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Abstract

Metal-organic frameworks (MOFs) are a class of porous crystalline solids that present as promising instruments for the removal of chemical warfare agents (CWAs). Owing to their remarkable porosities and large surface areas, MOFs possess superior adsorption, reactivity, and catalytic abilities, providing an ideal environment for target species capture and decomposition. The tunable networks of MOFs also allow for customization of their chemical functionalities, making them practicable in personal protective equipment and adjustable to dynamic environments.

While progress has been made in the tailoring of MOF-based materials for toxic chemical degradation applications, issues of small pore apertures and poor water stability have hindered their practicality. Recent breakthroughs have shown that zirconium-based MOFs have the highest potential among different MOFs for hydrolytic and oxidative degradation of CWAs; however, it remains unclear what combination of features enables efficient breakdown in the solid phase and under realistic environmental conditions of humidity. Furthermore, many puzzles still exist regarding how those features may change with respect to the specific toxic chemical and the mechanism of detoxification. Characterizing structure-property relationships of different Zr-MOFs with various CWAs in the presence of atmospheric moisture is essential to establishing design rules that will lead to effective degradation under relevant field conditions.

This dissertation focuses on the use of computational modeling to gain insight into the role of structure and topology in the molecular accessibility, mass transport, kinetics, and adsorption of water, nerve agents, and their simulants in Zr-based MOFs. With combined molecular dynamics (MD) and density functional theory (DFT) approaches, the effects of pore size, connectivity, and hydrophobicity/hydrophilicity on adsorbed species distribution, binding, residence time, and diffusion in Zr-MOFs are explored. In the first section, we provide a comprehensive overview of intrinsic catalytic reaction mechanisms in MOFs, the design of efficient degradation strategies in the aqueous and solid phases, and the tuning and functionalization of MOFs to enhance CWA removal under realistic battlefield conditions. In the second section, we utilize a combination of equilibrium and non-equilibrium MD simulations to investigate the transport diffusion properties of water in two main classes of Zr-MOFs. In the third section, we propose a combination of MOF design rules that lead to promising performance characteristics for hydrolysis operations in conditions of varying humidity, supported by MD simulations. We also we develop a code for

calculating the radial distribution function of adsorbed molecules in nonuniform systems. In the fourth section, we use MD and DFT approaches to evaluate whether those design rules remain relevant for degradation of different types of nerve agents, both by themselves and in the presence of water. We also investigate whether reaction sites and mechanisms are likely to remain the same for all nerve agents in all Zr-MOFs. The results of this dissertation contribute to the advancement of MOF-based strategies for the destruction of CWAs and highlight the potential of these materials to address the challenges associated with chemical warfare.

Chapter 1

Introduction* & Research Objectives

1.1 Chemical Warfare Agent Removal by Metal-Organic Frameworks

Chemical warfare agents (CWAs) are lethal weapons of mass destruction that have been utilized in military conflict since their introduction in World War I. The first ever recorded large-scale chemical attack was the release of chlorine gas by German troops against the Allies in 1915, which resulted in more than a thousand casualties [1,2]. Once this proof of their extreme toxicity and devastating effects came to light, continuous efforts were made to investigate and store various toxic compounds for use as fatal devices against soldiers and civilians [1,3]. The most significant use is dated to the Iraq–Iran War, where a massive chemical attack on the city of Halabja resulted in 200 fatalities in 1988 [4]. While the production and use of CWAs were prohibited by the Chemical Weapons Convention shortly after, in 1993 [2], their evolution remains ongoing, and military personnel face growing uncertainty in complex battlefield environments. Terrorist organizations have also increased the relevancy of chemical warfare agents used against civilians, the most notable incidents being fatal nerve agent attacks in the city of Matsumoto and a Tokyo subway system in the late 1990s. Advancements in personal protective equipment that incorporate highly efficient filtration media for the rapid capture and decomposition of CWAs are urgently needed to mitigate the extreme threat these chemical weapons pose to individuals and military operations.

Measures to protect against CWAs must occur before the chemicals reach their biological targets, as the time frame to apply effective treatment after exposure can be as short as minutes [3]. Current protective technologies have been developed using solid materials such as activated

carbons, which can collect and retain CWAs released into the atmosphere but cannot decompose them [5]. Metal oxides, mesoporous silica, zeolites, and surfactants have also been investigated [6,7]; however, complications including low adsorption capacities, competition with atmospheric constituents, deactivation of active sites, and slow reaction kinetics render these materials generally incapable of adequate chemical decomposition [7–9]. Research efforts have thus shifted to the design of adsorbents, particularly nanoporous materials, with the ability to both capture and efficiently degrade CWAs under operationally relevant field conditions [10]. Metal-organic frameworks (MOFs) are a class of porous crystalline solids that have sparked interest in this area. MOFs consist of metal ion clusters connected by multidirectional carbon-based bridging linkers, yielding pores with sites for both organic and inorganic chemistry [11]. With tunable networks that provide customizable chemical functionalities, MOFs are adjustable to dynamic environments, making them useful in a wide variety of practical applications, such as gas storage, separations, drug delivery, chemical sensing, and catalysis [11–13]. In recent years, MOFs have been identified as superior materials for detecting and breaking down target species, owing to their excellent adsorption, reactivity, and catalytic abilities [1]. Coupled with their exceptional porosities and large surface areas, many MOFs provide an ideal setting for the selective capture and detoxification of CWAs [1,8,9,11,14–17].

Although progress has been made in using MOF-based materials as catalysts for CWA degradation [16], it remains unclear what combination of features enables efficient chemical breakdown in the solid phase and under realistic environmental conditions of humidity. Furthermore, many puzzles still exist regarding how those features may change with respect to the specific toxic chemical and the mechanism of detoxification. Understanding the interactions of various MOF structures with various CWAs in the presence of varying levels of atmospheric

moisture is essential to establishing the design rules for a single MOF to achieve universal toxic chemical degradation in dynamic environments.

1.2 Properties of Chemical Warfare Agents

1.2.1 Nerve Agents, Vesicants, and Their Simulants

CWAs can be divided into several types, including nerve agents, blister agents (vesicants), blood agents, tear agents, and choking agents. The most common are nerve agents and vesicants, which can be further split into categories based on their chemical structures. Nerve agents belong to the chemical group of organophosphorus compounds. They can be either G-type or V-type, where G-type indicates fluorine (GB, GD, GF)- or cyanide (GA)-containing compounds, and V-type (VX) indicates sulfur-containing compounds [18]. G-type nerve agents, such as sarin (GB) and soman (GD), are among the most toxic of CWAs, causing inhibition of proper muscle responses in the body within seconds of exposure and death within minutes [18,19]. Blister agents are less threatening than nerve agents, primarily intended to injure rather than kill people [18]. There are three categories of blister agents, including mustards (HD, HN-1, HN-2, HN-3), arsenicals (L, HL, PD), and urticants (CX). Mustards are the most prominent members of the vesicant family [20], existing in the form of nitrogen mustard (HN) or sulfur mustard (HD). Damage from these CWAs usually occurs in the tissues, in the form of blisters on the skin or irritation of the eyes [21]. Still, like nerve agents, vesicants are typically disseminated as vapors or liquids and can be inhaled and readily absorbed through the skin. While nerve agents range in persistency, all vesicants are relatively persistent, making fatality a possibility depending on exposure conditions (especially in the case of repeated exposures).

This dissertation is primarily concentrated on the degradation of organophosphorus nerve agents such as GB, GD, and VX, but also briefly covers degradation of the blister agent HD. Due to their high toxicity, experimental research using CWAs can be hazardous and is restricted in most laboratories. The most straightforward approach to overcoming this challenge is to detect and analyze respective CWA simulants, as they mimic the chemical behavior of CWAs by exhibiting similar chemical and physical properties with lower toxicity [1]. The chemical structures of GB, GD, VX, and HD are shown in Figure 1.1, along with the chemical structures of their commonly used simulants.

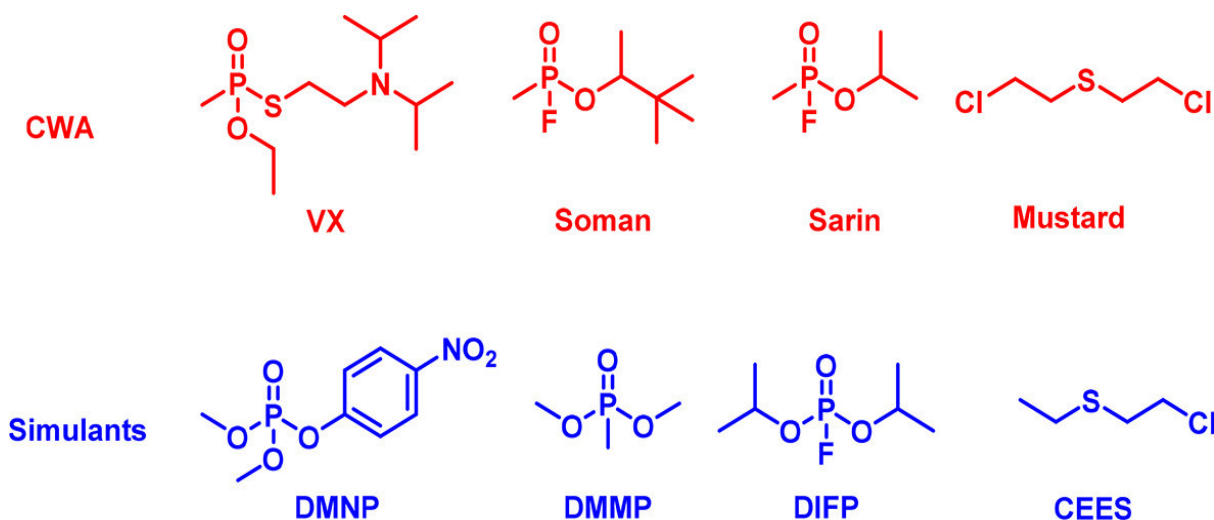


Figure 1.1. Representative examples of CWAs discussed in this work and their commonly used, less toxic simulants [16]. Reprinted with permission from ref. [16]. Copyright 2020 American Chemical Society.

We note that while these simulants have been widely utilized in experiments to help predict and correlate the degradation mechanisms and behaviors of their corresponding CWAs [1], it is unrealistic to expect that any simulant can satisfactorily represent all the properties of a given CWA [22]. For example, studies of organophosphate agent and simulant interactions in aqueous solution

have reported that DMMP and DIFP mimic the interactions of soman and sarin with water reasonably well [23,24]. In contrast, studies on the adsorption of nerve agents in MOFs have found that the adsorption properties of soman and sarin are poorly correlated with those of DMMP and DIFP, respectively [25,26]. DFT models of the hydrolysis reaction mechanism have also revealed that many commonly used simulants in the literature, like DMMP, demonstrate large energy barrier deviations from GB and GD [27], which underlines the risk of choosing simulants based on the literature precedent alone. In addition to closely matching the chemical structure of the CWA, the selection of an appropriate simulant evidently requires detailed knowledge and evaluation of the properties that strongly affect the process at hand, as the simulant that is most appropriate to simulate a particular process in a particular environment may not be the best choice for all processes in all environments [22,28]. First-principles calculations and other computational approaches have thus become of special importance in this field, both for gaining insight into the relevant properties of ideal simulants for experimental study and for modeling the behaviors of real CWAs in a given system of interest.

1.2.2 Degradation Mechanisms

The proposed mechanisms of CWA degradation in the current literature are predominantly hydrolysis and oxidation [1]. Nerve agent removal occurs mainly via hydrolysis but differs depending on the type of CWA, particularly with respect to the reaction products. As shown in Figure 1.2, hydrolysis of the nerve agent GD generates pinacolyl methylphosphonic acid (PMPA) and hydrofluoric acid. In contrast, ethyl methylphosphonic acid (EMPA) and the organosulfur compound 2-(diisopropyl)aminoethanethiol (DIAT) are the hydrolysis products of VX [29]. GB, not pictured here, hydrolyzes similarly to GD, with a hydrofluoric acid product accompanied by isopropyl methylphosphonic acid (iPMPA). Besides differences in their products, GB and GD have

greater volatility and reactivity to water than VX, persist for a shorter time in the environment (hydrolyze at a faster rate), and have less complex reaction mechanisms [30]. In general, the various alkyl methylphosphonic acid (AMPA) compounds produced in the degradation of these and other nerve agents can all be even further hydrolyzed into the stable product of methyl phosphonic acid (MPA).

