussion of the research program later in this report.

The moisture content within a window frame will also change over the life span of a unit. Therefore, the water vapour concentration between the interior of the unit and the exterior will also change. By reference again to Fick's Law, the effect of elevated humidity of the air to which the perimeter sealants are exposed is inversely proportional; that is, as the air becomes more humid, the time to fogging is reduced. Thus one would expect that in more humid service environments, or where humidity is increased locally within the framing by accumulation of water, the life span of insulating glass units would be reduced. This was demonstrated, in part, by the case study involving Swiggle Strip®.

Summary

In this section we have examined:

- why insulating glass units fog
- conventional methods to estimate time to fogging
- limitations of the methods

In particular, a careful consideration of the conditions that affect insulating glass unit lifespan should lead to the conclusion that direct comparison of performance of insulating glass units in different buildings should be carried out with caution; indeed, even within the same building there may be variations due to:

- orientation of the units (north, south, east west)
- service environment (perimeter sealant exposed to the building interior, for example)
- conditions of high humidity
- condensation on glass and frame surfaces
- runoff and accumulation of condensate within the frames
- manufacture (units of different constructions should not be compared directly)

Thus a method to directly assess performance would be desirable. The balance of this research document describes such a method and laboratory testing that was carried out to assess accuracy of the method.

Field Measurement to Predict Life Span

Existing Field Test Method

INTRODUCTION

A method to estimate time to fogging of insulating glass units installed in buildings was proposed by Spetz in the 1980s [26, 27]. The method involves a non-destructive, indirect determination of the insulating glass unit cavity dew-point temperature to estimate the degree of saturation of the desiccant contained in the spacer, from which can be inferred a likely time to fogging. The method is limited by the requirement to know the desiccant type and manufacturer, possible only if the IG unit manufacturer is still in business and cooperative. The method for measuring dew point temperature became ASTM standard E 576[35] but the application of the test method to estimate time to failure was not developed by ASTM into a standard and, therefore, it has not gone into general use. Several years ago, the authors were required to employ the method by a building owner. Through application of the method and subsequent research, improvements were identified to make the method practical and accurate. The goal of this research project is to attempt to verify the modified method, in an accelerated manner, in a laboratory setting.

EXISTING METHOD

The method proposed by Spetz is an outcome of the SIGMA "Field Correlation Study" previously described. During the first ten years of the study, annual examinations of the insulating glass units were made, including measuring dew point temperatures of the units installed within the window frames. Comparison of field measured dew point temperatures and subsequent occurrences of fogging of units revealed that field dew-point measurement could be used to assess remaining life span [26, 27]. By relating dew-point measurements to desiccant manufacturer's isostere charts (plots of desiccant saturation as a function of desiccant temperature and the dew point temperature of the air exposed to the desiccant), it was possible to estimate desiccant moisture content. It was found that units in which the estimated moisture content of the desiccant was approaching the maximum content were likely to fail within a short time.

Based on this analysis, the following evaluation scheme for insulating glass units in service was proposed [26]:

- Dew-point less than -80ºF (-62°C): there is almost no moisture in the IG unit cavity, thus the IG units can be expected to have a "very long expected future clear life";
- Dew-point between -80ºF (-62°C) and 0ºF (-18°C): there is some moisture in the cavity, thus the IG unit can be expected to have a future clear life less than units with a dew-point temperature less than < -80ºF (-62°C);
- Dew-point between 0ºF (-18°C) and +32ºF (0°C): there is "considerable" moisture in the air space, thus the IG units will have a relatively short future life. Estimation of remaining life span requires knowledge of the construction of the units, including the desiccant type and manufacturer (so that appropriate desiccant isostere charts can be used to relate measured dew point temperature to desiccant moisture content);
- Dew-point greater than 32ºF (0°C): permanent fogging of glass surfaces within the insulating glass unit (exposed to the cavity) can be expected to develop within two years.

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35 ASTM E 576, *Standard Test Method for Frost Point of Sealed Insulating Glass Units in the Vertical Position,* ASTM International, West Conshohocken, Pennsylvania, 1999.

As noted, the method used by Spetz to measure in-situ dew-point measurement was formalized as ASTM standard E 576.[36] This standard addresses only the method of measurement of dew-point temperatures for insulating glass units. It does not include Spetz's proposed assessment scale or other methodology for evaluating the performance of an insulating glass unit and its remaining service life, although there are reporting forms for voluntary submission of field dew point measurements for evaluation by the committee responsible for the standard.[37] Spetz authored two (2) articles in the 1980s [26, 27] in industry periodicals but there does not appear to have been any further, formal development of the method.

CRITIQUE OF THE EXISTING METHOD

The method proposed by Spetz can be used to make a long-term estimate of time to fogging of insulating glass units. However, as noted in the description of the third category, knowledge of construction of the tested units is required. In older buildings, such knowledge may be difficult to obtain, especially if the insulating glass manufacturer is unknown, or if known, is no longer in business. Since desiccant isostere charts are required to estimate moisture content of the desiccant, this is a significant limitation. Only the fourth category includes an estimate of time to fogging, but the time frame (permanent fogging within two years) is far too short to allow a building owner sufficient time to accumulate funds necessary for insulating glass unit replacement, particularly in large, modern high rise buildings in which insulating glass units form a significant part of the building envelope.

Modified Field Test Method

MODIFICATIONS

Clearly, there are limitations to the method proposed by Spetz. However, it should be possible to overcome the limitations in the same way that the method was first developed, by making repeated measurements of dew point temperature over time.

As discussed, over the life span of an insulating glass unit the moisture content, and thus the dew point temperature, of the cavity gas fill will increase. If the rise in dew point temperature can be tracked over time, and if a trend in the rate of rise can be determined, the trend can be used to predict when the dew point temperature would coincide with the temperature of the cavity side of the outboard pane of glass. The cavity side temperature of the outboard pane of glass is determined by the range of normal outdoor temperatures, the indoor temperature, the construction of the insulating glass unit, and orientation of the unit. Modifying the method proposed by Spetz to include a program of repeated measurement of dew point temperatures over time would eliminate the need to obtain specific information on the desiccant and other aspects of construction of the subject units, which may not be readily available, as discussed. Repeated measurements over time would also take into account the various affects on longevity as described earlier in this report, which may change over the life span of the unit.

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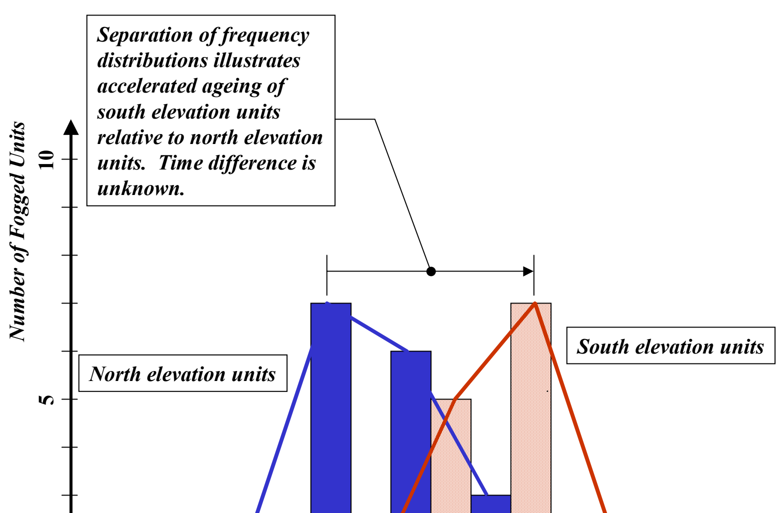
[36] ASTM E 576, *Test Method for Frost Point of Sealed Insulating Glass Units in the Vertical Position.*

[37] It is not known if any field dew point measurements have been submitted to the committee. There do not appear to have been any publications of data by ASTM of such information, so it may be that little, if any, data has been submitted to date.

Figures 18 and 19 **Field dew point measurement apparatus, as described in ASTM E 576. In the left photo, the unit is mounted on an insulating glass unit, in contact with the inboard pane of glass. A digital thermometer inserted into the unit measures the temperature of unit in contact with the pane. In the right photo, the apparatus has been removed (except for the suction cups), revealing a circle of condensation or frost on the cavity-side surface of the pane, directly beneath the chilled contact area of the apparatus. The temperature at which condensation or frost is first observed is recorded as the dew point temperature of the cavity gas fill.**

The modified measurement method was previously proposed by the authors in a paper to the ASTM *Symposium on The Use of Glass in Buildings* in 2002 [24]. The case study presented in that paper will also be used in this paper to describe the modifications. Dew point measurements were made in general accordance with ASTM E 576 (Figures 18 and 19).

Figure 11 illustrates results of field measurements of the dew point temperature of two groups of insulating glass units in a municipal building in Toronto, Ontario. Prior to measurement, it was assumed that even though the units were nominally identical in construction, of the same age, and within each of the two curtain walls the units were exposed to identical conditions, nevertheless there would be a range of dew point temperatures.[38] For convenience, dew point temperatures were measured in discreet steps of 10°C.[39] The two groups of units were exposed to identical conditions except for the exterior environment: one group faced north and the other south. When graphed together, the frequency histograms of dew point temperature "bins" revealed that as a group, the dew point temperature of units in the south elevation was warmer than that of the units in the north elevation. Setting aside the assumed cause, the two distributions can be taken to illustrate how the dew point temperature of a sample of insulating glass units in a building might change over time (Figure 20).



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38 This … its for certif … entical units, …

39 For l… lly made effici… ience of porta… cise frequ… sment.

Figure 20: Frequency distributions of field measured dew point temperatures, repeated from Figure 11. Single lines representing the maximum value in each "bin" have been added, for later use.

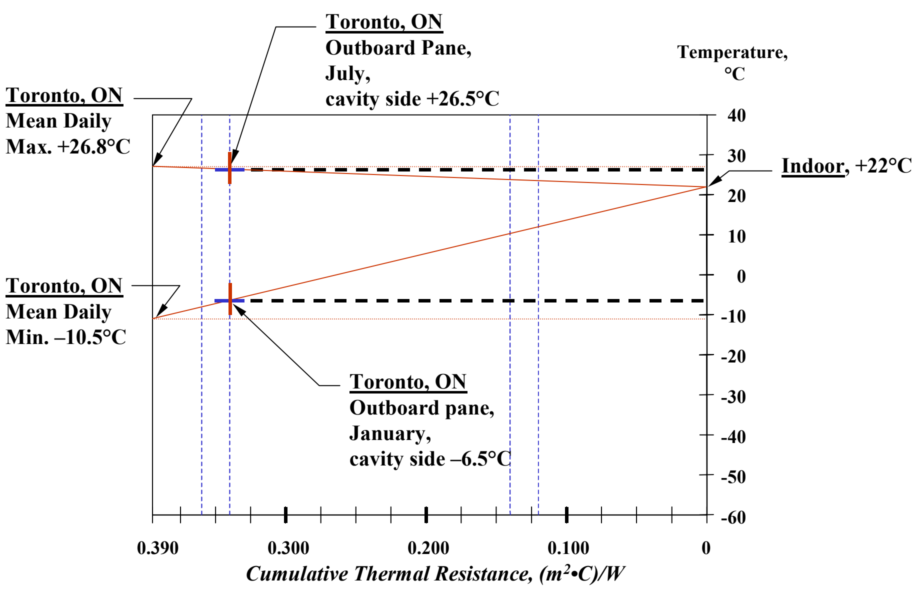

Figure 21: Simple thermal gradient for "normal" mean daily minimum and maximum temperatures for Toronto, Ontario. Mean daily maximum and minimum outdoor temperatures are used instead of design temperatures, to provide a more realistic range of temperatures in which fogging is likely to occur and be noticed by building occupants.

Fogging within an insulating glass unit will occur when the cavity-side temperature of (usually) the outboard pane of glass falls below the dew point temperature of the cavity gas fill. For the purpose of prediction, various temperature ranges could be used, such as design temperatures mandated by building codes or "normal" averages of temperatures. Design temperatures tend to be a severe representation of climate because the conditions occur infrequently, whereas "normal" temperatures occur more frequently and are therefore a better representation of conditions under which condensation is likely to occur. "Normal" weather conditions can be obtained from governmental agencies, often over the internet. Using mandated indoor conditions (from building codes, as previously discussed) simple thermal gradients can be prepared to determine the cavity side temperature of the outboard pane of glass (Figure 21).

The range of cavity side temperatures of the outboard pane of glass can be represented on a psychrometric chart (Figure 22). If the measured frequency distributions of dew point temperature are plotted together with the psychrometric chart, the resulting composite reveals the relationship between measured dew point temperatures and the cavity side temperature of the outboard pane of glass in an insulating glass unit (Figure 23).

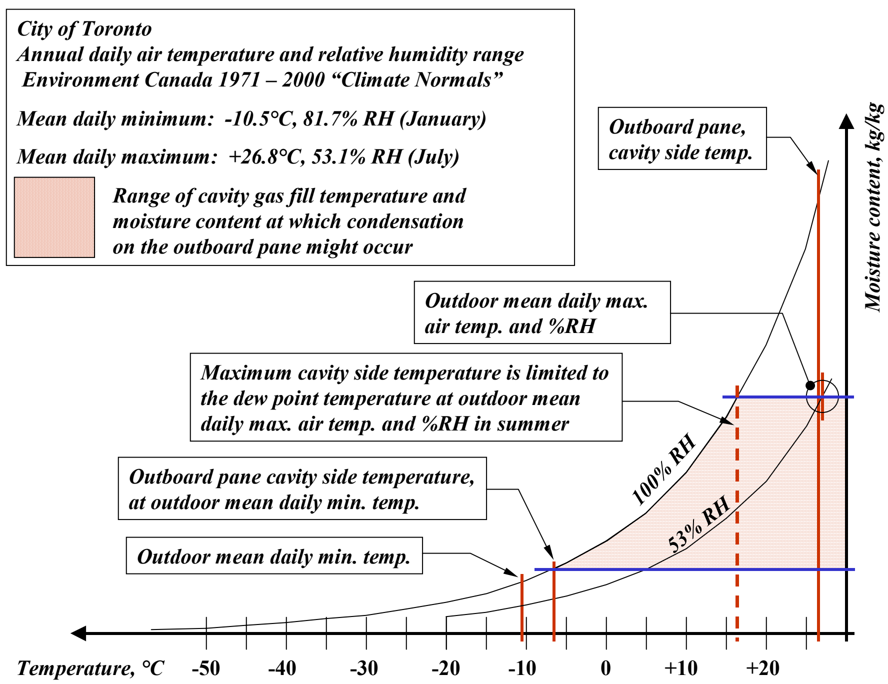

Figure 22: Psychrometric chart showing the range of outboard pane cavity side temperatures determined by the simple thermal gradient in Figure 18.

The composite plot shows that the dew point temperatures of some of the insulating glass units in the south elevation are within the range of "normal" cavity side temperatures of the outboard pane of glass. Thus there is a potential for fogging to occur. In fact, the municipality reported that several units had fogged and had been replaced, and several other units were observed to be fogged, consistent with the results of the field dew point measurements.

The composite plot also shows that dew point temperatures of insulating glass units in the north elevation were below the range of "normal" outboard pane cavity side temperatures. Thus there was a lower potential for fogging to occur at "normal" conditions.

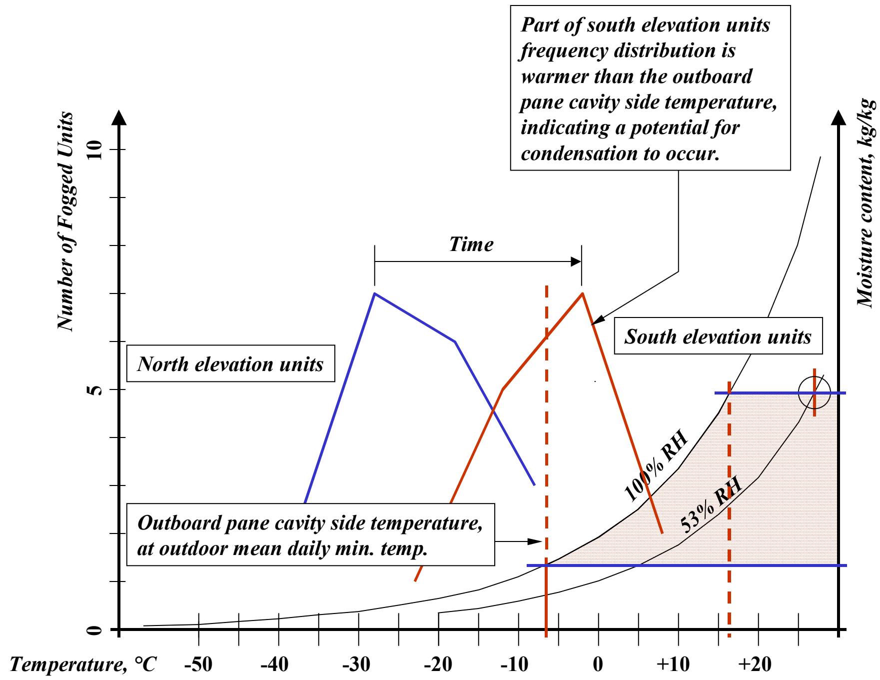

Figure 23: Frequency distributions of field measured dew point temperatures in the municipal building in Toronto, Ontario plotted together with the psychrometric chart from the previous figure. The frequency distribution for the units in the north elevation has moved into the range of cavity-side temperatures that can be expected to occur under "normal" weather conditions, indicating a potential for fogging. The frequency distribution for the north elevation units is still colder than the outboard pane cavity side temperatures, so the potential for fogging is less.

As noted, the difference in the position of the frequency distributions can be taken to indicate a progression of increase in dew point temperature. At some point the frequency distribution for the south elevation units would have been about where the frequency distribution for the north elevation units. The length of time for the distribution to have moved from one position to the next is unknown. Similarly, eventually the current position of the north elevation frequency distribution will move to about the position of the south elevation frequency distribution. Again, the length of time for the distribution to move from one position to the next is unknown. In both cases, repeated measurements of dew point temperature would reveal the rate of progression, upon which an estimate of future progression of the distribution could be determined (Figure 24).

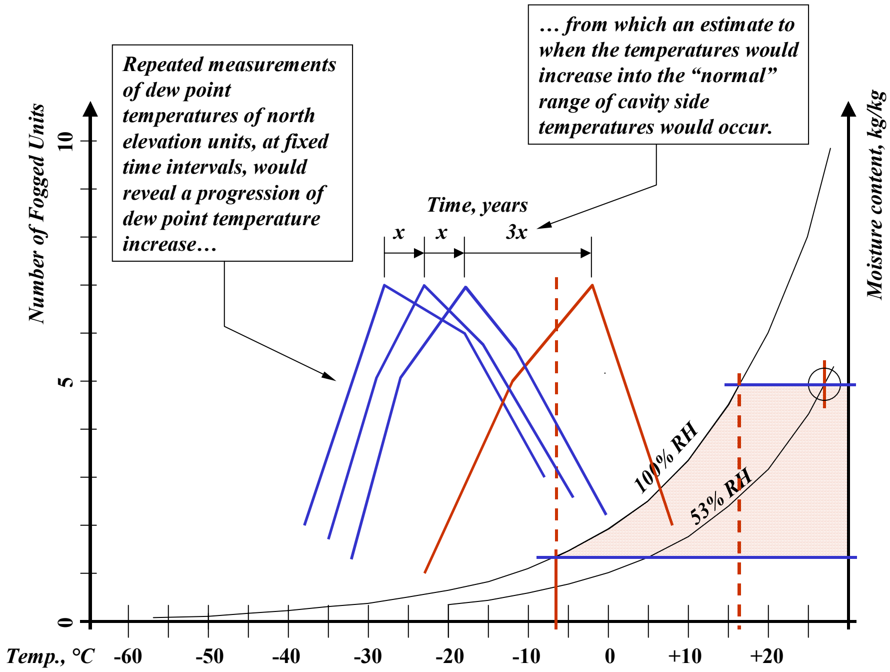

Figure 24. Repeated measurements of dew point temperature of the north elevation units at fixed intervals should reveal a progression of the frequency distribution of dew point temperatures, increasing in temperature with time. The time / temperature rise change between early measurements could be used to predict when the dew point temperatures would increase into the range of outboard pane, cavity-side temperatures that could be expected to occur, based on outdoor temperatures.

For this building, further measurements were not carried out. On the basis of previous replacements, reported occurrences of fogging, and the revealed dew point temperature distributions, the owner elected to replace all of the insulating glass units in conjunction with repairs to the curtain wall to address chronic water leakage problems.[40] Thus, confirmation of the modified method was not possible in this case. The research program described in this report was designed to confirm the modified method, in a controlled laboratory condition, in a compressed time frame.

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40 Another consultant had carried out a preliminary condition assessment of the curtain walls previously and had recommended to the owner that leakage repairs be timed to coincide with insulating glass unit replacement, on the assumption that units were already aged (about 24 years) and may need replacement within a few years. Since our subsequent measurements revealed that the dew point temperature of south elevation units were already within the range of "normal" outboard pane cavity side temperatures, the owner elected to proceed with repairs and replacement of the south elevation curtain walls immediately. Unexpectedly, funding was also obtained to carry out repairs at the north elevation, so the insulating glass units in that curtain wall were also replaced.

Research Program

Summary

Although an accepted failure rate for insulating glass units does not exist, it is understood from experience and from a limited field correlation study that insulating glass units can perform successfully for 15 to 34 years or more. A test program to evaluate a method to estimate failure rate in 'real time' would thus take many years to complete. As an alternative, accepted laboratory accelerated weather techniques could be used to induce failures in a sample of insulating glass units in a much shorter period of time, although, correlation of test time to "real time" is not certain. The intent was not to determine a specific correlation. Instead, the intent was to apply a performance measurement technique and determine if the technique could be successfully used to predict when units would fog.

Twelve (12) standard test size insulating glass units were tested. The test program consisted of:

- Initial examination of the units, including destruction of three (3) units to measure desiccant moisture content.
- Repeated cycles of exposure to elevated temperature and humidity to increase the rate of water vapour transmission into the cavity and thus increasing the cavity moisture content and dew point temperature.
- Between exposure cycles, the dew point temperature was measured with both sides of the units conditioned at room temperature (standard laboratory conditions).
- The dew point temperature of the units was measured between exposure cycles while the units were subjected to simulated indoor / outdoor exposure.

Mathematical models, based on test measurements, were developed to predict future dew point temperatures and time to fogging. Subsequent dew point temperature measurements were compared against predicted values to refine the models.

The intent of exposing one face of the units exposed to "outdoor" conditions was to determine the effect of desiccant temperature on dew point temperature. As previously discussed, the moisture storage capacity of desiccants used for insulating glass units improves with decreasing temperature. It was unknown how this might affect time to fogging estimates: for instance, if dew point measurements were made during cold weather, would the time to fogging estimate be longer, the same, or shorter than an estimate made during warmer weather? Simulated outdoor exposure would reveal how the desiccant in the test units would depress the dew point temperature of the cavity gas fill.

Method

INITIAL EXAMINATION

The test units were obtained from a Toronto area insulating glass unit manufacturer with certification from the Insulating Glass Manufacturers Alliance (IGMA) for units of this construction.[41] The units were received by Gerald R. Genge Building Consultants Inc. and

[41] At present, IGMA certification is granted upon successful performance to either the CGSB-12.8 or ASTM E 2190 series performance test programs.

delivered to the Insulating Glass Laboratory at Bodycote Materials Testing Canada Inc. in late April 2004.

After conditioning at standard laboratory conditions (22ºC ±3ºC in accordance with CGSB-12.8 and EN-1279-02, 23ºC ±3ºC in accordance with ASTM E 2188), various non-destructive measurements were made of the test units. These are recorded in Appendix D. The intent was to document the "as-received" condition of the units and in so doing, confirm that the units were reasonably consistent.

