

Are These the Right Gloves? Solubility & Maximum Protection

By James Moseman

Most workers in the chemical and associated industries will come into close contact with a hazardous substance on the job, in the lab or during education. Consequently, interest in injury prevention remains high. Engineering controls such as containment, ventilation and material substitution provide the best means of chemical protection. However, chemicals must eventually be manipulated, transported or dispensed, which introduces the potential for dermal contact. Many users slip on the first pair of gloves they find, but a poorly selected glove can swell or dissolve within a few minutes. Conversely, gloves may cost \$300 per pair, a high price to pay if a less expensive pair would suffice. So, the correct chemical/rubber match has a strong economic advantage. Therefore, elastomeric protective gloves are an important defense that must be selected systematically.

OSHA's PPE (29 CFR 1910.138) and lab safety (29 CFR 1910.1450) standards require a methodology in selecting appropriate gloves. The agency's Process Safety Management standard (29 CFR 1910.119) requires hazard assessments of PPE among many other elements.

Analysis of potential release scenarios and human exposures requires the selection of the correct protective glove material, which can change depending on the scenario.

With multiple articles, books and vendor charts covering protective garments and gloves, this article focuses on an abstract method for matching the correct glove to the solvent in use. Permeation charts

exist for some pure chemicals and a few mixtures, but the performance of glove polymers varies considerably with solvent. Also, charts may or may not suggest acceptable alternatives, as mixtures of solvents greatly complicate the issue.

Theory: Permeation & Diffusion

The broad and general model of solvent permeation (i.e., the progression of the chemical through the barrier material, P) into films is described by equation 1:

$$P = S \times D$$

where S is the solubility of solvent in the protective film and D is the diffusion coefficient

Solubility is the amount of a penetrant that can be dissolved per unit volume of the rubber film. Strictly speaking, *diffusion* is the movement of one substance through another as driven by a concentration difference while *permeation* is that diffusion coefficient multiplied by the solubility. For the best chemical resistance of clothing, it seems prudent to minimize the solubility and diffusion processes.

Initially, for any chemical to move or diffuse through a barrier, the chemical must be soluble in the polymer to enter, then advance. Once the solvent has successfully moved into the outer polymer surface, it can then march through the film to reach the wearer. These are two separate phenomena not explained by a single model, but the selection of base polymer material by chemical insolubility tends to solve both issues of dissolution and transfer.

Dissolution

The development of polymers faced technical issues decades ago. Selection of an effective solvent to dissolve, hold and deposit a polymer was a challenge. Over time, it became apparent that similar solvents behaved in much the same way involving a particular polymer. The familiar chemistry expression that "like dissolves like" remains the guiding principle.

IN BRIEF

•Engineering controls such as containment, ventilation and material substitution provide the best means of chemical protection. However, chemicals must eventually be manipulated, transported or dispensed, which introduces the potential for dermal contact.
•This article focuses on an abstract method based on evolving polymer science that OSH professionals can use to rapidly screen and select polymer protective glove materials.

James Moseman holds a B.S. and an M.S. in Chemical Engineering, and an M.S. in Engineering Management. He has held OSH roles at chemical, pharmaceutical and vaccine processing sites, and has additional experience in electronics manufacturing, petroleum servicing and project engineering. Moseman has taught college-level courses, and has authored or coauthored several articles.

Pioneering chemist Joel Hildebrand (1936; Hildebrand & Scott, 1950) suggested a method based on thermodynamic properties. He devised a solubility parameter, δ , which is a function of the solvent's heat of vaporization, ΔH_v and molar volume, V_m (equation 2):

$$\delta_{solvent} = \sqrt{\frac{\Delta H_v}{V_m}}$$

The heat of vaporization, ΔH_v is the amount of energy required to transform a unit quantity of liquid completely to a gaseous state. Analogous solubility parameters ($\delta_{polymer}$) were then assigned to polymers based on trial-and-error experimentation (Table 1). Dissolution potential is then represented by the arithmetic difference in the parameters for a given solvent-polymer combination. The smaller the difference between the two solubility parameters, the more affinity the material has toward the solvent.

In the case of chemical protective equipment, optimum protection is revealed by the largest difference between solvent and elastomer solubility parameters. For example, it appears that a polypropylene film would be an ineffective barrier to the solvents acetone, xylene and chloroform based on the similarity of the δ_s . On the contrary, however, a much larger difference exists between the parameters for polypropylene and methanol meaning that polypropylene is a good barrier film for methanol and similar species.