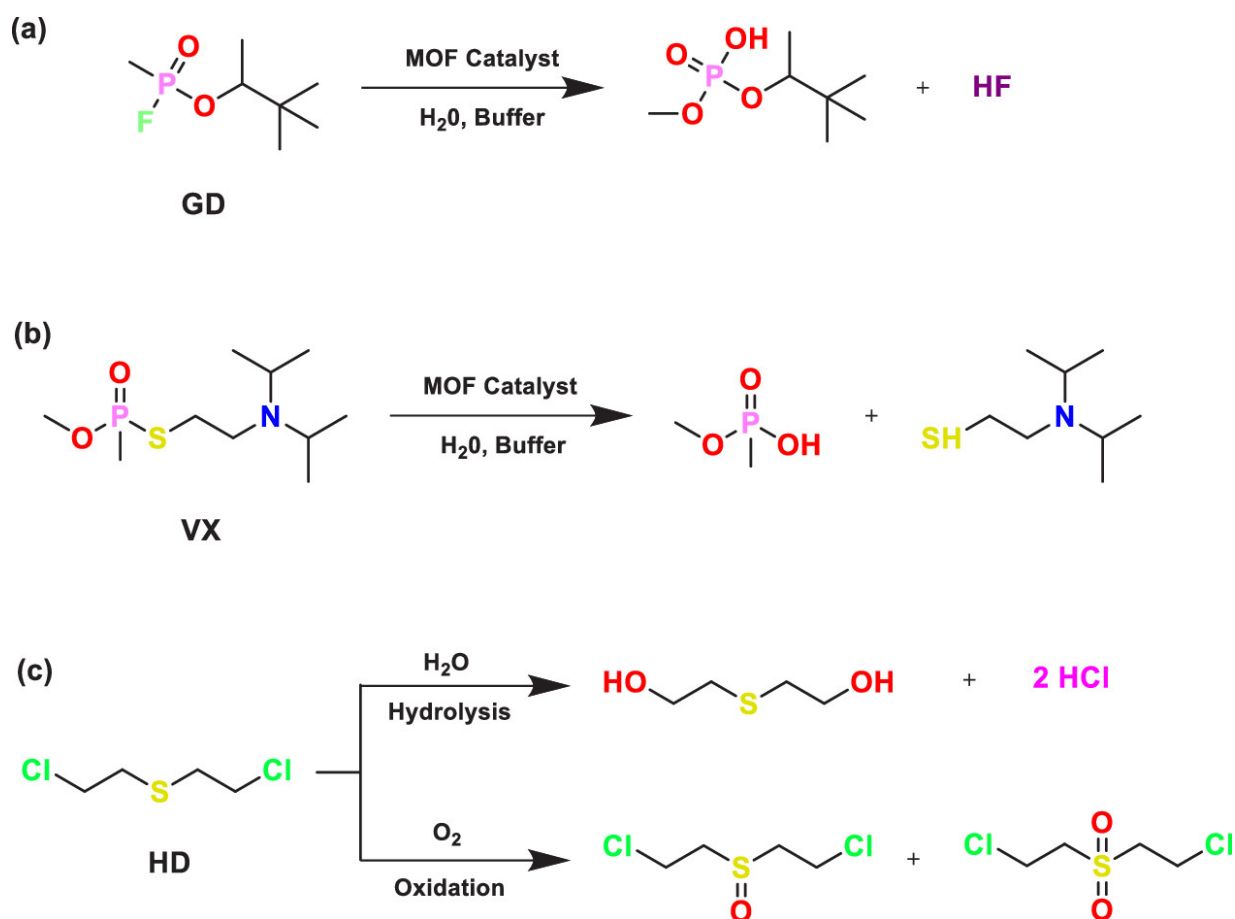


Figure 1.2. Schematic illustration of detoxification/hydrolysis pathway of CWAs. (a) Nerve agent GD; (b) nerve agent VX; (c) vesicant agent HD [1,6,17]. Reprinted with permission from ref. [1] and reproduced with permission from refs. [6,17]. Copyright 2021 American Chemical Society, 2017 Elsevier, and 2016 Wiley-VCH, respectively.

Degradation strategies for HD include hydrolysis, dehydrohalogenation, and selective oxidation [11,31,32]. An important obstacle of degradation via hydrolysis, which arises in both mustard agent and nerve agent removal, is the formation of acid byproducts that can lead to catalyst poisoning and inhibition of subsequent reactions. While this issue can often be confronted with modifications to materials and operating conditions, the hydrolysis of HD (Figure 1.2c, top) is also primordially rate-limited by the compound's immiscibility in water [33,34]. Likewise, the degradation of sulfur mustard by dehydrohalogenation is considered too slow [11] since it typically requires a high pH environment that is corrosive to most materials [34]. Given these roadblocks, oxidation is the most effective mechanism for HD removal in real-time applications. Sulfur mustard oxidation can be partial or complete, producing desirable and undesirable products. Partial oxidation to sulfoxide (HDO; Figure 1.2c, bottom left) is an attractive decontamination strategy, as this product displays improved chemical stability that makes it rather inert towards biological systems [33]. On the other hand, complete oxidation produces the di-oxidized product sulfone (HDO₂; Figure 1.2c, bottom right), which has vesicant properties similar to the parent HD [35]. Selective partial oxidation is therefore required for the safe degradation of HD to the nontoxic HDO [33,35]. For a 100% selective reaction to be achieved, mild oxidizing agents such as photosensitizers must be used [31] and exceedingly careful monitoring must be enforced to avoid detrimental over-oxidation to HDO₂ [33].

1.3 Structural Features of Promising MOFs

While MOFs offer a large variety of structures for use against CWAs and emerging hazards, their exploitation depends critically on understanding the structure–activity relationships needed for efficient uptake and decomposition under operationally relevant battlefield conditions. A

principal quality to consider when evaluating these materials for CWA removal is thus their stability and reactivity toward environmental constituents, particularly water. MOF functionality in humid conditions can be determined by several thermodynamic and kinetic factors, including the strength and geometry of metal–linker coordination bonds, pore sizes and connectivity, hydrophilic or hydrophobic framework components, and metal ion valency [36]. Many MOFs show limitations of weak mechanical and chemical stability in the presence of water that stems from hydrophilic functional groups, easily accessible active sites, water-susceptible linkages between metal nodes and ligands [37], or some combination of the three. In chemical reaction applications, these features can also lead to problems beyond structural stability, such as hindered target species adsorption and slow reaction kinetics. This section outlines the key attributes contributing to strong water stability and performance in MOFs and introduces the types of MOFs considered well-suited for CWA degradation via hydrolysis and oxidation.

1.3.1 Nodes and Linkers

The metal ion may be the most important factor when evaluating MOF stability in humid conditions. A study by Lee et al. [38] showed that the chemical stability of MOFs is inversely correlated to the strength of the coordination bonds between metal centers and their ligands [39]. MOFs with weak linkages are susceptible to linker hydrolysis or linker exchange, where water attack on the nodes leads to the breaking of these bonds, resulting in phase changes or framework collapse. One method for combatting thermodynamic favorability toward framework degradation is designing MOFs using Pearson’s HSAB theory [40], with hard–hard or soft–soft node–linker combinations. MOFs with high oxidation state metals (such as Cr^{3+} , Fe^{3+} , Al^{3+} , and Zr^{4+}) and organic carboxylate ligands have been widely investigated for applications involving humidity [37,41,42], as metals with small ionic radii and high positive charges make hard acids, thus binding

very strongly to the oxygen atoms of carboxylate ligands, which are hard bases. Some examples of highly thermodynamically stable MOFs include MILs, ZIFs, pyrazolate-containing frameworks, and zirconium-based MOFs [43]. Zr-based MOFs, specifically, have been proven to possess unprecedented stability in humid environments [13,41,44], owing to the Coulombic interactions between their negatively charged termini of linkers and highly oxophilic Zr^{IV} centers [43]. MOFs with heavier low-valent metals coordinated to soft ligand donors have also been considered [45] due to the likelihood of stronger host–guest binding interactions from metal centers with radially expanded valence orbitals. However, it is understood that softer metal–ligand bonds tend to be more rapidly hydrolyzed than their hard–hard counterparts [45].

From a kinetic standpoint, framework degradation can be combatted by incorporating chemically unreactive metal atoms. A study by Kang et al. [46] on the isotypic MOFs MIL-53-Al, MIL-53-Cr, and MIL-47-V showed that chemical stability in water decreases in the order of $\text{Cr} > \text{Al} > \text{V}$ or with respect to the degree of metal ion inactivity [36]. Likewise, a study by Towsif Abtab et al. [47] described a Cr^{III} -based MOF with extraordinary water stability enabled by the metal's inertness. Nevertheless, the unreactive nature of metal ions such as Cr^{III} makes synthesizing crystalline MOFs of this type extremely difficult [48,49].

1.3.2 Pore Sizes and Connectivity

In the absence of thermodynamic stability, one way of avoiding MOF hydrolysis in humid conditions is through steric factors, like increasing the coordination of the metal nodes [50]. Higher node connectivity can effectively block the access of water molecules to vulnerable metal–linker bonds, eliminating the possibility of framework collapse. For example, a study by Emerson et al. [51] demonstrated that an unconventional triaminepentacarboxylate acid ligand forms a highly linked porous coordination polymer with Cd^{II} metal ions, whose exceptional connectivity yields a

hydrolytically stable MOF towards CO₂ sorption. However, high connectivity in MOFs is often accompanied by small pore openings, which limit the accessibility and abundance of potential binding sites to target species in chemical reaction applications [7]. In fact, a key issue with many MOFs for toxic species removal (with or without chemical stability) is pore openings that are smaller than or comparable to the molecular sizes of CWAs.

In chemically stable MOFs, a well-known strategy for improving site accessibility is defect engineering, or the removal of organic linkers to increase the aperture size of the framework and decrease the coordination of the metal nodes [17]. Defect engineering allows for the creation of hierarchical porosity in MOFs, which can excavate hidden active sites and increase the volumetric uptake of toxic chemicals [52,53]. Although promising, defect characterization and topological tuning to obtain a precise balance between site access and desired kinetic efficiency is a major unsolved challenge [54]. While linker removal can increase pore volume, enabling better adsorption and diffusion of guest species, it can also result in the formation and exposure of undercoordinated sites, which interact strongly with guest molecules and decrease kinetics. An example of this was shown in a defect study by Wang et al. [55], who observed that the introduction of missing linkers to the UiO-66 Zr-MOF promoted interactions between adsorbed IPA and coordinatively unsaturated metal sites that were strong enough to outweigh the effects of increased pore volume, ultimately decreasing adsorbate diffusion through the framework. Another defect study by Ghosh et al. [56] additionally revealed that structural impurities in the form of missing linkers in UiO-66 made the MOF more hydrophilic. These combined results suggest that in CWA degradation operations, defect exposure would eliminate one problem while introducing another; CWA removal would be less hindered by small pore openings and poor site access but more hindered by reaction inhibition from the strong binding of decomposed products [19,57] or

competition with environmental water for active sites [58]. Given these drawbacks, MOFs with intrinsic hierarchical porosity present as favorable alternatives.

1.3.3 Hydrophilicity and Hydrophobicity

In any case, the overall effectiveness of an MOF towards toxic species removal depends heavily on its affinity for water. While strong node–linker bonds or high activation energies can prevent issues like framework hydrolysis, extreme hydrophilicity or hydrophobicity of the framework can seriously hinder or interfere with the efficiency of the degradation reaction. The shape of the water vapor adsorption isotherm can indicate the level of hydrophilicity or hydrophobicity in a nanoporous adsorbent material, as shown in Figure 1.3. Adsorbents with type I, type II, and type IV isotherms are classified as hydrophilic. In MOFs of this type, environmental water will adsorb into the pores at very low pressures, dispersing to available active sites to participate in adsorbate–adsorbent interactions.

