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Original article

Evaluating the Protective Effectiveness of Rubber Glove Materials Against Organic Solvents Upon Repeated Exposure and Decontamination

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ABSTRACT

Background: Glove reuse poses risks, as chemicals can persist even after cleaning. Decontamination methods like thermal aeration, recommended by US OSHA, vary in effectiveness. Some studies show promising results, while others emphasize the importance of considering both permeation and tensile strength changes. This research advocates for informed glove reuse, emphasizing optimal thermal aeration temperatures and providing evidence to guide users in maintaining protection efficiency.

Methods: The investigation evaluated Neoprene and Nitrile gloves (22 mils). Permeation tests with toluene and acetone adhered to American Society for Testing Materials (ASTM) F739 standards. Decontamination optimization involved aeration at various temperatures. The experiment proceeded with a maximum of 22 re-exposure cycles. Tensile strength and elongation were assessed following ASTM D 412 protocols. Breakthrough time differences were statistically analyzed using *t*-test and ANOVA.

Results: At room temperature, glove residuals decreased, and standardized breakthrough time (SBT)₂ was significantly lower than SBT₁, indicating reduced protection. Higher temperature decontamination accelerated residual removal, with Δ SBT (SBT₂/SBT₁) exceeding 100%, signifying restored protection. Tensile tests showed stable neoprene properties postdecontamination. Results underscore thermal aeration's efficacy for gloves reuse, emphasizing temperature's pivotal role. Findings recommend meticulous management strategies, especially post-breakthrough, to uphold glove-protective performance.

Conclusions: Thermal aeration at 100°C for 1 hour proves effective, restoring protection without compromising glove strength. The study, covering twenty cycles, suggests safe glove reuse with proper decontamination, reducing costs significantly. However, limitations in chemical-glove combinations and exclusive focus on specific gloves caution against broad generalization. The absence of regulatory directives on glove reuse highlight the importance of informed selection and rigorous decontamination validation for workplace safety practices.

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1. Introduction

Concerns have been raised in the field regarding the feasibility of reusing gloves. On the fourth day following initial contact, the

pesticide acetamiprid was found to be released from both neoprene and nitrile gloves [1]. After exposure, significant amounts of benzoic acid could be extracted from nitrile and latex glove materials [2]. Latex gloves, reused by turning inside-out after water cleaning,

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showed insufficient protection according to biomonitoring of the aromatic diamines *p*-toluenediamine (PTD) and *p*-phenylenediamine (PPD) in hairdressers' urine [3]. Additionally, polycyclic aromatic hydrocarbons (PAHs) were detectable in fire turnout jackets even after decontamination [4]. Available evidence suggests that the decontamination process may not be effective and could potentially increase the absorption of toxic substances through a phenomenon known as "wash-in" [5]. Increasing permeation rates were reported in experiments involving intermittent contact with chemicals without decontamination [6]. Therefore, exercising caution while reusing gloves without proper decontamination is of utmost importance [1,2].

The US OSHA recommends employing forced air circulation with heated air over protective clothing for extended durations to eliminate internal or matrix contamination [7]. This process facilitates the migration and evaporation of many volatile organic chemicals from the materials. It's crucial to note that the effectiveness of this method relies on the volatility of the contaminating chemicals. Thermal decontamination has proven effective in removing contaminants from elastomers' matrices [8]. A study demonstrated the efficiency of thermal aeration in eliminating toluene and acetone from neoprene and nitrile synthetic rubber gloves [9]. Aeration at 100°C for 24 hours removed 99% of trapped ethyl acetate from a unique nitrile butadiene rubber glove with nanocomposite clay material exposed to ethyl acetate [10]. According to Gao et al. [11], after 11 repeated cycles, thermal decontamination led to a 9% increase in the mean breakthrough time and a 2% decrease in the mean steady-state permeation rate. Neoprene gloves, re-exposed to a mixture of *N,N*-dimethylformamide, and methyl ethyl ketone in a 5-day cycle, maintained protection efficacy comparable to new gloves through aeration decontamination at 70 or 100°C [12].

Including textile tensile strength in glove certification could enhance the evaluation of glove integrity and performance [13,14]. The tensile strengths vary among disposable nitrile gloves due to the elastomer formulations and serve as parameters in evaluating glove degradation [13]. Tensile property changes have been used to indicate material degradation in protective gloves under real-world usage conditions. For example, Douglas et al. [15] assessed alterations in the tensile strength and barrier integrity of various medical gloves during hospital clinical use. Chemicals and heat significantly affect the tensile properties. The elastic modulus of the nitrile exam gloves was considerably damaged by using an ethanol-based hand rub, diluted bleach, or soap [16]. The changes in nitrile and latex gloves' tensile strength increased with the number of alcohol-based hand rub (ABHR) applications [17]. Heat levels significantly decreased the tensile strength of firefighters' bunker gear [18]. Tensile strength and ultimate elongation are consistently reduced with the number of re-exposure cycles with heat decontamination [14]. Effective decontamination should consider both permeation and tensile property changes.