One particularly useful feature of the Hildebrand theory is that it lends itself to handling mixtures. Commercial solvents, such as degreasing products, often are mixtures of two or more distinct chemicals. For the purposes of calculation, the Hildebrand solubility parameter for a mixture is the prorated value of constituents by volume fraction. Volume fraction is different from mass fraction due to differing densities of liquids, so care must be taken to adjust values accordingly.

For example, 1 L each of three combined solvents (acetone, xylene and methanol) is then one-third by

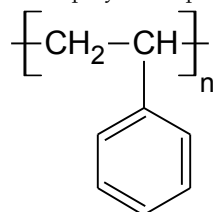
volume of all three. The mixture's net solubility parameter would be:

$$\frac{1}{3} \times 19.7 + \frac{1}{3} \times 18.2 + \frac{1}{3} \times 29.7 \text{ or } 22.5 \text{ MPA}^{1/2}$$

Rather than guessing, an initial choice of a good barrier film can, therefore, be made given all the appropriate solubility parameters. A comparison of tabulated Hildebrand parameters for the chemical can be compared against those for potential gowning materials. One can calculate missing solubility parameters for solvents based on readily available enthalpy of vaporization data. Where values for polymer or blends are absent, Small's (1953) method is a useful tool for estimating the polymer solubility parameter. In this equation, MW is the molecular weight of the polymer repeating unit, d is the density of the polymer and G is a tabulated cohesion parameter (Table 2) applied for functional groups appearing within the repeating polymer unit. The $\delta_{polymer}$ is then given by equation 3:

$$\delta_{polymer} = \frac{\Sigma G}{V} = d \frac{\Sigma G}{MW}$$

As an example, the polymer repeating unit:



results in a cohesion parameter is estimated as follows:

$$\delta_{polymer} = \frac{1.05(133 + 28 + 735)}{104}$$

$$\delta_{polymer} = 9$$

Tables 7, 8 and 9 on pp. 46 and 47 provide some additional values and examples of the information described in this article.

Table 1
Hildebrand Parameters

Material	Solubility parameter (MPA ^{1/2})
Acetone	19.7
Carbon tetrachloride	18.0
Ethyl acetate	18.2
Benzene	18.7
Chloroform	18.7
Polypropylene	19.0
Methanol	29.7

Table 2
Small's Cohesion Parameters

Functional group	G (cal/cm ³) ^{1/2} /mol
	214
	133
	28
CH4	93
	735

Note that copolymers formulated into the rubber as well as key elastomer properties, such as cross-link density or fillers such as carbon black, contribute to chemical solubility and resistance even though they have been addressed so far. Cross-linking reduces the uncoiling of the polymer chains, a key event in penetrant swelling or complete glove degradation.

Cohesion Parameters

The Hildebrand solubility parameter theory works well for most polymer/solvent systems. However, some modeling error exists for important polar solvents such as acetone. Hansen developed a three-parameter model for solubility in 1966 and it has been included in his many publications since. This approach disassembles the Hildebrand parameter, now called the total cohesion parameter, δ_t , into three separate components: (d)ispersion, (p)olar and (h)ydrogen bonding parameters. The Hansen components represent forces of attraction or repulsion forces due to varied electrical charges on individual molecules. The resulting relationship between the interaction parameters is given by equation 4:

$$\delta_d^2 + \delta_p^2 + \delta_h^2 = \delta_t^2$$

Furthermore, Hansen's method provides an interaction radius for each polymer. The three cohesion parameters then represent a point in 3-D space with a surrounding sphere sized by its interaction radius. A solvent-material combination with its corresponding cohesion parameters resting inside that sphere would be active. This active solvent would be effective in dissolving (penetrating and uncoiling) the polymer. However, for a barrier polymer, coordinates of the selected solvent outside the sphere would be a favorable incompatibility. That polymer would resist dissolution by the solvent, and minimal dissolution would thereby minimize penetration.

Table 3 provides several values of interaction parameters for important solvents and rubbery materials. These are from Hansen (2007) (Table 13.1 for the elastomers and from the appendix of the same reference for the solvents). From the Hansen system, δ_t , is equivalent to the single Hildebrand, δ .

