

Acrylonitrile Content as a Predictor of the Captan Permeation Resistance for Disposable Nitrile Rubber Gloves

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ABSTRACT: The aim of this study was to determine whether the acrylonitrile (ACN) content influences the permeation resistance of disposable nitrile rubber (NBR) gloves to aqueous solutions of the pesticide captan. Attenuated total reflectance/Fourier transform infrared (ATR-FTIR) spectrophotometry at $2237 \pm 5 \text{ cm}^{-1}$ was used to measure the ACN contents of seven different NBR gloves. The ACN contents of the gloves ranged from 12.7 to 29.9%. Permeation was conducted according to American Society for Testing and Materials (ASTM) Method F 739-99a with a gas chromatography/mass spectrometry analysis of captan in the hexane collection liquid. Significant correlations were found between (1) the ACN content and mass-to-area ratio and the logarithm of the steady-state permeation rate (SSPR; Pearson correlation coef-

ficient = 0.9227, $p \leq 0.05$), and (2) the ACN content and mass-to-area ratio and the ASTM normalized breakthrough detection time (NBT) at $0.25 \mu\text{g}/\text{cm}^2$ (Pearson correlation coefficient = 0.9471, $p \leq 0.05$). On average, the NBT increased 120 min for every 5% increase in the ACN content. The average SSPR ranged from 0.002 to $0.40 \mu\text{g}/\text{cm}^2/\text{min}$, a 200-fold difference. Increasing the ACN content resulted in decreased SSPR. ATR-FTIR was useful in determining the NBR polymer ACN content, surface homogeneity, and potential glove chemical resistance. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 103: 2057–2063, 2007

Key words: diffusion; elastomers; FTIR; infrared spectroscopy

INTRODUCTION

The selection of appropriate chemical protective clothing (CPC) relies on the assumption that batch lots and similar materials from different manufacturers will perform in the same manner. In contrast, studies have indicated that manufacturer and batch-lot variability among similar gloves can result in marked differences in chemical permeation performance in terms of the steady-state permeation rate (SSPR) and breakthrough time (BT).^{1–3} Mickelson and Hall¹ observed up to 10-fold differences in the BT of perchloroethylene through chemically resistant nitrile rubber (NBR) gloves from different suppliers. Perkins and Pool² reported considerable intermanufacturer and batch-lot variability in the permeation of 2-ethoxyethanol

acetate through similar NBR gloves. Batch-lot variability resulted in up to a twofold difference in the BT and up to fourfold differences in the cumulative mass permeated at 125 min. They found no relationship between the glass-transition temperature (an indicator of curing) and batch-lot variability in permeation through these gloves. Similar evidence can be found in the Forsberg and Keith's³ compendium of permeation and degradation data for CPC, in which large variations in BTs and SSPRs are reported for different CPC brands of similar materials.

Acrylonitrile (ACN) content variation in NBR gloves has been postulated as a factor in the variability in glove BTs and SSPRs among batch lots and different manufacturers.^{2,4} The speculation has also been made in the literature that the chemical resistance of nitrile gloves increases with increasing ACN content.^{5,6} More commonly, fuel and oil resistance has been known to increase with increasing ACN content from about 15 to 50%.^{7–10} Robertson et al.¹¹ presented preliminary data that indicated increasing the ACN monomer content from 26 to 39% resulted in a twofold increase in the BT of toluene through an NBR polymer. In contrast, Mueller¹² found that for the polar solvents methanol and methyl ethyl ketone, the permeability rate through NBR increased when the ACN content

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increased from 11 to 22%, although the permeability did not increase with increasing ACN content for two of the six organic solvents investigated. Thus, the chemical composition and properties should be considered when the chemical resistance of NBR gloves is evaluated. Furthermore, similar testing with aqueous pesticide formulations such as captan [i.e., *N*-trichloromethylthio-4-cyclohexene-1,2-dicarboximide (CASRN 133-06-2)] has not been conducted.