Following examination, the dew point temperature of all units was measured. For all units, no fog (condensation) was induced on the cavity side of the glass pane tested, indicating that the dew point temperature was less than about -73°C. Dew point measurements were made in accordance with CGSB-12.8[42] (Figure 25).

Figure 25: Dew point test apparatus used by the Insulating Glass Laboratory at Bodycote Materials Testing Canada Inc. Solidified carbon dioxide ("dry ice") is being added to the metal cylinder containing ethyl alcohol. The bottom of the cylinder (sheathed in foam rubber at the sides for handling) is in contact with the upper glass pane of the insulating glass unit, to provide local cooling. If the glass is cooled below the dew point temperature of the cavity gas fill, condensation will occur on the cavity side, similar to shown in Figure 19. File photo courtesy of Bodycote Materials Testing Canada Inc.

42 ASTM E 2188 requires measurement of dew point temperature in accordance with ASTM E 546 "or equivalent". The Insulating Glass Laboratory at Bodycote Materials Testing Canada Inc. uses the measurement technique described in CGSB-12.8-97, which is considered equivalent (it actually predates the ASTM E 546 method). Briefly, this involves placing a test unit horizontally on a box with a light shining from below, applying a metal cylinder filled with ethyl alcohol in contact with one pane of an insulating glass unit and adding solidified carbon dioxide ("dry ice") to the alcohol to reduce the temperature of the cylinder until condensation is observed on the cavity-side surface of the glass, immediately below the cylinder. The temperature at which condensation is observed is the dew point temperature of the cavity gas fill. If no condensation is observed, the unit is given a "No Fog" (NF) rating.

The equipment for field measurement of the dew point temperature of insulating glass units, as described in ASTM E 576, is considerably different than described in CGSB-12.8. However, it is almost identical as the equipment described in ASTM E 546[43], referenced by ASTM E 2188. However, all use solidified carbon dioxide as a cooling source and thus have the same practical lower limit of about -73°C.[44]

Detail observations are recorded in Appendix C and are summarized under Observations. Initial dew point measurements are recorded in Appendix A.

INITIAL DIRECT DESICCANT MOISTURE CONTENT MEASUREMENT

Three (3) units were destroyed to remove the desiccant for moisture (water) content measurement to determine content at the start of testing and maximum total moisture content. For each unit, the desiccant removed was weighed in bulk, a sample removed, weighed, dried in a crucible in an oven above 950°C, cooled, then weighed again to determine the initial moisture content. The remainder of the desiccant was then placed in a cabinet at room temperature and at 100% relative humidity. Periodically, the desiccant was removed and weighed. When no further weight gain was detected, the weight was recorded. These measurements were made in general accordance with the method described in the European Union EN-1279-02 standard.

Direct measurement of the desiccant moisture content in accordance with EN-1279-02 was necessary because as noted, following the dew point measurement methods of CGSB-12.8 or ASTM E 2188, usually no initial dew point temperature can be measured (ie. the dew point temperature is colder than about -73°C). However, it is understood that some water vapour is likely to be adsorbed by the desiccant during manufacture [22] and thus, some of the water vapour adsorption capacity of the desiccant is likely to be lost by the time the units are put into service. This will reduce the lifespan of the units. Such initial adsorbed water vapour can be detected by the direct desiccant moisture content measurement method of EN-2179-02 allowing a more thorough determination of insulating glass unit performance.

ELEVATED TEMPERATURE AND HUMIDITY EXPOSURE

The remaining nine (9) units were then subjected to repeated cycles of elevated temperature and high humidity, until fogging at room temperature (standard laboratory conditions) was observed. Exposure cycles began on April 28, 2004 and were completed on February 4, 2005. After each cycle, the units would be allowed to condition at room temperature (rest undisturbed and allowed to come to room temperature conditions) for at least 24 hours prior to dew point measurements being made.

The length of each exposure to elevated temperature and humidity was three (3) weeks. With additional time for conditioning at laboratory and simulated outdoor exposure conditions and dew point measurements, the overall length of each cycle was about 3 1/2 weeks. The time for conditioning and dew point measurement (but not exposure to elevated temperature and humidity) was occasionally extended to allow for vacation, statutory holidays, etc.

In the early part of the test program, all of the test units were exposed to elevated temperature and humidity in a chamber (HHC) meeting the requirements of the ASTM E-2188 standard. In this chamber an environment of 60 ± 3°C at 95 ± 5% relative humidity is maintained (except when

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43 ASTM E 546, *Standard Test Method for Frost Point of Sealed Insulating Glass Units,* ASTM International, West Conshohocken, Pennsylvania, 1995.

44 Solidified carbon dioxide (“dry ice”) sublimates from solid to gas at about -79°C. Due to heat gain through the dew point apparatus and through the insulating glass unit, the lowest dew point that can be consistently attained is about -73°C.

units are placed, or removed from the chamber, at which time the temperature is reduced to avoid sudden thermal stress to the units which could result in cracking of glass). As the program proceeded three (3) units were moved to a HHC meeting the requirements of CGSB-12.8, in which the relative humidity is maintained nominally at 100% RH but the temperature is cycled between 22 ± 3°C and 55 ± 3°C repeatedly (Figure 26). The intent of cycling is to induce mechanical stress on the perimeter sealants and a "pumping" action in the event one or more breaches through the perimeter seal develop.

Figure 26: CGSB-12.8 High Humidity Chamber in the Insulating Glass Laboratory at Bodycote Materials Testing Canada Inc. Insulating glass units are placed on a narrow end, held in place and separated by the "teeth" at the sides. The units are held off the bottom so that they do not sit in water. A water spray maintains 100% relative humidity in the cabinet. The water temperature is cycled between 22 ± 3°C (lab conditions) to 55 ± 3°C, inducing a change in the cavity gas fill volume. High temperature increases the s the permeability of the sealants, high humidity increases the rate of water vapour diffusion through the sealants, and changes in cavity gas fill volume causes mechanical stress to the sealants (when the units are sealed). File photo courtesy of Bodycote Materials Testing Canada Inc.

DEW POINT MEASUREMENT

Measurements at Room Temperature

Following each session of elevated temperature and humidity exposure, test units were allowed to "condition" at laboratory conditions for at least 24 hours. Dew point temperature measurements were then carried out in accordance with CGSB-12.8.

Detailed dew point measurements are recorded in Appendix A, and are summarized under Observations.

Measurements at Simulated Outdoor Exposure

Following dew point measurement at laboratory conditions, the units were subjected to simulated outdoor exposure by installing the test units in a window frame mounted horizontally on a chest freezer (Figure 27). The chest freezer was thermostatically controlled, capable of chilling to about -60°C. The freezer chamber temperature was controlled to -12°C. Initially, a temperature of about -6°C was desired, about the mid-range of wintertime temperatures in Toronto, based on "normal" average daily temperatures reported by Environment Canada.[45] However, it was found that at such a relatively warm temperature (compared to the potential of –60°C) the air in the freezer chamber stratified (likely because of heat gain through the window frame and surrounding wood framing ("buck"), with air temperatures at the top immediately below the window being warmer than at the bottom of the freezer chest. This caused control problems with the freezer. To correct this, a fan was installed in the chamber (Figure 33) to circulate air and the air temperature was reduced to -12°C, slightly colder than the "normal" average mean daily minimum temperature reported by Environment Canada but nevertheless not unusual for Toronto in the winter. This also provided the effect of a moving air film at the exterior face of the insulating glass units. The speed of air movement over the outside face of the insulating glass units was not determined.

Figure 27: Deep freeze unit at Bodycote Materials Testing Canada Inc. This chest freezer is capable of attaining temperatures of -60°C and was used to provide simulated outdoor exposure.

Room temperature conditions were standard laboratory conditions, about 22°C, within the laboratory temperature ranges of 22 ± 3°C required by CGSB-12.8, 24 ± 3°C required by ASTM E 2190, and 23 ± 2°C required by EN-1279-06.

The chamber was fitted with three (3) "capsule" florescent bulbs[46] to provide sufficient light to detect fogging during dew point measurement (Figure 33).

The test window frame was manufactured to order by a Toronto-area window manufacturer, from Alumicor Ltd. "970E Series" frame components, and consisted of (Figures 28 to 31):

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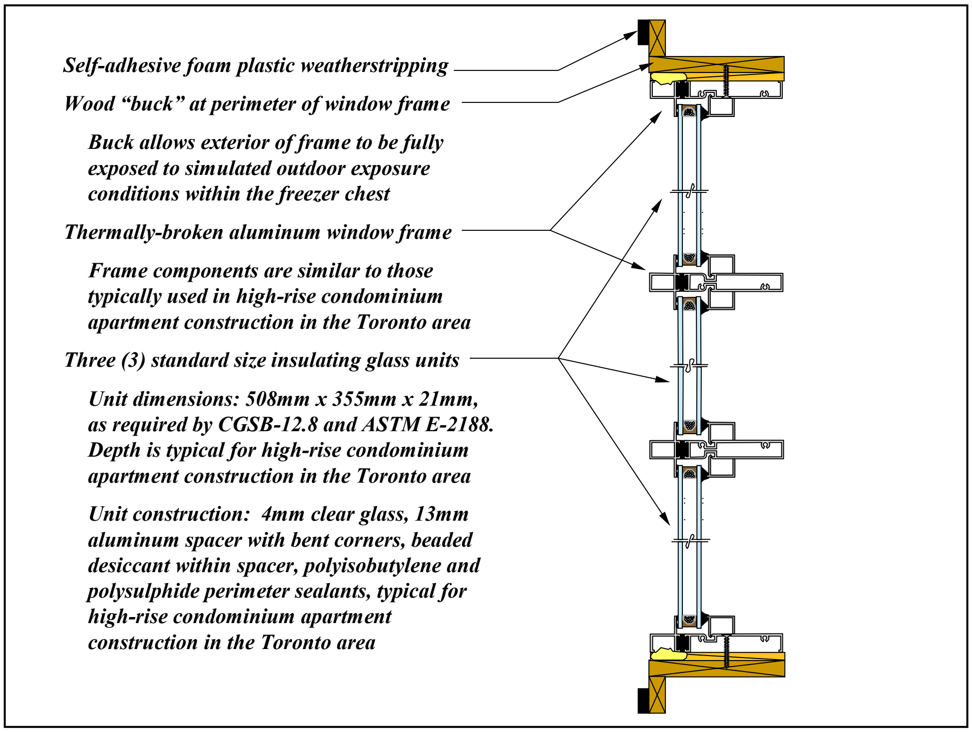
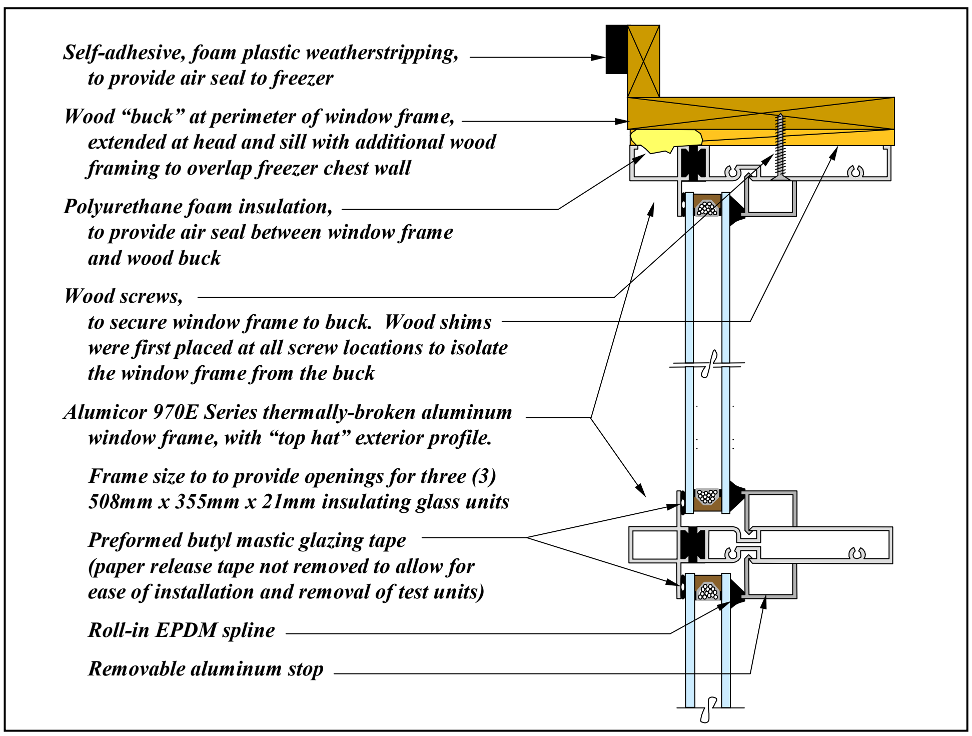
45 "Winter" was arbitrarily assumed to be defined by months with an average daily air temperature below 0°C.

46 "Light Capsule" florescent bulbs, model EFT28E28 by Panasonic.

- 19mm x 133mm (3/4 in. x 5 1/4 in.) thermally-broken extruded aluminum framing with "top hat" profile. Thermal break was a foamed PVC plastic. Framing was rolled and crimped to the thermal break. Mullion (vertical frame members) and rail (horizontal frame members) fastening were screw fastened together (screw-spline construction). All aluminum components had a clear anodized finish.
- Framing was designed for laid-in glazing of insulating glass units from the building interior on pre-shimmed butyl mastic glazing tape (the paper release tape was left on to allow units to be installed and removed with ease) on an exterior projecting leg, at the exterior face of the thermal break.
- Insulating glass units were retained in place with snap-in, double-leg aluminium stops with roll-in EPDM rubber splines between the stop and inboard pane of the insulating glass units.

Figures 28, and 29: **Outdoor exposure frame. At upper left, the exterior face exposed to the freezer chest, at right the room-side face. At upper right the interior face exposed to room conditions. The window frame was mounted to a wood buck to fit the freezer chest opening. Gaps between the frame and the wood buck, and the wood buck and the freezer were sealed to separate the cold environment within the chamber from the warmer laboratory environment.**

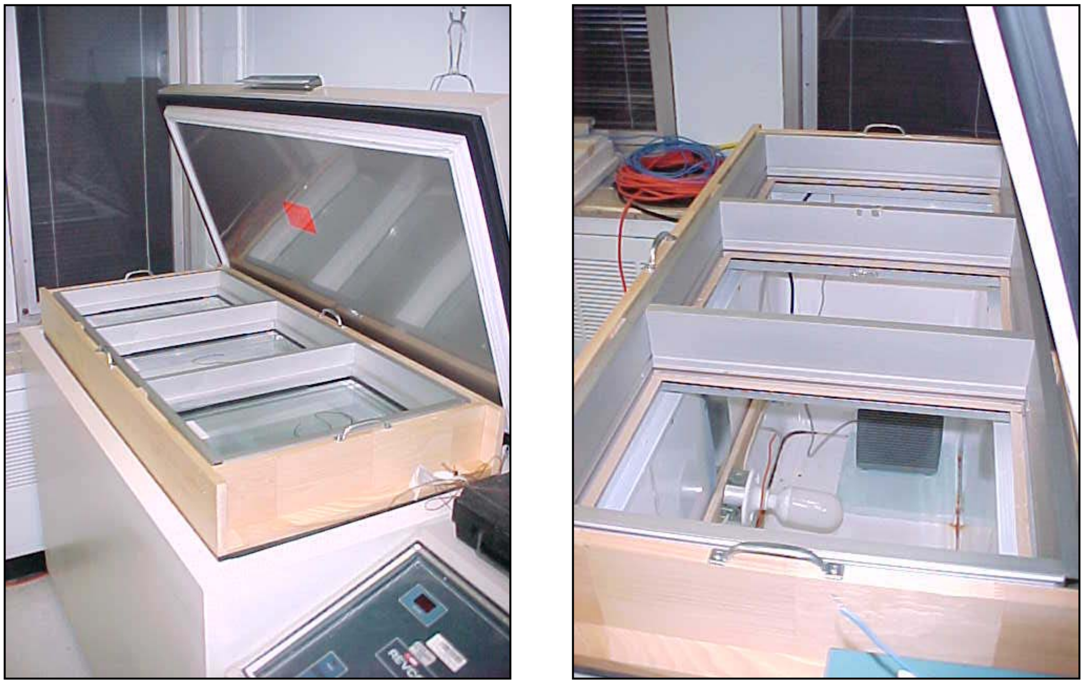




Figures 30 and 31: **Detail drawings of the outdoor exposure frame. The upper drawing is an overall section from head to sill. The lower drawing is a section through the upper half of the frame, showing construction details at the head rail and intermediate rail below. The lower half of the exposure frame is similar to the lower drawing. Jamb details are similar to the head.**

This type of framing is designed for insulating glass units 25mm (1 in.) overall thickness, usually comprising 6mm (1/4 in.) thick glass and a 13mm (1/2 in.) wide cavity. The test units were thinner, approximately 21mm, as is typically supplied for testing in accordance with CGSB-12.8 and ASTM E 2190[47]. To make up for this, the thickness of the glazing tape and the roll-in splines were increased in thickness.

This window framing is similar to the type of frames typically used for high-rise residential apartment construction in the Toronto area.[48]



Figures 32 and 33: Outdoor exposure frame mounted on the deep freeze unit, relocated to the Insulating Glass Laboratory at Bodycote Materials Testing Canada Inc. On the right photo, visible through the frame at the left side is one of three (3) outdoor grade fluorescent "capsule" lights suspended from the top of the freezer chest, used to provide illumination directly below the insulating glass units during dew point measurements, to aid in detecting the presence of induced fog. At the upper right corner is a fan unit that circulated air through the freezer chest, to prevent stratification of air and to provide a moving air film at the outdoor face of the insulating glass units.

The window frame was mounted to a wood frame ("buck"), with wood screws through the jamb mullions. A gap of about 13mm (1/2 in.) was provided between the window frame and buck. At screw locations, shims were installed prior to fastening to "float" the frame free of the buck. The gap between the frame and buck was sealed at the exterior face with a low-expansion, one

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47 Test units are typically made of 4mm (5/32 in.) thick glass and a 12mm (1/2 in.) wide cavity, for an overall thickness of 20mm (26/32 in.).

48 Thermally-broken aluminum window framing for high-rise residential apartment buildings is usually 25mm x 114mm (1 in. x 4 1/2 in.), open back. The frame used is more common for commercial building construction. It was selected to fit the freezer opening.

component polyurethane foam insulation. The manner of installation of the window frame within the buck is consistent with the requirements of National Standard of Canada CSA-A440.4.[49]

The frame was fitted with a thick foam plastic, self-adhesive weatherstripping to provide an air-tight seal to the freezer opening, to assist in maintaining cold conditions within the freezer chest.

Following installation of the test units in the outdoor exposure frame, the test units were allowed to "condition" at simulated outdoor exposure for at least 24 hours. The entire freezer unit was then moved to the dew point temperature measurement station and the dew point temperature determined while the units were still exposed to simulated outdoor exposure. The measurement method was otherwise in accordance with CGSB-12.8, as previously described.

Detailed dew point measurements are recorded in Appendix A, and are summarized under Observations.

FINAL EXAMINATION

Following the completion of elevated temperature and humidity exposure, all of the remaining units were visually examined. Observations are recorded in the following section.

FINAL DIRECT DESICCANT MOISTURE CONTENT MEASUREMENT

Following final examination, all of the units were destroyed for removal of the desiccant and determination of water vapour content. The results were compared against initial values and projected maximum water vapour adsorption capacity. The water vapour adsorption capacity of desiccant from breached and un-breached units was also compared. A detailed record of water vapour contents is included in Appendix B. A summary and assessment are included in the following sections.

Observations

INITIAL EXAMINATION

After conditioning at standard laboratory conditions various non-destructive, visual measurements were made of the test units. These are recorded in Appendix D and summarized following.

The units were of standard test size to fit within existing test equipment, nominally 355 mm x 508 mm (14 in. x 20 in.), double pane with 4 mm thick clear glass, and a 13 mm wide cavity.[50] The units were constructed with dual perimeter sealants, polyisobutylene (PB) primary sealant between the sides ("shoulders") of the spacer and the glass panes, and polysulphide (PS) secondary seal between the glass panels across the bottom of the spacer.[51] The spacer was aluminum, not thermally broken, with bent corners and one joint in a long side mechanically connected with a galvanized steel connector ("key"). Subsequent destruction of the units for desiccant removal revealed that the key was not sealed with PB primary sealant.

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[49] This standard is currently under revision. The installation method is consistent with the original version 1998 edition of the standard and with revisions discussed by the CSA technical sub-committee responsible for revising the standard (the principle author of this paper is an active member of the sub-committee).

[50] The size of, and construction of the test units is the same as required by the ASTM E 2188 test standard and to recently adopted European Union EN-1279 series insulating glass unit standards.

[51] Dual seal units were used because the rate of water vapour diffusion into the units was expected to be slow, and thus a maximum number of data points would be obtained.

The manufacturer of the test units was certified by the Insulating Glass Manufacturers Alliance (IGMA) to manufacture units of this type. Performance testing had been carried out to the CGSB-12.8-97 standard.[52]

At the sides ("shoulders") of the spacer in some units, openings for pneumatic desiccant filling of the spacer could be seen. The desiccant was a loose bead type. At some openings, desiccant was visible. When three (3) units were destroyed for desiccant removal, it was found that in all destroyed units there were two (2) fill openings, one in a "long side" spacer leg and the other in and adjacent "short side" spacer leg. Only these two legs were filled with desiccant. The openings were approximately 3mm (1/8 in.) in diameter. The desiccant filling technique was consistent with the Insulating Glass Manufacturers Alliance (IGMA) *Quality Procedures Manual*.

As noted, the desiccant was a loose bead type. It appeared to be a synthetic zeolite ("molecular sieve"), although the type (ie. 3A, 4A, etc.) could not be determined.

INITIAL DEW POINT MEASUREMENT

Following examination, the dew point temperature of all units was measured at lab conditions. For all units, no fog (condensation) was observed on the cavity side of the glass pane tested, indicating that the dew point temperature was colder than about -73°C. Dew point measurements were made in accordance with CGSB-12.8.

Results of the initial physical examination are recorded in Appendix C. Initial dew point measurements are recorded in Appendix A.

INITIAL DIRECT DESICCANT MOISTURE CONTENT MEASUREMENT

Three (3) units (nos. 4, 7 and 12) were destroyed for measurement of the moisture content of the desiccant. Desiccant was poured directly from opened spacers into pre-weighed glass specimen jars. The jars were sealed after weighing. Between 33.24 and 39.63 grams of desiccant was removed from each unit. Each jar was labelled with the test unit number. Desiccant fill levels were consistent with the Insulating Glass Manufacturers Alliance (IGMA) *Quality Procedures Manual*.

From each sample jar, about 10 grams[53] of desiccant was removed and placed into a pre-weighed ceramic crucible, covered, weighed, and placed, uncovered, into a furnace at a minimum temperature of 950°C for approximately two (2) hours. The crucibles were then removed, covered, and allowed to cool to room temperature conditions (usually overnight) in a sealed bell jar. After cooling, the crucibles were weighed again. The difference in weight was assumed to be entirely due to loss of adsorbed water from the desiccant. This revealed that between 1.3g and 1.6g of water had been adsorbed by the desiccant until the time of removal from the insulating glass units, representing a moisture content of between 1.37% and 1.62% by dry weight of the oven-dried samples.