This study aims to demonstrate the efficacy of aeration at various temperatures and recommend optimal thermal decontamination. We assessed glove reusability by analyzing permeation (standardized breakthrough time) and physical strength (tensile strength). Through scientific evidence, our research informs glove users about suitable methods for reuse while maintaining the expected protection efficiency.

2. Materials and methods

2.1. Gloves and chemicals

This study focused on two chemical protective gloves: Neoprene (Mapa® Stanzoil® N360, Category No.: 406950, Colombes Cedex,

France) and Nitrile (Mapa® Stansolv® A14, Category No.: 474019, Colombes Cedex, France). Both gloves share a length of 35.5 cm and a thickness of 22 mils. As per the manufacturer's test data, both gloves demonstrate breakthrough within 30 minutes when exposed to toluene and acetone.

The challenge chemicals for permeation tests were toluene (CAS: 108-88-3, grade purity: 99%, TLV®-TWA 20 ppm, vapor pressure: 21 mm-Hg, MW 92.14 g/mol, logK_{ow} 2.73) and acetone (CAS: 67-64-1, grade purity 99%, TLV®-TWA 250 ppm, vapor pressure: 180 mm-Hg, MW 58.08 g/mol, logK_{ow} -0.24). These two chemicals were the representative test chemicals for aromatic hydrocarbons and ketones by EN ISO 374-1:2016 [19]. Additionally, toluene is known to be absorbed through the skin, as indicated by Taiwan's OSHA skin notation criteria. Acetone was able to penetrate the skin [20].

2.2. Apparatus

The 2-inch ASTM-type permeation test cells (PTC-200) were sourced from Pesce Lab Sales, Inc. (Kennett Square, PA, USA), establishing an exposed glove material area of 20.26 cm². A Universal Tensile Testing Machine (Universal Testing System 3400 Series, INSTRON®, Norwood, MA, USA) was used for the tensile strength test.

The chemical analysis utilized a ToxicRAE pocket PID, PGM-30 (RAE Systems, Inc., CA, USA), with a lamp of 10.6 eV to detect the permeation of toluene and acetone. The detection range was 0.1–2,000 ppm, with a response time of 0.1 seconds. The resolution levels were 0.1 ppm for concentrations ranging from 0–99.0 ppm and 1 ppm for 100–2,000 ppm. The photoionization detector (PID) was calibrated using clean, dry air for zero calibration and 100 ppm isobutylene gas for span calibration before experiments. As the manufacturer's specifications, the correction factors were 1.1 for acetone and 0.5 for toluene [21]. This means the quantified ranges were 0.11–2,200 for acetone and 0.05–1,000 ppm for toluene. Hence, this study established the upper quantitative limit at 1,000 ppm for both chemicals. The data log capacity encompassed 4,000 records.

2.3. Methods

2.3.1. Permeation experiments

The permeation test employed an open-loop system adhering to ASTM F739-99 standards [22], as depicted in Fig. 1. Briefly, either the palm or back parts of the glove materials were shaped into 10 cm diameter circles. After washing with distilled water, specimens were conditioned in a desiccator for 24 hours at 25°C with a relative humidity of 30% to 80%, preparing them for permeation tests. The glove sample was placed between Teflon gaskets in the permeation apparatus. Two glass chambers, inserted into aluminum flanges and secured with torque-wrenched nuts, divided the test cell into two chambers. Preheated helium (He) at 100 mL/min flowed into the collection chamber (volume 100 mL) as the collection medium. In open-loop testing, the recommended flow rate is 50–150 mL/min for adequate mixing [22]. The PID detector monitored challenge solvent breakthrough by reading concentrations within the downstream He gas at 10-second intervals. The liquid challenge chemical was poured into the chamber up to the fill mark, covering the test sample's entire surface. The water bath system maintained the test temperature at 23 ± 1°C. The permeation test commenced with the challenge solution filling (0 minute). PID readings were continuously recorded and downloaded after the completion of each permeation experiment.

The permeation rate (P_i) at any time (T_i) was calculated using the formula $(C_i \times F)/(\text{exposed area})$ where C_i represented the