Common parameters of CPC chemical permeation performance include the normalized breakthrough detection time (NBT) and SSPR of American Society for Testing and Materials (ASTM) Method F 739-99a.¹³ The NBT is defined as the time at which the mass of the chemical permeated reaches 0.25 $\mu\text{g}/\text{cm}^2$ in a closed-loop test and 0.1 $\mu\text{g}/\text{cm}^2/\text{min}$ in an open-loop test. The SSPR is defined as the slope of the steady-state period ($\mu\text{g}/\text{cm}^2/\text{min}$).¹³

The ACN content can be analyzed in NBR gloves with infrared (IR) absorption spectrometry^{14,15} and with attenuated total reflectance/Fourier transform infrared (ATR-FTIR) spectrometry. In the latter, IR is used at $\text{C}\equiv\text{N}$ NBR bond stretching from 2200 to 2400 cm^{-1} .^{16,17} ATR-FTIR has also been used to measure the chlorine content in latex gloves.¹⁸

For ATR-FTIR, the depth of evanescent wave penetration (d_p), at which the intensity falls to about 13.5% of its value at the surface, is wavelength-dependent and can be estimated as follows:¹⁹

$$d_p = \frac{\lambda}{2\pi n_1 (\sin^2 \Theta - n_{12}^2)^{0.5}} \quad (1)$$

where λ is the IR wavelength of radiation, n_1 is the refractive index of the ATR crystal, n_{12} is the ratio of the sample refractive index to the ATR refractive index, and Θ is the angle of incidence ($^\circ$).

The sampling depth of the evanescent wave (d_s), at which the intensity falls to about 0.25% of its value at the surface, can be estimated as follows:¹⁹

$$d_s = 3d_p \quad (2)$$

With a Θ value of 45° and a refractive index of 2.42 for the diamond ATR crystal, d_p is about 0.8–1.1 μm at 2250 cm^{-1} for organic polymer materials with refractive indices between 1.5 and 1.6.²⁰ The sampling depth is therefore about 2.4–3.3 μm for such polymers. Popli and Dwivedi²¹ indicated the importance of an adequate sampling depth by showing potential polymer nonuniformity up to a distance of 0.5 μm from the surface.

The hypothesis of this study is that permeation resistance to the fungicide captan will increase with increasing ACN content. The specific aims were to (1) measure the ACN content in different disposable NBR glove brands and batches with ATR-FTIR, (2) conduct ASTM Method F 739 permeation testing of the pesticide captan through each glove material to determine the NBT and SSPR, and (3) perform multiple regression analysis of the ACN content, thickness, density, and mass-to-area ratio versus NBT and SSPR.

EXPERIMENTAL

Gloves and chemicals

The gloves were disposable, powder-free NBR exam gloves and clean-room gloves obtained from Fisher Scientific (Tustin, CA) and Life Guard (City of Industry, CA). The glove brands tested were Ansell, Best Manufacturing, Life Guard, Microflex, and Kimberly-Clark. The tested brands were coded as gloves A–F. The glove characteristics are presented in Table I. On the basis of previous ASTM Method F 739 permeation tests with captan, the palm regions of the gloves were tested.¹⁷ Poly(acrylonitrile-*co*-butadiene) reference materials with ACN contents of 10, 19–22, 30–35, and 37–39% (w/w) were obtained from Sigma-Aldrich (St. Louis, MO). The average weight percentage of acrylonitrile (ave-ACN) for each reference material was used to prepare a standard curve.