The remainder of the desiccant samples were then placed, uncovered, into a high-humidity cabinet at room temperature at 100% RH. The samples were removed periodically and weighed. After approximately one (1) month the weights were consistent, indicating that at the cabinet temperature, the desiccants had reached their maximum moisture adsorption capacity (since the environment was at 100% RH). The maximum moisture adsorption capacity varied between

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52 Pending acceptance of ASTM E 2188 and related standards by the Standing Committee for the model National Building Code of Canada (NBCC), IGMA continues to accept testing to CGSB-12.8-97 for units intended for the Canadian market, as required by the NBCC.

53 An arbitrary amount of about 10 g was selected for removal. Actual amounts varied between 9.23 and 10.03 g.

4.99g and 8.77g, representing a moisture content of between 26.52% and 61.31% by dry weight of the oven-dried samples. The upper value was very much higher than reported maximum moisture adsorption capacity for molecular sieve desiccant, such as reported in EN 1279-02, and likely indicates an error in measurement of the sample (from unit no.4).

Detailed results are recorded in Appendix B.

Desiccant extraction and moisture content measurements were carried out in general accordance with the European Union EN-1279-2 standard.

ELEVATED TEMPERATURE AND HUMIDITY EXPOSURE

First Modifications to Planned Exposure Scheme

After five (5) cycles (approximately 3 1/2 months) of elevated temperature and humidity exposure to the method described previously, the dew point temperature of all units was still less that -73°C, or "no fog" (designated as "NF" in table in Appendix A). It appeared that the units would not come to a fogged state within the remaining available laboratory time.[54] To increase the rate of water vapour transmission into the units, the perimeter seal of six (6) of the nine (9) units was breached by driving a small common finishing nail (2mm or 0.078 in. diameter) through the bottom of the spacer. Three (3) breached units (units. 5, 6 and 8) and three (3) unbreached units (units 9, 10 and 11)were returned to the ASTM E 2188 high humidity chamber (HHC). The three (3) remaining breached units (units 1, 2 and 3) were placed into a HHC that was operated in accordance with the CGSB-12.8 standard. The cycle time for both HHCs was reduced to one (1) week in anticipation of rapid failure of the breached units, to maximize the number of dew point temperature measurements obtained.

The intent of placing three (3) units in the CGSB-12.8 HHC was to accelerate failure. In both chambers, the temperature of the units is increased from laboratory conditions while the air is saturated with water vapour. Increasing the temperature causes the cavity gas fill to expand. In a sealed unit, this would cause the glass panes to deflect, stressing and causing dimension change of the perimeter sealants. In units that had been breached, pressure increase would be avoided by permitting the volume of the cavity gas fill to expand into the environment outside of the unit. Subsequent contraction of the cavity gas fill would draw in humidified air (nominally 100% RH) from the HHC (refer to Appendix D).[55] In the CGSB-12.8 HHC, the air temperature is cycled from a low of 22 ± 3ºC (laboratory conditions) to a high of 55 ± 3ºC every 180 minutes. As noted, in the ASTM E 2188 test chamber the temperature is increased from 22 ± 3ºC (laboratory conditions) to a high of 60 ± 3ºC and maintained[56], returned to laboratory conditions only when the chamber is opened to place or remove units[57]. Thus in the CGSB-12.8 HHC, for breached units there should be many more exchanges of relatively dry air within the insulating glass unit

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54 CMHC required testing and report submission within twelve (12) months of award of funding in mid-April 2004. Accordingly, the services of the Insulating Glass Laboratory at Bodycote Materials Testing Canada Inc. were contracted for a fixed number of cycles of testing.

55 Calculation revealed that in the CGSB-12.8 HHC, temperature increased from laboratory conditions should result in an exchange of approximately 10% of the cavity volume in each cycle (assuming that the unit completely warms up and cools down to the maximum and minimum temperatures in each cycle – that is, there is no lag due to thermal mass of the unit materials).

56 The European Union EN-1279-2 standard also requires constant elevated temperature (58 ± 5ºC) at ≥95%RH.

57 Cooling down of units to laboratory conditions is not specifically mentioned in the ASTM E 2188 standard. However, it is done to avoid sudden thermal shock that could result in cracking of glass panes.

cavity with the humidified air in the chamber. It would be reasonable to expect that units in the CGSB-12.8 HHC would fog earlier than units in the ASTM E 2188 HHC.

Initially, the reverse condition happened. The dew point temperature of one breached unit (no. 6) unit in the ASTM E 2188 HHC increased after the first cycle of exposure to -23°C. One breached unit (no. 1) in the CGSB-12.8 HHC remained "no fog" (less than -73°C). After a second one-week cycle, the situation reversed, with the dew point temperature of the breached unit in the CGSB-12.8 HHC increasing to -71°C and the dew point temperature of the breached unit in the ASTM E 2188 HHC returning to "no fog" (less than -73°C). The reason for the decrease in dew point temperature of the unit in the ASTM E 2188 HHC is unknown.

The dew point temperature of all of the remaining breached and unbreached units remained "no fog".

<u>Second Modification to Planned Exposure Scheme</u>

The rapid rise in dew point temperatures of two of the breached units after two (2) one-week cycles of exposure gave rise to concerns that all of the units might fail very rapidly, providing little data on which to estimate remaining life span. It was decided to reduce the size of the breach openings by inserting a standard argon gas sampling syringe[58] into each opening and sealing the annular space between the needles and openings with polyisobutylene sealant (Figure 34).

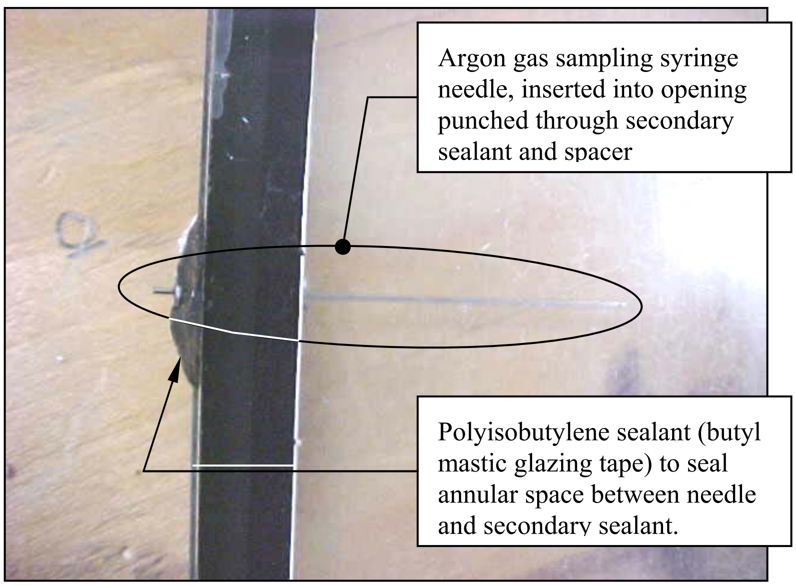

Figure 34: Unit no 1 (photographed at final tear-down) showing argon gas sampling syringe needle inserted through the centre of the spacer to provide a smaller breach opening into the cavity.

All of the units were returned to the CGSB-12.8 and ASTM E 2188 HHCs. Over the next five (5) one-week cycles, the lab condition dew point temperatures decreased in units 1 and 6 then started to increase again. Dew point temperatures were measured for unit 5 for two (2) cycles before returning to "no fog". The reasons for these reversals are unknown.

58 The needles are required for extraction of cavity gas for determining the quantity of argon gas within a claimed argon gas-filled unit (as a percentage of total gas fill) in accordance with CGSB-12.8-97.

The dew point temperature of all of the remaining breached and unbreached units remained "no fog".

Third Modification to Planned Exposure Scheme

At removal of the units after the fifth week after installing the argon gas sampling syringe needles, corrosion was noted on the needles of three (3) units (nos. 1, 2 and 3). All needles were removed and tested for air flow. Air flow was detected through three units (nos. 2, 5 and 8), only one of which had a measurable dew point temperature, and then only briefly before returning to a "no fog" state (no. 5). The other needles appeared to be plugged (units 1, 3 and 6), possibly by corrosion within the needles. This suggested the possibility that the increase in dew point temperature experienced in two of the other units (no. 1 and no.6) was due less to air exchange through the needles than to air exchange through other sources. The absence of measurable dew point temperatures in the un-breached units indicated that dew point temperature increase was not likely due to water vapour diffusion through the perimeter sealants.

By this point, seven (7) months had passed. The units had been exposed to twelve cycles of elevated temperature and humidity, a total of twenty-two (22) weeks. Although the dew point temperature of two (2) units was increasing, it continued to appear that the dew point temperature of the remaining breached units might remain "no fog". After further consideration, it was decided to replace the blocked needles in the two units that had measurable dew point temperatures (no. 1 and 6) and to remove the needles from the remaining four (4) breached units (no. 2, 3, 5 and 8). The breach openings were cleaned out by reaming to the same diameter with an electric drill and bit (Figure 35). All of the units were then returned to the HHC chambers for further exposure.

Figure 35: Typical breach opening reamed by 1.59mm (1 1/6 in.) drill bit. The interior of the cavity can be seen clearly through the opening.

The intent of keeping the argon gas sampling needles in the two (2) units with measurable dew point temperatures was a precaution against rapid failure of the remaining breached units. It was believed that the increase in dew point temperature of the two (2) units with argon gas sampling needles would be slower (as long as the needles remained open) because the inside diameter of the needles was much smaller than the reamed breach openings.

All units were subjected to eight (8) additional cycles of elevated temperature and humidity. Through these cycles, the dew point temperature of all breached units increased to about laboratory conditions. Elevated temperature and humidity cycling was halted when most units were observed in a fogged condition upon removal, indicating that further moisture gain was unlikely.

At the end of elevated temperature and humidity cycling, two (2) of the un-breached units remained "no fog" (no. 9 and 11). One (1) unit, (no. 10), rapidly gained moisture in the final two (2) cycles. Examination of this unit between cycles revealed failure (adhesion loss) of the secondary sealant at several locations.

A detailed record of dew point temperatures and observations during testing is included in Appendix A. The summary follows.

DEW POINT TEMPERATURE MEASUREMENT

Room Temperature Dew Point Measurements

After breach of the test units, and particularly after breach openings were reamed out, dew point temperatures could be measured, and increased very quickly. A composite graph of dew point measurements made at room temperature (standard laboratory conditions of 23 ±3°C) from the beginning to the end of the program is shown in Figure 36. Detailed measurements and notes are included in Appendix A.

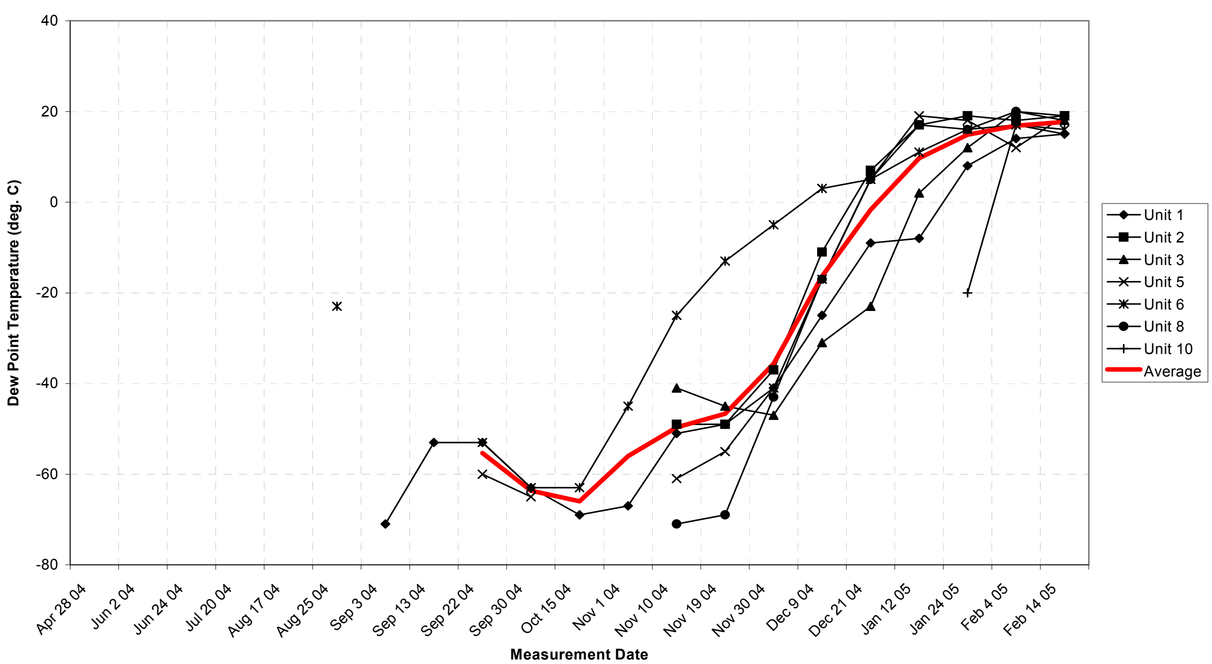

Figure 36: Composite plot of dew point temperatures measured at laboratory conditions for all breached units and one unbreached, "control" unit that fogged toward the end of the program (unit 10). The thick line is the average dew point temperature of the breached units, calculated after dew point measurements could be made on three (3) units. The general trend of the average dew point temperature shows a fairly constant increase until about January 2005, when the rate of increase began to decrease noticeably.

For many units, dew point temperatures at first decreased before settling into a general trend of increase. The reasons for the initial increases and decreases are unknown.

The plots of dew point temperature increase are very similar for all of the breached units, except for unit 6. The edge of one pane of glass of this unit was damaged during examination on November 1 2004, when the unit dew point temperature measurements were being made. The damage consisted of a crack extending to the boundary between the primary and secondary sealants on one face at one side of the unit. Subsequent examination at tear-down revealed that the secondary sealant had separated from the glass pane at this location, for the full depth of the secondary sealant. Coupled with expansion of the secondary sealant (to be discussed later), this may have created another breach that contributed to more rapid (earlier) gain of water vapour and increase in the dew point temperature.

Unit 6 was fitted with an argon gas sampling syringe needle in the breach opening, as was unit 1. It was believed that with a smaller diameter opening than the reamed breach openings, the degree of cavity gas fill exchange might be reduced, providing more data points for later analysis. The composite plot reveals that for unit 6, the rate of dew point temperature increase was, for a few exposure cycles, greater than the other units (likely due to the damage to one pane and the formation of an additional breach as discussed) before beginning to decrease. For unit 5, there was a sudden decrease in the rate of dew point temperature increase, then the rate increased, generally matching the units with reamed breach openings, before suddenly decreasing again. Upon inspection on January 12, 2005, corrosion of the argon gas sampling syringe needle was noticed and the needle was replaced. The rate of dew point temperature increased quickly accelerated afterward, matching that of units with reamed breach openings. Thus it would appear that the argon gas sampling syringe needles had little effect, and were more problematic, than much larger, and simpler, reamed breach openings.

<u>*Simulated Outdoor Exposure Dew Point Measurements*</u>

A composite graph of dew point measurements made at simulated outdoor exposure from the beginning to the end of the program is shown in Figure 37. Detailed measurements and notes are included in Appendix A.

The intent of exposure to simulated outdoor exposure was to examine the relationship of dew point temperature to desiccant temperature. When the units were subjected to simulated outdoor exposure, dew point temperatures could not be detected until room temperature dew point measurements increased above -23°C. Generally, dew point temperatures measured under simulated outdoor exposure were between 10°C and 57°C lower than dew point temperatures measured under isothermal room (laboratory) temperatures. The average difference was about 25°C (Figure 38).

During exposure, surface temperatures of window framing and insulating glass units was monitored from time to time with small battery-powered “Smartbutton” data-loggers from ACR Systems Inc. Freezer chamber and laboratory air temperatures were also monitored with the same data-loggers (Figure 39).

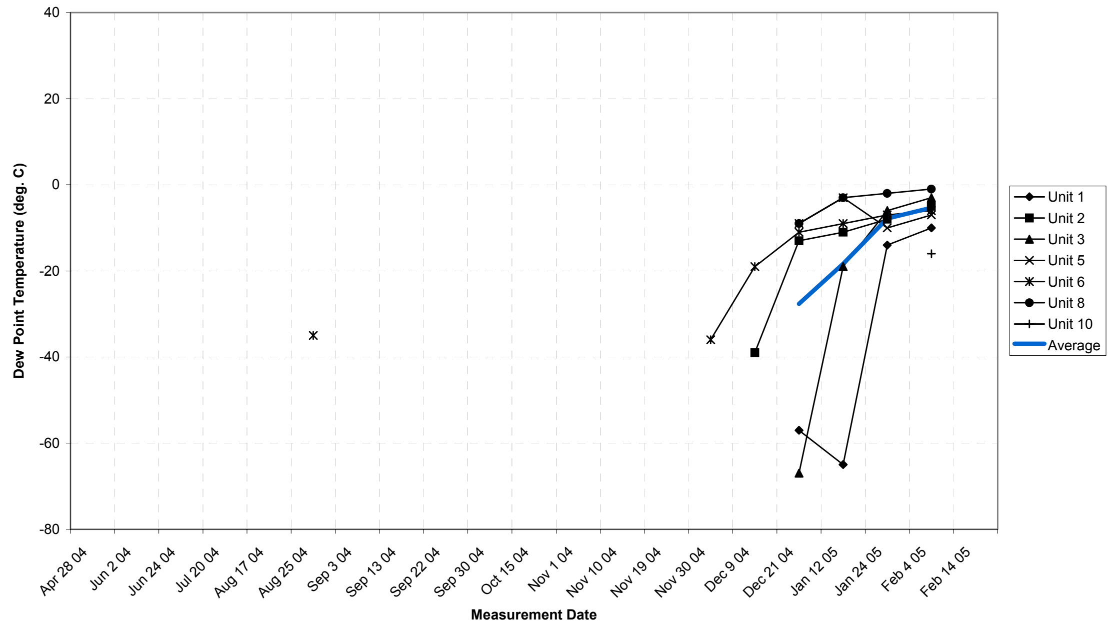

Figure 37: Composite plot of dew point temperatures measured at simulated outdoor conditions for all breached units and one unbreached, "control" unit that fogged toward the end of the program (unit 10). The thick line is the average dew point temperature of the breached units, calculated after a dew point measurements could be made on three (3) units.

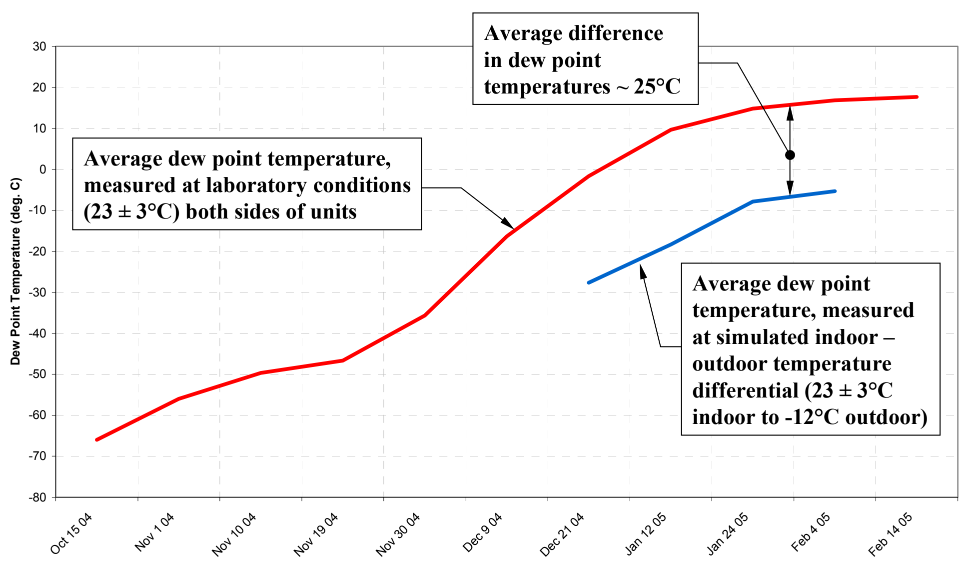

Figure 38: Composite plot of average dew point temperatures measured at laboratory and simulated outdoor conditions for all breached units. Measurements are shown after October 15, 2004 when dew point temperatures were generally increasing.

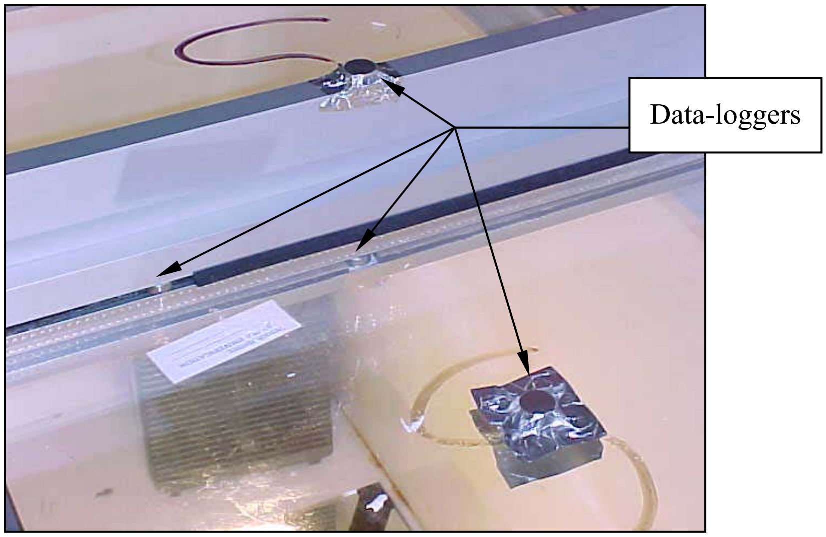

Figure 39: **Insulating glass unit, frame, and freezer chest (outdoor air) and laboratory (indoor air) temperatures were monitored for short periods of time with battery-powered dataloggers (most covered with self-adhesive aluminum foil tape for attachment to the test frame and insulating glass unit. The freezer chest air temperature was also monitored by the freezer control unit and laboratory air temperatures were also monitored by the building HVAC control system.**

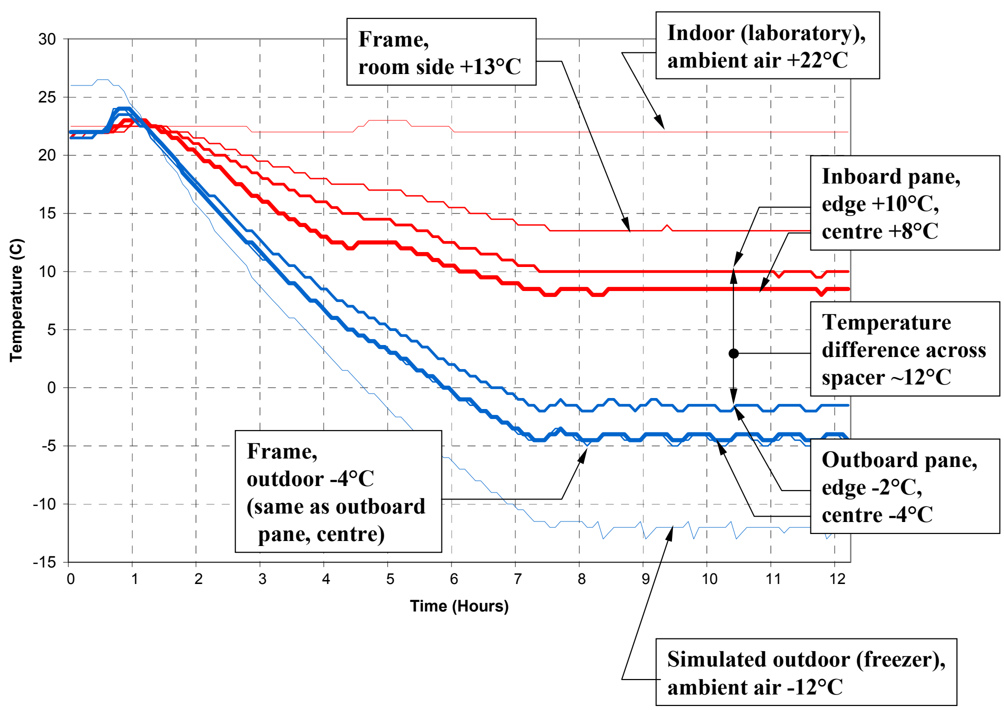

Figure 40: **Composite plot of surface temperatures of one (1) test unit during simulated outdoor exposure. The unit was installed in the exposure frame and the frame placed on the freezer chest at room temperature, then the freezer was turned on. The location of the data-loggers used to record these temperatures is shown in Figure 39.**

Temperature measurements made from the time of installation of the test frame on the freezer until steady-state conditions were achieved (Figure 40) revealed that the test frame and insulating glass units within cooled rapidly from room temperature conditions to simulated outdoor conditions.