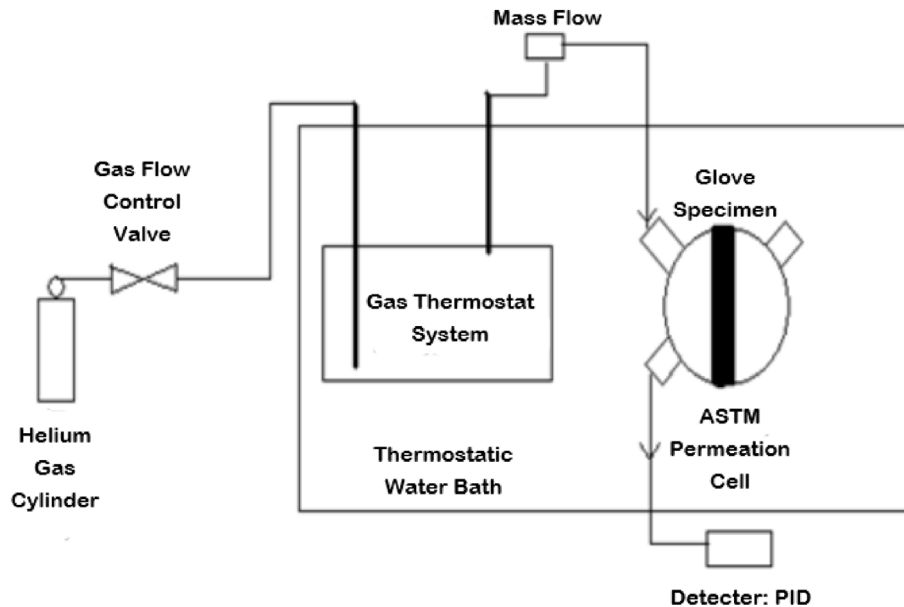


Fig. 1. Configuration of open-loop permeation experiment: The collection medium, continuous helium flow at 100 mL/min.

concentration of the challenge chemical in the collection medium (He) at T_i , F denoted the flow rate (100 mL/min), and the exposed area amounted to 20.26 cm². Permeation experiments were stopped when the permeation rate reached 0.1 $\mu\text{g}/\text{cm}^2/\text{min}$; at this point, the standardized breakthrough time (SBT) was recorded according to the ASTM F739-99 definition [22]. Following this criterion, when the PID readings indicated 10.8 ppm for toluene and 7.8 ppm for acetone, the experiment was promptly halted, and the corresponding time was recorded as the SBT.

2.3.2. Decontamination procedures

Post-experiment conclusion, specimens were taken from permeation cells and stored at room temperature. Initial measurements of challenge solvent concentrations on the surface facing the collection medium were conducted. Thermal decontamination was then carried out at varying temperatures (23°C, 40°C, 70°C, and 100°C) using a controlled oven (Model THS-A2-150, King Son Instrument Inc., New Taipei City, Taiwan) to determine the optimal temperature and duration. The time needed to reach a surface concentration of ND (0 ppm, i.e. below the limit of detection) was recorded. Subsequently, specimens were re-exposed to the challenge solvent, following the previously outlined permeation experiment setup.

2.3.3. Tensile strength and elongation analysis of the glove specimens

The tensile and elongation tests were conducted following the ASTM Method D 412 Standardized Test Methods for Vulcanized Rubber and Thermoplastic Elastomers – Tension Protocol [23], employing a universal tensile testing machine (Universal Testing System 3400 Series, INSTRON®, Norwood, MA, USA). The specimen was placed in the grips of the testing machine, and the tension was distributed uniformly over the cross-section. The rate of grip separation was 500 mm/min. The distance between the benchmarks was observed carefully to avoid parallax. The force (F in Kgf) at the time of rupture was recorded. The tensile strength T (Kgf/cm²) was obtained by F/A , where A was the cross-sectional area of the unstrained specimen in cm². Elongation was determined by dividing

the change in the test sample length ($L-L_0$) by the initial measurement (L_0), i.e., $E = 100 (L-L_0)/L_0$, subsequently expressed as a percentage (%). The tensile strength was measured both before and at the end of the repeated exposure permeation test.

2.4. Statistical analysis

Statistical analyses were conducted using MS Excel 2019 to process measurements and analyze data. To evaluate differences in STBs across repeated exposures, the student's t-test and one-way analysis of variance (ANOVA) were employed. Statistical significance was determined at a p -value <0.05.

3. Results

3.1. Preliminary assessment of residuals on the neoprene glove surfaces

Three neoprene glove specimens were exposed to toluene, resulting in an average SBT of 11.2 ± 0.44 minutes. Post-challenge solution removal, the specimens were placed in permeation cells at $23 \pm 1^\circ\text{C}$. Monitoring of residual toluene on the inner glove surface, facing the collection chamber, occurred at 2, 24, and 120 hours, revealing concentrations ranging from above 1,000 ppm to 0.5 ± 0.1 ppm (Table 1). PID readings reached 0 ppm at 168 hours (7 days), assuming no detectable residuals for the subsequent permeation experiments. After toluene removal, the initial permeation rate was $18.6 \mu\text{g}/\text{cm}^2/\text{min}$, elevated by glove surface residual permeation. Residuals decreased to 12.9 ± 1.7 ppm after 24 hours and further to 0.5 ± 0.1 ppm over 120 hours (Fig. 2). All second SBTs (SBT₂) were significantly shorter than the first (SBT₁), experiencing an approximately 83.7% reduction, with statistical significance at a p -value <0.05.