Analytical grade captan (99% purity) was acquired from Chem Service, Inc. (West Chester, PA). Captan 50-WP (48.9 wt % captan, 1.1% related derivatives,

TABLE I
Disposable NBR Gloves

Glove	Label description	Measured thickness (mm) ^a	Measured density (g/cm^3) ^b
A	Medical nitrile exam glove, powder-free	0.126 \pm 0.002	0.89 \pm 0.03
B, lot 1	Powder-free nitrile exam glove	0.113 \pm 0.002	1.08 \pm 0.03
B, lot 2	Powder-free nitrile exam glove	0.119 \pm 0.002	1.14 \pm 0.04
C	Powder-free nitrile exam glove	0.115 \pm 0.002	0.99 \pm 0.03
D	Powder-free nitrile exam glove	0.109 \pm 0.005	0.96 \pm 0.03
E	Powder-free nitrile exam glove	0.119 \pm 0.004	1.07 \pm 0.06
F	Nitrile clean-room glove, powder-free	0.107 \pm 0.003	0.98 \pm 0.05

^a $n = 60$.

^b $n = 6$.

and 50% inert ingredients) was obtained from Micro Flo Corp. (Memphis, TN). Certified ACS Plus nitric acid [used to prepare 10% (v/v) nitric acid to clean glassware] and Optima 2-propanol were from Fisher Scientific. Type I water from a Millipore (Marlborough, MA) Super-Q water deionizing system was used to prepare solutions of constant relative humidity (RH). Zero air (ultrahigh purity) and helium (99.999%) were from Air Products (Long Beach, CA).

A sodium dichromate (99.0%) saturated salt solution was prepared in Super-Q water to generate a $55 \pm 1\%$ RH atmosphere within a Pyrex vacuum desiccator (Fisher Scientific).²² RH was measured with a calibrated Control Co. Thermo-Hygro recorder (Fisher Scientific).

Equipment

IR spectra were obtained with a TravellIR portable ATR-FTIR analysis system (Smiths Detection, Danbury, CT), a single-beam spectrophotometer operated with SensIR QualID 1.40 and Omnic 6.0a software controlled by Windows XP. The crystal was a diamond in a single-reflection, horizontal ATR mode. The unit used a zinc selenide beam splitter. The spectral range was $4000\text{--}650\text{ cm}^{-1}$. The number of scans was optimized at 32 scans at a resolution of 4 cm^{-1} to account for the effects of background carbon dioxide and water on the reflectance spectra. Between each sample scan, the ATR crystal was cleaned with acetone and dried for 30 s, and a new background was collected under the same spectral conditions. A reading of 6 on the load pressure indicator ensured optimum intimate contact with the ATR crystal and was equal to $82 \pm 6\text{ kg/cm}^2$, as measured with a model BGI calibrated, direct-reading, portable force indicator with a model SBC 100 compression force sensor (Mark-10, Hicksville, NY).

Permeation testing was performed with an ASTM-type I-PTC-600 permeation cell (Pesce Lab Sales, Kennett Square, PA). The moving-tray shaker water bath used for the simultaneous immersion of the permeation cells was a Fisher Scientific model 127. Three copper-metal tubes ($35\text{ cm} \times 1.5\text{-cm o.d.} \times 1.3\text{-cm i.d.}$) were mounted across the two rails of the shaker after 1-mm-wide grooves were hacksawed into the bars and emery paper was used to smooth jagged edges. Three-prong clamps allowed the suspension of the permeation cells above and in the water as desired. Vernier calipers (Mitutoyo, Japan) facilitated the measurement of the glove dimensions, as did a digital micrometer screw gauge (L.S. Starrett Co., Athol, MA) for the glove thicknesses.

Glove density and thickness

The glove density was measured with the glove thickness, surface area, and mass data for 3.81-cm (1.5-in.)-

diameter disks cut from the palm region of six samples for each glove. The glove samples were conditioned overnight at $55 \pm 1\%$ RH before the thickness and mass measurements were collected. The glove disks were weighed with a Mettler AE 260 analytical balance (Fisher Scientific). Ten thickness measurements were taken for each glove sample.