In Hansen's (2007) theory, the square root of sum of the squares of the differences between solvent and polymer cohesion parameters would reflect position inside or outside that sphere of solvency. The overall computed difference is then divided by the tabulated interaction radius for the polymer to obtain a "relative energy difference," commonly abbreviated as a RED value. RED numbers are a dimensionless, numerical ratio. A value in excess of 1.00 for the RED number suggests that the solvent is not soluble in the polymer matrix and presents a good candidate for a barrier. In reverse, calculating a value less than 1.0 suggests that the polymer film would be a poor barrier to the solvent. The three-parameter approach provides better estimates than the single-parameter approach. Furthermore, practice shows that the solvent and polymer relationship results in the most dependable Hansen model performance (equation 5):

$$RED = \frac{\sqrt{4(\delta_{ds} - \delta_{dp})^2 + (\delta_{ps} - \delta_{pp})^2 + (\delta_{hs} - \delta_{hp})^2}}{R}$$

For chemical blends, the Hansen parameters can be prorated by volume fraction in the manner applied to Hildebrand parameters. It is then possible to appraise a chemical mixture's effect on rubber glove materials (see Tables 7-9, pp. 46-47, for sample Hansen parameters).

As an example, Table 4 presents a screen of potential rubber glove materials for 1,1,1-trichloroethane. RED numbers are calculated for various rubber materials for their interaction with 1,1,1-trichloroethane. The results are not comforting since only a single rubber has a RED number of more than 1.0. It is a premium \$300 glove.

What happens if all RED numbers are less than 1? The best rubber would be the material with the largest RED number or the largest differential in the Hildebrand parameters. OSH professionals must take caution in these applications because of potential degradation, swelling and solubility concerns. An immersion test of prescribed rubber candidates is always advisable before use. Thus, in estimating part of the barrier film effect, the more sophisticated Hansen method predicts polymer solubility behavior. Selection of an insoluble polymer barrier is critical in choosing high-performance PPE.

Table 3
Hansen Cohesion Parameters

Solvent or elastomer	Cohesion parameter (MPa ^{1/2})			
	δ_d	δ_p	δ_h	δ_t
Benzene	18.4	0	2.0	18.5
Xylene	17.8	1.0	3.1	17.9
Natural rubber	20.8	1.8	3.6	21.2
Butyl rubber	17.0	1.5	0.0	17.1
Polyvinyl chloride	16.1	7.1	5.9	18.6

Table 4
1,1,1-trichloroethane

Elastomer	RED No.
Butyl rubber	0.54
Neoprene	0.80
Nitrile rubber	0.77
Silicone rubber	0.45
Polyvinyl alcohol	0.93
Polyvinyl chloride	0.68
Viton	1.01

Dual Theory

The solubility principle presents one side of the polymer-barrier question when it expresses the barrier phenomena as a solubility (thermodynamic) effect. However, there is a dynamic effect known as *breakthrough time*. Failure of a soluble barrier material starts with the rapid formation a solvent-rich gel followed by continued unraveling of exposed rubber molecules. The rubber material travels into the solvent phase while the solvent diffuses through the film. In addition to swelling, poorly cross-linked or vulcanized rubber gloves can degrade and form small blobs of the rubber.

An active solvent (i.e., RED number < 1) will easily enter the barrier material, pool into microscopic cavities inside the polymer matrix and provide swift pathways through the film. The pooling effect, called plasticization, dramatically changes the polymer's structure. Self-diffusion of solvents within themselves is rapid compared to the movement through tangibly hindered polymers. Second, the base rubber is softened by the entering solvent, which facilitates structural rearrangement (uncoiling and strand relaxation) to even more intruding molecules. Finally, soluble chemicals can cause degradation of compatible polymers resulting in broken chemical bonds and cross-links.

Conversely, movement of solvent molecules through an insoluble rubber follows a tortuous path within the polymer entanglement. This process is diffusion. Movement through insoluble polymers is a mechanical, dynamic effect characterized by a solvent gradient normal to the film's surface. The eventual migration of the penetrant depends on the diffusion coefficient, temperature and the amount of open space within the elastomer. Relative to dissolution, diffusion is a slow process characterized by long breakthrough times of good rubber/solvent matches.

Ingressing solvent flux is a function of the microscopic holes within the polymer matrix called *free volume*. In diffusion, individual molecules move to vacant spaces within the matrix. Free volume may include vacancies in the elastomer matrix or in the interstitial area around the polymer grains about which a penetrant can jump (Figure 1). It is a great simplification to say jumping speed is a translational motion akin to random gaseous movement as the architectural properties of the polymer matrix are also important.