Similar patterns were noted in the neoprene/acetone combination (Table 1). Acetone concentrations on the inner surface of the gloves significantly spiked, reaching the PID's upper quantitative limit of 1,000 ppm after exposure to challenging chemicals. This suggests the persistent diffusion and desorption of chemical

Table 1
Surface residual monitoring of neoprene gloves (23°C)

Runs	1st permeation test SBT ₁ (min)	Time after 1st permeation test (hours)				2nd permeation test SBT ₂ (min)
		0	2	24	60 /120	
Residual concentrations (ppm)						
Toluene						
1	11.4	>1,000	603.0	14.0	0.4	9.5
2	11.5	>1,000	420.0	13.8	0.5	9.1
3	10.7	>1,000	276.0	11.0	0.6	9.5
MEAN ± SD	11.2 ± 0.4	>1,000	433.0 ± 163.9	12.9 ± 1.7	0.5 ± 0.1	9.4 ± 0.2*
Acetone						
1	20.8	>1,000	108.0	1.3	0	0.3
2	19.5	>1,000	177.3	3.5	0	0.3
3	20.4	>1,000	174.9	3.0	0	0.2
MEAN ± SD	20.2 ± 0.7	>1,000	153.4 ± 39.3	2.6 ± 1.2	0 ± 0	0.3 ± 0.01*

SBT, standardized breakthrough time.

* The differences between SBT₁ and SBT₂ were significant at p -value <0.05.

† The acetone surface concentration reached “zero” after 60 hours.

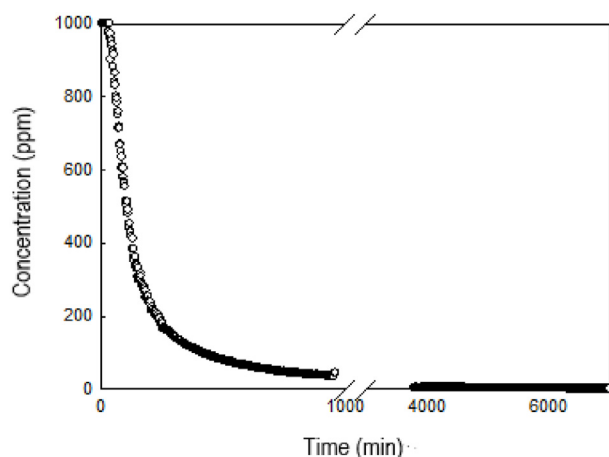


Fig. 2. Decay of residuals on the glove interior surface (the collection chamber of the permeation cell) at 23°C (test combination: neoprene/toluene).

molecules from the internal part of the glove material to its inner surface, continuing the permeation process. Over time, surface concentrations declined, and after 24 hours, the residual acetone concentration dropped to 2.6 ± 1.2 ppm. Notably, SBT₂s accounted for only 1.7% of the SBT₁s, underscoring that the protective effect endured for less than 2% of the breakthrough time of brand-new gloves. This implies that some chemicals were entrapped within the polymers, failing to effectively vaporize at room temperature. If the glove were reused in this manner, chemical breakthrough would occur more rapidly.

3.2. Temperature effects on decontamination

3.2.1. Decontamination time across different temperatures

Apart from 23°C, decontamination was conducted at three additional temperatures: 40°C, 70°C, and 100°C. After the first permeation experiments, specimens were aerated at these temperatures, and surface chemical concentrations were tracked until PID readings indicated ‘zero’ (Fig. 3). The duration to achieve ‘zero’ surface contamination declined with rising temperature: 16 hours at 40°C, 2 hours at 70°C, and 1 hour at 100°C. Gloves are the final defense against dermal exposure to organic solvents in occupational settings. After tasks, gloves are often doffed but not immediately discarded; they could be stored at room temperature for

future use. Our findings reveal that when gloves encounter breakthroughs, a significant timeframe (approximately 60 to 120 hours) is necessary for solvent volatilization within glove materials at 23°C. Elevated temperatures accelerate the removal of solvents from glove polymers, thereby efficiently restoring their protective effectiveness. Thermal aeration is crucial for accelerating the restoration of protective performance, warranting attention to glove management strategies.

3.2.2. Changes in the standardized breakthrough times following decontamination at various temperatures

After optimizing decontamination durations at various temperatures (refer to Fig. 3), permeation tests were conducted pre- and post-decontamination at 40°C for 16 hours, 70°C for 2 hours, and 100°C for 1 hour. Means and standard deviations of SBTs are detailed in Table 2. Δ SBT (%) was calculated as the SBT₂ to SBT₁ ratio (as shown in Fig. 4). Most substantial differences emerged at 23°C, surpassing variations at different temperatures. For neoprene/toluene, Δ SBT was 83.9% at 23°C (Table 1), while others ranged from 95.3% to 102.8%. In neoprene/acetone, Δ SBT was 46.5% at 23°C, with other results spanning 98.6% to 102.7%. After 100°C decontamination, Δ SBTs for toluene and acetone in neoprene and nitrile gloves exceeded 100%. Elevated temperature expedited residual removal by enhancing chemical movement within gloves. A Δ SBT of approximately 100% suggests the protection of reused gloves resembles that of new ones post-heating decontamination. However, Δ SBT for nitrile gloves showed a larger variation than neoprene, possibly due to differences in glove manufacturing quality.