ACN content

The poly(acrylonitrile-*co*-butadiene) reference materials were sliced into thin sections, conditioned overnight at $55 \pm 1\%$ RH, and analyzed by ATR-FTIR. The 10% ACN reference material was liquid, and a 100- μL drop was placed on the ATR crystal and covered it, without applied pressure. At least five measurements were made for each reference material. IR reflectance analysis was performed at $2237 \pm 5\text{ cm}^{-1}$, the absorbance maximum for the $\text{C}\equiv\text{N}$ NBR bond stretching (Fig. 1). As indicated in Figure 1, the $\text{C}\equiv\text{N}$ NBR region is free from interference for both the glove and reference material. In addition, this region is free from interference from water and carbon dioxide in air.^{23,24}

The outer and inner glove surfaces were measured to assess interferences from releasing agents and excess coagulants expected to be present on the surfaces. The outer surface often contained textured, rough surfaces. Thus, the inner surface provided a smooth surface for ATR-FTIR analysis.

Five gloves were selected randomly out of a box, and the inner surfaces were rinsed with 25-mL volumes of hexane five times to remove surface residues, as confirmed by an ATR-FTIR analysis of the cleaned surfaces. The palm region was cut from the gloves, air-dried, and conditioned overnight at $55 \pm 1\%$ RH. Reflectance spectra (Fig. 1) were collected at five ran-

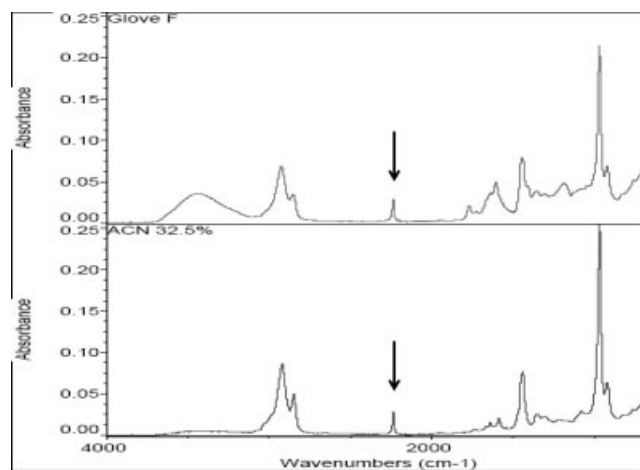


Figure 1 Sample IR reflectance spectra (from 4000 to 600 cm^{-1}) of glove F and the poly(acrylonitrile-*co*-butadiene) reference material with an ave-ACN value of 32.5%. The $\text{C}\equiv\text{N}$ NBR bond stretching region is indicated by the arrows.

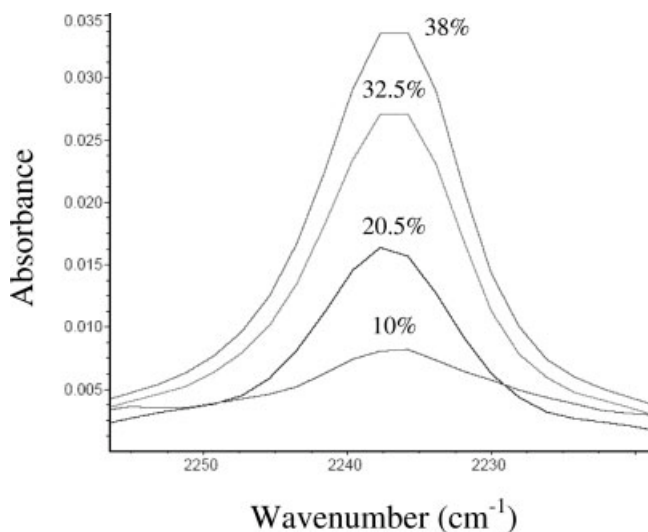


Figure 2 Sample IR reflectance spectra of the $C\equiv N$ NBR bond stretching region for poly(acrylonitrile-*co*-butadiene) reference materials with specific ave-ACN values of 10, 20.5, 32.5, and 38%. The IR reflectance measurements were taken at $2237 \pm 5 \text{ cm}^{-1}$.

dom locations of each sample and reference material. Mean absorbances and within-glove and between-glove precisions were compared at each of these absorbance maxima.