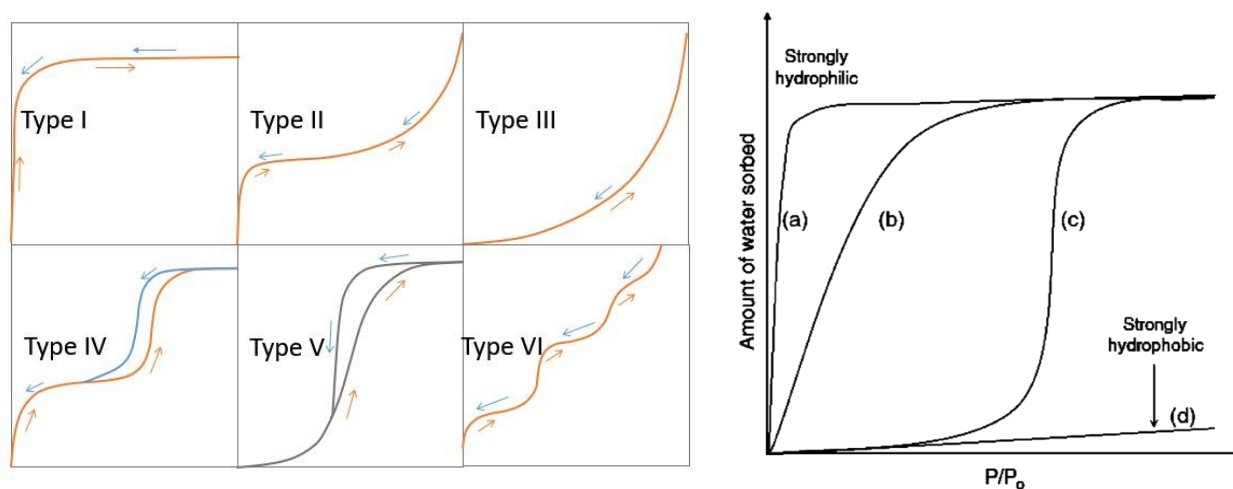


Figure 1.3. Adsorption isotherms for water in different types of nanoporous adsorbents near room temperature. IUPAC classification of adsorption isotherm types (left) and adsorption patterns with respect to hydrophilicity (right) [50,59–61]. Reprinted with permission from ref. [60] (left) and from refs. [50,59] (right). Copyright 2019 Royal Society of Chemistry, 2014 American Chemical Society, and 2008 Elsevier, respectively.

The more hydrophilic the material, the more water–framework interactions will precede interactions with target species, lowering active site accessibilities and target species reaction rates. These obstacles make hydrophilic MOFs a poor choice for chemical reaction applications in settings with large atmospheric moisture levels [15].

Hydrophobic MOFs show promise in this regard, as their resistance to chemical degradation by water [62] makes them chemically stable in humid conditions and unrestricted by competitive adsorption upon water exposure [63]. Early studies explored hydrophobic materials such as Zn-based [64] MOFs and -CF₃ functionalized Ni₈-based [65] MOFs, finding that they were well equipped for adsorption and retention of nerve agent and mustard gas simulants compared to hydrophilic MOFs such as HKUST-1 [16,64]. Strongly hydrophobic MOFs like zeolitic imidazolate frameworks (ZIFs) tend to prevent water adsorption into their pores altogether. Their adsorption isotherms are type III, indicating no appreciable uptake of H₂O until near the saturation vapor pressure of water [56]. This absence of adsorbed water lessens the need for the previously discussed attributes of strong node–linker bonds or high connectivity, broadening the structural and topological criteria for effective MOF performance towards CWA degradation via oxidation. However, strongly hydrophobic MOFs are impractical for degradation via hydrolysis, where the presence of water is required for the reaction to proceed [66]. What is more, recent work by Wang et al. [5] showed that the activity of solid-phase MOFs towards CWA simulant hydrolysis can improve dramatically with increases in relative humidity, suggesting that the ability of generous numbers of external water molecules to enter MOF channels along with target species may be equally as important to hydrolytic degradation efficiency as the prevention of water–framework interactions.

In such cases where water adsorption in the MOF pores is needed or desired, competition for active sites can be combatted by functionalizing internal hydrophobicity. Most water-stable MOFs are classified as internally (or partially) hydrophobic [56], exhibiting adsorption isotherms that are type V. This style of uptake proceeds like that of the curve (c) in Figure 1.3, with low adsorption in the low-pressure region, followed by quick filling of the material to saturated adsorption capacity [50]. In these MOFs, water molecules can adsorb into the pores and be available to participate in target species hydrolysis without clustering around and reacting at open metal sites. Of course, depending on the pore size and connectivity of the MOF, this barrier preventing interactions of H₂O molecules at active sites may lead to hydrogen bonding and pore filling of adsorbed water [67,68]. Such behavior can limit the ability of target species to adsorb and diffuse throughout the framework, which is yet another obstacle that interferes with CWA degradation rates. Establishing a perfect balance of stability, topology, and water affinity that diminishes these challenges would be a major stride in developing ideal MOFs for the given application. Studies have also shown that MOFs without intrinsic water stability or hydrophobicity can be chemically modified to acquire these features for aqueous applications [69,70], suggesting that MOFs with only one or two desired attributes may still be worth considering.

1.4 Research Approach & Contributions

The goal of this dissertation is to elucidate design rules of metal-organic frameworks for the efficient decomposition of chemical warfare agents. Through computational modeling, we aim to identify the key characteristics of MOF structure and topology crucial for optimizing CWA accessibility, molecular mass transport, kinetics, and adsorption under realistic environmental conditions. In Chapter 2, we give an overview of the main computational methods used in our

research, which include density functional theory (DFT) calculations, Monte Carlo (MC) simulations, and classical molecular dynamics (MD) simulations. The material in subsequent chapters covers our major contributions to this field, with respect to the following objectives:

♦ **Objective 1 (Chapter 3):** Literature review.

Approach: A comprehensive literature survey is conducted on recent advancements in the computational and experimental studies of MOFs for the degradation of nerve agents, blister agents, and their simulants, with a primary focus on degradation via hydrolysis and oxidation strategies in Zr-based MOFs.

Contributions:

1. Key design considerations for efficient degradation concerning CWA type and reaction mechanism are summarized.
2. Insight is given into the future research directions necessary for filling the gaps in current understandings.

♦ **Objective 2 (Chapters 4 & 5):** Evaluate the influence of pore structure and water affinity on the performance potential of Zr-MOFs under realistic environmental conditions.

Approach (Chapter 4): Equilibrium and non-equilibrium MD simulations are carried out to examine the mass transport behavior of water in UiO-66 and NU-1000, two types of Zr-MOFs with significant differences in topology and hydrolytic activity.

Contributions (Chapter 4):

1. Evaluation of water molecule flux and transport diffusion coefficients in Zr-MOFs using temperature-induced chemical potential gradients.

2. Insight into the influence of surface interactions and pore structure on the transport diffusion of water through each framework, and what that indicates about the potential of each MOF for chemical reaction applications in high humidity environments.

Approach (Chapter 5): MD simulations are carried out to examine the behavior of water at various loadings in NU-1000, a Zr-MOF with the characteristic attributes (strong node-linker bonds, expansive pores, and internal hydrophobicity) for structural stability and hydrolytic efficiency in the presence of water.

Contributions (Chapter 5):

1. Proposal of three design criteria that, once combined, could yield a promising MOF for solid-state hydrolysis applications.
2. Molecular-level assessment of water behavior in a MOF equipped with these three criteria through self-diffusion, residence time, and radial distribution function analyses.
3. Insight into whether these design rules are expected to be useful when applied to nerve agent hydrolysis, and whether MOF functionality is expected to be impacted by water exposure at varying levels of humidity.
4. Development of a method for calculating radial distribution functions in systems where guest particles are *not* uniformly distributed throughout the simulation cell.

◆ **Objective 3 (Chapter 6):** Identify reaction sites and reaction mechanisms for nerve agent hydrolysis in Zr-MOFs, including the role of water.

Approach: MD simulations and DFT calculations are carried out to examine the behavior of organophosphorus nerve agents (sarin and soman) in NU-1000, a Zr-MOF with sites accessible from two different framework regions, both in pure form and in mixtures with water.

Contributions:

1. Evaluation of CWA binding energies to determine preferential regions of adsorption in a MOF with multiple site environments.
2. Evaluation of CWA radial distribution functions to determine preferential active site interactions, giving insight into the likely mechanism of nerve agent binding to the metal node.
3. Comparison of pure water in the MOF to water in a mixture with CWAs to confirm the hypothesized hydrolytic functionality of a MOF with these design rules in the presence of atmospheric moisture (from the previous study).
4. Investigation of water interactions with each of the two CWAs to better understand the likely role of water in the hydrolysis reaction mechanism.
5. Comparison of the behaviors and interactions of two CWAs in the same MOF to determine whether hydrolysis of each CWA is likely to proceed by the same reaction steps.

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Chapter 2

Computational Methods

The following section provides a brief overview of the computational methods used in this dissertation, which include density functional theory (DFT) calculations, Monte Carlo (MC) simulations, and molecular dynamics (MD) simulations. The major principles of each computational technique are provided, along with descriptive examples of their application in this work concerning the characterization and evaluation of structure-property relationships in Zr-based MOFs.

2.1 Density Functional Theory

Density functional theory (DFT) is a quantum mechanical method used to calculate the electronic structures of many-bodied systems of atoms, molecules, and solids. For all electronic structure theories, a major difficulty is ascertaining the proper treatment of electron-electron interactions [1]. Theories such as Hartree-Fock, Møller–Plesset perturbation theory, and configuration interaction rely on the computation of the atomic or molecular wavefunction to characterize these interactions, which requires massive computational effort and limits their utilization towards complex systems [1,2]. Alternatively, DFT does not require a wavefunction, instead operating based on the computation of electronic density distributions. Given its ability to map many-body problems into single-body problems, DFT can provide higher electronic energy accuracy at a lower computational cost than other methods. Accordingly, DFT can be used to analyze much larger atomic and molecular systems.

2.1.1 Equivalent Systems of Non-Interacting Particles

The DFT scheme assumes that electrons do not interact with one another, modeling many-bodied systems as sets of one-electron, non-interacting Schrödinger equations (otherwise known as Kohn-Sham equations) [3]:

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + v_{eff}(r)\right)\varphi_i(r) = \varepsilon_i\varphi_i(r) \quad (2.1)$$

where $\hbar$ is Planck's constant, m is the mass of the particle, $v_{eff}(r)$ is the local effective external potential in which the non-interacting particles move, and ε_i is the orbital energy of the corresponding Kohn-Sham orbital φ_i . The orbitals yielded are used to obtain the density $\rho(r)$ of the fictitious system of non-interacting particles:

$$\rho(r) = \sum_{i=1}^N |\varphi_i(r)|^2 \quad (2.2)$$

which by summation of the contributions from each particle equals the same density as that of the many-body system of interest. Two theorems by Hohenberg and Kohn [4] are the governing principles of DFT, which suggest by the following statements that single-particle charge density can be chosen as the fundamental variable for the description of the ground state of a system of interacting electrons [5]:

- All physical quantities are a functional of the electron density $\rho(r)$ of the system, in particular the total energy.

- The physical (or real) electron density of a system is the one minimizing the total energy functional of the system (variational principle).

The total energy of a system is therefore expressed as a functional of the system's charge density:

$$E[\rho] = T_s[\rho] + \int dr v_{ext}(r) \rho(r) + E_H[\rho] + E_{xc}[\rho] \quad (2.3)$$

where $v_{ext}(r)$ is the external potential acting on the system due to electrostatic repulsion between nuclear cores (typically approximated by a pseudopotential), T_s is the approximate kinetic energy of the non-interacting particles, calculated as follows:

$$T_s[\rho] = \sum_{i=1}^N \int dr \varphi_i^*(r) \left(-\frac{\hbar^2}{2m} \nabla^2 \right) \varphi_i(r) \quad (2.4)$$

E_H is the Hartree energy, which accounts for electrostatic (Coulombic) interactions between particles, calculated as follows:

$$E_H[\rho] = \frac{e^2}{2} \int dr \int dr' \frac{\rho(r)\rho(r')}{|r-r'|} \quad (2.5)$$

and E_{xc} is the exchange-correlation energy, which accounts for the remaining electronic energy not included in the non-interacting kinetic and electrostatic terms. In practice, all these equations rely on determination of the effective external potential, otherwise known as the Kohn-Sham potential:

$$v_{eff}(r) = v_{ext}(r) + e^2 \int \frac{\rho(r')}{|r-r'|} dr' + \frac{\delta E_{xc}[\rho]}{\delta \rho(r)} \quad (2.6)$$

where the final term of the right-hand side of the equation is the exchange-correlation potential, often denoted as $v_{xc}(r)$.