The ability of the polymer matrix to stretch and conform to the penetrant affects the solvent's diffusivity. Understandably, small solvent molecules as measured by their atomic size will travel through free volume much more quickly than large solvent molecules. Minute molecules can slip through the interstitial areas and the vacant sites.

Free volume seems to occur near polymer segment discontinuities such as cross-link points and at the end of polymer strands. It can be affected by mechanical stress such as wringing or stretching of the film. Therefore, a rubber with longer polymer strands and less cross-linking is advantageous for penetrant minimization, but sufficient cross-linking is required to control strand rearrangement. Both of these properties vary widely with base rubber materials, meth-

ods of production and formulation so that categorical recommendations and models are difficult. Silicone rubbers tend to be flexible materials; this contributes to their porosity and poorer barrier behavior.

Additives

Rubbers are heterogeneous compounds composed of approximately 10 chemicals, including accelerants, vulcanizing agents and fillers. Some rubbery polymers are actually inflexible before modification with plasticizing fillers to create a bendable film. Raw polyvinyl chloride (PVC) is an example. A phthalate plasticizer used in PVC increases its free volume and affords avenues of increased penetration since liquid-liquid diffusion is faster than liquid-solid diffusions. Therefore, plasticized glove materials are theoretically poor candidates for dermal protection from solvents.

On the other hand, inactive solids such as carbon black or silica tend to decrease free volume. Carbon black is an industrial chemical added to most rubbers for performance enhancement. This loading reduces swelling linearly as a function of the added filler. These particles are small but contribute another interlinked network within the elastomeric environment. One drawback is that rubbers heavily loaded with carbon black can shed carbon black in a chalking effect that would be undesirable for personal use.

Breakthrough

The crucial property of PPE is breakthrough time. In practical terms, it is the amount of time a pair of gloves delays chemical intrusion. Breakthrough is a function of film thickness, ambient temperature and the diffusivity of a particular solvent in a complementary polymer. Any factor that decreases free volume will reduce the speed of the solvent diffusing through the barrier material. Furthermore, once the free volume becomes sufficiently small or the solvent molecule diameter amply large, penetration proceeds slowly as the polymer has to stretch to accommodate the solvent. Butyl rubber has notoriously small pores making it resistant to gaseous diffusion (including air) while natural rubbers have relatively large free volumes.

Figure 1
Simple Polymer Representation

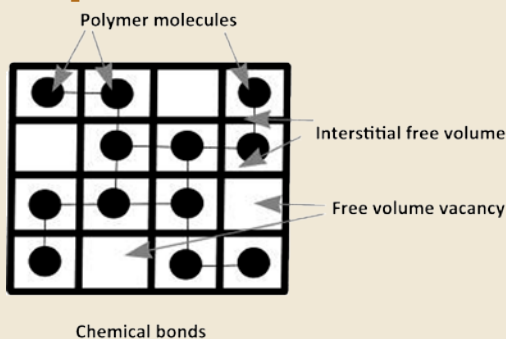
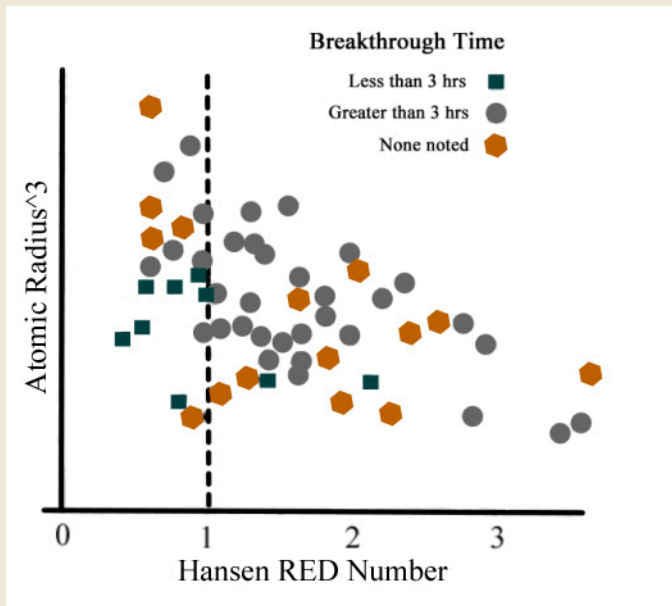