Permeation experiments

The detailed procedure used in this study is provided elsewhere^{25,26} and is based on ASTM Method F 739-99a.¹³ In summary, glove materials were conditioned overnight in a desiccator with $55 \pm 1\%$ RH. The material was held between two Teflon gaskets and the Pyrex chambers of the I-PTC-600 permeation cell by a uniform torque as specified by the manufacturer. A volume of 217 mg/mL of the captan formulation in water was equilibrated to $30.0 \pm 0.5^\circ\text{C}$ for 30 min, and this was followed by vortex mixing for 30 s before 10 mL was pipetted into the challenge side of each permeation cell. The three cells were immersed in the water bath at $30.0 \pm 0.4^\circ\text{C}$ with a horizontal shaking speed of $26.1 \pm 0.4 \text{ cm/s}$ to minimize the concentration gradients. This was confirmed by prior observation of the challenge solution opacity at different shaker speeds and permeation cell orientations. At permeation time intervals of 30, 60, 90, 120, 240, 360, and 480 min, a 100- μL aliquot of the collection solution was removed for analysis by gas chromatography/mass spectrometry (GC-MS). An analysis of the captan was performed with a previously described GC-MS method.²⁰

Quality assurance procedures included tests for leaking of the assembled permeation cell and challenge- and collection-side solvent back-diffusion as outlined elsewhere.^{25,26}

Statistical analyses

We used Student *t*, analysis of variance (ANOVA), correlation, and regression analyses in our statistical analyses and, when appropriate, nonparametric methods. The results were deemed significant if the *p* value was not larger than 0.05. In our study, at least triplicate samples were used to define arithmetic means, standard deviations (SD), and coefficients of variation (CV). Linear regression analyses allowed the calculation of slopes, *y* intercepts, corresponding SDs, Pearson correlation coefficient (*r*) values, and *p* values. Multiple regression, correlation, and ANOVA analyses were performed with Stata version 9 (StataCorp, College Station, TX). Tests for the normal distribution of individual variables were conducted with the Shapiro-Wilks, Shapiro-Francia, and skewness/kurtosis normality tests. When necessary, the transformation of variables was evaluated with ladders of powers, normal quantile plots, and Box-Cox regression analyses.

RESULTS AND DISCUSSION

ACN content

The IR reflectance results for the poly(acrylonitrile-*co*-butadiene) reference materials produced a linear standard curve between ave-ACNs of 10 and 38% with $r = 0.996$ ($p \leq 0.05$). Figure 2 shows the spectral region between 2200 and 2240 cm^{-1} . The maximum absorbance at $2237 \pm 5 \text{ cm}^{-1}$ was plotted versus the ave-ACN (w/w). The standard curve was then used to determine the ave-ACN within the NBR gloves.

The maximum absorbance of the glove samples at $2237 \pm 5 \text{ cm}^{-1}$ was similar to that of the reference materials, as shown in Figure 3, which uses the same

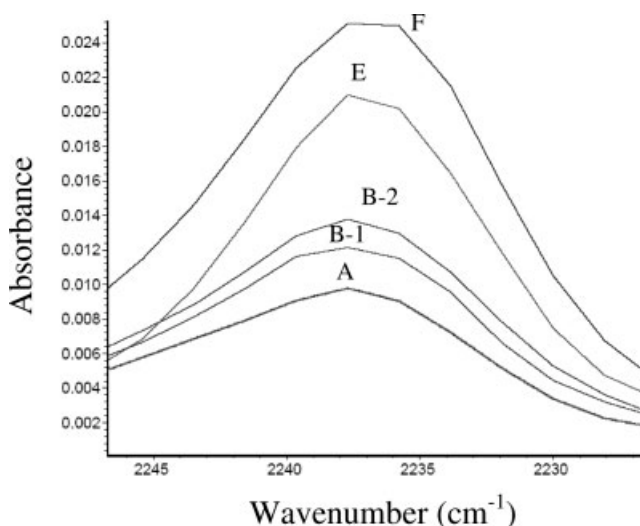


Figure 3 Sample IR reflectance spectra of the $C\equiv N$ NBR bond stretching region for disposable, powder-free NBR gloves A, B-1 (glove B, lot 1), B-2 (glove B, lot 2), E, and F. The IR reflectance measurements were taken at $2237 \pm 5 \text{ cm}^{-1}$.