At the end of the project, additional dew point temperatures measured at before and after the 12 hour minimum conditioning time indicated little temperature variation, confirming that the desiccant had come to equilibrium with the cavity gas fill (Figure 41). The temperature of the desiccant under steady-state conditions was estimated to be between -2°C and +10°C, for an average of +4°C. The temperature of the unit cavity under steady-state conditions was estimated to be between -4°C and +8°C, for an average of +4°C.

Simulated Outdoor Exposure Extended Measurements				
Unit #	Feb 7	Feb 7	Feb 8	Feb 10
	3 Hrs	12 Hrs	24 Hrs	48 Hrs
312-05	-6	-7	-7	
312-06	-7	-6	-6	-6
312-08	-3	-1	-1	-2

Figure 41: Dew point temperatures measured at 3, 12, 24 and 48 hours of simulated outdoor exposure, following the final cycle of high temperature and humidity exposure. Note that there is very limited variation in temperature, indicating that the desiccant had cooled and come to equilibrium with the cavity gas fill very quickly. For these temperatures, the freezer was already operating and cold, and the outdoor exposure frame was similarly chilled, so that the decrease in temperature of the units was faster than shown in Figure 33.

Final Examination

Following the completion of elevated temperature and humidity exposure, all of the units were examined. In all units, generally, the exterior faces of both glass panes were severely etched by the constant high humidity exposure. The perimeter polysulphide sealant appeared to have become harder and exhibited surface cracking ("alligator skin" appearance) common to aged organic sealants.

In all units, local separations (adhesion loss) of the perimeter secondary sealant from glass surfaces were observed. Usually, the adhesion loss did not extend across the depth of the secondary sealant (ie. from outside the unit to the primary sealant) and there were no corresponding separations of the primary sealant from glass surfaces. Exceptions included units 6 (which had sustained damage to the glass edge, as previously described) and both remaining "successful" control units 9 and 11 in which secondary sealant separations extended the full depth of the secondary sealant. In unit 10, the "control" unit that failed rapidly toward the end of exposure, secondary sealant separations were extensive and there were corresponding separations in the primary sealant (Figure 17). Separations between the secondary sealant and the glass panes were more extensive in the sealed "control" units that in the breached units, and more extensive in the breached units exposed to elevated temperature and humidity in the ASTM E 2188 HHC than those in the CGSB-12.8 HHC.

In all units, loose desiccant beads were found in the cavity. These beads had come from breach openings made in the spacer. In all units, beads had settled between the spacer and the glass panes (Figure 16). When the glass panes were removed, it was found that the depth of perimeter sealant was about half of what it appeared to be based on the contact area on the glass panes, visible from the exterior of the units. Examination of the three (3) units destroyed for initial desiccant moisture content measurement showed only minor reduction in the depth of the sealant vs. glass contact area on the glass panes, and no visible gap into which desiccant could settle.

Destruction of the units involved cutting through the perimeter of the insulating glass units with a knife, to separate the spacer from the glass panes. During destruction, considerably more effort was required to cut through the sealants of units that had been exposed to the ASTM E 2188 HHC than to the CGSB-12.8 HHC. This is a subjective observation.

Observations made during the final examination and tear-down are recorded in Appendix C.

FINAL DIRECT DESICCANT MOISTURE CONTENT MEASUREMENT

Following elevated temperature and humidity exposure, all nine (9) units (nos. 1, 2, 3, 5, 6, 8, 9, 10, and 11) were destroyed for measurement of the moisture content of the desiccant. Desiccant was poured directly from opened spacers into pre-weighted glass specimen jars. The jars were sealed after weighing. Between 33.40 and 41.83 grams of desiccant was removed from each unit. Each jar was labelled with the insulating glass unit number. The measured desiccant fill levels were consistent with the Insulating Glass Manufacturers Alliance (IGMA) *Quality Procedures Manual*.

From each sample jar, about 10 grams[59] of desiccant was removed and placed into a pre-weighed ceramic crucible, covered, weighed, and placed, uncovered, into a furnace at a minimum temperature of 950°C for approximately two (2) hours. The crucibles were removed, covered, and allowed to cool to room temperature conditions (usually overnight) in a sealed bell jar. After cooling, the crucibles were weighed again. The difference in weight was assumed to be entirely due to loss of adsorbed water from the desiccant. This revealed that between 0.99g and 2.02g of water had been adsorbed by the desiccant, representing a moisture content of between 10.67% and 25.06% by dry weight of the oven-dried samples.

Broken down into groups, the results of desiccant moisture content determinations reveal:

- For the two (2) breached units with argon gas sampling syringes installed in the breach openings, final desiccant moisture content was 1.75g (unit no. 1 from the CGSB-12.8 HHC) and 1.78g (unit no. 6 from the ASTM E 21.88 HHC), representing a moisture content of 21.47% and 22.06% respectively by dry weight of the oven-dried samples.
- For the two (2) other breached units in the CGSB-12.8 HHC, final desiccant moisture content was 1.49g (unit no. 2) and 1.75g (unit no. 3), representing a moisture content of 21.85% and 21.88% respectively by dry weight of the oven-dried samples.
- For the two (2) other breached units in the ASTM E 2188 HHC, final desiccant moisture content was 1.74g (unit no. 6) and 1.95g (unit no. 5), representing a moisture content of between 22.06% and 23.81% respectively by dry weight of the oven-dried samples.
- For the one (1) sealed "control" unit (unit 10) that rapidly failed at the end of exposure in the ASTM E 2188 HHC, final desiccant moisture content was 2.02g, representing a moisture content of 25.06% by dry weight of the oven-dried sample.

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59 An arbitrary target of about 10 g was selected for removal for oven drying. Actual removed amounts varied slightly, from 8.31 and 10.27 grams.

- For the two (2) other sealed "control" units in the ASTM E 2188 HHC, final desiccant moisture content was 8.93g (unit no. 11) and 9.28g (unit no. 9), representing a moisture content of between 12.99% and 10.67% respectively by dry weight of the oven-dried samples.

Detailed results are recorded in Appendix B.

Desiccant extraction and moisture content measurements were carried out in general accordance with the European Union EN-1279-2 standard.

Assessment

Effect of Program Modifications

The initial goal was to induce fogging through elevated temperature and humidity exposure only. Test units were modified during the program to induce fogging, necessary to meet funding program deadlines. Calculations indicate that as much as 10% of the cavity volume could be exchanged in each cycle of heating and cooling (refer to Appendix D). It is therefore likely that the majority of water vapour gain into the breached units was through exchange of dry air from within the units with humid air from the HHCs.

This assessment is supported as follows:

- Following breach, particularly after breach openings were cleared, dew point temperatures immediately became measurable (ie. warmer than -73°C) whereas the remaining sealed units remained "no fog".
- Initial desiccant moisture content measurements indicate that at room temperature conditions, the maximum moisture adsorption capacity of the desiccants incorporated in the test units was 26.52% (unit no. 12), 26.70% (unit no. 7) and 61.31% (unit no. 4) by dry weight of desiccant. The highest value appears to be in error, based on typical reported maximum moisture adsorption capacities of about 25% at standard laboratory conditions, such as reported in EN 1279-02. If this value is ignored, the two remaining values are in very close agreement (only 1% difference). An average of these values would be 26.61%. For the two (2) sealed "control" units in the ASTM E 2188 HHC that remained "no fog", the final desiccant moisture contents 12.99% (unit no. 9) and 10.67% (unit no. 11) by dry weight, for an average of 11.83%. Although there were local separations of the perimeter secondary sealant from the glass panes, there was no evidence of a clear breach extending through the primary sealant to the cavity. This suggests that the moisture gain by the desiccant must have been due to diffusion through the perimeter sealants. Thus, perhaps as much as (26.61% - 11.83% =) 14.78%, representing about 55% of the total adsorbed water vapour in the desiccants of the two sealed, "no fog" units could be due to water vapour diffusion.

The inducement of earlier fogging raises a question as to whether the results form a reasonable basis for development of a calculation method to estimate time to fogging. We believe so. The reason for this belief lies in the behaviour of the sealed "control" units. As reported, two (2) of the units remained "no fog" whereas the dew point temperature of one (1) unit (no. 10) increased very quickly at the end. Examination revealed that a breach through the secondary and primary sealants had developed. It is known from laboratory confirmation testing to standards such as CGSB-12.8 that breaches can develop during the test program.[60] Examination by the authors of

[60] Breached units submitted for confirmation testing to CGSB-12.8, for example, will fail rapidly during test. It is for this reason that the authors of the CGSB-12.8 standard included an "initial seal" test to detect breached seals.

prematurely fogged units removed from buildings have also revealed the presence of breaches as the likely cause of fogging.

CGSB-12.8 VS. ASTM E 2188 HHC EXPOSURE

The dew point temperature measurements reveal a small difference in performance of breached insulating glass units exposed to high temperature and humidity in the CGSB-12.8 HHC as compared to the breached units exposed in the ASTM E 2188 HHC. Final desiccant moisture content of units with dew point temperatures at approximately room temperature was an average of (unit no. 1: 21.47%, unit no. 2: 21.85%, unit no. 3: 21.88%) of 21.73% of dry desiccant weight for units exposed in the CGSB-12.8 HHC, slightly less than for units exposed in the ASTM E 2188 HHC (unit no. 5: 23.81%, unit no. 6: 22.06%, unit no. 8: 23.23%, unit no 10: 25.06%) at an average of 23.54% of dry desiccant weight. The difference in averages is about 8%. This difference may be due to the slightly higher temperature in the ASTM E 2188 HHC.

Destruction of the units after the last cycle also revealed a difference in ageing of sealants of units exposed in the ASTM E 2188 HHC as compared to units exposed in the CGSB-12.8 HHC. The perimeter sealants of units exposed in ASTM E 2188 HHC were harder to cut through. This hardening of sealants may have lead to the adhesion failure, breach of seal, and rapid rise of dew point temperature of unit 10 at the end of the test program. As the sealants became harder, flexibility and extensibility necessary to accommodate movement would have been lost. Deflection or movement apart of the glass panes would occur in response to the higher temperature within the HHC and resulting expansion of the cavity gas fill.

It is worth noting that the other two “control” units also exhibited partial breaches of sealants. Given the sealant failure in unit 10, it would seem reasonable that these two units would also experience seal failure with further exposure and rapid increases in dew point temperature. This would have provided very few sets of dew point temperatures for analysis and prediction modelling. Thus it may be that breaching the units was beneficial in that it may have provided more data for analysis. This cannot be confirmed now, but it is an important consideration for future studies.

SEALANT DISTORTION

As noted, in the breached units, loose desiccant beads had settled between the spacer and glass panes. The gap into which the beads had settled appeared to have formed during high humidity exposure.

It is known that insulating glass unit sealants will absorb moisture when exposed to elevated temperature and humidity [11, 12, 20]. Polysulphide sealants are particularly susceptible. Absorption of moisture causes expansion of the sealant, forcing apart the glass panes. In turn, this stretches the primary sealant, reducing is effective depth and its resistance to water vapour diffusion. We believe this occurred in the test units. Unfortunately, overall thickness measurements were not made prior to destruction for desiccant removal so movement apart of the glass panes cannot be confirmed numerically.

EFFECT OF DESICCANT TEMPERATURE

The intent of measuring dew point temperatures at room temperature conditions and simulated lab outdoor exposure was to determine the effect of temperature on dew point reduction by the desiccant (as a function of increased adsorption capacity). In addition, the results can be used to

It is customary to advise the client (the insulating glass unit manufacturer) of adverse results of this test and to allow the client to withdraw the test samples and re-submit new ones, rather than proceed and, most likely, have the units fail. The “initial seal” test is not included in the ASTM E 2188 or in the EN-1279-2 test programs.

determine if it would be more appropriate to field test for dew point temperature during warmer weather or colder weather.

From December through March,[61] the daily average outdoor air temperature varies between –0.4°C and –6.3°C with daily maximums to a high of 4.1°C and daily minimums to a low of –10.5°C. Extreme maximum temperatures range from a high of 25.6°C to a low of –31.3°C. Thus the freezer chamber temperature of -12°C was slightly colder than the average minimum temperature, but still within the range of temperatures that could be expected in Toronto.

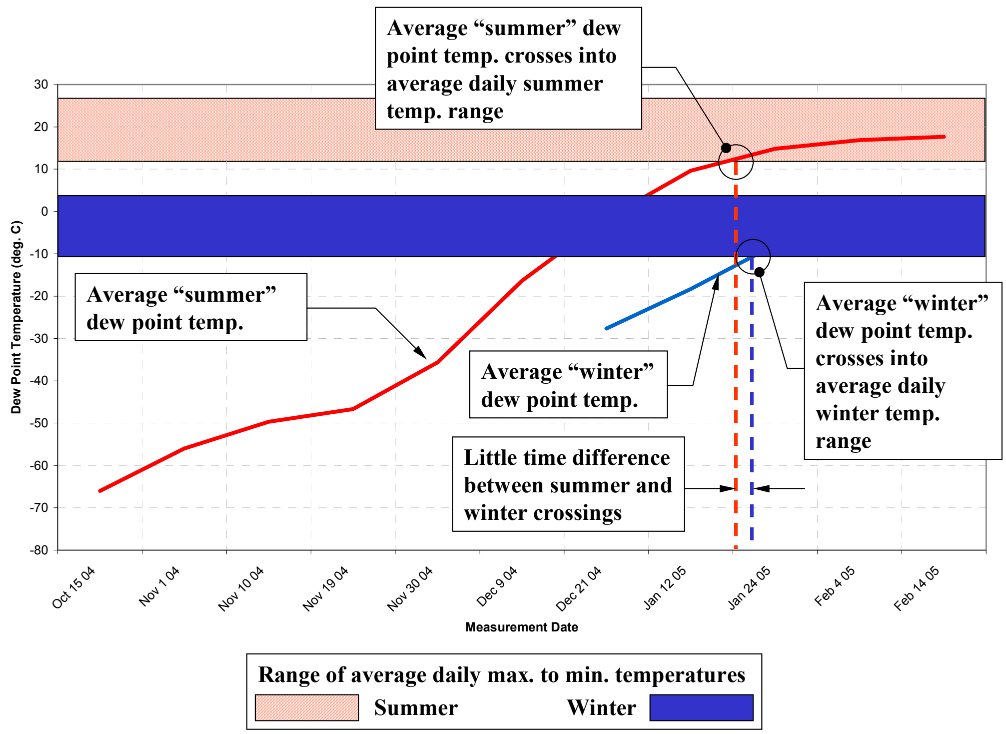

Figure 42: Composite plot of average "summer" (lab condition) and "winter" (simulated outdoor exposure) dew point temperatures and average daily maximum to minimum temperature ranges for Toronto, Ontario. Note that the average "summer" and "winter" dew point temperatures cross into the corresponding outdoor temperatures at about the same time.

Coincidentally, the standard laboratory air temperature of about 22°C (22 ± 3°C is required by CGSB-12.8 and EN-1279-02, 23ºC ±3ºC by ASTM E 2188) is similar to outdoor temperatures experienced in the Toronto area in the summer. From June through August,[62] the daily average outdoor air temperature varies between 17.8°C and 20.8°C with daily average maximums to a high of 26.8°C and daily minimums to a low of 11.9°C. Extreme maximum temperatures range from a high of 38.3°C to a low of 0.6°C.

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[61] The months of December through March were somewhat arbitrarily chosen to represent winter, when the daily average outdoor temperature is below 0°C. In the Toronto area, fall conditions may persist through the month of December with little snow cover; January and February are usually cold and snowy, and March can be wintry with cold temperatures and snow cover or more spring-like.

[62] June through September were arbitrarily chosen to represent winter conditions, based on the author's life-long experience in the Toronto area. For these months, the daily average outdoor temperature is also above about 18°C.

These daily maximum, daily minimum and extreme minimum temperatures can be plotted together with the average dew point temperatures measured in the test program (Figure 42). This composite plot reveals that the first incidence of fogging is likely to be in the summer, rather than in the winter when glass surface temperatures are lower, although the difference in time may be small. This is consistent with anecdotal reports and field observations by the authors, of units that are fogged in the summer but return to a fog-free condition with the return of cold weather. This suggests that the better time to carry out dew point measurements upon which to estimate remaining life span is in the summer, rather than in winter.

The composite plot shows only the average of measured dew point temperatures at summer (laboratory) and winter (simulated outdoor) temperatures. At each measurement period, there was a variation in dew point temperatures amongst the test units. This variation can be shown by adding "high – low bars" to each average, representing dew point temperatures within one (1) standard deviation or about ±34% (total ±68%) from the average (Figure 43).[63]

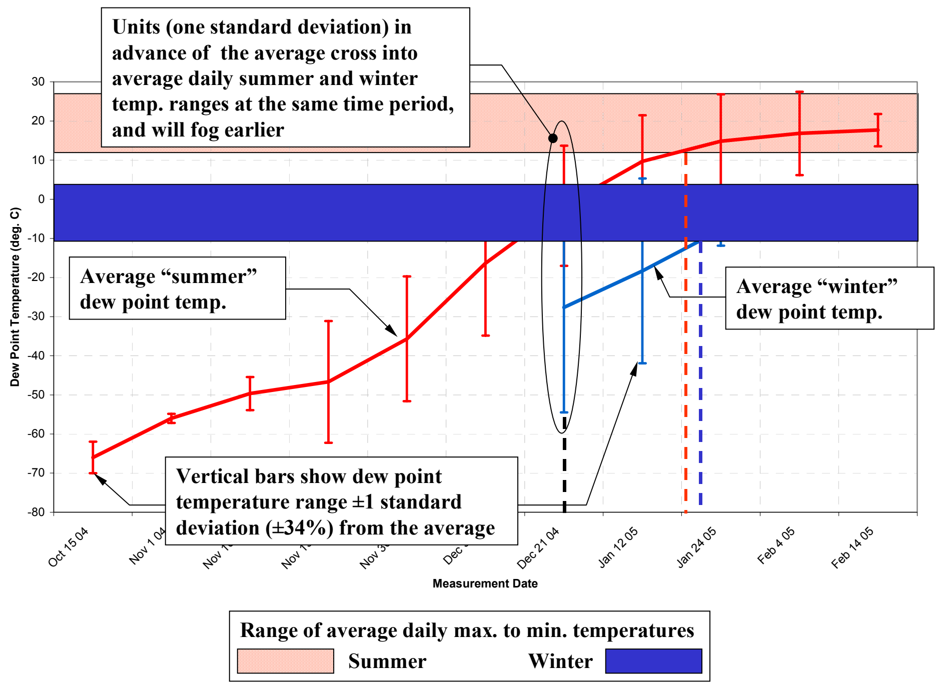

Figure 43: Composite plot of average "summer" and "winter" dew point temperatures and average daily maximum to minimum temperature ranges for Toronto, Ontario. High-low lines at each measurement period are one (1) standard deviation to above (ahead of) and below (behind) the average dew point temperature.

The variation in dew point temperature reveals that some units can be expected to fog several measurement periods prior to the average, and that as for the average, fogging may occur at about the same time in the summer or winter.

An alternative method of presenting the above data is to calculate "normal" distribution curves for the data. This returns us to the diagrams presented in the discussion regarding the modified

[63] Statistical calculations assume that the test units are a sample of a much larger "normal" population, and that by applying the Central Limit Theorem, the dew point measurements of the test units are themselves "normal". Calculations were performed with formulae included in Microsoft Excel.

field measurement method (Figures 20 to 24). When the normal distribution curves of dew point temperatures at "summer" (laboratory) conditions are plotted together (Figure 44) a progression of increase in dew point temperature is revealed (the shape of the curves changes over time, becoming narrower (decreasing standard deviation) and more peaked (increasing kurtosis) as the dew point temperature of more of the units approach the "summer" (laboratory) conditions, the rate of dew point temperature change decreases, and therefore the variation of dew point temperatures about the average decreases). The cumulative distribution curves graph can then be combined with a psychrometric chart on which the summer outdoor temperature range is plotted, to show the relationship between dew point temperature increase and environment (Figure 45). The portions of the curves extending beyond the average daily minimum temperature (or the cavity side temperature of the outboard pane of glass, if significantly different) gives an indication of the number of units likely to be in a fogged condition.

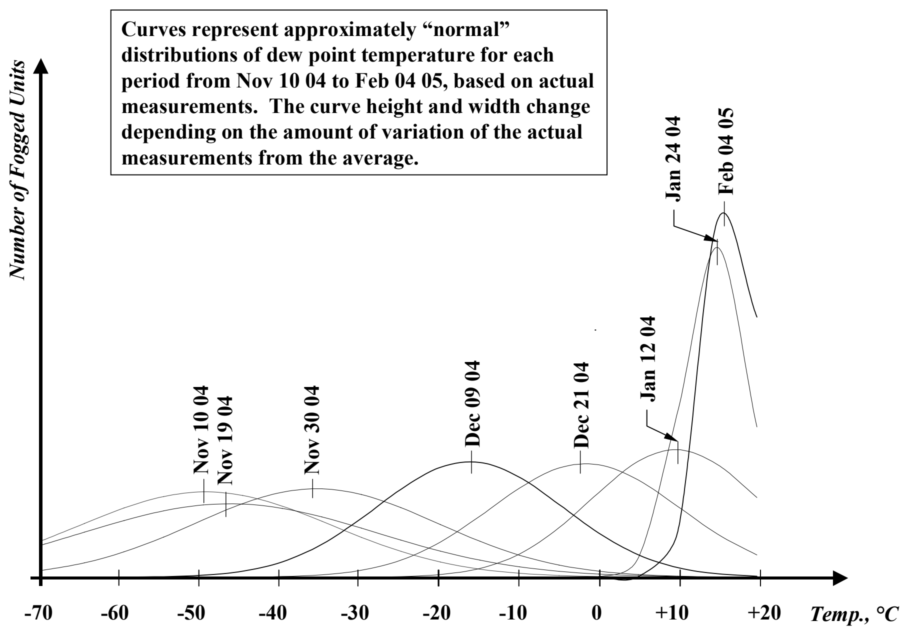

Figure 44: Composite plot of "normal" distributions of dew point temperatures, based on actual measurements. This graph shows the distributions only. The curves tend to become more narrow and more peaked with time, as the units approach laboratory (summer outdoor for Toronto) conditions.