The exchange-correlation potential is the singular unknown variable in the Kohn-Sham equation and must be approximated for the equation to be fully solved [6]. While the exchange-correlation energy makes up a very small percentage of the total energy in the system, its contribution to the behavior of the system is significant and cannot be overlooked [7]. Alas, calculation of adequate approximations is extremely complex. The simplest and most standard of all functionals used in DFT is the local density approximation functional (LDA), which calculates the overall exchange-correlation energy based on the exchange-correlation energy per particle of an electron gas with spatially uniform density [8]. Given its assumption that density is the same everywhere, LDA tends to generate overpredictions of correlation energy and underpredictions of exchange energy [9]. Newer and enhanced functionals such as the generalized gradient approximation (GGA) and hybrid functionals have been developed that provide corrections to some of the errors generated by LDA and can offer reasonably accurate approximations for a wide variety of advanced systems. Nevertheless, no functional is universally applicable and improvement of existing functionals is ongoing.

2.2 Classical Methods

Monte Carlo (MC) and molecular dynamics (MD) simulations are atomistic methods of computational analysis, centered around exploring configuration space when a system is in some form of equilibrium [10]. Atomistic simulations rely on the Born-Oppenheimer approximation, which enables classical treatment of the motion of atomic nuclei through decoupling from

electronic motions. Molecular energy is considered as a sum of independent terms including nuclear spin energy, electronic energy, vibrational energy, and rotational energy. Electronic cloud effects are explicitly captured through the assignment of partial charges within the molecular geometry, and intermolecular and intramolecular interactions are described using force fields [11]. In both MC and MD methods, distributions of nuclear positions, velocities, and forces in systems of atoms and molecules are generated under the application of specific thermodynamic conditions. These properties can then be analyzed through data output postprocessing and/or visualization.

2.2.1 Monte Carlo Simulation

MC methods are a collection of stochastic computational techniques that make fundamental use of random samples to generate approximate numerical solutions to complex integrals. Rather than estimating random quantities in a deterministic manner, MC methods employ random quantities to provide estimates of deterministic quantities [12]. The objective of an MC simulation for modeling a system of atoms or molecules is to generate an ensemble of energetically feasible representative configurations through application of random perturbations, resulting in conformations from which probabilities and relevant thermodynamic observables may be calculated [13]. Expectation values for observable functions can be written as follows:

$$\langle A \rangle = \frac{\int A(q)P(q)dq}{\int P(q)dq} \quad (2.7)$$

where q represents a configuration of the system and $P(q)$ is the probability of finding the system in that configuration [10]. This probability depends on the energy of that configuration by the following relation:

$$P(q) \propto e^{-E(q)/k_B T} \quad (2.8)$$

where k_B is the Boltzmann constant and T is the temperature. In addition to moving particles, MC methods can also involve adding or removing particles, which is how specified chemical potentials are achieved [11]. Whether or not a random perturbation is accepted depends on how the move alters the total energy of the system. If the energy goes down, the move is always accepted. If the energy goes up, a random number between 0 and 1 is generated, and the move is only accepted if the random number is less than the probability $e^{-\Delta E/k_B T}$ [10]. The values of desired properties are calculated for each accepted configuration, and final properties are obtained by averaging over the number of configurations at the end of the simulation.

2.2.2 Molecular Dynamics Simulation

In contrast to MC simulation, MD simulation is a deterministic technique that utilizes a time approach to calculate the evolution of energy in a system. The governing principle of MD is the use of numerical integration to solve for Newton's equations of motion:

$$f_i = m_i \frac{\partial^2 r_i}{\partial t^2} \quad (2.9)$$

where the force of a particle, f_i , is equal to the mass of the particle, m_i , multiplied by its acceleration. The estimation of the dynamics of particles in a system most commonly takes place by the following process, also known as the Verlet algorithm [11,14]:

1. Having the initial location of a particle, its potential energy is estimated as the sum of its molecular interactions.

2. The force acting on the particle is calculated as the negative derivative of its potential energy:

$$f_i = m_i \frac{\partial^2 r_i}{\partial t^2} = - \left(\frac{\partial U(r_1, r_2, \dots, r_N)}{\partial r_i} \right) \quad (2.10)$$

3. Employing the Taylor expansion, the positions of the particle are estimated at times $t + \Delta t$ and $t - \Delta t$:

$$r(t + \Delta t) = r(t) + \Delta v(t) + \frac{1}{2} (\Delta t)^2 a(t) + \dots \quad (2.11)$$

$$r(t - \Delta t) = r(t) - \Delta v(t) + \frac{1}{2} (\Delta t)^2 a(t) - \dots \quad (2.12)$$

where r represents the coordinates of the particle, v represents its velocity, and a represents its acceleration.

4. Summing Equations 2.11 & 2.12, the new position of the particle can be estimated as a function of its previous and current locations and its acceleration:

$$r(t + \Delta t) = 2r(t) - r(t - \Delta t) + (\Delta t)^2 a(t) \quad (2.13)$$

5. The velocity of the particle can be estimated based on the previous and new locations of the particle and the timestep:

$$v(t) = \left(\frac{1}{2\Delta t}\right) [r(t + \Delta t) - r(t - \Delta t)] \quad (2.14)$$

Physical conditions of the system of particles are controlled using ensembles, which hold three state variables constant over the course of the simulation, including the total particle number (N). Common ensembles are the microcanonical ensemble (NVE), where volume and energy are fixed, the canonical ensemble (NVT), where volume and temperature are fixed, and the isothermal ensemble (NPT), where temperature and pressure are fixed. Ensembles like NVT and NPT that involve constraining temperature and/or pressure are better suited for simulating realistic experimental conditions and give more useful information about system properties than the NVE ensemble [10,13]. The tradeoff is that these ensembles are more complicated, requiring some combination of thermostats, barostats, time rescaling, and length rescaling to maintain temperature and pressure at the desired value.

The timestep used to integrate the equations of motion is the most important parameter within MD, as it determines the level of accuracy and the required amount of computational effort [10]. Typical timesteps are on the order of femtoseconds, with smaller timesteps giving better accuracy but being more computationally expensive. The accuracy of MD simulations is also largely dependent on the force field parameters employed for modeling the system of interest. In atomistic simulations, force fields are a set of equations made up of bonded and non-bonded terms that are employed to describe particles and reproduce their properties. Bonded parameters are used to describe interactions with two atoms (bonds), three atoms (angles), or four atoms (dihedrals) [13] in a system of interacting particles by the following relations:

$$E_{bonds} = \sum_{bonds} \frac{1}{2} k_b (r - r_0)^2 \quad (2.15)$$

$$E_{angles} = \sum_{angles} \frac{1}{2} k_a (\theta - \theta_0)^2 \quad (2.16)$$

$$E_{torsions} = \sum_{torsions} k_\varphi [1 + \cos(n\varphi - \delta)] \quad (2.17)$$

where r_0 is the equilibrium bond distance, θ_0 is the equilibrium value of the angle, φ is the torsional angle defined by a quadruplet of atoms, and k_b , k_a , and k_φ are bond, angle, and dihedral coefficients, respectively [15]. Non-bonded parameters are used to describe van der Waals (VDW) interactions (interactions between uncharged particles) and Coulombic interactions (long-range interactions between charged particles). The most widely used potential to describe VDW interactions is the Lennard-Jones potential [16], expressed as:

$$E = \sum_{i,j} 4\varepsilon_{ij} \left[\left(\frac{\sigma_{ij}}{r_{ij}} \right)^{12} - \left(\frac{\sigma_{ij}}{r_{ij}} \right)^6 \right] \quad (2.18)$$

where r is the distance between two interacting particles, ε is the dispersion energy, and σ is the size of the particle, or the distance at which the particle-particle potential energy is zero. Coulombic pairwise interactions, when relevant to the system, can be added to the non-bonded potential by the following:

$$E = \sum_{i,j} \frac{q_i q_j}{\varepsilon r_{ij}} \quad (2.19)$$

where q_i and q_j are the charges on the two interacting atoms and ε is the dielectric constant [15]. The force field potentials that govern the values of these parameters are typically determined experimentally or from quantum mechanics [13]. Force fields mainly differ with respect to the type of system they are tailored to and their degrees of complexity [17]. Different force fields for the same type of system will often employ different parametrization strategies or different methods of addressing the physical structure of the model. For example, some force fields exercise an “all-atom” approach where each atom type in the system is assigned its own parameters, while other force fields make use of a “united-atom” approach where the atoms in a molecule are treated as a single particle. Potentials such as CHARMM [18], AMBER [19], OPLS [20], UFF [21], TRAPPE [22], and DREIDING [23] are among the most widely used classical force fields in MD simulation [24,25]. Still, many other force fields exist today, and the continuous development of system-specific force fields makes up a large branch of MD simulation research.

2.3 Property Characterizations

2.3.1 Binding Energy

Binding energy, otherwise known as interaction energy, is the minimum energy required to separate a particle from a system of particles or to disassemble a system of particles into individual parts [26]. When studying the interactions of guest species in MOFs, calculations of binding energy can provide valuable insight into the affinity of the MOF for guest particles, as well as the sites or framework locations where guest particles are most likely to adsorb. Binding energy can be evaluated by calculating the difference between the combined energy of two bound objects and the energy of each object if it were isolated:

$$\Delta E_{bind} = E_{AB} - (E_A + E_B) \quad (2.20)$$

where E_A and E_B are the energies of the isolated objects, and E_{AB} is the energy of their interacting assembly [27]. For the example of a guest molecule interacting with the metal node of a MOF, E_A would be the energy of the isolated guest molecule (water, CWA, etc.), E_B would be the energy of the isolated MOF node, and E_{AB} would be the total energy of the structure when the guest molecule is bound to the node. This calculation can be executed using DFT approaches. First, a geometry optimization is run on the entire structure to find the lowest energy configuration of the molecule bound to the node. The optimized structure is then read into three separate calculations in which the single point energies (potential energies in a given atomic arrangement) of the bound structure, the molecule, and the node are evaluated.

2.3.2 Adsorption Isotherm

Adsorption isotherms have been universally employed as a standard procedure for the determination of the specific surface area of solids [28]. Guest species adsorption isotherms are commonly explored in studies of CWA removal by MOFs, as they provide information about MOF surface area and pore size distribution. Furthermore, the shape of water adsorption isotherms in MOFs is known to be indicative of their level of hydrophilicity or hydrophobicity [29], giving insight into their potential for CWA degradation operations under humid conditions. Adsorption of an ideal gas at isothermal conditions can be described by the Langmuir isotherm:

$$\theta = \frac{q}{q_m} = \frac{K_{eq}P}{1 + K_{eq}P} \quad (2.21)$$

where θ is the fractional occupancy of the adsorption sites, K_{eq} is the adsorption equilibrium constant, and P is the partial pressure of the adsorbate. The fractional occupancy can also be defined as the ratio of the amount of gas adsorbed onto the solid (the uptake), q , to the maximum amount of gas particles that can be adsorbed by the adsorbent, q_m [30].

In place of experiments, grand canonical Monte Carlo (GCMC) simulations are the most convenient and powerful tool for studying the adsorption properties of gases and mixtures in porous materials like MOFs [31]. Adsorption isotherms can be obtained by conducting a series of GCMC simulations in which the average gas particle loading in a MOF at equilibrium is evaluated at a range of pressure points. The uptake quantity from simulations is representative of the absolute adsorption, or the total amount of molecules in the adsorption area. To compare GCMC results with experimental values, a bulk equation of state can be used that measures the difference between the absolute adsorption and the number of molecules that would be present in the absence of gas-solid interactions, otherwise known as excess adsorption [32]. The relationship between absolute adsorption and excess adsorption is as follows:

$$n_{ex} = n_{abs} - V_{pore}\rho_{bulk} \quad (2.22)$$

where n_{ex} and n_{abs} are the excess and absolute number of adsorbed molecules, ρ_{bulk} is the bulk fluid density of the adsorbed species at the adsorption temperature and pressure, and V_{pore} is the pore volume of the adsorbent material [31,32].