Figure 2
RED Number vs. Atomic Radius³



Sophisticated models exist to predict the breakthrough time for a specific rubber glove given a large number of parameters specific to the finished glove. Although average constants exist for a particular family of rubbers, these could not be reduced or adjusted for consistent projection. These models can work well for some barrier films under certain conditions, but no model fits all scenarios. Furthermore, using lab-derived constants might not correlate with actual rubber materials used in gloves. A broad search of manufacturers' charts

and reference values replete with different blends, fillers and production techniques create great uncertainty in the model. However, it is evident from all charts that an insoluble polymer/solvent always produces a breakthrough time of more than 2 hours. A chart drawn from Hansen (2007) and modified for presentation shows the measured breakthrough times for the one protective material (Figure 2). When a RED number greater than 1 was tested by a solvent, no breakthrough in less than 3 hours was noted except in two cases with small solvent molecules. All but two green boxes lay to the left of the RED number ≥ 1 . For more validation, the author created a table fixed with 16 common solvents and eight of the most used elastomers in gloving. Hansen (2007) parameters were used to project good pairing; a few inconsistencies existed but they are not attributed to solubility model. During the swelling demonstration conducted for this article, it was found that natural rubber was a good match for 100% pure ethanol, as predicted by the models, despite being rated poorly by the permeation chart. Consequently, it is possible that poor results listed in vendor charts may be erroneous, and caused by other experimental factors.

Table 5
Hansen Parameters Use

Description	δ_d	δ_p	δ_h	Interaction radius
Nitrile rubber	19.8	17.8	3.2	19.0
Natural rubber	15.8	8.8	19.4	13.3

Table 6
Parameters Model vs. Chart

Solvent	Nitrile rubber RED no.	Natural rubber RED no.
Ethanol	1.06	1.64
Mineral spirits	1.03	0.72
Xylene	0.91	0.51

Demonstration

An excellent display of the theory's utility is a one-on-one comparison of immersion tables and model predictions. There are differing sources for interaction constants including Hansen (2007). Furthermore, various parameters exist for natural rubber in differing exposures and, being a naturally derived material, its physical composition varies with source. Moreover, Hansen (2007) has provided parameters specifically for chemical resistance (Table 5).

Ansell's (2003) permeation and degradation resistance guide for its gloves provides qualitative information for material/solvent pairings, rating excellent performance as a green material, a yellow as good and red as not recommended. This was cross-referenced against for three solvents and two elastomers glove materials. Ansell reports results measured by permeation testing (ASTM Method F 739) where one side of the rubber swatch is exposed to the pure

solvent and a detector measures the appearance of the solvent exiting the reverse side of the swatch. Steady state flux of solvent through the film is also measured by Method F 739.

Calculated RED numbers were tabulated (Table 6) with corresponding cells shaded green, yellow or red based on Ansell's data. Table 6 shows that the three-parameter cohesion model indicated that a rubber would resist a solvent, both permeation charts and the Hansen (2007) parameter-based model completely concurred. In some cases, the tables showed other potential acceptable glove/solvent combinations that were not sanctioned by the interaction parameter method. Critically, the parameter model did not produce false positive selections.

As a demonstration of "like dissolves like," natural rubber when immersed in mineral spirits exhibited 20% swelling following a 1-hour immersion at room temperature. Nitrile rubber, a poor glove material for xylene as predicted by the Hansen (2007) parameters, exhibited 25% by volume when exposed to xylene. Both pairings would exemplify a PPE assessment failure. Photos 1 and 2 depict a side-by-side comparison of before-and-after photos of a nitrile rubber glove swatch soaked in xylene for 1 hour.

Finally, the author compared a table of solvent/rubber RED numbers against the Ansell table and found extensive consistency. Therefore, RED numbers are excellent predictors of glove performance.

Conversely, the lack of a breakthrough time is a potential concern with the interaction model. ASTM Method F 739 provides accurate breakthrough times and steady-state permeation rates. An alternative method to complete PPE assessments with a solubility screen is to invoke a qualitative permeability hierarchy derived from comparable transmission rates of vapor and gases. The following list of rubbery materials is presented in order of increasing permeability: Butyl < Neoprene < Urethane < Nitrile < Natural Rubber < Silicone. Butyl is the least porous of all rubber and should be used with insoluble penetrants, while silicone gloves should be reserved for high-temperature resistance or low-temperature flexibility. Laminate gloves have unknown interaction parameters and gas transmission rates. Therefore, it is impossible to rank the performance of the base material until it is published.