TABLE II
ACN Contents for NBR Gloves

Glove	Ave-ACN (%) ^a	Average within-glove CV (%) ^a	Within-glove CV range (%)	Between-glove CV (%) ^a
A	12.7 ± 0.5	3.2	0.5–5.9	3.9
B, lot 1	14.8 ± 0.7	4.2	0.8–8.5	4.7
C	15.6 ± 0.8	2.4	0.5–6.9	5.1
B, lot 2	16.9 ± 0.7	3.0	1.3–4.3	4.1
E	18.0 ± 0.7	3.4	0.6–9.3	3.7
D	19.7 ± 4.7	17	1.2–31	24
F	29.9 ± 1.1	2.0	0.5–5.3	3.7

^a $n = 25$.

scale (cm^{-1}) as Figure 2. The ave-ACN value was significantly different among all glove samples ($p \leq 0.05$), including the two glove B lots (Table II). Clean-room glove F contained 34–58% more ACN than the other NBR exam gloves. This glove was selected because the label claim indicated that plasticizers, pigments, and fillers were not present in the glove, and this increased the available ACN content.

The measured ave-ACN values within the glove samples ranged from 12.7 to 29.9% (Table II), over a twofold difference. In contrast, Perkins and Pool² reported an ACN monomer content of 26–39%, before the addition of plasticizers, in thicker (3.8-mm) chemically protective NBR gloves. Robertson et al.¹¹ also reported ACN monomer contents ranging from 26 to 39% for NBR lattices used for gloves of unspecified thicknesses. The amounts of plasticizers and other additives were not reported in either of these studies. With the clean-room glove F excluded, the ACN contents of the disposable NBR exam gloves ranged from 12.7 to 21%, and this indicated (1) varying ACN contents of the NBR latex among the gloves and/or (2) variable plasticizer, pigment, and additive contents among these similar gloves.

The within-glove CVs for ave-ACN values for different regions of the glove palm were less than 10%

for all gloves except glove D. The average within-glove CV for glove D was 17% (range = 1.2–31%), and the between-glove CV was 24%. In contrast, all other between-glove CVs were less than 6%. For multiple regression analyses, an F test was conducted to test the equality of variances between all gloves.²⁷ Glove D did not meet the requirements for the homogeneity of variances ($p \leq 0.05$) and was excluded from the multiple regression analyses. These results indicated poor manufacture or lot quality for glove D.

Permeation testing

The results of the 8-h permeation tests are summarized in Table III. In general, the NBT increased and the SSPR decreased with increasing ACN content. Clean-room glove F with the highest ACN content had the highest NBT at 420 ± 120 min and the smallest SSPR at 0.0017 ± 0.0015 $\mu\text{g}/\text{cm}^2/\text{min}$. In contrast, glove A with the lowest ACN content had the lowest NBT at 35.9 ± 3.6 min and the largest SSPR at 0.40 ± 0.10 $\mu\text{g}/\text{cm}^2/\text{min}$.

Excluded glove D had the lowest NBT value of all the glove samples and the second highest SSPR, despite an ave-ACN value of about 20%. The glove quality and uniformity appeared to affect the glove permeation performance. Previous studies have used ATR-