3.3. Tensile tests of the neoprene gloves

The neoprene glove, exhibiting greater stability than the nitrile counterpart in terms of STB and Δ SBT (Fig. 4), underwent tensile testing postpermeation with toluene and acetone. Subsequent decontamination at various temperatures (23°C, 40°C, 70°C, and 100°C) for 24 hours was conducted. Strength (Kgf/cm²) and elongation (%) were parameters for tensile properties (Fig. 5). No elongation values reduced beyond -2% post-decontamination. An inverse correlation for acetone showed a strength reduction from -12.7% (23°C) to -20.5% (100°C), while toluene exhibited no significant trend. A two-way ANOVA indicated no significant effect of temperature or chemicals on elongations or tensile strength (p -value >0.05). This suggests that heat does not significantly alter the physical characteristics of the glove rubber materials.

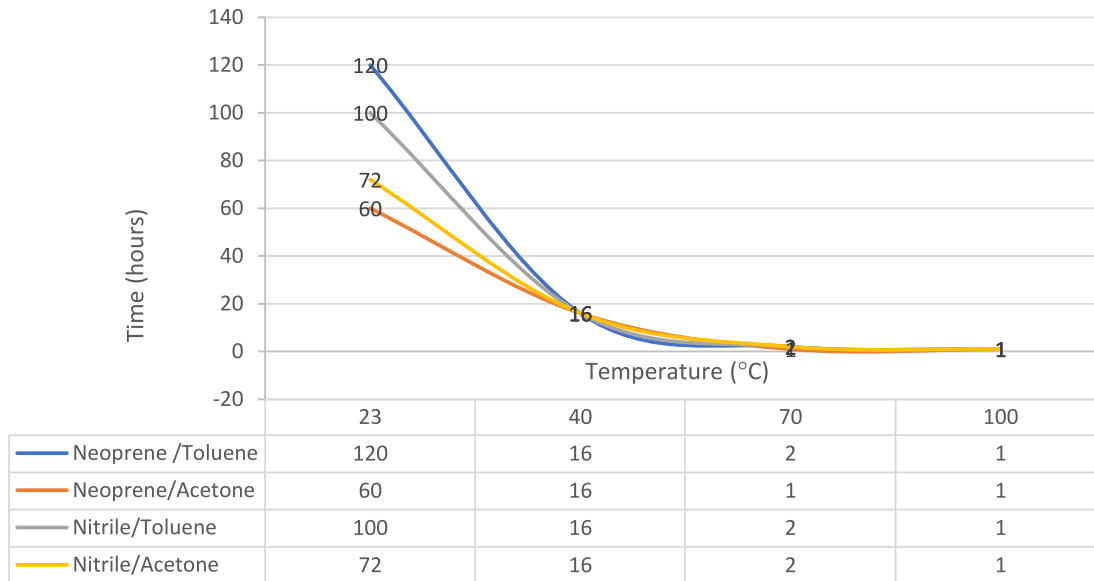


Fig. 3. Time to attain 'zero' chemical concentrations on glove interior surfaces at different temperatures.

Table 2

The standardized breakthrough time (in minute) of the 1st (SBT₁) and 2nd (SBT₂) permeation tests with decontamination at different temperatures

Decontamination condition	Neoprene/Toluene		Neoprene/Acetone		Nitrile/Toluene		Nitrile/Acetone	
	SBT ₁ [†]	SBT ₂ [†]	SBT ₁ [†]	SBT ₂ [†]	SBT ₁ [†]	SBT ₂ [†]	SBT ₁ [†]	SBT ₂ [†]
40°C, 16 hrs.	10.3 ± 0.5	9.9 ± 0.2	20.6 ± 1.1	21.2 ± 1.1	46.4 ± 3.8	40.8 ± 6.9	12.8 ± 0.5	9.7 ± 2.2
70°C, 2 hrs.	10.8 ± 0.6	10.6 ± 0.5	21.3 ± 1.2	21.0 ± 0.4	57.7 ± 9.1	31.2 ± 8.2	13.4 ± 0.4*	11.5 ± 0.7*
100°C, 1 hr.	10.5 ± 0.1	10.8 ± 0.3	20.1 ± 1.2	20.4 ± 0.1	46.8 ± 3.5	51.7 ± 6.8	12.9 ± 0.1	13.1 ± 0.3

SBT, standardized breakthrough time.

* Significant difference with *p*-value <0.05.

[†] The SBT₁ and SBT₂ were expressed as mean ± standard deviation with the data from triplicate tests.

3.4. Repeated exposure to the neoprene gloves

The neoprene/toluene combination was chosen to validate the maximum repeated exposure cycle for assessing the stability of physical characteristics. Following the optimized results in Fig. 3, identical glove samples underwent a 1-hour decontamination at 100°C to eliminate residuals. Subsequently, the samples were exposed to toluene again for the permeation tests. This exposure and decontamination cycle was repeated 22 times with 5 glove samples. Fig. 6 depicts the trends in SBT and ΔSBT (%) during repeated decontamination cycles, utilizing the means derived from five glove samples. The mean SBTs were 10.4 ± 0.5 min for new swatches, 9.8 ± 1.0 min for the 10th cycle, and 9.0 ± 0.6 min after 22 cycles. SBT changes consistently remained below 15% throughout the 22 cycles. The one-way ANOVA results revealed a *P*-value of 0.0483, suggesting significance close to the threshold. Tukey's honest significance test indicated no significant difference in SBT between each cycle. When excluding the 22nd cycle, the *P*-value increased to 0.0653, implying insignificant variation in SBTs. A prior study demonstrated that breakthrough time did not significantly change for the neoprene/toluene combination under identical decontamination conditions [9]. However, it is crucial to note the differing glove thicknesses.