Finally, gloves with a 4-hour breakthrough time might seem advantageous except that the author has never worn a particular set of gloves longer than 1 hour. The accumulation of perspiration and heat affect dexterity and it invites cases of dermatitis. For most applications, the qualitative hierarchy with hourly glove changes is sufficient grading regarding breakthrough.

Field Applications

OSHA's technical manual (Section VIII, Chapter 1III, Protective Clothing Selection Factors) describes three factors that must be addressed when selecting protective materials: permeation, penetration and degradation. An advantage of using Hansen (2007) parameters is data entry into a spreadsheet, data management and report genera-

tion. With ease, an experienced spreadsheet user can build a multipage workbook that contains glove and solvent interaction data. A third workbook sheet can then display the calculated RED numbers, thereby producing a glove recommendation for a particular application.

This was the author's method, and the spreadsheets are illustrated here as figures. Thus, calculation of RED numbers can represent the first step of a PPE assessment as required by OSHA. Changes in the hazardous substance inventory or PPE stocked at a facility can be instantly reassessed, published and communicated to exposed workers.

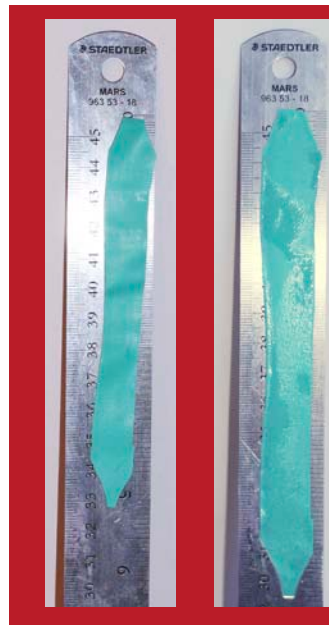
Furthermore, Hansen (2007) provides nearly 700 interaction parameters for individual solvents and approximately 450 interaction parameters for rubbers, plastics and composites. Ansell's guidance provides an informative matrix of seven glove elastomers as exposed to 152 chemicals. Despite the completeness of that guide, no method is available to address mixtures that frequently occur in industry and lab environments. Since thousands of chemicals are in use and in an infinite number of mixtures, the published charts provide limited guidance. This may not be an issue in simple manufacturing locations where no more than a dozen hazardous substances are used or where safety data sheets offer protection recommendations.

Conversely, a research lab environment may use more than 1,000 chemicals in a multitude of mixtures. OSHA's Laboratory Safety Standard (29 CFR 1910.1450) requires a chemical hygiene plan that addresses PPE equipment requirements. Manual assessment of every chemical or mixture is impractical (and incomplete) if a vendor lookup table is used. Using the mixture rules, interaction parameters can be estimated for any boutique chemical applied with a laboratory. This PPE prediction could then be tested with an immersion in the solvent and review of magnitude of swelling.

In the future, Small's (1953) method of estimating interaction parameters for new polymers or blends provides a means for uncatalogued polymers when matched with solvent physical data. Heats of vaporization are widely published, so a Hildebrand interaction can be estimated using equation 2 (p. 41). Thus, one can complete preliminary analysis in a hypothetical setting before exposure begins.

Caveats

As with any PPE, inspection and proper use are vital. When in doubt, an immersion test showing little enlargement (< 10%) over 1 hour will identify an appropriate glove/solvent match. A premeasured



Photos 1 and 2: Before-and-after images show nitrile swelled by xylene.

Table 7

Elastomer Properties, Sample Hansen Numbers

Description	δ_d	δ_p	δ_h	δ_{total}	Interaction radius
Butyl rubber	18.0	0.0	3.0	18.2	9.0
Neoprene	24.6	8.6	6.4	26.8	20.4
Ethylene-propylene rubber	18.6	-3.4	4.4	19.4	10.7
Polyisoprene	16.6	1.4	-0.8	16.7	9.6
Nitrile rubber	19.8	17.8	3.2	26.8	19.0
Natural rubber	20.8	1.8	3.6	21.2	14.0
Polydimethyl siloxane	13.8	5.0	1.2	14.7	14.3
Polyurethane	17.9	13.3	10.7	24.7	17.1
Polyvinyl alcohol	17.0	9.0	18.0	26.3	4.0
Polybutadiene	8.8	2.5	1.2	17.4	3.8
Polyvinyl chloride	17.5	6.5	5.5	19.5	6.3
Viton	11.6	23.0	5.0	26.2	21.6

strip of rubber soaked in the chemical of interest, then quickly remeasured upon withdrawal will reveal the degree of swelling by a percentage of length change. Swelling is never a positive indication.