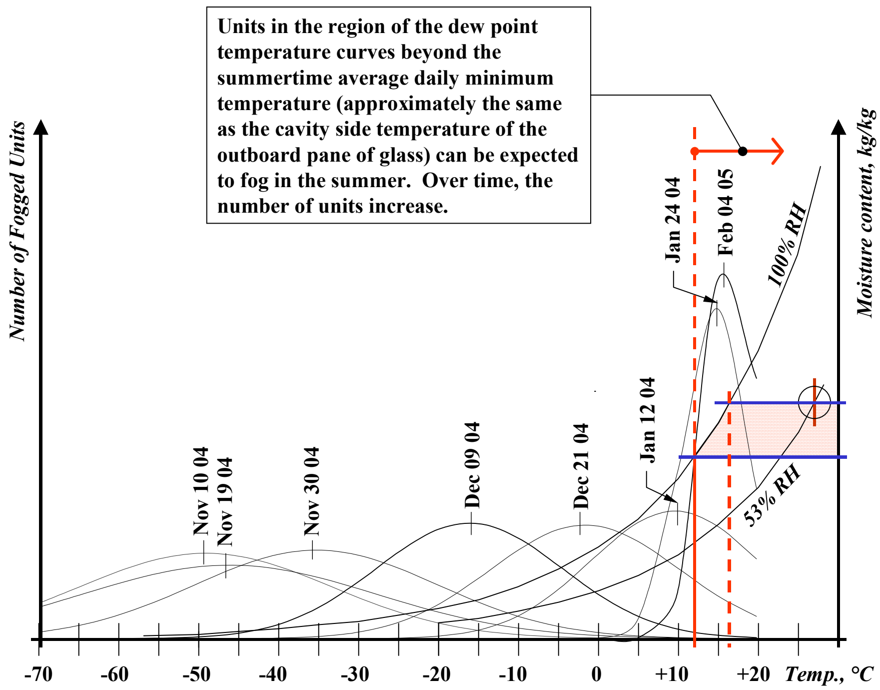

Figure 45: Composite plot of "normal" distributions of dew point temperatures together with a psychrometric chart on which the summer average daily temperature range is plotted. The portions of the curves extending beyond the average daily minimum temperature indicate the number of units that are likely to have become fogged.

OTHER POTENTIAL DESICCANT TEMPERATURE EFFECTS

Temporary Fogging

Dew point temperature measurements were made when the insulating glass units, in particular the desiccant, had reached steady-state conditions in the laboratory and in the outdoor exposure frame, and the desiccant had reached equilibrium conditions with the cavity gas fill. For the insulating glass unit construction that was tested, this occurred very quickly. However, temporary fogging appears on occasion when the outdoor temperature decreases rapidly. Some time is required for desiccants to remove water vapour from the cavity of an insulating glass unit; it does not occur instantly.

Temporary fogging of insulating glass units is of concern to insulating glass unit manufacturers because of the potential for fogging in newly manufactured insulating glass units removed from the factory and installed in buildings within a short period of time. The "dry down" rate of insulating glass units has been studied by others [28] although under isothermal, room (laboratory) temperature conditions (ie. the units were not exposed to an indoor - outdoor temperature differential). The dry-down rate is affected by the type of desiccant material, quantity of desiccant material, overall size of the insulating glass unit, and for "conventional" insulating glass units incorporating a hollow "air spacer" (such as the test units), the size, number and spacing of openings in the spacer which separate the desiccant hidden in the spacer from the insulating glass unit cavity. Generally, the dry-down rate is slower with silica gel desiccant only (compared to a 3A molecular sieve), with less desiccant, and with smaller and fewer openings in the spacer. For insulating glass units in which the desiccant is incorporated within the spacer material or in a carrier medium such as a desiccated matrix, the encapsulating medium may also retard dry-down [29].

The causes of temporary fogging are also of concern when carrying out field dew point measurements. Care should be taken to limit the potential for rapid and significant temperature change on the test day. A protocol similar to that used for thermographic evaluation of building envelopes should be considered, such as ASTM C 1060[64], it restricts testing to days with limited ambient air temperature change and limited solar gain. The test conditions should be about the same for each measurement session. In addition, given the wide variance of insulating glass unit constructions, consideration should be given to a repeated testing of a designated "base line" unit during the test day to track any change in dew point temperature during the test time which could, conceivably, extend several hours. Any noticeable change in dew point temperature of the "base line" unit could be used to make adjustments to the measured dew point temperature of other units tested the same day.

Centre of Glass Fogging

When fogging occurs under "real life" conditions (that is, it is not locally induced with specialized equipment), it is common for fog to appear in the centre-of-glass area before it appears in the edge-of-glass area. Elmahdy [30] reports results of computer modelling of insulating glass unit thermal performance which reveals that for the outboard pane of glass, under simulated outdoor exposure conditions, the exterior surface temperature is as much as 5°C colder in the centre-of-glass area than in the edge-of-glass area. The cause of this is thermal bridging through the spacer that directly connects the cold outside pane of glass to the warmer inside pane of glass. This is the reverse of the much better known effect of cooling of the edge-of-glass area of the inboard pane, relative to the edge-of-glass area, which gives rise to local room-side surface condensation (which can contribute to premature fogging of units, as previously discussed). These variations in glass surface temperature were also detected in the temperatures recorded by data-logger during this test program (Figure 40) although to a lesser extent.

As a result of the temperature variation from the edge-of-glass area to the centre-of-glass area, it is possible for the desiccant to be warmer than much of the glass area. When the desiccant is warmer, there is more water vapour in the cavity gas fill; if the centre-of-glass area is sufficiently chilled, condensation may occur in the centre-of-glass area. This suggests that a time to fogging assessment based on warm weather dew point measurements should be tempered with a caution that fogging may occur somewhat earlier, depending on weather conditions and exposure (for instance, windows with high solar exposure: the centre-of-glass area may cool down faster than the more massive framing into which the perimeter of the unit, containing the desiccant, is set). Field dew point measurement may not automatically take this into account, particularly if dew point measurements are made on days with minimal temperature change and with lower solar gain. This needs further examination.

[64] ASTM C 1060, *Standard Practice for Thermographic Inspection of Insulation Installations in Envelope Cavities of Frame Buildings,* ASTM International, West Conshohocken, Pennsylvania, 2002.

Prediction of Time to Fogging

General Description of Method

Attempts were made during the test program to mathematically predict time to fogging of the test units. This was unsuccessful. It was decided to withhold development of a new model until the exposure program was terminated, then use the data obtained to develop a model. Several prediction models were attempted using the commonly available spreadsheet program Microsoft Excel. The most accurate is described in this section.

The prediction model uses the "Forecast" function in Excel to work with existing data to predict future data. Principally, this function uses the average and standard deviation of the data at as many measurement periods as are provided. An estimate of likely future data is calculated by linear regression. The general form of equation used is:

$$\mathbf{y = a + ßx + e}$$

Where **y** = dependent variable, calculated on **x** (dew point temperature)

a = variable affecting the value of **y**

ß = variable affecting the value of **y**, based on **x**

x = independent variable (measurement date)

e = variation in **y**, preferably as close to zero as possible

This equation is solved for **y** by repeated iterations, to arrive at a minimum value for **e** (ie. a minimum variation with an average of zero). The coefficients **a** and **ß** are determined by the condition that the sum of their squares is as small as possible.

The laboratory ("summer") weather condition dew point temperatures were used because there were more sets of these temperatures, and because the analysis showed that the time to fogging was about the same when dew point temperatures were measured at "summer" (laboratory) and "winter" (simulated outdoor) temperature conditions.

Prediction of time to fogging can be considered in three steps:

Step 1: No Prediction Possible

The apparatus used for field measurement of dew point temperature of the insulating glass unit cavity gas fill uses solidified carbon dioxide ("dry ice") to cool the cavity-side surface of one of the glass panes until condensation occurs. Dry ice sublimates at about –79°C. However, because of heat gain through the test equipment and from the test unit, a general practical lower limit of field measured dew point temperature is likely to be somewhat warmer (in the laboratory, using dry ice as a cooling source, the practical lower limit is about –73°C). As long as the dew point temperature of the cavity gas fill is lower than this temperature, it cannot be measured and therefore, no prediction of time to fogging can be made.

The time at which the dew point temperature of the cavity gas fill will become measurable, and thus time to fogging estimate can begin, is unknown. This will vary from one building to the next, for the various reasons discussed earlier in this report. Periodic trials should be carried out to detect when dew points are measurable. As previously discussed, one should not rely on a first instance of temporary fogging as an indication of when to begin a monitoring program because the subsequent time to fogging may be too short to accumulate funds for replacement at a reasonable rate. Monitoring for the first instance of measurable dew point temperatures could be done with a smaller number of units to limit costs. Once measurable dew point temperatures are detected, the size of the monitoring sample can be increased to provide more data for accurate prediction of time to fogging.

Thus, insulating glass units must already be aged prior to a monitoring program being established. Based on experience to date with field measurement of dew point temperatures, this could be many years. For example, in the case study of the municipal building, after about 24 years of service, some units in the sample did not have measurable dew point temperatures, although most did (and some had already fogged). The lower limit of dew point temperature measurement, about –73°C, is very low compared to normal outdoor temperatures in the larger urban area of Canada.[65] It is assumed that the time remaining between when dew point temperatures first become measurable and the "normal" range of summertime outdoor ambient air temperatures is sufficient to provide ample lead time to plan and accumulate funds for replacement or repair. The laboratory test programs for durability assessment (CGSB-12.8, ASTM E 2188, and EN-1279-2) provide an indication that there would be sufficient lead time, since the pass / fail criteria is a maximum *measurable* dew point temperature of only -40ºC, and experience has proven that for the most part, insulating glass units of the types successfully tested to the laboratory programs are capable of achieving very long life spans. Indeed, it is the general long length of life span that gives rise to the need for a time to fogging prediction method.

Nevertheless, in some cases, such as condominium corporations, it may be necessary to budget for the cost of replacement or repair in the time between installation of units (nominally from the time of occupancy of a new building) to when dew point temperatures become measurable. The only way to do this is to assume a nominal life span and begin accumulating funds accordingly; as dew point temperatures become measurable, the timing could be adjusted by the method suggested in this report. The difficulty in this approach is selecting a reasonable nominal life span for the initial period. One must rely on experience, tempered with a critical examination of a sample of insulating glass units, window frames, and other service conditions to identify conditions that may adversely affect life span (as discussed earlier in this report). This approach is not recommended, but as noted, may be necessary in some cases.

STEP 2: PREDICTION OF THE AVERAGE DEW POINT TEMPERATURE

Once dew point temperatures are measurable, it is possible to begin time to fogging predictions.

It is proposed that prediction of time to fogging should only be calculated when the majority of the units in the sample set have measurable dew point temperatures. It is reasonable to expect that a more accurate prediction would be made with more data (dew point measurements) at each measurement period. Further work is required to determine how large of a "majority" is required (ie. 51%, 66%, etc.). For our analysis we proceeded with time-to-fogging prediction only when dew point temperatures could be measured for all breached test units, after the November 10, 2004 measurements, after about five (5) months of exposure.[66]

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65 As discussed in the introduction, the intent of this research is to develop a tool for owners of buildings with large areas of the building envelope comprised of insulating glass units. Part of the reason for this is that there is a cost associated with performance monitoring and forecasting over time, thus the cost for testing becomes much smaller when compared with the total cost of replacement. This is not to say that this prediction method could not be used by the owners of smaller buildings, or perhaps individual, unique buildings with particular unit constructions or constraints on replacement that make replacement cost very large compared to the cost of performance monitoring and forecasting.

66 Unit 10, the intentionally unbreached "control" unit that rapidly increased in dew point temperature at the end, was ignored.

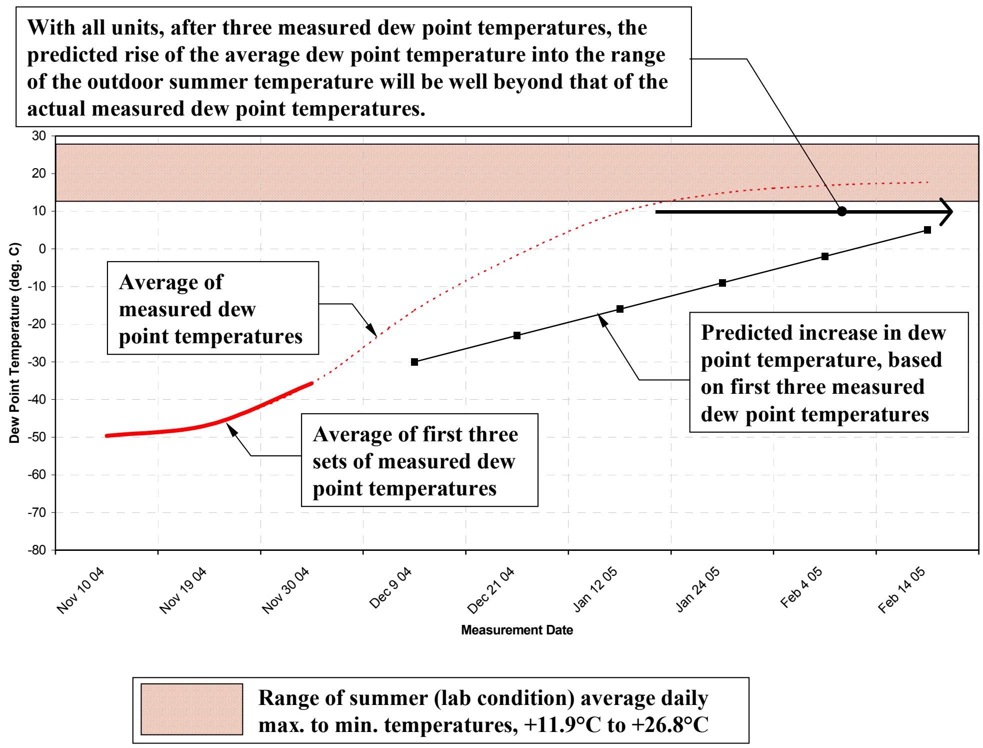
The average measured dew point temperatures increased into the range of "normal" summertime outdoor air temperatures for Toronto toward the end of the January 12, 2005 measurement period. Three (3) hypothesis were made to predict the coincidence of average dew point temperature and "normal" summertime outdoor air temperatures, based on the first three (3), four (4) and five (5) measured sets of dew point temperatures following November 10, 2004 (Figures 39, 40 and 41). The method was as follows:

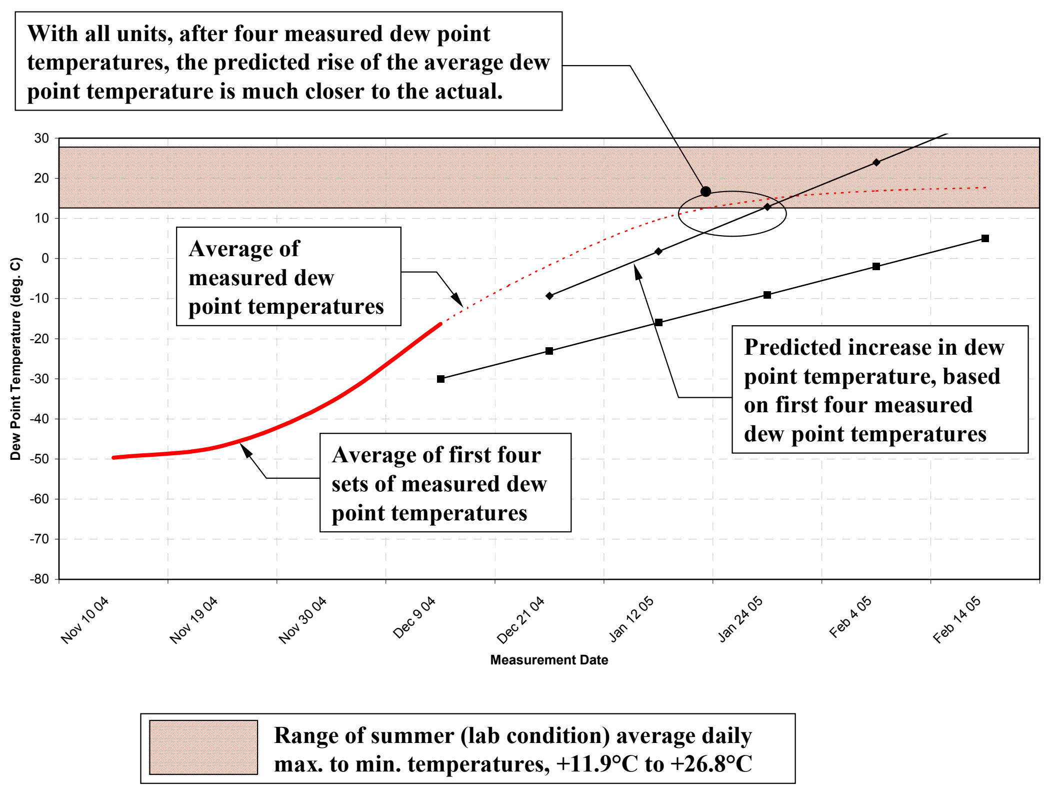
- Actual average: at each measurement period the average was calculated using the embedded "AVERAGE" function in MS Excel. The average values were graphed as an XY line graph. Calculation data and results are shown in Appendix F.
- Predicted average: using average dew point measurements for the first three (3), four (4) and five (5) periods, predictions of the average of future dew point temperatures were made using the embedded "FORECAST" function in MS Excel. The results were added to the graph as three separate lines. Data and results of calculations are shown in Appendix F.

The accuracy of these predictions increased as more dew point temperature sets were added, as follows:

- First prediction: the predicted dew point temperatures did not increase into the range of "normal" summertime outdoor temperatures within the time period of the test program (Figure 46).
- Second prediction: the predicted dew point temperatures increased into the range of "normal" summertime temperatures in the January 24, 2005 measurement period, one (1) period lather than the actual (Figure 47).
- Third prediction: the predicted dew point temperatures increased into the range of "normal" summertime temperatures in the January 12, 2005 measurement period, coinciding exactly with the actual (Figure 48).

The results of the first prediction are not good, but the results of the second and third predictions are in very good agreement with the actual test data. This indicates that with an increased number of measurements, accuracy is increased. However, none of the predictions show the decrease in the rate of dew point temperature increase that occurs within the range of "normal" summertime outdoor temperatures. This could be predicted if more measured dew point temperatures were used, but by then there would be little advance warning of impending fogging and replacement, so there would be little benefit to further measurement other than precision.





Figures 46 and 47: **Composite plot of average measured dew point temperature for all six (6) breached units, "normal" summertime outdoor air temperatures for Toronto, Ontario, and the first and second predictions of dew point temperature increase, based on the first three (3) average measured dew point temperatures.**

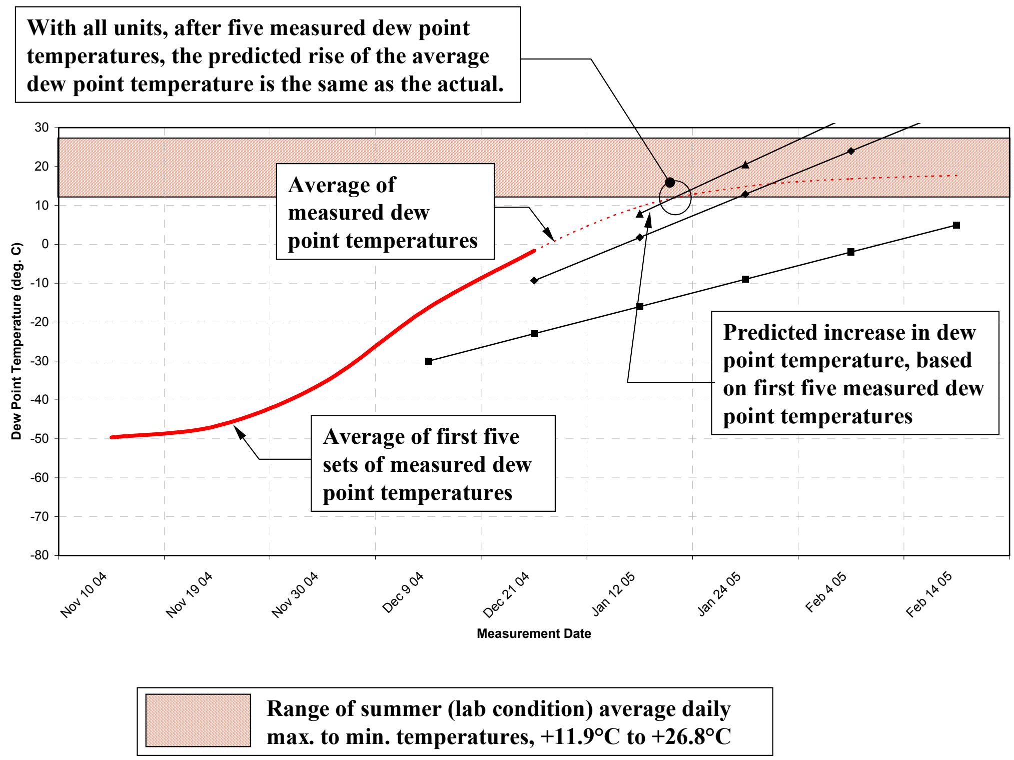


Figure 48: Composite plot of average measured dew point temperature for all six (6) breached units, "normal" summertime outdoor air temperatures for Toronto, Ontario, and the first, second and third predictions of dew point temperature increase, based on the first three (3), four (4) and five (5) average measured dew point temperatures.

The prediction of time to fogging was repeated after units 1 and 6 were removed. The intent of this analysis was to determine if removal of these units would increase or decrease the accuracy of prediction. Since these units were fitted with argon gas syringe sampling needles to reduce gas exchange, blockage of the needles occurred, and damage to unit 6 resulted in an additional breach of the seal, dew point temperatures did not increase in the same general pattern as for the other four (4) units. The time to fogging for these two units might be different, and might skew the predictions for the remaining units, possibly accounting for the noted inaccuracies. In a "real life" monitoring situation, these two units could represent a sub-population, such as was found in the municipal building case study previously discussed, where differences in performance of insulating glass units in the north and south elevations (and therefore, likely different times to fogging) were discovered.

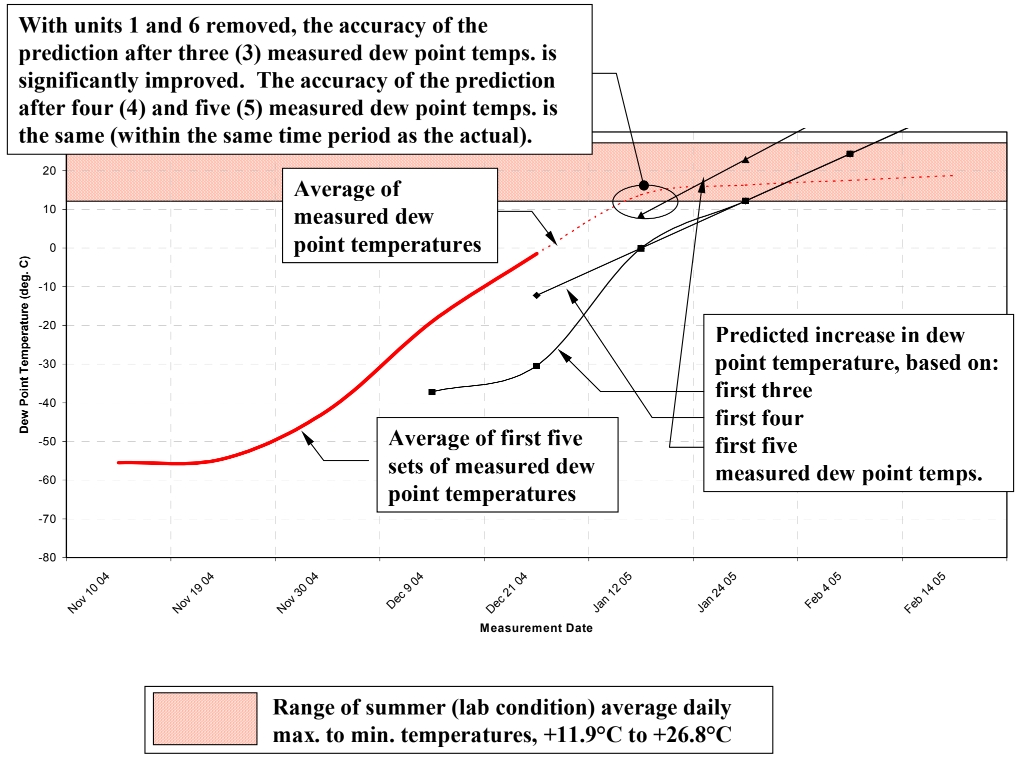


Figure 49: Composite plot of average measured dew point temperature for the four (4) breached units without argon gas syringe sampling needles in the breach opening, "normal" summertime outdoor air temperatures for Toronto, Ontario, and the first, second and third predictions of dew point temperature increase, based on the first three (3), four (4) and five (5) average measured dew point temperatures. Note that although the first prediction is more accurate than when all six (6) units were used, the second and third predictions are about the same, within the same measurement periods.