TABLE III
ACN Contents and Captan Permeation Data for Disposable NBR Gloves^a

Glove	Ave-ACN (%)	NBT (min) ^b	SSPR ($\mu\text{g}/\text{cm}^2/\text{min}$) ^c	AD (g/cm^2)
A	12.7 ± 0.5	35.9 ± 3.6	0.40 ± 0.10	11.21 ± 0.01
B, lot 1	14.8 ± 0.7	75.2 ± 12.6	0.06 ± 0.03	12.20 ± 0.01
C	15.6 ± 0.8	59.7 ± 13.4	0.10 ± 0.08	13.57 ± 0.01
B, lot 2	16.9 ± 0.7	114 ± 43	0.10 ± 0.04	11.38 ± 0.01
E	18.0 ± 0.7	126.6 ± 2.2	0.06 ± 0.03	10.46 ± 0.01
D	19.7 ± 4.7 ^d	32.6 ± 3.4	0.38 ± 0.13	12.73 ± 0.02
F	29.9 ± 1.1	420 ± 120	0.0017 ± 0.0015	10.49 ± 0.01

^a ASTM Method F 739 permeation testing was conducted with an aqueous-emulsion, 217 mg/mL WP-50 captan formulation and with hexane as a collection solvent.

^b Time at which 0.25 $\mu\text{g}/\text{cm}^2$ captan was first detected in a closed-loop permeation test.

^c Linear slope of the permeation curve.

^d The within-glove CV ranged from 1.2 to 31%. All other glove brands and lots had CVs lower than 10%.

FTIR to assess the surface composition and homogeneity of acrylate and methacrylate copolymer blends,^{21,28} showing that IR reflectance can be used to assess polymer homogeneity for quality assurance. In this study, ATR-FTIR was useful in determining the uniformity of the ACN content within the NBR glove materials.

The average SSPR ranged from 0.002 to 0.40 $\mu\text{g}/\text{cm}^2/\text{min}$, a 200-fold difference. When clean-room glove F, with a high ACN content, was excluded, up to a sevenfold difference in the SSPR was then observed between the exam gloves. A 1.7-fold difference in the SSPR existed between the two glove B lots. For the average NBT, the differences were 12-, 3.5-, and 1.5-fold, respectively. These results were comparable to the previously reported 10-fold differences in the BT between glove brands and 2-fold differences in the BT between batch lots.^{1,2}

Multiple regression analysis

Tests for normality indicated that the transformation of the SSPR, thickness, and density variables was needed to meet the assumptions for regression analyses. Within the Box-Cox family of transformations, the log transformation of the SSPR was selected as optimal with Stata. The resulting plot of the logarithm base 10 of the SSPR, called here log SSPR, versus the ave-ACN value was linear with $r = 0.9216$ ($p \leq 0.05$). The thickness and density variables were not easily transformed. However, the product of the thickness and density resulted in a measure of the mass-to-area ratio (g/cm^2), called here the area density (AD), that was normally distributed. Thus, final regression analyses were performed for both the NBT and log SSPR versus the glove ave-ACN and AD values.

A significant inverse correlation existed between the NBT and log SSPR with $r = -0.9031$ ($p \leq 0.05$). In comparison, a similar correlation between the NBT and log SSPR has been observed for alkylbenzene isomers through chemically protective NBR gloves with $r = -0.69$ ($p \leq 0.05$).²⁹ Also, a correlation between the NBT and lag time has been reported for xylene isomers through chemically protective NBR gloves with $r = 0.748$ ($p \leq 0.025$).³⁰ Similarly, these studies all used hexane as a collection solvent and closed-loop permeation tests with no indication of degradation or swelling. This type of relationship between the NBT and SSPR may not exist for other types of permeation systems, as described in ASTM Method F 739.¹³

A significant correlation was also present between the thickness and log SSPR with $r = 0.8289$ ($p \leq 0.05$). Assuming Fick's first law is obeyed, we can relate the square of the thickness to the lag time:³¹

$$\text{Lag time} = L^2/6D \quad (3)$$

where L is the thickness (cm) and D is the diffusion coefficient (cm^2/s). From the linear plot of the mass

permeated per unit of area ($\mu\text{g}/\text{cm}^2$) versus time (s), the lag time is related to the SSPR by the following expression:

$$\text{Lag time} = -b/\text{SSPR} \quad (4)$$

where b is the y intercept ($\mu\text{g}/\text{cm}^2$) of the linear steady-state plot. Substituting for the lag time, the SSPR is related to the thickness:

$$\text{SSPR} = -6bD/L^2 \quad (5)$$

The resulting correlation between log SSPR and the inverse square of the thickness was $r = -0.8374$ ($p \leq 0.05$), which suggests that the product of the y intercept and diffusion coefficient did not vary significantly between the different glove permeations for captan. Further research is needed to evaluate the relationships between the SSPR, lag time, thickness, and diffusion coefficient.