Any polymer that flakes, dissolves or discolors in vitro is not acceptable and the rubber should be questioned. Properly formulated and vulcanized gloves rarely disintegrate when dramatically swollen unless exposed to an aggressive chemical (e.g., fuming nitric acid). In the case of an exposure following PPE failure, a retroactive interaction parameter estimate might reveal whether a particular glove material should have been applied. If the selection was proper, the investigation should switch its focus from the assessment to the glove manufacture or operator practice.

Moreover, gloves that are not mechanically challenged by liquid influx can be reused. Such gloves will rapidly desorb any penetrant if left to dry with ventilation. Proper storage and correct tagging of gloves is required so that the correct gear is matched to each operation. Multiple pairs of gloves should be available for rapid exchange during one shift. Although elite elastomers might cost considerably more, a lower-cost glove can often be acceptable. Economics should dictate the material selected only if both options provide complete protection. Solubility parameters provide no information about the mechanical reliability of barriers (e.g., cut and abrasion resistance).

Finally, the grail of PPE/solvent selection would be the programming of a computer application to complete the parameter estimation, interaction and glove recommendation. A database of known values of interaction parameters could be augmented with estimation models resulting in an assessment report. Whether low, medium or high, qualitative economics and porosity ratings could be applied as an expert system. Consequently, a database of hazardous materials and mixtures could be programmed and updated annually with ease. Perhaps NIOSH or OSHA could efficiently produce one program for universal use.

Conclusion

A method exists to rapidly screen and select polymer protective glove materials based on evolving polymer science. A single parameter solubility method can be used with tabulated or estimated parameters to select candidate glove material(s). Alternatively, a more sophisticated three-parameter system facilitates exact glove choice with less risk and

uncertainty. The advantage is that it will reveal favorable insolubility based on the RED number. A spreadsheet of hazardous chemicals can rapidly screen thousands of chemicals for PPE selection. Insoluble polymer/solvent pairs coupled with a qualitative porosity rank and hourly glove changes provide the wearer with dermal protection. Assessment coupled with good storage, maintenance and training practices will improve employee safety. **PS**

References

- Ansell. (2003). Chemical resistance guide: Permeation and degradation data. (7th ed.). Retrieved from www.ansellpro.com/download/Ansell_7thEditionChemicalResistanceGuide.pdf
- Forsberg, K. & Keith, L.H. (1999). *Chemical protective clothing performance index* (2nd ed.). New York, NY: John Wiley & Sons.
- Forsberg, K., Van den Borre, A., Henry, N. III, et al. (2014). *Quick selection guide to chemical protective clothing*. New York, NY: Wiley
- Hansen, C. (2007). *Solubility parameters: A user's handbook* (2nd ed.). Boca Raton, FL: CRC Press.
- Hildebrand, J.H. (1936). *The solubility of nonelectrolytes*. New York, NY: Reinhold.
- Hildebrand, J.H. & Scott, R.L. (1950). *Solubility of nonelectrolytes* (3rd ed.). New York, NY: Dover.
- Krevelen, D.V. (2009). *Properties of polymers* (4th ed.). Cambridge, MA: Elsevier Press.
- Lind, F. (2012). *Fluid effects in polymers and polymeric composites*. Berlin, Germany: Springer Science and Business Media.
- Mark, H. (2003). *Encyclopedia of polymer science and technology* (3rd ed.). Hoboken, NJ: Wiley-Interscience.
- Mark, J.E. (1999). *Polymer data handbook*. New York, NY: Oxford University Press.
- Mark, J.E. (2005). *The science and technology of rubber* (3rd ed.). Cambridge, MA: Elsevier Academic Press.
- Miller-Chou, B.A. & Koenig, J.L. (2003). A review of polymer dissolution. *Progress in Polymer Science*, 28(8), 1223-1270.
- Neogi, P. (Ed.). (2006). *Diffusion in polymers*. New York, NY: Marcel Dekker.

Reis, R.A., Oliveira, J.V. & Nobrega, R. (2001). Diffusion coefficients in polymer-solvent systems for highly concentrated polymer solutions. *Brazilian Journal of Chemical Engineering*. Retrieved from www.scielo.br/scielo.php?script=sci_arttext&pid=S0104-66322001000400003

Schneider, N.S. (1990). Comparison of toluene diffusion in natural rubber and in butyl rubber. Symposium paper.