2.3.3 Mean-Squared Displacement

Mean-squared displacement (MSD) is a measure of the deviation of the position of a particle over time, often employed as a method of characterizing the speed at which particles move

[33]. Using MD simulations, the deviation of each particle in a system can be measured and combined in an ensemble average to give the total MSD at each timestep:

$$MSD = \lim_{n \rightarrow \infty} \langle [z(t) - z(0)]^2 \rangle \quad (2.23)$$

where $z(t)$ is the position of the particle at time t . MSD is based on Brownian motion and is directly proportional to the self-diffusion coefficient, D , which quantifies the mobility of a moving species at equilibrium. Self-diffusion coefficients of guest particles in MOFs provide insight into the strength of their interactions with the framework and the influence of MOF structure and topology on their diffusion and distribution behaviors. Once the MSD is obtained at each timestep of a simulation, the self-diffusion coefficient can be calculated as the slope of MSD versus time:

$$D = \frac{1}{2d} \lim_{t \rightarrow \infty} \frac{\langle [z(t) - z(0)]^2 \rangle}{t^\alpha} \quad (2.24)$$

where d is the dimensionality of the particle displacement, and α is the diffusion mode of the system, or the level of restriction present in the motion of interacting particles. Depending on whether the structure of a given MOF is uniform in all three dimensions, self-diffusion coefficients may need to be evaluated separately in the x, y, and z directions ($d = 1$).

The diffusion mode is also determined from the MSD by calculating the slope of the log of MSD versus the log of time. Fickian diffusion mode ($\alpha = 1$) is representative of standard Brownian motion, typically encountered in bulk systems where molecules can diffuse in three dimensions and MSD increases linearly with time [34,35]. Anomalous diffusion modes such as subdiffusion ($\alpha < 1$) and superdiffusion ($\alpha > 1$) are apparent in systems where diffusion behavior

deviates from that of the bulk. Single-file diffusion ($\alpha = 0.5$), for example, is representative of confined fluid motion due to particle crowding or narrow channels [36]. This type of subdiffusion is particularly relevant in studies of guest species in MOFs, especially those with small pore sizes and high connectivity.

2.3.4 Radial Distribution Function

Radial distribution function (RDF) is a property that describes the average distribution of particles around a central reference particle. It is the most useful measure of the structure of a fluid at molecular length scales, giving a statistical description of the local packing and particle density of a system [37]. In systems of MOFs, RDF analyses can be used to evaluate the distance of guest species from different active sites on the metal nodes and the density of guest particles around active sites on the metal nodes, illuminating preferential binding sites and guest-host interaction affinities. RDF data can also be used to determine the ordered arrangement of clustered molecules in the porous framework. For particles of a given type, the RDF is calculated as:

$$g(r) = \frac{\langle \rho(r) \rangle}{\rho} = \frac{dn_r}{4\pi r^2 dr \rho} \quad (2.25)$$

where $\rho(r)$ is the local density of particles at a distance r from the reference site, and ρ is the bulk density of particles in the system. The coordination number, n_r , is the average number of particles found in a spherical shell of thickness dr around the reference site at a given distance.

RDFs can be easily calculated for uniform systems of particles using MD simulations. To start, a cutoff distance is defined that signifies the maximum distance from the reference particle in which relevant interactions can occur. Particles at a distance greater than the cutoff distance

from the reference site are not considered in the calculation. A bin number is also defined, which tells the simulation software the number of spherical shells that the distance between the reference particle and cutoff should be divided into. An illustration of this division of bins is provided in Figure 2.1a. If the cutoff distance, r_c , from the reference particle is 10 Å, and the bin number is 100, the simulation software will calculate a series of RDFs in each of the 100 bins, all having a thickness of $dr = 10 \text{ Å} / 100 = 0.1 \text{ Å}$.

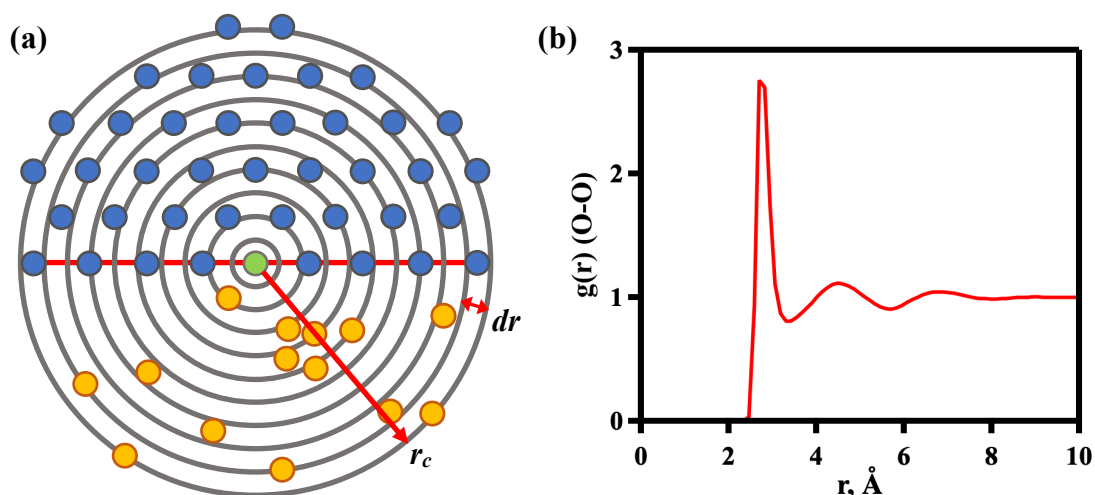


Figure 2.1. Calculation of radial distribution function, $g(r)$. (a) Visualization of spherical shell division around a reference particle (green) for RDF calculations. Top half (blue) illustrates completely uniform particle distribution ($g(r) = 1$), bottom half (yellow) illustrates regions of high and low density ($g(r) > 1$ and $g(r) < 1$, respectively). (b) Oxygen-oxygen RDF for liquid water.

Once the cutoff distance and number of bins have been established, the local density of particles around the assigned reference particle (or reference particle type) is calculated for each bin as the number of particles in the bin divided by the volume of the bin. The bulk density is a constant value, calculated as the total number of particles (of a given type) in the entire system divided by the volume of the system. The RDF for each bin is then obtained by Equation 2.25. This is the

definition of $g(r)$ implemented by LAMMPS [38], the MD simulation software used in this dissertation.

If a bin has $g(r) = 1$, $\rho(r) = \rho$, and the distribution of particles in the bin is completely uniform with respect to the rest of the system. If a bin has $g(r) > 1$, $\rho(r) > \rho$, indicating that there is a dense region of particles in the bin relative to the number of atoms in the system. The opposite is true if $g(r) < 1$, as this indicates that $\rho(r) < \rho$ and there is a cavity or a low-density region of particles in the bin. As shown in Figure 2.1b, the distribution of particles throughout the cutoff sphere can be observed by plotting the $g(r)$ values calculated in each bin versus the radial distance, r , of each bin from the reference site. Several peaks of $g(r) > 1$ spanning a long range between the reference particle and the cutoff are characteristic of highly ordered systems such as crystalline solids, whereas fewer peaks at a shorter range are representative of liquid and vapor phase systems with more entropy and more vacant space [39]. Like that of Figure 2.1b, RDF curves for liquid and vapor phase systems are expected to converge to a value of $g(r) = 1$ before reaching the cutoff distance. This is because the disordered nature of liquids and gases causes their structures to vary over time, making particle positions less correlated to each other beyond nearest-neighbor interactions. The more disorder there is, the closer the radial distance is at which average bin densities begin to resemble that of the bulk system.

When performing RDF calculations in systems of MOFs, the reference particle of interest is often one of the active sites on the metal node, and the interactions of interest are those with the adsorbed species. The active site/guest particle RDF is calculated for every active site of the specified type in the system at every timestep. Figure 2.2 illustrates how the RDF of guest particles in the NU-1000 Zr-MOF would be evaluated if the reference particle was the oxygen atoms of the Zr-O sites on the metal nodes.

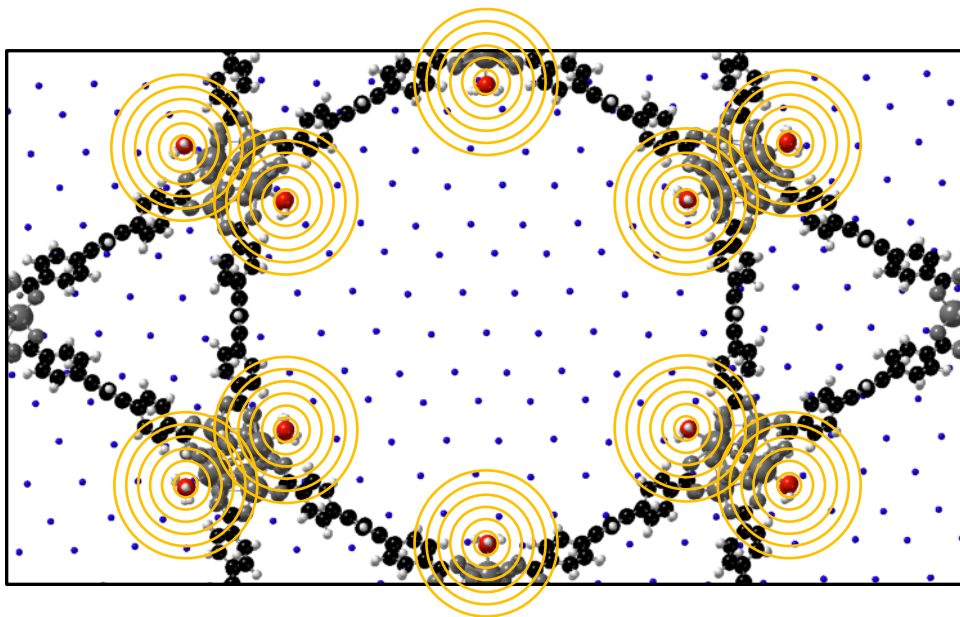


Figure 2.2. Illustration of cutoff spheres for each reference particle when evaluating the RDF of a uniformly distributed guest species (blue) with Zr-O site oxygens (red) in the NU-1000 Zr-MOF.

The RDF for each individual site is taken as an average over the values calculated for that site at each timestep, and the total RDF is taken as an average over those time-averaged values calculated for all the sites in the system. If the guest particles have a relatively uniform distribution and are interacting with all the available sites in the MOF, the number of particles within the cutoff sphere will be more or less the same for every reference atom. Furthermore, the distribution of particles throughout the bins in the cutoff sphere will be more or less the same for every reference atom. In such a case, the calculation of RDF as described by LAMMPS is sufficient for portraying the true behavior of the system, because the bulk density of the entire system is proportional to the bulk density of the particles within the volume of any given cutoff sphere. However, the calculation of bulk density by this definition is not appropriate for characterizing atoms that are not uniformly distributed throughout the simulation cell [38]. A visualization of nonuniform particle distribution in the NU-1000 MOF is shown in Figure 2.3.