The correlation between the NBT and thickness was $r = -0.6626$ ($p \leq 0.05$). In this model, the thickness only explained 44% of the variance. The range of thicknesses was narrow, and the thickness was not normally distributed. The thickness was not used as a variable in multiple regression analyses. No significant correlations were found between the density and the parameter thickness, ave-ACN, NBT, and log SSPR.

Multiple regression analyses resulted in significant correlations ($p \leq 0.05$) between

1. The ave-ACN value and AD inversely with log SSPR.
2. The ave-ACN value and AD directly with the NBT.

The ave-ACN value and AD were correlated with log SSPR with $r = 0.9227$ ($p \leq 0.05$):

$$\log \text{SSPR} = (-0.136 \times \text{ave-ACN}) - (0.050 \times \text{AD}) + 1.71 \quad (6)$$

When AD was excluded, the correlation between ave-ACN and log SSPR was still robust, with $r = 0.9216$ ($p \leq 0.05$). With data provided by Brun et al.³² for NBR membranes, a correlation ($r = 0.9993$, $p \leq 0.05$) was observed with ACN contents ranging from 51 to 75% with the liquid-gas permeation of butadiene. Comparable studies using liquid-liquid permeation testing and lower ACN contents were not available.

The ave-ACN and AD values were correlated with the NBT with $r = 0.9471$ ($p \leq 0.05$):

$$\text{NBT} = (24.4 \times \text{ave-ACN}) + (122 \times \text{AD}) - 447 \quad (7)$$

This indicated that ave-ACN and AD accounted for about 90% of the NBT variation. On average, the NBT

increased by about 120 min for every 5% increase in ave-ACN. Robertson et al.¹¹ reported a twofold increase in the BT associated with a 13% increase in ACN for the permeation of toluene through an NBR polymer. Thus, the ACN content of an NBR polymer is an important factor and should be included in the CPC selection process when chemical permeation and breakthrough are expected to occur.

Although the ACN content and AD were shown in this study to play significant roles in the permeation resistance of commercial NBR gloves, with the model accounting for about 85–90% of the variation, additional factors may also affect NBR glove performance. The addition of fillers, pigments, and plasticizers will reduce the ACN content. Thus, further research is needed to determine the influence of these parameters, as well as the properties of the curing process (e.g., glass-transition temperature and crosslinking density)^{2,33} and other NBR properties that can be measured with standardized tests.^{34,35} It is to be noted, however, that Perkins and Pool²³ did not find a relationship between the glass-transition temperature and batch-lot variability in permeation through chemically resistant NBR gloves.

CONCLUSIONS

Over a twofold difference in the ACN content was observed for the disposable NBR gloves examined. The permeation results indicate that the ACN content plays a significant role for both the SSPR and NBT during captan permeation through NBR gloves. Increasing the ACN content resulted in longer NBTs and decreased the SSPR. Regression analyses also revealed that the ACN content explained a significant amount of the variation in both the NBT and SSPR between disposable NBR glove brands and batch lots. In addition, ATR-FTIR was useful in determining NBR polymer surface homogeneity and has potential application in quality assurance testing during the manufacturing process and by end users in the CPC selection process. Further research is needed to assess the influence of the ACN content on the permeation of different chemical classes through NBR gloves and other CPC. In addition, further research is needed to examine the influences of other chemical and mechanical properties of NBR gloves on chemical permeation.

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