When units 1 and 6 were removed from the prediction model, the initial prediction (based on three (3) average measured dew points) is much more accurate, showing an increase into the range of "normal" summertime outdoor air temperatures one (1) time period later than the actual, the same as the second prediction with all six (6) units, and with units 1 and 6 removed. The prediction curve is also not linear, with the initial two (2) predicted dew point temperatures being very low before increasing sharply. The second and third predictions are about the same, in both cases being within the same future time measurement periods (Figure 49). This indicates that units 1 and 6 have a distinct influence on at least the first prediction model, but there is an additional influence on that model.

A review of the actual dew point temperature record (Figure 50, similar to Figure 36 but with dew point temperatures from November 10, 2004 onwards only) reveals that the improvement in the accuracy in the first prediction without units 1 and 6 is likely because the trend of the first three (3) measured dew point temperatures for unit 6 was decreasing, and for unit 5 the rate of increase of measured dew point temperatures was slower than for other units. Together, these conditions could be expected to exert a damping effect on predicted dew point temperature increase.

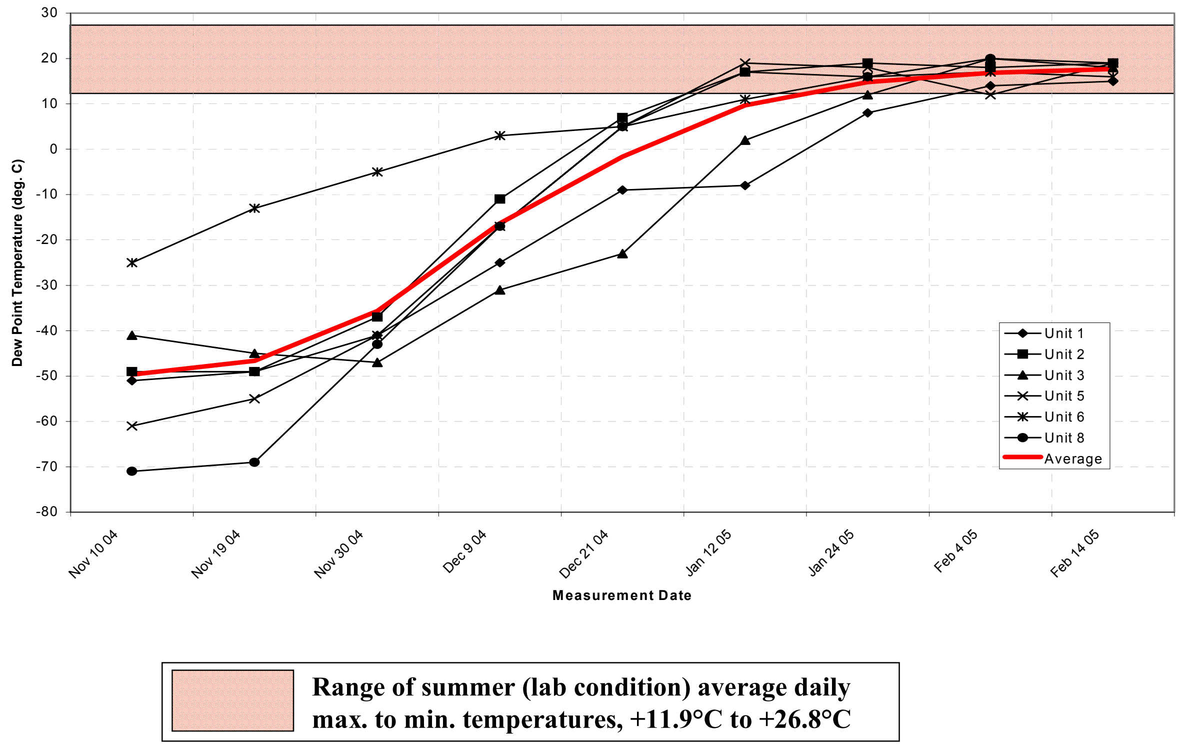


Figure 50: Measured dew point temperatures for all six (6) breached units, from November 10, 2004 to the end of the test program, with the "normal" summertime outdoor ambient air temperature range for Toronto, Ontario superimposed. The red line is the average of measurements. Comparison with Figures 41 and 42 show how variations in temperature trends for different units affect predictions of future point temperatures.

In addition, the first three (3) measured dew point temperatures for unit 3 were decreasing. This would exert a further damping effect on the first prediction model. For the second and third prediction models, dew point temperatures for unit 3 increased sharply which would have corrected the damping effect, allowing the prediction model to rise as shown in Figure 42. To confirm this, units 1 and 6 were reinstated and unit 3 was removed from the prediction model (Figure 51). As expected, the first prediction model becomes more accurate, increasing into the range of "normal" summertime outdoor air temperatures two (2) time periods later than the actual. The second prediction also becomes more accurate, increasing into the range of "normal" summertime outdoor air temperatures in the same time period as the actual. Generally, the temperatures for all three predictions noticeably increased.

Does this suggest that units 1 and 6 and different than the others, and should be excluded? Or unit 3, for that matter? In hindsight, with all of the actual, measured dew point temperature data in hand (i.e. at February 14, 2005), it would appear not. However, at the time of prediction, when the time of coincidence of the actual average temperature with the range of "normal" summertime outdoor air temperature unknown, it is more difficult to determine. The general trend of changes in the coincidence of the first prediction with the range of "normal" summertime outdoor air temperatures with the exclusions tried suggest that units 1, 3, and 6 are having an effect and probably should be considered suspect. It seems reasonable to exclude unit 3 since its dew point temperatures are decreasing and therefore, its time to fogging should be somewhat longer than the other units for which dew point temperatures are increasing. Unit 3 might in fact represent a different population of units, or it could simply be an oddball that would lie to the extreme of a frequency distribution of dew point temperatures.

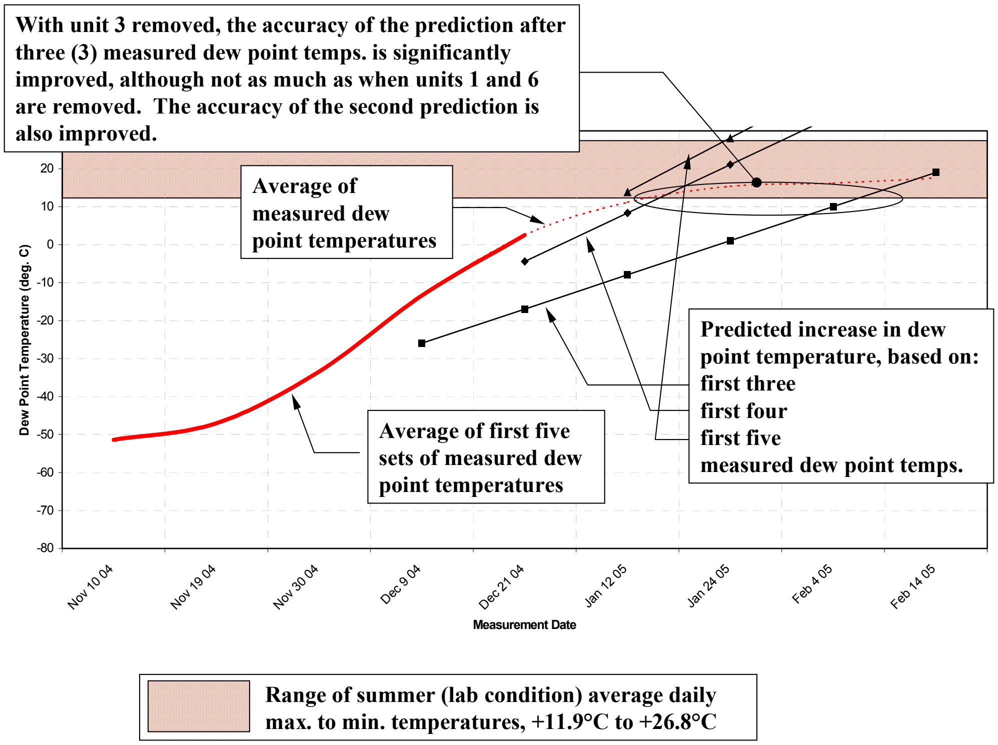


Figure 51: Composite plot of average measured dew point temperature for all units except unit 3, "normal" summertime outdoor air temperatures for Toronto, Ontario, and the first, second and third predictions of dew point temperature increase, based on the first three (3), four (4) and five (5) average measured dew point temperatures. Note that the first prediction is more accurate than when all six (6) units were used, but not as accurate as when units 1 and 6 were excluded, and the second prediction is more accurate (by one time period) than when all units are used and when units 1 and 6 are excluded.

From this analysis the following conclusions can be drawn:

- At least three (3) sets of measured dew point temperatures are needed to make a prediction of time to fogging.
- The accuracy of prediction (in hindsight) will change, and become more accurate, as more sets of dew point temperatures become available.
- The accuracy of prediction can be increased by careful review of trends of dew point temperature increase, comparing trends for individual units to the overall, and making repeated predictions without suspect units.

Trial-and-error removal of units from a sample to improve accuracy of predictions can be beneficial, but it should be carried out with care. In the case shown, it would appear that unit 3 could be set aside. However, with more measured data, the performance of unit 3 became similar to the general trend and so could be included. Thus this unit did not represent a different sub-population of units, but merely was an extreme variant (for a while) with a significant impact, due to the small size of the sample.

In a building that may have a variety of exposure conditions, the presence of sub-populations of units with different times to fogging can be expected to occur. This was demonstrated by the case study of the municipal building. Rather than trying to sub-divide a sample to identify such populations (as in the analysis of the test data), a critical review of exposure conditions should be carried out at the beginning of the project to identify potential sub-populations, and samples should be established accordingly.

Sample sets that are separated to identify sub-populations of units have less diversity. As previously discussed, for a given population of units, it is reasonable to expect that there will be a range of dew point temperatures at each measurement period; thus there will be some units with dew point temperatures warmer than the average that can be expected to fog earlier than the average. Since smaller sub-samples have less diversity, the ability to detect units with dew point temperatures warmer than the average may be reduced. Such detection could be advantageous in planning and accumulating funds for future repairs or replacement, as will be discussed in the following section.

Stage 3: Broadening the Prediction

Assuming that the sample is "normal",[67] the variation in dew point temperatures about the average can be measured by the standard deviation. The same method used to predict future average dew point temperatures (the "Forecast" function in MS Excel) can also be used to predict future standard deviation of dew point temperatures from the average, and thus the future variation of dew point temperatures. This would allow prediction of when units with dew point temperatures in advance of (warmer than) the average may fog.

Following from the discussion in the last section, unit 3 was removed from the data set. For the remaining units, the actual and future predicted average and standard deviations were then plotted as follows:

- Actual average: at each measurement period the average was calculated using the embedded "AVERAGE" function in MS Excel. The average values were plotted as an XY line graph. Calculation data and results are shown in Appendix F.
- Actual standard deviation: at each measurement period the standard deviation of measurements about the average was calculated using the embedded "STDEV" function in MS Excel. The standard deviations were used to define the extent of Y-error bars for each average value, which adds high-low bars to each point on the graph. For each average dew point temperature, this shows the range of one (1) standard deviation above (warmer) and below (colder) than the average (Figure 45). Data and results of calculations are shown in Appendix F.
- Predicted average: using average dew point measurements for the first three (3), four (4) and five (5) periods, predictions of the average of future dew point temperatures were made using the embedded "FORECAST" function in MS Excel. The results were added to the graph as three separate lines. Data and results of calculations are shown in Appendix F.
- Predicted standard deviation: using the standard deviation average of dew point measurements for the first three (3), four (4) and five (5) periods, predictions of the standard

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[67] In the absence of any data indicating otherwise, it is assumed that the distribution of a sample of a population of units would be "normal", that is, that the average (mean), median and mode coincide, the distribution of data is symmetrical about this coincident value, and the distribution is such that one (1) standard deviation to either side of the mean are contain 64.27% of the data, two (2) standard deviations contain 95.45% of the data, and three (3) standard deviations contain 99.73% of the data. A "normal" distribution is illustrated in Figure 45.

deviation about the average of future dew point temperatures were made using the embedded "FORECAST" function in MS Excel. The standard deviations were then used to define the extent of Y-error bars for each predicted average value, which adds high-low bars to each point on the graph. Data and results of calculations are shown in Appendix F.

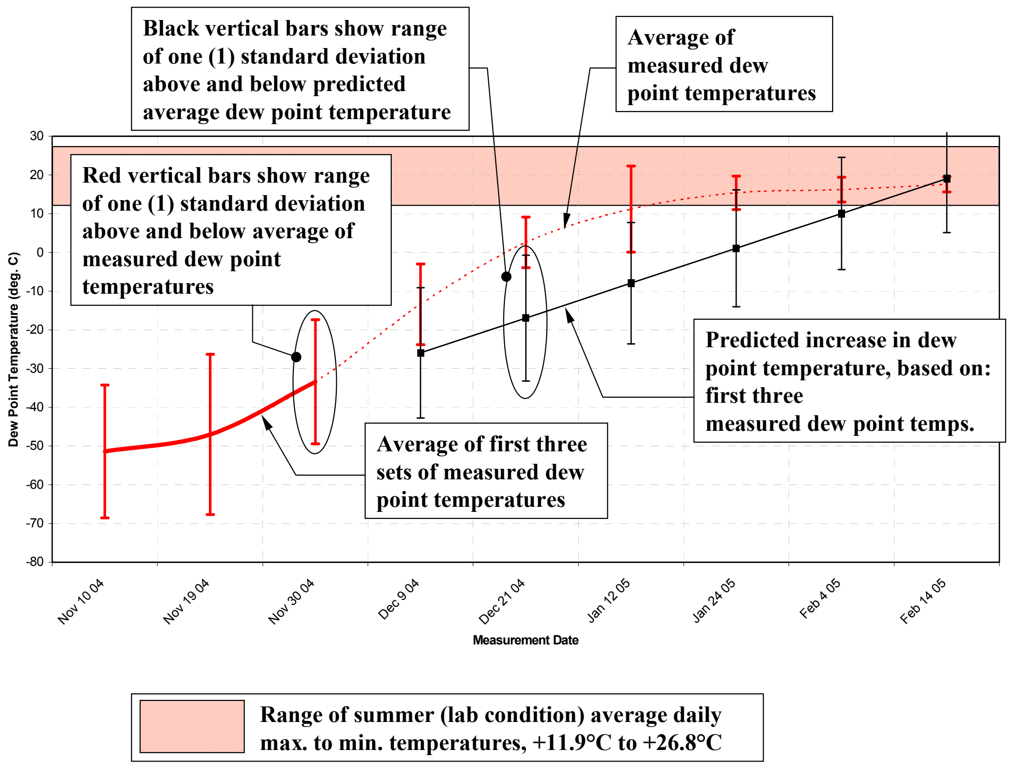
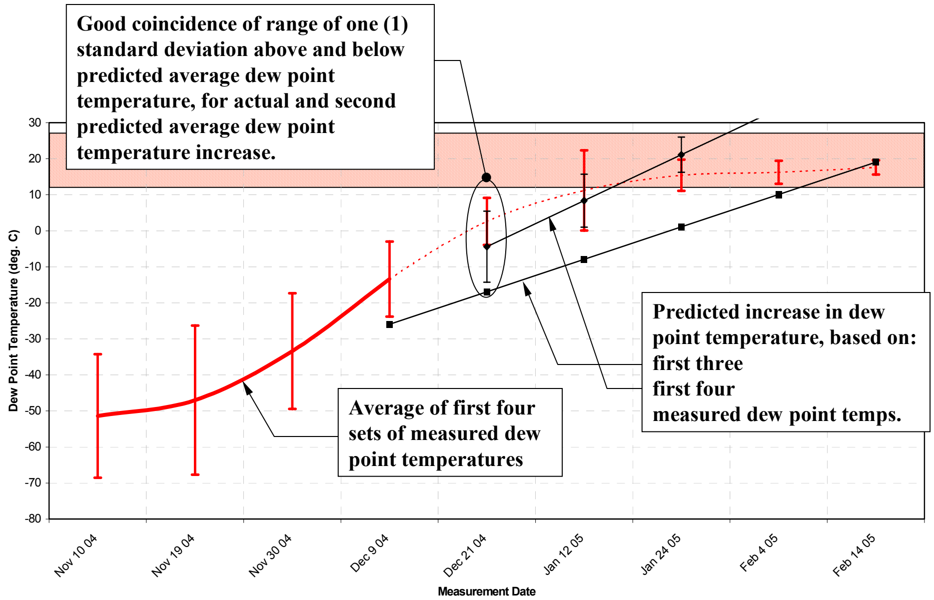
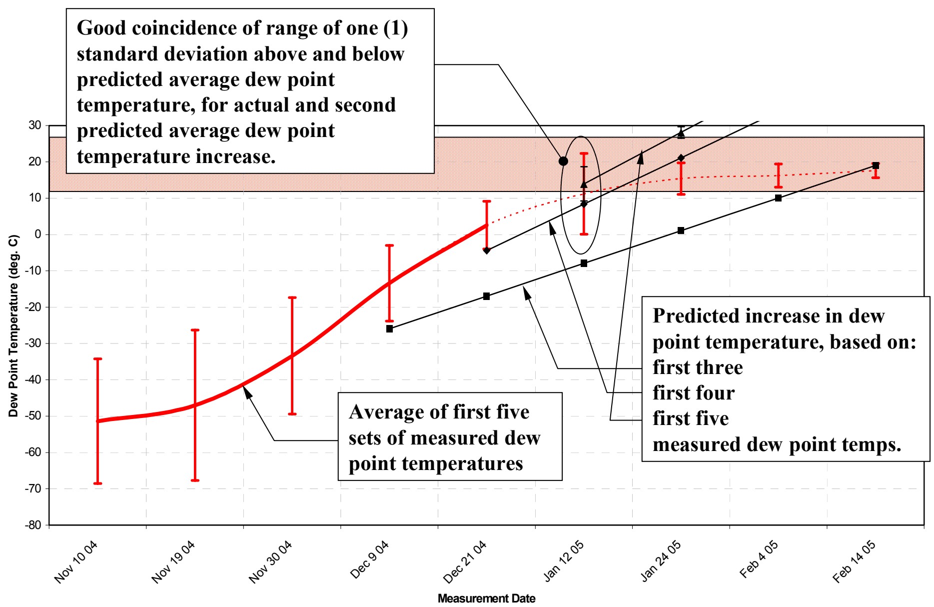
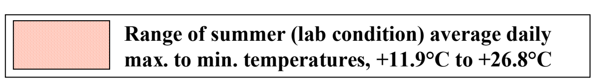


Figure 52: Composite plot of average measured dew point temperature for five (5) of the six (6) breached units (unit 3 is omitted), "normal" summertime outdoor air temperatures for Toronto, Ontario, and the first prediction based on the first three (3) average measured dew point temperatures. Vertical bars were added to show predicted range of one (1) standard deviation of dew point temperature above (warmer) and below (colder) than the average.

The composite plots show a poor match of one (1) standard deviation about the average, for actual measured dew point temperatures and the first prediction (Figure 52). However, the match improves for the second and third prediction: units with dew point temperatures one (1) standard deviation in advance of the average would increase into the range of "normal" summertime outdoor air temperature about one (1) measurement period in advance of the average (Figures 53 and 56).







Figures 53 and 54: Composite plot of average measured dew point temperature and the second and third predictions based on the first four (4) and five (5) average measured dew point temperatures. Vertical bars were added to show predicted range of one (1) standard deviation of dew point temperature above (warmer) and below (colder) than the average.

A standard "normal" distribution, the distribution of data is symmetrical about the peak of the curve (Figure 55), with 50% of the data lying to each side. The average, mode, and median values are the same. One (1) standard deviation in advance of the average includes about 34% of the units. Thus if one (1) standard deviation in advance of the average is tracked, about 84% of the units should be included in the prediction model.

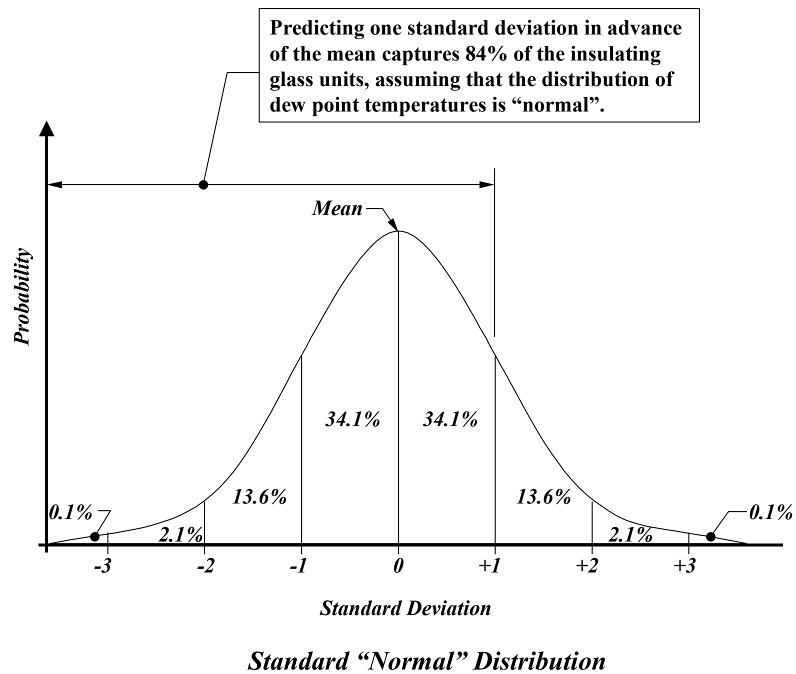


Figure 55: Standard "normal" distribution subdivided into standard deviations. Note that the areas beneath the curve within the standard deviations are not equal. Predicting when one (1) standard deviation in advance of the average dew point temperature coincides with the "normal" summertime outdoor air temperature range captures dew point temperatures of 84% of the units of the sample set.

It is possible to predict more than one (1) standard deviation in advance of the average. Whether or not this is necessary depends on the financial sensitivity of the building owner or sometimes, on legislated requirements. For example, in the case of reserve fund plans for condominium corporations in Ontario, all foreseeable capital reserve and replacement items greater than $500 must be included in the plan which would likely require predicting at least three standard deviations in advance of the mean. This is a severe requirement because the cost of replacement of a single insulating glass unit is about this amount. Other, more reasonable, limits may be desirable by a building owner and should be established at the beginning of the monitoring program so that an appropriate point in advance of the mean can be predicted and tracked over time.[68] Note that lower limits (for instance, one (1) standard deviation in advance of the average, as shown) would require the owner to be able to fund some replacements or repairs from

[68] Author's experience. Insulating glass unit manufacturers often have a minimum size charge, below which all units cost the same, irrespective of size. Replacement contractors also have fixed costs, irrespective of size (pick-up of units from the manufacturer, mobilization to site, etc.).

operating funds. Knowing the number of units and their value that is being tracked and considered in the reserve fund plan, predictions of the value of the remainder could be made and sufficient funds kept on hand.