4. Discussions

Gloves are frequently reused in the field without effective decontamination, raising concerns about their protection efficacy.

Recommended decontamination methods include heated air, hot water, cleaning agents, and liquid laundry detergent with water. Unfortunately, both manufacturers and protective clothing authorities provide few specific recommendations. There is no definitive list with specific methods for particular chemicals and materials, as it depends on the individual chemical-material combination involved.

Firstly, our findings confirm that glove materials provide varying levels of protection against different chemicals. Toluene exhibited an earlier breakthrough than acetone in the tested nitrile glove (see Table 1), while nitrile demonstrated the reverse pattern (see Table 2). The permeation behavior is influenced by factors such as diffusivity and solubility [24]. Additionally, variations could be attributed to differences in molecular size and polarity. Breakthrough times (BTs) appear to be influenced by the molar volumes and octanol-water partition coefficients (logK_{ow}), serving as a surrogate for the polarity and solubility of the chemicals [24,25]. This limitation applies to the application of any single research result. The glove permeation data were restricted to each particular combination, and they cannot be extrapolated to different chemicals or different gloves.

The glove materials effectively retained substantial quantities of toluene and acetone in this study. A previous study highlighted significant extractable chemicals in both latex (27%) and nitrile gloves (64%) following exposure to 40 mg/mL benzoic acid for 48 hours [2]. Under room temperature (23°C), toluene molecules required 120 hours (5 days) to dissipate most residuals from the polymers effectively. In contrast, acetone molecules accomplished this in just 60 hours (2.5 days), notably quicker than toluene

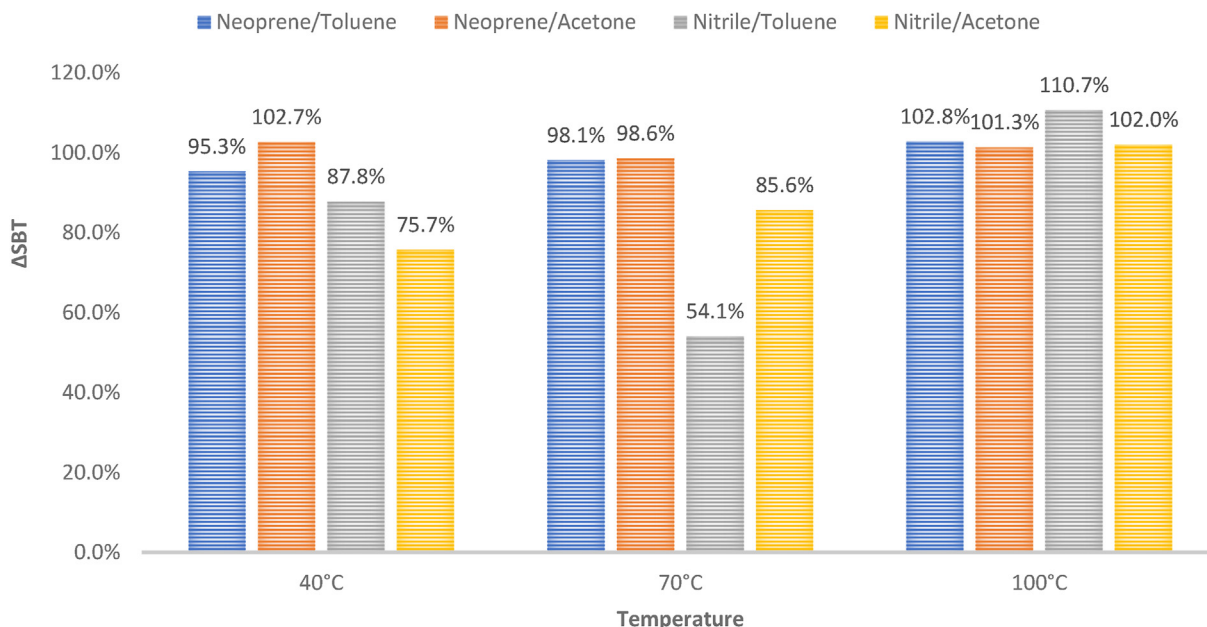


Fig. 4. Change in SBT (% Δ SBT) following decontamination at various temperatures

Δ SBT (%) = $(SBT_2/SBT_1)\%$; SBT_1 was the SBT of the 1st permeation test, and SBT_2 was the SBT of the permeation test after decontamination. SBT, standardized breakthrough time.