Small, P. (1953). Some factors affecting the solubility of polymers. *Journal of Applied Chemistry*, 3(2), 71-80.

Yu, V. & Senichev, V.V. (2014). Solubility of selected systems. In G. Wypych (Ed.), *Handbook of solvents* (pp. 243-303). Toronto, Ontario: ChemTec Publishing.

Zeng, W., Du, Y., Xue, Y., et al. (2007). Solubility parameters. In J. Mark (Ed.), *Physical properties of polymers* (3rd ed.) (pp. 289-303). New York, NY: Springer.

Zellers, E.T. (1993). Modeling the temperature dependence of N-methylpyrrolidone permeation through butyl and natural rubber gloves. *AIHA Journal*, 54(9), 465-479.

Zhang, H. (2006). The permeability characteristics of silicone rubber. *Proceedings of the 2006 SAMPE Fall Technical Conference*. Retrieved from https://imageserv5.team-logic.com/mediaLibrary/99/D116_20-Haibing_20Zhang_20et_20al.pdf

Table 8

Penetrant Properties, Sample Hansen Numbers

Name	δ_d	δ_p	δ_h	δ_{total}
1,1,1-trichloroethane	16.8	4.3	2.0	17.5
Acetone	15.5	10.4	7.0	19.9
Acetonitrile	15.3	18.0	6.1	24.4
Acrylonitrile	16.0	12.8	6.8	21.6
Benzene	18.4	0.0	2.0	18.5
Carbon tetrachloride	17.8	0.0	0.6	17.8
Chloroform	17.8	3.1	5.7	18.9
Cyclohexane	16.8	0.0	0.2	16.8
Dioxane	19.0	1.8	7.4	20.5
Ethanol	15.8	8.8	19.4	26.5
Methanol	15.1	12.3	22.3	29.6
Methyl ethyl ketone	16.0	9.0	5.1	19.1
Methylene chloride	18.2	6.3	6.1	20.2
Nitromethane	15.8	18.8	5.1	25.1
Pentane	14.5	0.0	0.0	14.5
Pyridine	19.0	8.8	5.9	21.8
Toluene	18.0	1.4	2.0	18.2
Water	15.5	16.0	42.3	47.8

Table 9

Select RED Numbers for Common Solvents & Rubbers

	Butyl rubber	Neoprene	Ethylene propylene rubber	Polyisoprene	Nitrile	Natural rubber	Silicone rubber	Polyurethane	Polyvinyl alcohol	Viton
111-trichloroethane	0.54	0.80	0.81	0.43	0.77	0.58	0.45	0.74	0.93	1.01
Acetone	1.36	0.90	1.43	1.26	0.63	1.10	0.60	0.39	0.64	0.69
Acetonitrile	2.12	1.02	2.10	1.89	0.50	1.46	0.99	0.49	0.85	0.42
Acrylonitrile	2.01	0.91	2.00	1.85	0.41	1.37	1.02	0.37	0.78	0.52
Benzene	0.14	0.77	0.39	0.50	0.95	0.39	0.73	0.93	1.03	1.24
Carbon tetrachloride	0.27	0.84	0.50	0.33	0.97	0.45	0.66	0.98	1.09	1.23
Chloroform	0.46	0.72	0.64	0.75	0.81	0.60	0.66	0.66	0.76	1.09
Cyclohexane	0.41	0.92	0.61	0.19	1.00	0.59	0.55	1.00	1.11	1.19
Dioxane	0.57	0.64	0.57	1.00	0.87	0.59	0.88	0.71	0.75	1.20
Ethanol	2.12	1.07	1.88	2.25	1.06	1.64	1.33	0.62	0.15	1.01
Methanol	2.62	1.23	2.32	2.68	1.16	1.94	1.57	0.76	0.37	1.00
Methyl ethyl ketone	1.12	0.85	1.26	1.01	0.62	0.93	0.50	0.47	0.73	0.77
Mineral spirits	0.58	1.01	0.73	0.24	1.03	0.72	0.45	1.02	1.11	1.15
Pentane	0.85	1.12	0.93	0.46	1.10	0.91	0.37	1.07	1.15	1.12
Pyridine	1.05	0.55	1.15	1.16	0.50	0.70	0.84	0.41	0.71	0.95
Xylene	0.14	0.80	0.47	0.46	0.91	0.51	0.62	0.85	0.94	1.16