Just as dew point temperatures in advance of the mean can be predicted, so too can dew point temperatures behind the mean. Depending on the number of units, the projected cost, and the time span, of repair or replacement, it may be possible to spread the accumulation of funds over a range of time periods. The effect of this can be assessed by repeated iterations of the reserve fund plan. The graphical "Condition Index" technique developed by Gerald R. Genge Building Consultants Inc. would be particularly useful in this regard [2].

Laboratory vs. "Real" Time

Generally, for the test units, the predictions give advance notice of time to fogging of two (2) to four (4) time periods. This does not seem like very much advance notice of impending "failure", but the following must be considered:

- A correlation between the exposure to elevated temperature and relative humidity, and the length of exposure, to "real time" is unknown.
- The time to fogging for the breached test units was much shorter than for the un-breached units, which did not fog except for unit 10 in which a breach developed unassisted. Thus the rate of water vapour gain across the perimeter seal of the breached units was much faster than for the un-breached units, in turn, because of the exposure to elevated temperature and humidity, the rate of water vapour gain of the un-breached units would be greater than in "real time".
- Predictions were begun only when all units had measurable dew point temperatures. Two (2) units (1 and 6) had measurable values earlier; thus there is a potential for predictions of time to fogging to be made earlier.

Thus a prediction of time to fogging of two (2) to four (4) weeks under laboratory accelerated conditions likely represent much longer lengths of "real time". This could be demonstrated by repeating the laboratory testing without an imposed time limit and therefore, without intentional breach of the test units. However, as noted, there is a concern that development of an unassisted breach in unit 10 and the subsequent rapid increase of dew point temperature might result in too few data sets for longer-term time to fogging predictions to be made. Perhaps the best demonstration would be by field trials in which dew point measurements of insulating glass units installed in buildings are recorded and predictions made. Such a demonstration is beyond the scope of this study.

Conclusions

Results of the Research Program

This report began with a review of the fundamentals of insulating glass unit performance, continued with a detailed discussion of the factors affecting life span, a review of current methods of predicting life span, and then presented a method for field estimation of life span (time to fogging). A laboratory experiment to confirm the method was described, carried out, and the results presented and analyzed. Although lengthy, the intent of this progression was to show that methods of estimation of life span without physical, in-situ measurement of performance are likely to be unreliable. Predictions of time to fogging based on the progressive results of the experiment, using embedded functions in a readily available spreadsheet program (MS Excel) were shown to be accurate, when compared against actual laboratory data.

It can therefore reasonable to conclude that a method to predict time to fogging of insulating glass units has been identified and proven accurate.

In summary, the method consists of:

- Establishment of a representative sample of the population of insulating glass units in a subject building. A critical review should be carried out to determine the likelihood that there may be sub-populations that may have different times to failure, and thus should be tracked separately. Multiple samples should be established accordingly.
- Periodic, indirect, measurements of the dew point temperature of the cavity gas fill of sample units. Measurements should be made in warm weather because dew point temperatures can be measured earlier than during cold weather. This allows more sets of dew point measurements to be made which in turn should allow for longer-term predictions of time to fogging.
- After at least three (3) sets of dew point temperatures have been accumulated, preparation of predictions of time to fogging. Readily available prediction tools, such as the "Forecast" function in MS Excel, can be used. As more measurements are made, predictions should be repeated to improve the accuracy of the estimated time to fogging.

Predictions of time to fogging require analysis of local weather trends and assessment of the thermal performance characteristics of the subject insulating glass units to establish weather conditions under which fogging within the unit cavity would occur. For high performance units incorporating low-e coatings, argon gas fill, and warm-edge spacers, more sophisticated thermal performance modelling tools than used in this report may be needed, such as *FramePlus* from Enermodal Engineering / NRCan or *Window* from Lawrence Berkley National Laboratory (LBNL).

The length of advance notice of time to fogging is limited by currently available dew point measurement equipment. Using solidified carbon dioxide ("dry ice") as a coolant, a practical lower limit of dew point detection is about -73°C. Generally, the dew point temperature of new insulating glass units would be colder than this lower limit. The length of time required for the dew point temperature to increase above this lower limit and thus become measurable is unknown. Building owners may wish (or be required to, in the case of condominium owners) to begin setting aside funds to fund replacement or repair of insulating glass units before dew point temperatures become measurable. In such cases, a provisional time to fogging must be assumed. Once dew point temperatures become measurable and sufficient measurements have been accumulated to allow time to fogging predictions to be made, the financial plan for replacement or repair can be adjusted. Although practical, this approach is inherently contradictory. There is, therefore, a need to develop better dew point measuring equipment, capable of measuring dew point temperatures colder than about -73°C. Such development is beyond the scope of this research study.

Despite this limitation, as noted, the experiment described in this paper has proven that an accurate estimate of time to fogging can be made. It is recommended that that the method described in this report be put into service to assist building owners to more accurately plan for capital replacements or repairs.

Further Study

Further studies to demonstrate the prediction model are recommended, as follows:

- Laboratory assessment, using accepted techniques of accelerated weathering, although without intentional breach of the perimeter seal. Accelerated weathering could include exposure in high humidity and temperature chambers only as done for this program, and / or exposure in an accelerated weather apparatus such as used for CGSB-12.8, ASTM E 2188, and EN-1279-02 test programs, although the rate of induced water vapour diffusion would be lower. Consideration of the potential for sealant failure, breach, and a too rapid rise of dew point temperature to provide sufficient data for long-range prediction of time to fogging must be carefully considered. The length of exposure time required to increase dew point temperatures into the range of “normal” summertime outdoor ambient air temperatures, without intentional breach of the seal, is unknown.
- In-situ, field measurements and predictions of time to fogging. Subject buildings should be selected in which insulating glass units have measurable dew point temperatures. Such a program could be lengthy, depending on the age of the units monitored and the type and severity of conditions affecting life span.

The reasons for such studies are as follows:

- Modifications to the test program described in this paper were necessary to further accelerate the time to fogging. Although breach of the perimeter seal can occur in reality, and there is some indication that the intentional breaches made in the test program may have been beneficial, it would be preferable not to tamper with the physical condition of the test units to eliminate any doubts that the test results and subsequent analysis are valid.
- There exists no clear correlation between laboratory methods of accelerated water vapour transmission into the test units and “real time” rates of water vapour transmission. In-situ, field measurements of dew point temperatures, prediction of time to fogging, and comparison against actual time to fogging would demonstrate the potential length of advance notice of time to fogging.
- A detailed procedure for in-situ, field measurement of dew point temperature should be established to ensure consistent and correct application of the method. The ASTM E 576 standard may be used as a starting point, but further considerations must be addressed, including:
  - Temperature effects on the moisture adsorption capacity of desiccants, and thus the time at which measurements should be made (for example, at any summertime condition, or at conditions approximately coincident with standard laboratory conditions). The ASTM C 1060 standard for thermographic examination of buildings may be useful as a model for weather factors to be considered.

- The time interval between measurements.
- Sample size.

These further studies are beyond the scope of this research program.

Respectfully submitted,

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ALM Consulting

Appendix A
Laboratory Dew Point Temperature Measurements

Dew Point Temperature Record

Unit #	← Units Before Breach →									
	Apr. 28 2004		June 2 2004		June 24 2004		July 20 2004		August 17 2004	
	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer
312-01	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-02	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-03	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-04	NF	N/A								
312-05	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-06	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-07	NF	N/A								
312-08	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-09	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-10	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-11	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-12	NF	N/A								

Unit #	→ After Breach with Nail Only				→ Needles Installed into Breach Openings									
	August 25 2004		Sept. 3 2004		Sept. 13 2004		Sept. 22 2004		Sept. 30 2004		Oct. 15 2004		Nov. 1 2004	
	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer
312-01	NF	N/A	-71	N/A	-53	NF	-53	N/A	-63	N/A	-69	N/A	-67	N/A
312-02	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-03	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-04														
312-05	NF	N/A	NF	N/A	NF	N/A	-60	N/A	-65	N/A	NF	N/A	NF	N/A
312-06	-23	-35	NF	N/A	NF	N/A	-53	N/A	-63	N/A	-63	N/A	-45	NF
312-07														
312-08	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-09	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-10	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-11	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-12														

Unit #	→ Needles Replaced (1 and 6), Needles Removed and Breach Openings Reamed Out											
	Nov. 10 2004		Nov. 19 2004		Nov. 30 2004		Dec. 9 2004		Dec 21 2004		Jan 12 2005	
	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer	Lab	Freezer
312-01	-51	NF	-49	N/A	-41	NF	-25	NF	-9	-57	-8	-65
312-02	-49	NF	-49	NF	-37	NF	-11	-39	7	-13	17	-11
312-03	-41	N/A	-45	NF	-47	N/A	-31	NF	-23	-67	2	-19
312-04												
312-05	-61	N/A	-55	N/A	-41	N/A	-17	NF	5	-9	19	-3
312-06	-25	NF	-13	NF	-5	-36	3	-19	5	-11	11	-9
312-07												
312-08	-71	N/A	-69	N/A	-43	N/A	-17	NF	5	-9	17	-3
312-09	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-10	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-11	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A	NF	N/A
312-12												

Unit #	→ Unit 1 Needle Replaced				Tear-Down		Extended Measurements		
	Jan 24 2005		Feb 4 2005		Feb 14 2005		Feb 7	Feb 8	Feb 10
	Lab	Freezer	Lab	Freezer	Lab	Freezer	Freezer	Freezer	Freezer
312-01	8	-14	14	-10	15				
312-02	19	-8	18	-5	19				
312-03	12	-6	20	-3	18				
312-04									
312-05	18	-10	12	-7	19		-6	-7	
312-06	16	-7	17	-6	16		-7	-6	-6
312-07									
312-08	16	-2	20	-1	19		-3	-1	-2
312-09	NF	N/A	NF	N/A	NF				
312-10	-20	NF	17	-16	15				
312-11	NF	N/A	NF	N/A	NF				
312-12									

Notes:

1. Standard laboratory conditions maintained for Lab dew point measurements: approximately 22°C up to 24.9°C.
2. Freezer temperature immediately below test frame: -10°C +/- 1°C. Standard laboratory conditions in room.
3. Freezer dew point measurements are taken on days following date shown (ie. overnight cooling in test frame, 3 units at a time)
4. NF = No Fog (no condensation on surface 3) at lowest possible dew point, -73°C.
5. N/A = dew point temperature not measured in freezer since no dew point measured in lab.
6. Prior to breach, all units were subject to high humidity for three (3) weeks each cycle, in accordance with ASTM E2188. Units were breached with a 0.078 in. diameter common finishing nail, driven through the secondary sealant and the back of the spacer bar into the cavity. Clear openings were not visible into the cavity.
7. After breach, units 1, 2 and 3 were subject to high humidity for one (1) week each cycle, in accordance with CGSB-12.8-97.
8. After breach, units 5,6 and 8 were subject to high humidity for one (1) week each cycle, in accordance with ASTM E2188.
9. Units 9, 10 and 11 were not breached and units condinued to be exposed to high humidity in accordance with ASTM E2188, but for one (1) week cycles following breach.
10. Before and after breach, all units were installed in and removed from the high humidity test chambers at the same time.
11. Unit 1 on Sept. 3 04 had a dewpoint of -71°C in the lab. Freezer dp was not checked since lab dp was so low.
12. Unit 6 failed to register a dp above -73°C from Sept. 3 onwards.
13. On Sept. 3 2004, all breached units were fitted with argon samping syringe needles through the breach openings, with the annular space between needle and opening sealed to thesurrounding secondard sealant with PIB (Tremco 440 glazing tape).
14. On Sept. 13, 2004, unit 1 had warmed to -53°C in the lab but remained NF after installation and exposure in the freezer rack.
15. On Sept. 22, 2004, based on freezer rack results for unit 1 on Sept. 12, 2004, dew point temperature for units 1, 5 and 6 were not measured in the freezer rack (NF result expected).
16. On Sept. 30, 2004, dew point temperature for units 1, 5 and 6 was not measured in the freezer rack (NF result expected).
17. Following Sept. 30, 2004 measurements, the time interval between measurements was increased to two (2) weeks since there was little increase in dew point temperatures.
18. On Nov. 1, 2004, corrosion of argon gas sampling needles was noticed in units 1, 2 and 3. All needles were removed and fitted to syringes to check for air flow. Air movement was audibly detected through needles had been installed in units 2, 5, and 8. This raised a possibility that increased dew point temperature in units 1 and 6 was not due to cavity gas exchange through the needles but through other breaches.
19. On Nov. 1, 2004, all units were examined and found to have some local, very small, areas of adhesion loss of secondary sealant 1-2mm in depth, none extending completely through the secondary sealant. In unit 1, at the short side normally at the bottom of the unit when installed in the E 2188 HHC, there is a depression in the secondary sealant, with some fibres protruding from the sealant. The spacer was not visibile. In unit 6, at one face of one corner, a glass fracture was found that extended to the secondary / primary sealants boundary. At this location, the secondary sealant was separated from the glass. It is possible that these conditions are effective breaches that are resuling in water vapour gain into the the cavities of units 1 and 6 and increase in dew point temperatures.
20. Based on Nov. 1, 2004 unit examination, visibly corroded needles were disposed of and visibly corrosion-free needles through through which air movement was audibly detected were installed in units 1 and 6. Annular gaps were re-sealed with PIB. In units 2, 3, 5 and 8, the openings originally punched with a nail were reamed out with a 0.062 in (1/16 in.) diameter drill bit to create clear openings into the unit cavities. The intent of these modifications was to hasten cavity gas exchange and increase in desiccant moisture content and thus, increases in dew point temperature.
21. During examination on Nov. 1, 204, unit 6 was struck and a second, much larger fracture was created, also extending to the secondary / primary sealants boundary. It is expected that this will result in more rapid increase in dew point temperature.
22. On Nov. 1, 2004, following modification, all units were returned to the HHCs for one (1) week exposure.
23. On Nov. 10, 2004, the dew point temperature of all units showed a significant increase. Based on previous attempts, only the three 'warmest' units were installed into the freezer rack for dew point measurement (units 1, 2 and 6). After overnight conditioning, all the dew point temperature of all units was NF (ie. below about -73 deg. F.). All units were then returned to HHCs.
24. On November 19, 2004, the dew point temperature of most units had changed little. An exception was unit no. 6. The increase is likely due to damaged suffered on Nov. 1, 2004.
25. On November 19, 2004 units 2, 3 and 6 were installed in the freezer frame. These units were selected because they had the warmest dew point temperatures at lab conditions. On November 22, 2004, the dew point temperature of all three units was NF at -73 deg. C. Unit 6 was chilled to the minimum temperature possible, -76 deg. C but was still NF. All six (6) units were then returned to the HHCs (after warming to lab conditions for units 2, 3, and 6).
26. On November 30, 2004 units 1, 2 and 6 were installed in the freezer frame. These units were selected because they had the warmest dew point temperatures at lab conditions. On December 1, 2004, the dew point temperatures of all three units were measured, only unit 6 was above NF at -36 deg. C. All six (6) units were then returned to the HHCs (after warming to lab conditions for units 1, 2 and 6).
27. Following lab temperature dew point measurement on December 9 2004, all units were installed into the freezer rack. Units 1, 2 and 6 were placed into the freezer rack on December 9 for dew point measurements on December 10, and units 3, 5 and 8 were placed in the freezer rack on December 10 (Friday) for dew point measurement on December 13 (Monday). All units were returned to the HHCs on Tuesday, December 14 2004.
28. Following lab temperature dew point measurement on December 21 2004, all units were installed into the freezer rack. Units 1, 2 and 6 were placed into the freezer rack on December 21 for dew point measurements on December 22, and units 3, 5 and 8 were placed in the freezer rack on December 22 for dew point measurement on December 23. All units were then stored at lab conditions over the Christmas break and returned to the HHCs on Tuesday, January 4 2005.
29. Following lab temperature dew point measurement on January 12 2005, all units were installed into the freezer rack. Units 1, 2 and 6 were placed into the freezer rack on January 12 for dew point measurements on January 13, and units 3, 5 and 8 were placed in the freezer rack on January 13 for dew point measurement on January 14. All units were then returned to the HHCs on Tuesday, January 14 2005.
30. On January 13, 2005 the argon gas sampling syringe in unit 1 appeared plugged. The small increase (warming) of dew point temperature from the previous cycle was likely due to the limited cavity / HHC gas exchange as a result. The needle was removed and replaced with a new needle following lab condition and freezer rack dew point measurements.

31. On January 24, 2005, the dew point for unit 1 had increased 10 deg. C, which suggests that as suspected, the plugged argon gas sampling syringe needle had affected dew point temperature increase. The small increase in dew point temperature of this unit from December 21 2004 to the January 13 2005 measurements appears to confirm that the principle cause of dew point temperature increase is due to insulating glass unit cavity / HHC chamber gas exchange, with perhaps a small amount of diffusion through the sealants and / or through the syringe orifice occurring.
32. On January 24 2005 lab condition dew point temperature measurements revealed a sharp increase in dew point temperature for unit 10. A physical review by Bodycote revealed local debonding of the secondary sealant at one location, for the full depth of the bond line (ie. to the primary sealant). It could not be confirmed, but is suspected that when in the HHC, since this is a sealed unit, the glass panes move apart (no measurements were made but plate behaviour is expected for such small units) and cause the primary sealant to 'fail' cohesively or adhesively, providng a large opening for cavity / HHC gas exchange. Since dew point was detectable at laboratory conditions, this unit was subsequently included in the freezer rack 'outdoor' exposure dew point measurement group.
33. January 24 2005 dew point measurements for units 5 and 8 revealed a decrease in dew point temperature, for both units -1°C at lab conditions. Both units have drilled breach openings, without needles. A visual review of the breach openings revealed no apparent blockage. The reasons for apparent cessation of the moisture gain are unknown. Freezer rack dew point measurements revealed a similar halt in dew point temperature gain, confirming the lab condition measurements. After dew point measurements, the units were returned to the HHCs for further exposure.
34. On February 3, 2005 the units were removed from the HHCs. The cabinet temperature was approximately 28°C. Units 2, 3 and 6 had visible fog in the cavity. Units 5, 8 and 10 had small amounts of water in the cavity. Units 14, 9 and 10 had neither visible fog nor water in the cavity. On the basis of these observations, further HHC exposure was stopped and the units were scheduled for tear-down to remove the desiccant for direct moisture content measurement, after lab condition and freezer rack dew point measurements.
35. During 'outdoor' exposure in the freezer rack, dew point temperatures for units 5, 6 and 8 were measured 3 hours after installation, at 24 hours after installation (the normal measurement time), and again the following day, after 48 hours after installation. The intent was to check if dew point temperature would vary significantly with time. Previous temperature monitoring via 'smart button' dataloggers revealed that the units cooled from lab conditions to lower, stable temperatures after about 7 hours exposure. After 3 hours exposure, the dew point temperatures were -6°C, -7°C and -3°C. After 24 hours exposure, the dew point temperatures were -7°C, -6°C and -1°C, as noted in the table. After 48 hours exposure, the dew point temperatures were -6°C, -2°C for units 6 and 8 (a third measurement for unit 5 was not made, to accommodate unit 10 in the freezer rack). This reveals that dew point temperature suppression due to temperature change is very fast. The rate of dew point temperature suppression varies with quantity of desiccant type, desiccant spacer bar configuration (hole size and spacing, for conventional aluminum spacers), quantity of desiccant, and unit size (Kilthau, GPD 2001). Dew point temperature suppression may not be as fast in units of dissimilar configuration. In particular, the effect of size needs to be considered when taking dew point temperature measurements of a given population of units of differing sizes, a factor to be considered in field testing.
36. Prior to tear-down of the units at the end of the project, lab condition dew point was measured again, for all units. In general, there was between 1°C and 2°C difference in temperature, with the dew point temperature of some units increasing and in others decreasing. Possible reasons for variation include operator error or incomplete equilibriation of the desiccant with the cavity volume. The amount of difference is, however, minor and within normal ranges of experimental accuracy.
37. At tear-down, the dew-point temperature of unit 5 had increased to +19°C. This is 7°C higher than the previous measurement (Feb 4, 2005 but only 1°C higher than the measurement prior to that (Jan 24 2005). This suggests an error in the previous (Feb 4 2005) measurement.

Simulated Outdoor Exposure Extended Measurements				
Unit #	Feb 7 3 Hrs	Feb 7 12 Hrs	Feb 8 24 Hrs	Feb 10 48 Hrs
312-01				
312-02				
312-03				
312-04				
312-05	-6	-7	-7	
312-06	-7	-6	-6	-6
312-07				
312-08	-3	-1	-1	-2
312-09				
312-10				
312-11				
312-12				

Effect of Air Exchange via Breach Openings				
	Final Cycle		Tear-Down	
Unit #	Feb 4 2005		Feb 14 2005	
	Lab	Freezer	Lab	Freezer
312-01	14	-10	15	
312-02	18	-5	19	
312-03	20	-3	18	
312-04				
312-05	12	-7	19	
312-06	17	-6	16	
312-07				
312-08	20	-1	19	
312-09	NF	N/A	NF	
312-10	17	-16	15	
312-11	NF	N/A	NF	
312-12				

Notes re: Effect of Air Exchange via Breach Openings:
1. The lab condition dew point measured in the previous period to Feb 4 2005 (on Jan. 24 2005) was +18°C. The slightly higher dew point temperature measured on Feb 14 2005 suggests that the dew point temperature of +12°C on Feb 4 2005, shown in the above chart, was incorrect.
2. Repeated measurements were made as the water vapour content of the desiccants approached capacity at lab conditions, based on previous water vapour adsorption capacity assessment (also at lab conditions). Similar measurements were not made earlier when the water vapour content of the desiccants would have been less, so it is unknown if there might be a more marked contrast between dew point temperature before and after simulated outdoor exposure and induced partial cavity gas exchange when the desiccant water vapour content is less.