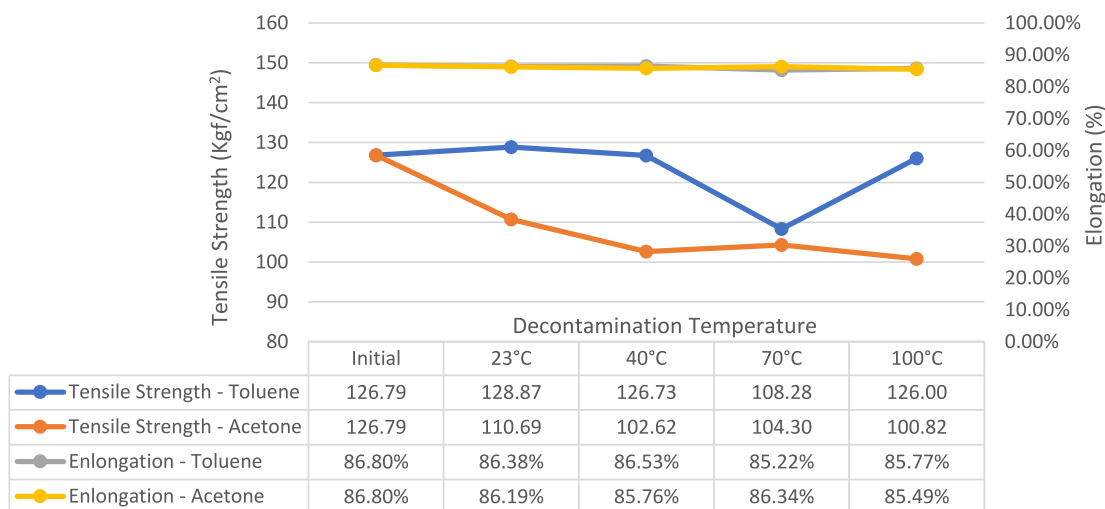


Fig. 5. Tensile test results of neoprene gloves following initial permeation tests and 24-hour decontamination at various temperatures.

molecules. In a study examining gasoline, diesel, bioethanol, and biodiesel permeation [26], the composition of permeated vapors showed enrichment in components with high vapor pressure. This observation suggests that chemicals possessing high vapor pressure evaporate more rapidly from materials. Consequently, the decontamination process for acetone, with a high vapor pressure of 180 mm-Hg, is shorter than that for toluene, which has a vapor pressure of 21 mm-Hg.

SBT_2 s were shorter than SBT_1 s for both challenge chemicals when subjected to aerial decontamination at 23°C. In a re-exposure cycle spanning 5 days, gloves decontaminated through aeration at 25°C exhibited reduced breakthrough times for N, N-dimethylformamide (DMF), and methyl ethyl ketone (MEK), as compared to new, unexposed gloves [12]. The indication of a “zero” PID reading does not guarantee the absence of substances on the surface or within the polymer of glove materials. Our study was

unable to detect chemical molecules confined within the polymers. This suggests that these molecules were captured by the glove polymers and partitioned between the chemical flux and the polymer following the initiation of the second permeation experiment. The trapping phenomenon was particularly pronounced for acetone in neoprene gloves. Neoprene gloves are derived from the free-radical polymerization of chloroprene ($CH_2=CCl-CH=CH_2$), with chlorine as a polar site that attracts polar molecules like acetone, as observed in this investigation. The partition coefficient $\log K_{ow}$, a surrogate of polarity, might be critical in the interaction between chemicals and gloves material [25,27,28].

The variations in Δ SBT% diminished with increasing decontamination temperature, as depicted in Fig. 4. All Δ SBT% values surpassed 90% (ranging from 91.5% to 102.0%) for decontamination at 100°C. Aeration was determined to be as effective as or even more effective than alternative methods like water washing, dry

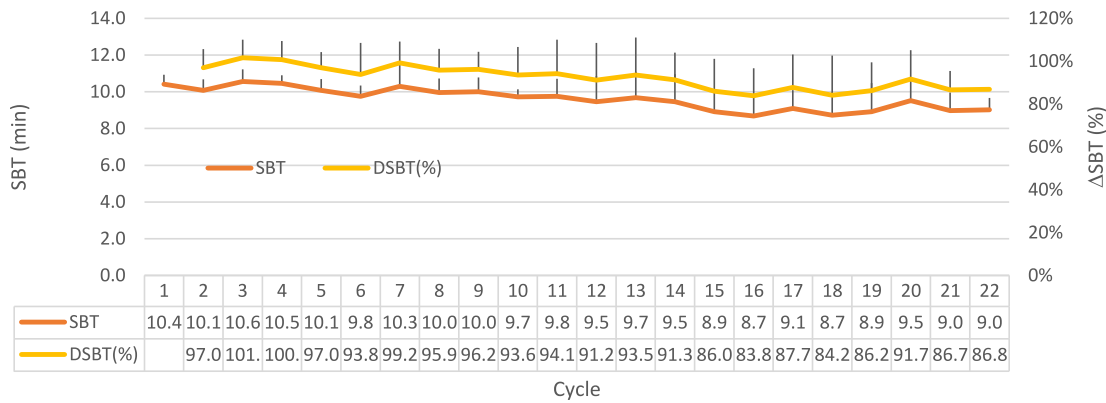


Fig. 6. Trends in mean SBT and Δ SBT (%) for neoprene gloves with repeated toluene exposure and 1-hour 100°C decontamination. SBT, standardized breakthrough time.

cleaning, and Freon cleaning, according to Ziskin et al. [29]. Specifically, 'hot air' aeration shows heightened effectiveness, particularly when temperatures exceed 38°C. Similarly, Gao et al. reported insignificant differences in the breakthrough times of repeated exposure cycles following thermal decontamination at 100°C for 16 hours, involving neoprene gloves are challenged with acetone and toluene [14]. By supplying the required activation energy per the Arrhenius relationship, heat application accelerates solvent evaporation from the glove surface and molecular movement within the polymer [30]. As a result, the diffusion process from the inside of the glove materials to the surface is accelerated.