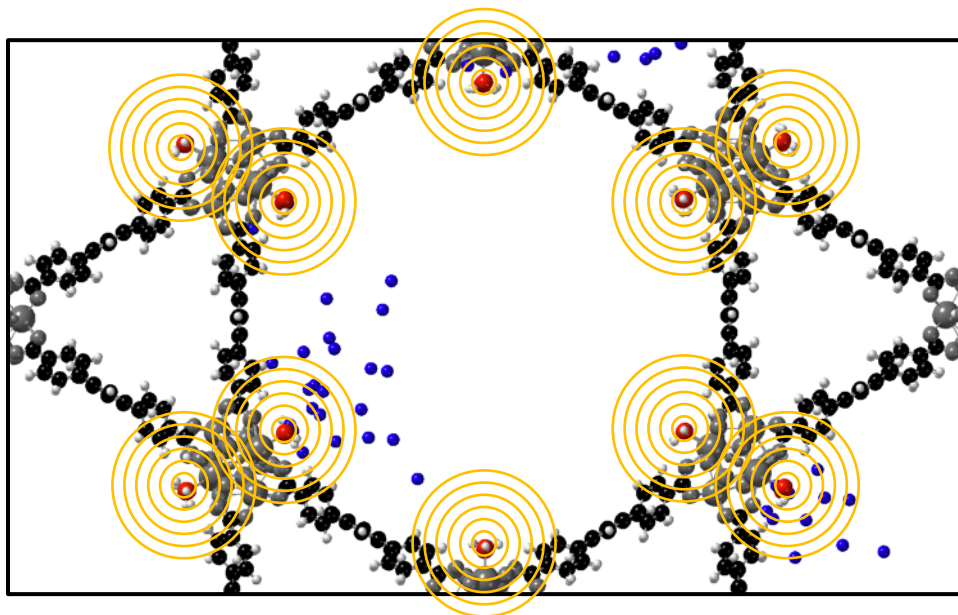


Figure 2.3. Illustration of cutoff spheres for each reference particle when evaluating the RDF of a nonuniformly distributed guest species (blue) with Zr-O site oxygens (red) in the NU-1000 Zr-MOF.

As illustrated in Figure 2.3, the clustering of particles in random areas throughout the simulation cell causes the number of particles present in each reference atom's cutoff sphere to vary. Given that the calculation of RDF involves averaging over all the reference atoms in the system, and that bulk density is taken as a constant value corresponding to the number of guest particles in the entire simulation box volume, two issues come to light:

1. The overall average may include sites that have zero particles in their vicinity, causing peak intensity and broadness to be distorted.
2. The ratio of local to bulk density is not meaningful at sites where very many or very few particles are located, resulting in divergence of the RDF curve as it approaches the cutoff distance.

Due to these roadblocks with RDF calculations in LAMMPS, we developed our own code to perform RDF analyses for nonuniformly distributed guest species in systems of MOFs. Using particle coordinates from MD simulations as input, the code uses two criteria to filter out reference particles not participating in relevant interactions: distance to the nearest neighbor and total number of surrounding neighbors. At every time step, the radial distance of each reference particle (A) to the remaining particles (B) in the system is calculated. If the distance between A and the nearest B is sufficiently far, or the number of Bs in the cutoff sphere surrounding A is a small fraction of the total number of Bs in the system, the RDF for that A at that timestep is not included in the overall average. Furthermore, when calculating RDFs for reference particles that have not been filtered out of the average, the code does not evaluate bulk density based on the number of particles in the simulation box. Instead, bulk density is redefined as the total density of particles in the respective cutoff sphere (which can vary based on reference particle location and simulation timestep). Figure 2.4 shows a comparison of the calculations of active site/guest particle RDFs by our code and by LAMMPS for a system of water molecules nonuniformly distributed in NU-1000.

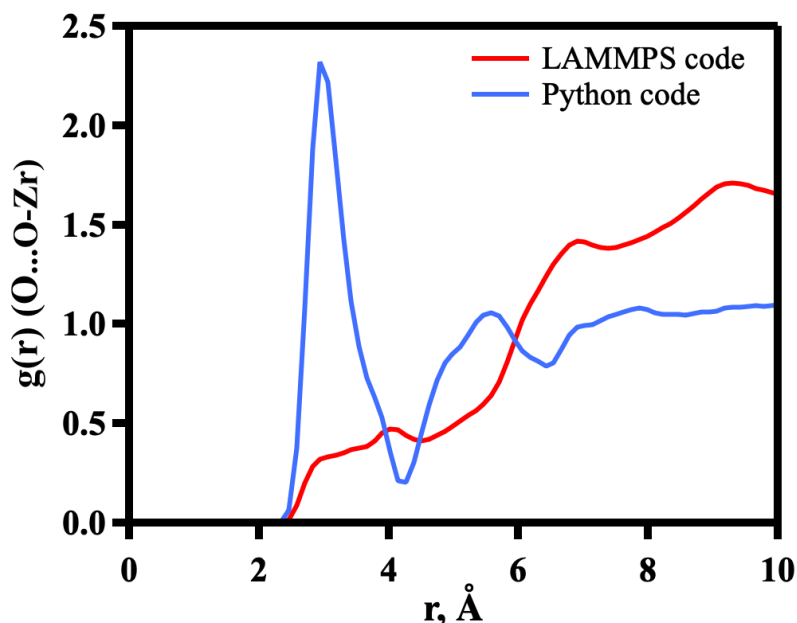


Figure 2.4. Comparison of RDF results from our Python code and from LAMMPS for oxygen-oxygen interactions between water molecules and μ_3 -OH active sites in the NU-1000 Zr-MOF.

By redefining bulk density and enforcing criteria concerning reference particles included in the average, RDF trends can be revealed for guest species in MOFs that cannot be captured by the MD simulation software.

The accuracy of this code was tested by running the calculation for a system of bulk water and comparing the results to those produced for the same system by LAMMPS. The RDF curves from each calculation method are shown in Figure 2.5. Further discussion on details of the code can be found in Chapter 5 of this dissertation.

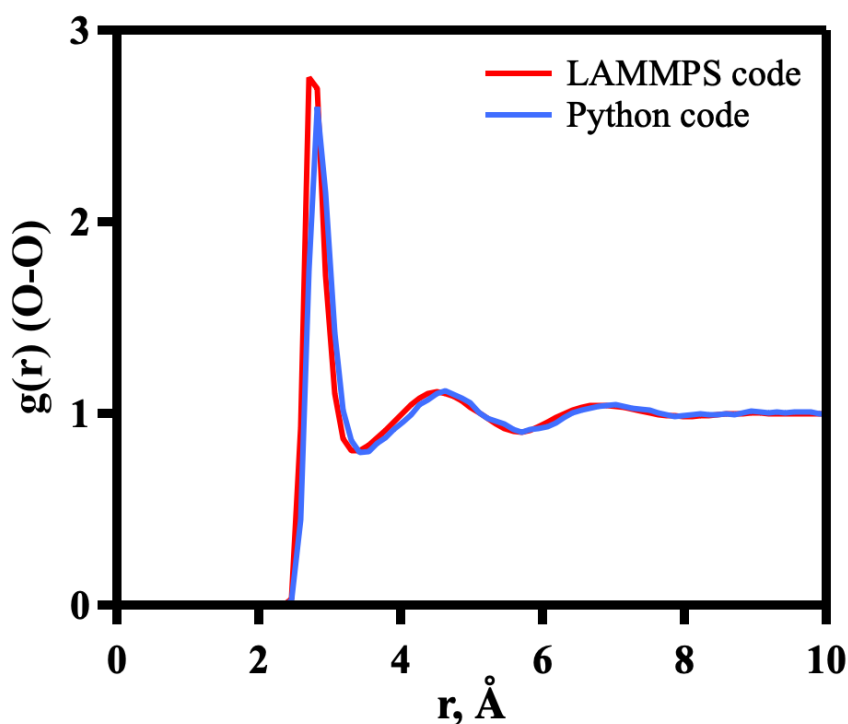


Figure 2.5. Comparison of RDF results for bulk water oxygen-oxygen interactions. The figure compares RDF results calculated directly by LAMMPS code to results calculated using LAMMPS coordinate data as an input to our Python 3 code.

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Chapter 3

Advances in Metal-Organic Frameworks for the Removal of Chemical Warfare Agents: Insights into Hydrolysis and Oxidation Reaction Mechanisms*

3.1 Nerve Agent Hydrolysis

In the heterogeneous catalytic hydrolysis of organophosphorus-based nerve agents, MOFs with Zr_6 nodes and displaceable -OH and -OH₂ ligands such as UiO-66, NU-1000, and MOF-808 are among the fastest synthetic catalysts reported to date [1-6]. While the effectiveness of these MOFs towards nerve agents and simulant hydrolysis has been widely examined both experimentally and computationally, several puzzles still exist regarding the most kinetically favored hydrolysis mechanism, the performance of solid-state materials, and the role of environmental water. This section overviews the existing research findings and details areas lacking sophisticated insights.

3.1.1 Proposed Hydrolysis Mechanisms in Zr-MOFs

Two main mechanisms are commonly proposed for the hydrolysis of organophosphorus nerve agents and their simulants in Zr-MOFs. These pathways are mainly differentiated by the participation of free H₂O and the resulting mode of nerve agent binding on the MOF SBU (secondary building unit, i.e., inorganic metal cluster), as shown in Figure 3.1. The elementary steps are as follows: (i) binding of the organophosphorus compound to an open Lewis acidic metal site; (ii) nucleophilic attack at phosphorus by either an external water molecule (Figure 3.1a) or by the ligand group (OH or OH₂) that terminates the adjacent metal site of the node (Figure 3.1b);

(iii) elimination of the leaving group from the organophosphorus compound by scission of the P-X bond (P-F bond in GB and GD, P-S bond in VX); and (iv) removal of the monodentate (Figure 3.1a) or bidentate (Figure 3.1b) hydrolyzed product from the active site [6-9].

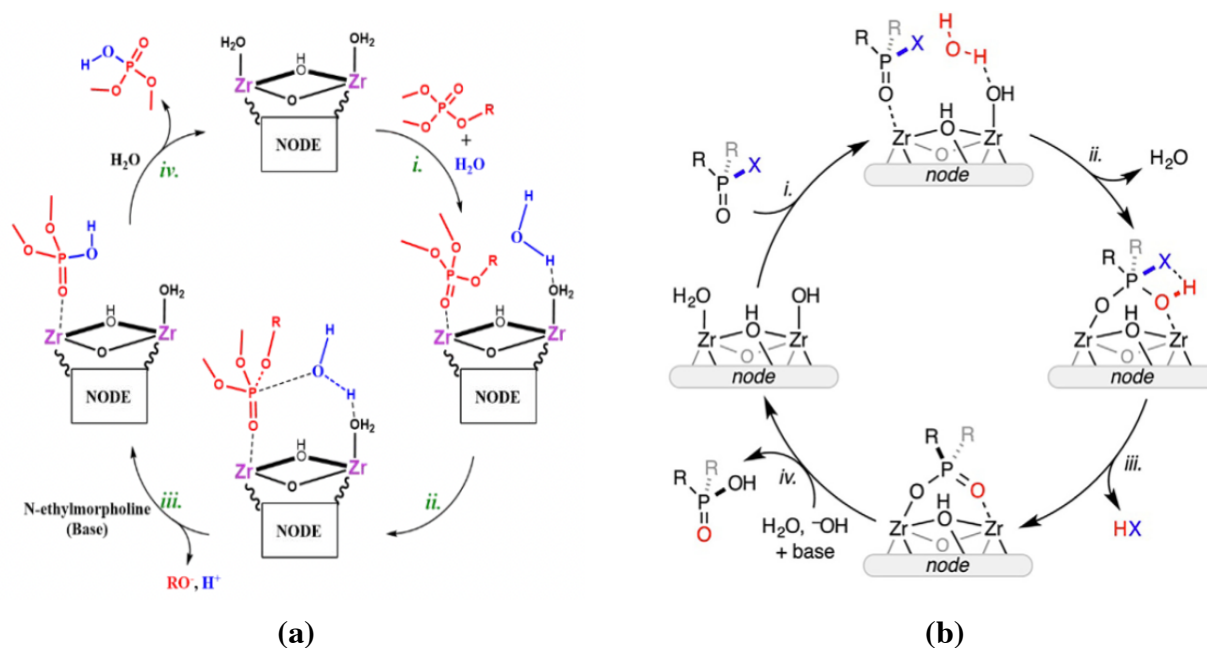


Figure 3.1. Mechanistic scheme for hydrolysis of organophosphorus nerve agents and their simulants on Zr^{IV}-MOFs. (a) Reaction with nucleophilic attack by displaced -OH₂ and monodentate product binding on metal nodes (example using DMNP) [8]. (b) Reaction with nucleophilic attack by adjacent -OH and bidentate product binding on metal nodes [6]. Reprinted with permission from ref. [8] (left) and ref. [6] (right). Copyright 2021 Royal Society of Chemistry and 2020 American Chemical Society, respectively.