Appendix B
Desiccant Water Content Measurements

Desiccant Moisture Content Measurements

Unit #	Desiccant Weight			Desiccant Sample Moisture Content							
	Jar	Jar & Desiccant	Desiccant only	Crucible without Lid	Crucible with Lid	Crucible with Lid & Desiccant Sample	Desiccant Sample Only Before Drying	Crucible with Lid & Desiccant Sample after Drying	Desiccant Sample Only After Drying	Desiccant Sample Moisture Content	Desiccant Sample Moisture Content
	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(%)
312-01	194.24	233.79	39.55	20.05	31.53	41.43	9.90	39.68	8.15	1.7500	21.47
312-02	188.53	227.25	38.72	17.42	30.24	38.55	8.31	37.06	6.82	1.4900	21.85
312-03	188.64	228.67	40.03	19.99	32.42	42.17	9.75	40.42	8.00	1.7500	21.88
312-04	189.26	225.33	36.07	17.44	29.44	39.08	9.64	38.95	9.51	0.1300	1.37
312-05	189.34	222.74	33.40	19.88	30.92	41.06	10.14	39.11	8.19	1.9500	23.81
312-06	189.95	228.75	38.80	19.56	30.81	40.66	9.85	38.88	8.07	1.7800	22.06
312-07	188.23	217.25	29.02	20.04	31.51	41.55	10.04	41.39	9.88	0.1600	1.62
312-08	188.34	227.97	39.63	17.60	29.78	39.01	9.23	37.27	7.49	1.7400	23.23
312-09	189.54	228.20	38.66	20.21	32.12	42.39	10.27	41.40	9.28	0.9900	10.67
312-10	188.68	230.51	41.83	18.02	29.47	39.55	10.08	37.53	8.06	2.0200	25.06
312-11	188.45	224.45	36.00	19.90	31.10	41.19	10.09	40.03	8.93	1.1600	12.99
312-12	188.66	221.90	33.24	19.98	32.41	42.44	10.03	42.28	9.87	0.1600	1.62
	A	B	C	D	E	F	G	H	I	J	K
			(B - A)				(F-E)		(H - E)	(G - I)	(J / I) x 100

Unit #	Desiccant Remainder Saturated Moisture Content								Comments
	Jar & Desiccant Remainder	Desiccant Remainder Only	Desiccant Remainder Only, Adjusted for Initial Water Content	Jar & Desiccant Remainder After Saturation	Desiccant Remainder Only After Saturation	Desiccant Remainder Moisture Content After Saturation	Desiccant Remainder Moisture Content After Saturation, Adjusted for Initial Water Content	Desiccant Moisture Adsorpton Capacity	
	(g)	(g)	(g)	(g)	(g)	(g)	(g)	(%)	
312-01									
312-02									
312-03									
312-04	203.49	14.23	14.04	211.90	22.64	8.41	8.60	61.31	Jar #1 April 29, 2004 (dry)
									& June 2, 2004 (saturated)
312-05									
312-06									
312-07	207.22	18.99	18.68	211.90	23.67	4.68	4.99	26.70	Jar #2 April 29, 2004 (dry)
									& June 2, 2004 (saturated)
312-08									
312-09									
312-10									
312-11									
312-12	211.87	23.42	23.04	217.60	29.15	5.73	6.11	26.52	Jar #3 April 29, 2004 (dry)
									& June 2, 2004 (saturated)
	L	M	N	O	P	Q	R	S	
		(L - A)	M x (100 - K) / 100		(O - L)	(P - M)	(P - N)	(R / N) x 100	

Notes:

1. Desiccant Moisture Adsorption Capacity is calculated with Desiccant Remainder before and after saturation. The before saturation values are adjusted to account for moisture already present in the desiccant.
2. The calculated desiccant moisture adsorption capacity for unit 4 is very much higher than for units 7 and 12. The jar and desiccant remainder after saturation (col. L) was checked and found to be accurate, which indicates that the jar (col. A) and / or jar & desiccant (col. b) initial measurements must have been incorrect.
3. Prior to breach of units 1, 2, 3, 5, 6 and 8, all units were subject to high humidity testing in the ASTM E 2188 high humidity chamber.
3. Following breach, units 1, 2 and 3 were subject to high humidity testing in the CGSB-12.8 high humidity chamber, in which temperature is varied from 22+/-3oC to 55^{o}C with a constant water spray, therefore at constant 100% RH.
4. Following breach, units 5, 6, 8, 9, 10 and 11 were subject to high humidity testing in the ASTM E-2188 high humidty chamber, in which temperature is held constant at 60 +/-3^{o}C and 95 +/-5% relative humidity.
5. Units 1, 2, 3, 5, 6 and 8 were breached during the program to hasten failure, as described in the "Unit Dew Point Record" spreadsheet.
6. During final desiccant moisture content measurement, the crucible containing desiccant was spilled as it was being moved to the furnace. Prior to spill, the desiccant + crucible mass was 40.22g. After the spill, the desiccant + crucible mass was 38.55g. The after-spill crucible + desiccant was subjected to drying and used for calculation in the above table.
7. During final desiccant moisture content measurement, the crucible containing desiccant was spilled during removal from the furnace. No desiccant was lost but some foreign matter was introduced into the dried desiccant (char from gloves used to grasp the crucible during recovery). The mass of the crucible and contents was 39.69g. The crucible and contents were then returned to the furnace for additional drying (2 hours). The mass after drying was 39.68g. This mass was used in the calculations in the table.
8. Dwell time in the furnace was 2 hrs. 54 minutes for samples of desiccant from units 4, 7 and 12. Dwell time for samples of desiccant from units 1, 2, 3, 5, 6, 8, 9, and 10 was 2 hours 15 minutes. Dwell time for samples of desiccant for unit 1 (after spill) and unit 11 was 2 hours. Furnace temperature exceed the minimum required by EN-1279-2 of 950^{o}C (up to 1025^{o}C).

Appendix C
Test Unit Dimensions & Condition

Unit Dimensions

Unit #	Unit Dimesions						Sealant Dimensions						Comments
							Primary		Secondary		Overall		
	Width	Length	Upper Lite	Cavity	Lower Lite	Overall	Lo	Hi	Lo	Hi	Lo	Hi	
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	
312-01	505	355	3.8	13.6	4.0	21.4	4.59	6.30	4.60	5.20	9.05	10.19	Desiccant visible, erupting from one fill hole. Primary seal width reduced at fill holes to 2.2 mm and 2.3 mm.
312-02	507	355	3.8	13.4	4.0	21.2	2.70	5.48	4.11	5.38	8.57	9.59	Primary seal width reduced at fill holes to 2.55 mm and 3.21 mm.
312-03	506	355	3.9	13.3	4.0	21.2	3.61	4.08	3.93	4.94	8.34	10.32	Two joints in spacer. Primary seal width reduced at fill holes to 2.55 mm and 3.61mm.
312-04	507	355	4.0	13.3	3.8	21.1	4.39	6.30	5.04	6.35	9.08	10.04	One lite, glass chip in exposed face at edge. Primary seal width reduced at fill holes to 2.63 mm and 3.04 mm.
312-05	505	353	3.8	13.3	3.9	21.0	4.17	5.80	4.20	4.72	8.73	10.14	Primary seal width reduced at fill holes to 2.77 mm and 3.70 mm. Fill holes partly visible but not desiccant.
312-06	505	354	4.0	13.4	3.9	21.3	4.16	4.41	4.36	5.78	8.25	10.00	Primary seal width reduced at fill holes to 2.95 mm and 4.05 mm. Fill holes partly visible but not desiccant.
312-07	507	354	3.9	13.5	3.9	21.3	4.04	4.86	4.44	5.64	7.43	9.66	Primary seal width reduced at fill holes to 2.86 mm and 4.20 mm. Fill holes partly visible but not desiccant.
312-08	508	355	3.8	13.4	3.9	21.1	4.62	5.62	3.88	5.58	8.96	9.98	Two joints in spacer. Primary seal width reduced at fill holes to 3.75 mm and 3.88 mm. Fill holes partly visible but not desiccant.
312-09	508	355	4.0	13.3	4.0	21.3	2.86	4.68	4.53	5.48	7.81	9.50	Primary seal width reduced at fill holes to 3.85 mm and 3.48 mm. Fill holes partly visible but not desiccant.
312-10	507	356	4.0	13.4	4.0	21.4	3.32	5.94	3.47	5.70	7.74	9.85	Two joints in spacer. Primary seal width reduced at fill holes to 4.35 mm and 4.60 mm. Fill holes partly visible but not desiccant.
312-11	508	356	3.9	13.3	3.9	21.1	2.52	4.36	4.72	5.55	7.42	9.20	Two joints in spacer. Primary seal width reduced at fill holes to 3.65 mm and 3.78 mm. Fill holes partly visible but not desiccant.
312-12	508	356	3.9	13.4	4.0	21.3	3.37	5.17	4.43	5.33	7.32	9.84	Primary seal width reduced at fill holes to 3.10 mm and 3.67 mm. Fill holes partly visible but not desiccant.
Means:	507	355	3.9	13.4	3.9	21.2	3.70	5.25	4.31	5.47	8.23	9.86	
							4.47		4.89		9.04		

Typical Comments:

1. Construction: AM, CC with one (1) closure joint in a long side 75 mm from corner, galv. steel MC with no primary sealant injection, wrap or packing. Joints not welded.
2. Desiccant: MS, injected into spacer through two (2), 3mm dia. holes at nearest diagonally opposite corner in one shoulder, one in short leg, one in long leg, approx. 47 mm from corner.
3. Sealants: PB + PS. No skips visible but some reduced contact (air bubbles). Hi & Lo measurements usually mid-side although if less, Lo measurements at filling holes.
4. Dimensions: glass thickness and cavity width measured at centre of glass. Typically, sealants at one long side are squeezed, overall thickness is slightly reduced.

Unit Condition at end of Program

Unit #	Width	Length	Perimeter	Comments
	(mm)	(mm)	(mm)	
312-01	505	355	1720	Side A: 1.0 + 4.0 + 3.0 + 27.0 + 4.0 + 9.0 = 36.3 cm / 172.0 cm = 21% length of debonded secondary seal
				Side B: 3.5 + 2.0 + 4.0 + 24.0 + 1.0 + 13.7 = 48.2 cm / 172.0 cm = 28% length of debonded secondary seal
312-02	507	355	1724	Side A: 1.3 + 1.0 + 1.4 + 1.5 + 3.0 + 42.0 = 50.2 cm / 172.4 cm = 29% length of debonded secondary seal
				Side B: 1.0 + 1.0 + 1.0 = 3.0 cm / 172.4 cm = 1.7% length of debonded secondary seal
312-03	506	355	1722	Side A: 1.5 + 8.5 + 9.0 + 21.5 + 1.0 + 23.0 + 0.8 + 15.0 = 80.3 cm / 172.2 cm = 46% length of debonded secondary seal
				Side B: 10.5 + 0.5 + 2.2 + 0.8 + 0.8 + 11.5 + 11.0 + 0.5 + 0.6 + 0.8 + 0.8 + 0.5 + 0.9 = 41.4 cm / 172.2 = 24% length of debonded secondary seal
312-05	505	353	1716	Side A: red discolouration in secondary seal, breach through primary seal at top right corner.
				Side B: 1.0 + 24.0 + intermittent 1.5 total + 0.5 + 8.0 + 3.5 + 30 + 13.5 + 10 = 92 cm / 1716 = 53% length of debonded secondary seal
312-06	505	354	1718	Side A: 2.0 cm / 171.8 cm = 1% length of debonded secondary seal
				Side B: 4.0 + 1.0 + 11.5 + 7.5 + 50.8 + 1.0 + 11.5 + 8.5 (cracked glass) = 95.8 cm / 171.8 = 56% length of debonded secondary seal
				Side B: Glass cracked during examination on November 1, 2004. Breach through secondary and primary seal at this location.
312-08	508	355	1726	Side A: No breaches detected.
				Side B: 3.5 + 4.0 + 11.5 + 4.5 + 2.5 + 1.0 + 1.0 + 3.0 + 4.0 + 8.0 + 9.0 = 52 cm / 172.6 = 30% length of debonded secondary seal
312-10	507	356	1726	Side A: 35.6 + 50.4 + 2.5 + 2.1 + 9.5 + 46.0 (intermittent) = 146.1 / 172.6 cm = 85% length of debonded secondary seal
				Side B: 1.0 + 1.0 (corrosion of spacer observed) + 10.5 + 1.0 + 11.0 + 50.0 + 4.0 + 3.0 = 81.5 cm / 172.6 = 47% length of debonded secondary seal
				Side B: Within 50.0 cm breach there was also a 1.0 cm breach through primary seal.
312-11	508	356	1728	Side A: 2.0 + 0.5 + 13.5 + 13.5 + 2.0 + 1.0 + 1.5 + 2.5 + 2.0 + 16.5 + 2.7 + 1.5 + 1.5 + 2.5 = 63.2 cm / 172.8 cm = 37% length of debonded secondary seal
				Side B: 4.3 + 2.5 + 3.5 + 1.0 + 2.0 + 50.8 + 1.0 + 3.0 + 1.0 = 69.1 cm / 172.8 = 40% length of debonded secondary seal
312-12	508	356	1728	

Notes:
1. Units 4, 7 and 12 were destroyed at the beginning of the test program.
2. Data for unit 12 is missing.
3. The glass pane with the identification label was designated as Side 'A', the other pane was designated as Side 'B'.
4. Units were placed into the HHCs standing on the same, narrow end. "Top" therefore refers to the narrow end that would normally be at the top when inside the HHCs; "bottom" refers to the narrow end that would normally be at the bottom when inside the HHCs.
5. All units had loose desiccant in the cavity, except for the "control" units 10, 11 and 12. Loose desiccant beads came from breach openings made in the spacer. Typically, loose beads were trapped between the spacer and the glass panes.
6. During tear-down, sealants of units exposed to the CGSB-12.8 HHC were easier to cut through than sealants of units exposed to the ASTM E 2188 HHC (subjective assessment).

Appendix D
Cavity Volume Change Calculations

1. General

Cavity volume change is calculated using Charles' Law,

$$\mathbf{V = kT}$$

where

V = *volume of cavity, cm*^{3}
k = *constant*
T = *absolute temperature of cavity gas fill, Kelvin*
= *t (temperature in °C) + 273°C*

For increased volume (V_1 to V_2) due to temperature change (T_1 to T_2),

$$\frac{V_1}{kT_1} = \frac{V_2}{kT}$$

solving for V_2 (volume at changed temperature),

$$V_2 = \frac{V_1 kT_2}{kT_1}$$

which reduces to

$$V_2 = \frac{V_1 T_2}{T_1}$$

2. Cavity Dimensions and Volume

Cavity width = average unit width less perimeter secondary sealant over bottom of spacer
(3mm per side, 6mm total measured),
= 355 mm – 6 mm
= 349 mm

Cavity length = average unit length less secondary sealant,
= 507 mm - 6 mm
= 501 mm

Cavity depth = 13.4 mm average (measured)

Cavity volume = width x length x depth,
= 349 mm x 501 mm x 13.4 mm
= 2,342,976.6 mm^3

Subtract volume of one short and one long side filled with desiccant (assumed),
= (349 mm + 501 mm) x (5 mm x 12 mm meas.)
= 51,000 mm^3

Net cavity volume, V_1 = $2{,}342{,}976.6\ mm^3 - 51{,}000\ mm^3$
= $2{,}291{,}976.6\ mm^3$
= $2{,}292\ cm^3$

3. Increase in Volume from Lab Conditions to HHC

Using CGSB-12.8 HHC cyclic temperatures of 22 ± 3°C to 55 ± 3°C,

$$V_2 = \frac{V_1\ T_2}{T_1}$$

$$= \frac{2{,}292\ cm^3 \times (273°C + 55°C)}{(273°C + 22°C)}$$

$$= 2{,}548\ cm^3$$

Volume change,
$V_2 - V_1$ = $2{,}548\ cm^3 - 2{,}292\ cm^3$
= $256\ cm^3$

Percent change,
= (volume change / V_1) • 100
= ($256\ cm^3$ / $2{,}292\ cm^3$) • 100
= 11.1%

Using ASTM E 2188 HHC static temperature of 60 ± 3°C and lab condition of 23 ± 3°C,

$$V_2 = \frac{V_1\ T_2}{T_1}$$

$$= \frac{2{,}292\ cm^3 \times (273°C + 60°C)}{(273°C + 23°C)}$$

$$= 2{,}578\ cm^3$$

Volume change,
$V_2 - V_1$ = $2{,}578\ cm^3 - 2{,}292\ cm^3$
= $286\ cm^3$

Percent change,
= (volume change / V_1) • 100
= ($286\ cm^3$ / $2{,}292\ cm^3$) • 100
= 12.5%

4. Decrease in Volume from Lab Conditions to Simulated Outdoor Exposure

From lab conditions of 23 ± 3°C to average cavity temperature of +2°C (see Figure 33),

$$= \frac{2{,}292\ cm^3 \times (273°C + 2°C)}{(273°C + 22°C)}$$

$$= 2{,}137\ cm^3$$

Volume change,
$V_2 - V_1$ = $2{,}137\ cm^3 - 2{,}292\ cm^3$
= $-155\ cm^3$

Percent change,
= ($-155\ cm^3$ / $2{,}292\ cm^3$) • 100
= -6.8%

Appendix E
Selected Climate Data for Toronto, Ontario

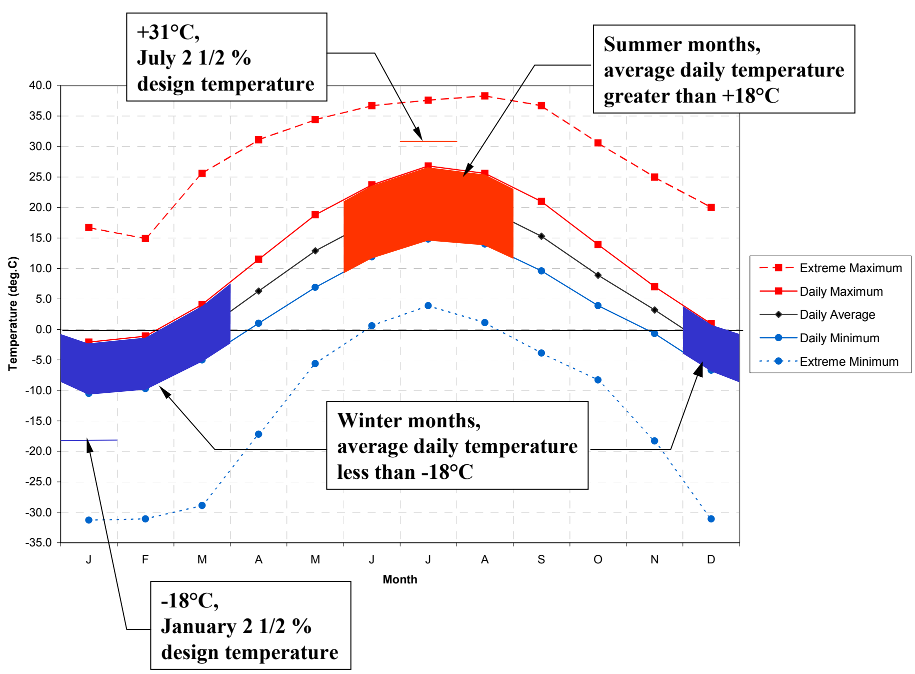
TORONTO LESTER B. PEARSON INTERNATIONAL AIRPORT 1971 - 2000

Latitude: 43° 40' N Longitude: 79° 36' W Elevation: 173.40 m
Climate ID: 6158733 WMO ID: 71624 TC ID: YYZ

Temperature:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily Average (°C)	-6.3	-5.4	-0.4	6.3	12.9	17.8	**20.8**	19.9	15.3	8.9	3.2	-2.9
Standard Deviation	3.0	2.7	2.3	1.7	2.0	1.5	1.3	1.3	1.2	1.6	1.5	2.7
Daily Maximum (°C)	-2.1	-1.1	4.1	11.5	18.8	23.7	**26.8**	25.6	21.0	13.9	7.0	0.9
Daily Minimum (°C)	**-10.5**	-9.7	-5.0	1.0	6.9	11.9	14.8	14.0	9.6	3.9	-0.7	-6.7
Extreme Maximum (°C)	16.7	14.9	25.6	31.1	34.4	36.7	37.6	**38.3**	36.7	30.6	25.0	20.0
Extreme Minimum (°C)	**-31.3**	-31.1	-28.9	-17.2	-5.6	0.6	3.9	1.1	-3.9	-8.3	-18.3	-31.1
Design Temperatures:												
January 2 1/2% (°C)	-18											
July 2 1/2% Dry Bulb / Wet Bulb (°C)							31 / 23					
Humidity:												
Average Vapour Pressure (kPa)	0.4	0.4	0.5	0.7	1.0	1.4	1.7	1.7	1.4	0.9	0.7	0.5
Average Relative Humidity - 0600LST (%)	81.7	81.3	81.2	78.8	80.0	82.6	84.5	88.6	89.5	87.1	84.7	83.7
Average Relative Humidity - 1500LST (%)	74.3	70.8	65.4	56.5	53.9	55.1	53.1	56.2	59.4	62.8	71.2	75.5

Notes:

1. Temperature and humidity data, excluding design temperatures, taken from "Climate Normals" for the 1971 - 2000 period, Environment Canada, www.weatheroffice.ec.gc.ca
2. Design temperature data taken from the Ontario Building Code, 1997 edition.
3. The equivalent July 2 1/2% design relative humidity, based on the given dry bulb and wet bulb temperatures, is about 52% (determined with a psychrometric chart).



Appendix F
Prediction Model Data

Average (Mean) and Standard Deviation Analysis

Model Starts at November 10
Using Units 1, 2, 3, 5, 6, and 8

Time Period	1	2	3	4	5	6	7	8	9
Date	Nov 10 04	Nov 19 04	Nov 30 04	Dec 9 04	Dec 21 04	Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
312-01	-51	-49	-41	-25	-9	-8	8	14	15
312-02	-49	-49	-37	-11	7	17	19	18	19
312-03	-41	-45	-47	-31	-23	2	12	20	18
312-05	-61	-55	-41	-17	5	19	18	12	19
312-06	-25	-13	-5	3	5	11	16	17	16
312-08	-71	-69	-43	-17	5	17	16	20	19
Std. Dev.	15.9	18.5	15.4	11.8	12.0	10.7	4.1	3.3	1.8
+1 Std Dev	-34	-28	-20	-5	10	20	19	20	19
Mean	-50	-47	-36	-16	-2	10	15	17	18
-1 Std Dev	-66	-65	-51	-28	-14	-1	11	14	16

Prediction using three data points

Time Period		4	5	6	7	8	9
Date		Dec 9 04	Dec 21 04	Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
Forecast Std. Dev.		16	16	15	15	15	15
+1 Std Dev		-14	-7	-1	6	13	20
Forecast Mean		-30	-23	-16	-9	-2	5
-1 Std Dev		-46	-39	-31	-24	-17	-10

Prediction using four data points

Time Period		5	6	7	8	9
Date		Dec 21 04	Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
Forecast Std. Dev.		11	10	8	7	5
+1 Std Dev		2	12	21	31	40
Forecast Mean		-9	2	13	24	35
-1 Std Dev		-21	-8	4	17	30

Prediction using five data points

Time Period		6	7	8	9
Date		Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
Forecast Std. Dev.		10	9	7	6
+1 Std Dev		18	29	41	52
Forecast Mean		8	21	33	46
-1 Std Dev		-2	12	26	40

Model Starts at November 10
Using Units 2, 3, 5, and 8

Time Period	1	2	3	4	5	6	7	8	9
	Nov 10 04	Nov 19 04	Nov 30 04	Dec 9 04	Dec 21 04	Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
312-02	-49	-49	-37	-11	7	17	19	18	19
312-03	-41	-45	-47	-31	-23	2	12	20	18
312-05	-61	-55	-41	-17	5	19	18	12	19
312-08	-71	-69	-43	-17	5	17	16	20	19
Std. Dev.	13.2	10.5	4.2	8.5	14.4	7.9	3.1	3.8	0.5
+1 Std Dev	-43	-44	-38	-11	13	22	19	21	19
Mean	-56	-55	-42	-19	-2	14	16	18	19
-1 Std Dev	-69	-65	-46	-27	-16	6	13	14	18

Prediction using three data points

Time Period		4	5	6	7	8	9
Date		Dec 9 04	Dec 21 04	Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
Forecast Std. Dev.		0	-4	2	0	-2	-4
+1 Std Dev		-37	-34	2	13	23	33
Forecast Mean		-37	-30	0	13	25	37
-1 Std Dev		-37	-26	-2	13	27	42

Prediction using four data points

Time Period		5	6	7	8	9
Date		Dec 21 04	Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
Forecast Std. Dev.		4	2	0	-2	-4
+1 Std Dev		-8	2	13	23	33
Forecast Mean		-12	0	13	25	37
-1 Std Dev		-16	-2	13	27	42

Prediction using five data points

Time Period		6	7	8	9
Date		Jan 12 05	Jan 24 05	Feb 4 05	Feb 14 05
Forecast Std. Dev.		10	10	10	10
		19	33	48	62
Forecast Mean		9	23	38	52
		-1	13	27	42

Notes:

1. For a normal distribution, +/- one standard deviation includes (34.1 x 2 =) 68.2% of the data.
2. For a normal distribution, +/- two standard deviations includes [(34.1 + 13.6) x 2 =] 95.4% of the data.
3. For a normal distribution, +/- three standard deviations includes [(34.1 + 13.6 + 2.1) x 2 =] 99.6% of the data.

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