No notable distinctions were observed in the tensile strength and change in elongation (%) across various temperatures and chemicals. Aerating neoprene gloves at high temperatures does not diminish their strength, as shown by this study. Neoprene rubber can be safely used in applications with temperatures up to 121°C [31]. Repeated applications of alcohol-based handrub altered the strength and elongation properties of various medical exam nitrile gloves, while no such effects were observed on latex gloves [17]. The chemicals altered the strength of the glove polymers instead of the heat. The losses of tensile strength and ultimate elongation due to the thermal aeration were smaller than those from the acetone exposure with thermal decontamination [14]. Thermal aeration significantly improved the decontamination efficiency without affecting the strength of the glove polymers. For the neoprene/toluene combination to reach no detectable toluene on the glove surface, the decontamination time decreased from 120 hours at 23°C to 1 hour at 100°C. The tensile strength decreased by 1.03%, and elongation (%) fell by 0.79%, a negligible difference.

The SBTs for the neoprene/toluene combination undergo marginal changes after 21 cycles of repeated exposure, with a $p = 0.0483$, approximately 0.05. The decontamination to prolong the usability of the gloves is still limited. Gao and Tomasovic reported no significant changes in decontamination at 100°C for 16 hours for 7 or 10 repeated cycles with varying glove/chemical combinations [14]. A decreasing trend of SBT was observed for the butyl/toluene combination, but there was no significant change for nitrile/toluene nor neoprene/toluene for 7 re-exposure cycles. Eleven cycles of exposure/decontamination were the maximum of the prolonged uses for 14 chemical protective clothing (CPC) (including gloves and clothing) against 12 liquid chemicals [9]. The changes in BT showed various trends, including increasing (4/22), decreasing (2/22), roughly no change (5/22), and majorly erratic (7/22) by thermal decontamination. Following exposure to N, N-dimethylformamide (DMF) and methylethylketone (MEK), neoprene gloves can undergo efficient decontamination by subjecting them to temperatures of either 70°C or 100°C, allowing for their reuse [12]. To ensure comparability, we included the first 10 cycles, which is a common

repetition number in previous studies. Our findings indicate that the SBTs did not change significantly ($p = 0.595$).

The established decontamination process incurs a projected electricity cost of \$0.4 USD per hour using a 2-KW oven or dryer for one-hour heat aeration. With the 2023 industrial electricity unit price in Taiwan at \$0.2 USD per kilowatt-hour, assuming a reuse cycle of 10 for each glove, the electricity cost amounts to \$4 USD. Compared to the market price of \$16 USD per pair for the tested neoprene gloves, the employer can achieve a minimum of 75% savings by purchasing new gloves less frequently, reducing hazardous waste management expenditure. Notably, the oven can decontaminate multiple pairs of gloves simultaneously, although details are not provided here.

A notable limitation is the study's restricted assessment of chemical-glove combinations, limiting its applicability to various chemicals and glove materials. Findings may not generalize to different pairings. Additionally, the focus on two-glove products excludes thinner chemically-protective gloves from evaluation. The intentional repetition of the neoprene/toluene combination for 22 cycles was due to its known permeation characteristics. Deciding to reuse gloves demands critical professional judgment. This protocol underscores the necessity to validate the decontamination process when contemplating glove reuse.

4.1. Conclusion

The study comprehensively assesses the impact of thermal decontamination on SBT and glove properties. Optimal conditions, specifically at 100°C for an hour, result in a Δ SBT% exceeding 90% with no significant effects on strength and elongation. SBTs remains consistent over 20 cycles, indicating the reliability of the decontamination process. Multiple reuses of CPC is considered safe with effective decontamination, ensuring both functionality and material integrity. The assessment of glove material strength is crucial in determining reusability.

Regulations from OSHA in the USA, EU, and Taiwan lack specific directives on glove reuse or decontamination. Employers are urged to provide suitable chemical protective clothing based on hazard assessments and permeation considerations [7]. Permeation, a gradual movement of trapped chemical molecules through glove materials results in detectable residuals on the surface. Caution is advised regarding single-use glove reuse; workers should promptly remove gloves after tasks. In the absence of proper decontamination, used gloves should be replaced with new ones following breakthrough occurrences.

Following the study's protocol, glove selection relies on chemical-specific permeation data, and the decontamination procedure must undergo rigorous testing for reusability. Meticulous

documentation in the personal protection equipment (PPE) or dermal protection program is recommended.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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