Several factors contribute to the likelihood of a given mechanism, and competing opinions exist on node configurations and reaction steps that are most kinetically favorable. The first step of -OH₂ displacement during nerve agent coordination to the Zr-MOF seen in Figure 3.1a,b is often considered rate-limiting. Evidence of this is demonstrated in a DFT study by Momeni and Cramer [7], who evaluated the energetics of sarin hydrolysis on hydrated and dehydrated Zr-MOF nodes, as shown in Figure 3.2. The proposed hydrated reaction pathway corresponds to steps i–iii of

Figure 3.1a, while the proposed dehydrated pathway resembles steps i–iii of Figure 3.1b but with coordination of the nerve agent to an open metal site rather than one occupied by an $-OH_2$ ligand. The results for the hydrated pathway (Figure 3.2a) reveal that on UiO-66 and NU-1000 nodes, the displacement of the $-OH_2$ group by GB requires higher energy to reach the transition state than the nucleophilic attack of GB by the free water molecule. For this reason, preliminary dehydration of the SBUs has been widely considered to improve hydrolytic efficiency in these MOFs.

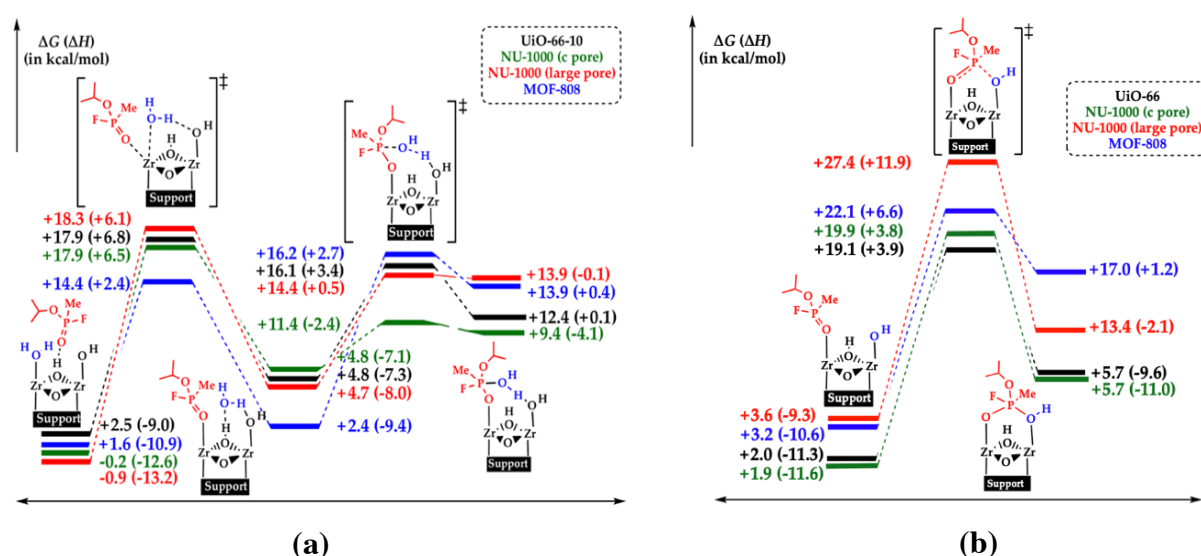


Figure 3.2. Free energies and enthalpies for hydrolysis of sarin on Zr^{IV}-MOFs. (a) Reaction on hydrated metal nodes. (b) Reaction on dehydrated metal nodes [7]. Reprinted with permission from ref. [7]. Copyright 2018 American Chemical Society.

Discussions on SBU dehydration are often associated with NU-1000, an excellent Lewis acid catalyst due to the high concentration of easily accessible Lewis acidic oxozirconium clusters in its structure [10]. Dehydration of these clusters further enhances Lewis acidity, which can, in some cases, improve the activity of the MOF towards the catalytic breakdown of nerve agents. An example of this was presented in an experimental study on nerve agent removal in Zr-MOFs by Mondloch et al. [2], who observed that intentional dehydration of the nodes of NU-1000 (in an

aqueous pH 10 buffered solution) accelerated its hydrolysis of the nerve agent simulant DMNP by 13.5 min. However, unlike in step iv in Figure 3.1a,b, this study found that the NU-1000 node did not rehydrate to its original node configuration throughout hydrolysis. This is a potentially promising result, as it implies that the rate-limiting -OH_2 displacement step may be continuously avoided during consecutive hydrolysis cycles in dehydrated NU-1000 (as opposed to just one initial cycle). On the other hand, one may raise a question of whether the reported efficiency of hydrolysis is simply dependent on the reaction conditions, given that a lack of participation by external water has frequently been demonstrated to introduce more problems than it solves.

As shown in Figure 3.2, for instance, Momeni and Cramer [7] found the activation free energies associated with the nucleophilic attack on GB by a terminal OH group in dehydrated UiO-66, NU-1000, and MOF-808 to be substantially higher than the activation free energies for the same materials using H_2O as the nucleophile and -OH as a general base. In addition to this increased energy barrier, the absence of H_2O in step ii of the dehydrated reaction mechanism is proposed to result in hydrolysis products binding to the SBU in a bidentate mode, corresponding to strong interaction energies that could increase the likelihood of product inhibition [9]. Support of this was found in the computational work of Troya [11], who similarly determined that the lowest-energy reaction path of GB on dehydrated UiO-66 includes the binding of the IMPA product in a bidentate manner, with a measured binding energy 80.1 kJ/mol stronger than the binding energy of monodentate IMPA from hydrolysis on hydrated UiO-66. Convincing evidence of potentially irreversible product binding was also provided in a DFT study by Mendonca et al. [9], who measured the binding energies of hydrolysis products on several Zr^{IV} -MOF nodes and found that all the bidentate anions of GB, GD, and VX had strong binding with the tested SBUs of NU-1000, defective UiO-66, and MOF-808 ($\Delta G_{\text{bind}} < -70$ kJ/mol). Consequently, the reaction

between nerve agents in dehydrated MOFs is thought to likely be non-catalytic under realistic environmental conditions, especially if an external water source is unavailable or uninterested in displacing the reacted phosphonate group in step iv of the hydrolysis mechanism (post-HX elimination) [7,11].

The role of external water in accelerating nerve agent removal was recently emphasized in the work of Liao et al. [3], who discovered that the operation of NU-1000 and MOF-808 in aqueous solution rather than under vacuum [11,12] resulted in a striking increase in the number of catalytic turnovers that each MOF could execute in the degradation of DMNP. This finding was attributed to the increase in the availability of water for hydrolysis, the ability of liquid water to displace some fraction of reaction-inhibiting product species from the metal node, the ability of liquid water to solubilize and stabilize displaced products, and the availability of an external water reservoir to dilute displaced products and render them less competitive as node sorbents [3]. On the basis that many potentially catalytic Zr-MOFs can recruit substantial amounts of water from humid air [3], these results lead to the conclusion that there is potential for multiple catalyst turnovers to be observed during hydrolysis in Zr-MOFs in the realistic solid-state application. Unfortunately, few papers have attempted to study the specific role of varying environmental water levels in each hydrolysis mechanism stage.

We note that current understandings of the hydrolysis mechanism largely depend on a range of assumptions, one of the most improbable being that nerve agents will have no competition with atmospheric water when attempting to adsorb at open metal sites. As a result, the level of interference external water molecules might have in the initial coordination and consistent recoordination of nerve agents to Zr-MOF nodes is not well understood. For example, a combined DFT and AIMD study by Chen et al. [13] investigated the hydrolysis of DMNP in NU-1000 and

found that external H₂O exhibits unfavorable binding with dehydrated (distorted) NU-1000 metal nodes. The calculated binding free energy of a single water molecule at an open metal site was +29 kJ/mol, suggesting that nerve agents and their simulants would not likely have to compete with water to bind to Zr sites in this MOF. This aligns with the previously discussed experimental findings of Mondloch et al. [2], which indicated that dehydrated NU-1000 did not experience rehydration throughout DMNP hydrolysis in a buffered solution. However, a more recent experimental study on GB adsorption in NU-1000 by Son et al. [14] demonstrated completely contradictory results to those of Mondloch et al. [2] and Chen et al. [13], reporting that hydrated NU-1000 outperformed dehydrated NU-1000 in the uptake of GB under both wet and dry conditions. The preliminary removal of aqua ligands was shown to have enhanced the hydrophilicity of the MOF, thus enhancing interactions between water molecules and active sites and preventing the binding of CWA molecules to the dehydrated SBUs.

The discrepancies in the literature between separate accounts of similar systems draw attention to the need for broader research efforts that capture the full picture of nerve agent hydrolysis. Many questions remain unanswered regarding the role of environmental water, along with several other reaction variables that have been virtually addressed. If water molecules have no interest in interacting with the MOF, will they be present in the vicinity of the metal nodes to participate in the reaction? If water molecules are too interested in interacting with the MOF, will nerve agents realistically be able to beat them to active sites or displace them? What about the affinity of different nerve agents for different metal site environments? What about the affinity of different nerve agents for water and vice versa? All these factors are expected to influence the role of water in the reaction mechanism and are thus expected to influence the mechanism itself. We encourage more thorough computational study from the quantum level to better understand the

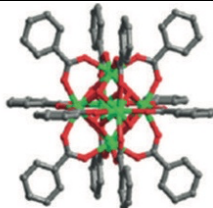
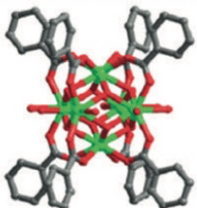
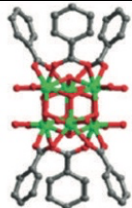
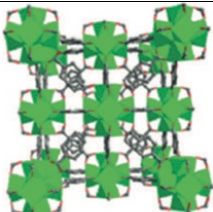
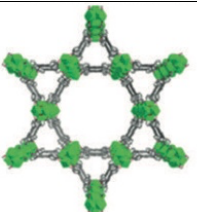
role of water in nerve agent hydrolysis and to begin exploring the possibility of diverse reaction mechanisms based on the type of nerve agent and the type of MOF.

3.1.2 Topology and Reaction Conditions

Regarding the Zr-MOF hydrolysis energetics reported by Momeni and Cramer [7] in Figure 3.2a, we emphasize the differences in transition state structures between MOFs of different types (and even between different pore environments within a single MOF). Of particular interest is the case of MOF-808, whose rate-determining step was not found to be water displacement like the other materials but the nucleophilic attack by displaced H₂O. While details of the reaction mechanism are often varied, possible support of this observation was found in a DFT study by Koning et al. [15] on the degradation of Novichok nerve agents by MOF-808, which similarly reported nucleophilic attack by an external H₂O at the P atom of the CWA as the highest activation energy transition state of the associated hydrolysis reaction mechanism. Differences in the variations of transition state free energies from the H₂O displacement step to the nucleophilic attack step for each system in Figure 3.2a indicate that the structuring of organic linkers greatly impacts the local environment and electronic structure of the metal node [7]. The topological differences between pristine UiO-66, NU-1000, and MOF-808 with respect to pore structure and node coordination are illustrated in Table 3.1, along with their reported surface areas, water affinities, adsorption capacities, structural stabilities, and reusabilities.

Of the three Zr-MOFs, defect-free UiO-66 has the smallest linker connectivity and pore sizes. Each Zr₆ node of pristine UiO-66 is connected to twelve small BDC linkers, yielding pore apertures of only 6–11 Å in size. Studies of adsorption and chemical reactions in UiO-66 [16,17] show that these features limit guest species interactions to the external surface of the MOF, rendering only about 0.5% of the metal nodes catalytically active [18]. Further evidence of this

effect is presented in investigations of Zr-MOF hydrolysis of DMNP by Mondloch et al. [2], who showed that the large 10–31 Å cages and low connectivity of NU-1000 (8-coordinated) enabled a much larger percentage of nodes to act as catalysts for simulant hydrolysis compared to UiO-66. The facilitated delivery of target species to the interior of the MOF resulted in a half-life for hydrolysis of DMNP that was remarkably shorter with NU-1000 ($t_{1/2} = 15$ min) than with defect-free UiO-66 ($t_{1/2} = 45$ min).

Properties	Zr-based Metal-Organic Frameworks		
	UiO-66	NU-1000	MOF-808
SBU	$[\text{Zr}_6(\text{u}_3\text{-O})_4(\text{u}_3\text{-OH})_4]^{12+}$	$[\text{Zr}_6(\text{u}_3\text{-O})_4(\text{u}_3\text{OH})_4(\text{H}_2\text{O})_4(\text{OH})_4]^{8+}$	$[\text{Zr}_6(\text{u}_3\text{-O})_4(\text{u}_3\text{-OH})_4(\text{HCOO})_6]^{6+}$
Organic linker	BDC ²⁻	TBAPy ⁴⁻	BTC ³⁻
Connectivity	12-connected ditopic	8-connected tetratopic	6-connected tritopic
Topology	fcu	csq	spn
Window size (Å)	6	31	14
Pore size (Å)	8/11	10/31	4.8/18.4
Node			
Structure			
Surface area (m ² /g)	~ 1200 [19]	~ 2300 [20]	~ 2000 [21]
Water affinity	Hydrophilic	Internally hydrophobic	Hydrophilic

Water adsorption capacity (g/g)	~ 0.4 [22]	~ 1.0 [23]	~ 0.6 [22]
Structural stability*	Stable in water and acid/base conditions [24]	Stable in water and acid/base conditions [25]	Stable in water and acid/base conditions [26]
Reusability	Reusable, robust cycling performance in water [22]	Reusable, subject to capillary-force-driven channel collapse with repeated cycles in the presence of water [27]	Reusable, significant decrease in surface area with repeated cycles in the presence of water [22]

BDC²⁻ = benzene-1,4'-dicarboxylate (terephthalate); BPDC²⁻ = biphenyl-4,4'-dicarboxylate; BTBA⁴⁻ = 4,4',4'',4'''-(biphenyl-3,3',5,5'-tetrayltetrakis(ethyne-2,1-diyl))tetrabenzoate; TBAPy⁴⁻ = 1,3,6,8-tetrakis(*p*-benzoate)pyrene; BTC³⁻ = benzene-1,3,5-tricarboxylate. * Stability in the range of pH = 0–11, instability in the form of ligand leaching reported for all three Zr-MOFs at pH = 12 and higher [25].

Table 3.1. Structure and properties of selected Zr-based MOFs: UiO-66, NU-1000, and MOF-808. Zr, green; O, red; C, gray; and hydrogen atoms are omitted for clarity [18,28]. Node and structure illustrations reproduced with permission from refs. [18,28]. Copyright 2015 Wiley-VCH.

That said, a later study by Moon et al. [18] showed that despite NU-1000 having the largest pore sizes of the three MOFs, the 6-connected MOF-808 (5–18 Å pores) was found to have by far the shortest hydrolysis rate of DMNP at $t_{1/2} = 0.5$ min. Key geometrical and energetic data measured in the DFT study by Momeni and Cramer [7] showed an increasing trend in Zr-H₂O bond distances and a decreasing trend in Mayer bond order and electrophilicity indices of these sites in each MOF with decreasing linker coordination, suggesting that the binding of water to Zr atoms is weaker in MOFs with lower linker connectivity. This would explain the higher energetic favorability towards H₂O displacement in hydrated MOF-808 than in hydrated UiO-66 or NU-1000 and the tendency of MOF-808 to have the highest kinetic efficiency of the three materials. It was also found in the work of Mendonca et al. [9] that the binding free energies of water molecules

at Zr-MOF nodes weaken in the order of NU-1000 (c pore) > defective UiO-66 > NU-1000 (large pore) > MOF-808, indicating that pore size plays a supplementary role in the water–node interaction strength. Such results suggest that the most crucial topological design rule for efficient nerve agent removal in chemically stable MOFs is the coordination of the metal nodes to the organic linkers, given that the MOFs in question are equipped with sufficiently large pores. In a MOF like NU-1000 (whose metal sites are accessible from two very different pore environments), the preferential pore location of nerve agent molecules should therefore be considered, as this preference could potentially dictate the ability of the nerve agent to displace -OH_2 when attempting to bind to the metal node.

Until now, most of the CWA decontamination kinetics reported in the literature have not been for MOFs in the solid phase but rather in solution. Furthermore, in many of the discussed findings, the Zr-MOFs are not utilized in neat water but in aqueous media with specific pH values achieved by adding buffers [29]. The effectiveness of these materials for degradation has, therefore, largely depended on the presence of a buffer solution, which facilitates the reaction, deprotonates water molecules, and removes unwanted acidic hydrolysis byproducts [1]. Evidence of this was explicitly demonstrated in the work of de Koning et al. [30], who measured the degradation rates of VX in the presence of several Zr-MOFs in solutions of N-ethylmorpholine (NEM) buffer vs. pure water. As shown in Figure 3.3, all the tested MOF catalysts achieved greatly enhanced hydrolysis of VX when operating in a pH 10 buffer solution. When executed in water, organophosphate hydrolysis was slower or even absent and often incomplete due to catalyst poisoning from nerve agent degradation products occupying catalytic sites [30].

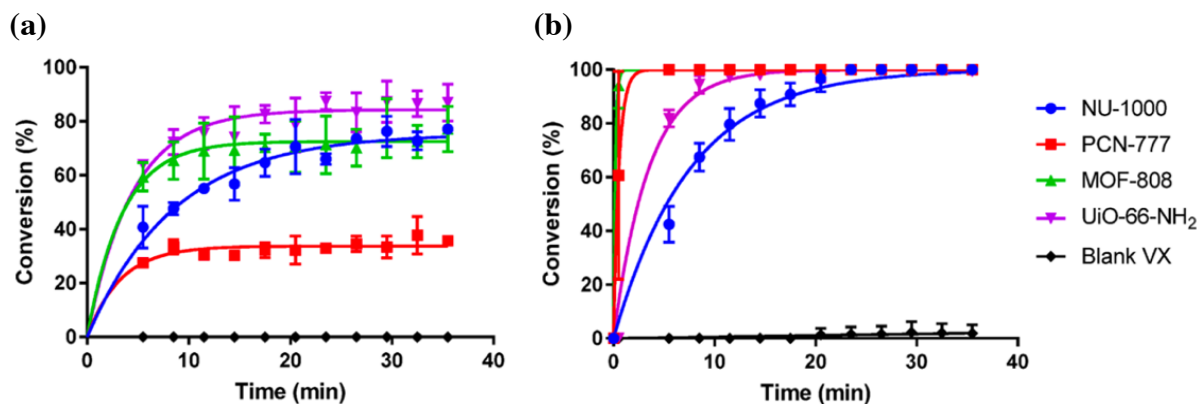


Figure 3.3. Degradation rates of VX in various aqueous-phase Zr-MOFs. (a) Pure water solution. (b) NEM buffer solution [30]. Reprinted with permission from ref. [30]. Copyright 2017 American Chemical Society.

We also emphasize that the trends in conversion % versus time with respect to each type of MOF do not carry over from Figure 3.3a–b, as is evident from PCN-777 having the least efficient degradation of VX in pure water while having the most efficient degradation of VX (along with MOF-808) in NEM buffer. These results suggest that current research efforts employing hydrolysis by MOFs in buffered solution may not provide an adequate evaluation of the features of promising MOFs for their realistic application as heterogeneous catalysts in protective equipment. Reports of hydrolysis by aqueous-phase MOFs (even in pure water) also fail to provide insight into the crucial effects of atmospheric moisture levels.

One of the few works considering the solid-phase implementation of MOFs under humid conditions is that of Ryu et al. [4], who evaluated the impact of water loading on Zr-MOF functionality towards hydrolysis of GD and VX. By measuring degradation rates under pretreatment conditions of 0, 60, and 80% RH, it was found that UiO-66, the amino-functionalized UiO-66-NH₂, and MOF-808 all showed a high decomposition ability of both nerve agents regardless of the air humidity conditions. Comparison of these Zr-MOFs to the relatively more

hydrophilic Zr-based catalyst $\text{Zr}(\text{OH})_4$ provided additional insight into the impact of water affinity on hydrolytic performance, as shown in Figure 3.4.

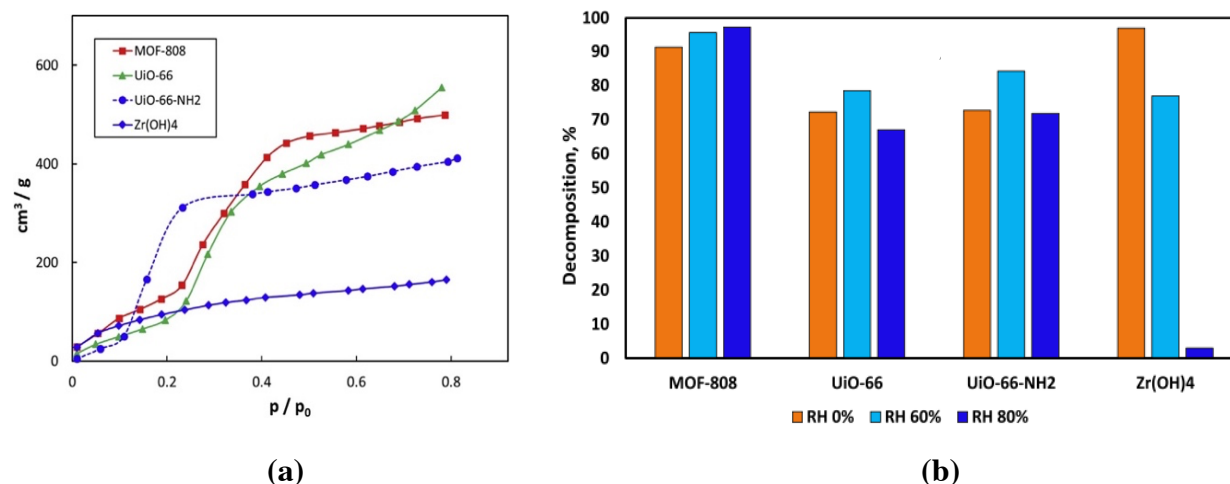


Figure 3.4. Properties of Zr-based reactive materials exposed to water in the solid phase. (a) Water adsorption isotherms at room temperature; (b) comparison of GD degradation performances at $t = 5$ min according to pretreatment conditions of 0, 60, and 80% RH [4]. Reprinted with permission from ref. [4]. Copyright 2019 Elsevier.

Water adsorption isotherms in Figure 3.4a demonstrate that UiO-66, MOF-808, and UiO-66-NH₂ exhibit type II or type IV adsorption, while $\text{Zr}(\text{OH})_4$ exhibits type I adsorption [4]. This indicates that $\text{Zr}(\text{OH})_4$ has a high degree of hydrophilicity, which was shown to reduce the ability of the material to decompose CWAs in humid environments. The study reported that $\text{Zr}(\text{OH})_4$ was capable of efficient nerve agent decomposition but only before the active sites on the nodes became blocked by water molecules at $\sim 80\%$ RH, as shown in Figure 3.4b. Interestingly, while UiO-66 and MOF-808 are indeed more hydrophobic than $\text{Zr}(\text{OH})_4$, these MOFs' adsorption isotherms indicate unrestricted water adsorption. Water condensation in the pores of both materials occurs from 20 to 40% relative humidity, which is considered unusually low for water-stable MOFs [16].

Such results imply that an internally hydrophobic Zr-MOF like NU-1000 may exhibit even more efficient hydrolysis than these materials under humid conditions.

Regarding topology, the findings of Ryu et al. [4] followed the trends observed for the same MOFs in buffer solution, showing that the degradation rates of nerve agents by MOF-808 were greater than those by the UiO-66 series. As seen in Figure 3.4b, the hydrolytic efficiency achieved by MOF-808 was impressive, with >90% decomposition of GD in under 5 min. This result does not necessarily align with expectations, considering that solid-phase decomposition lacks a high pH buffer to accelerate hydrolysis and neutralize phosphate acid products that bind to and poison the MOF catalyst [31]. Investigating further, a similar analysis of the effects of water exposure on CWA decontamination kinetics was found in the work of Wang et al. [31], who explored GD, VX, and DMNP hydrolysis in solid-phase UiO-66, UiO-66-NH₂, and NU-1000. This study had vastly different results than those of Ryu et al. [4], showing overall slower hydrolysis rates and very different reactivity trends in solid-state decontamination than in solution decontamination. Comparisons of GD hydrolysis rates of Zr-MOFs in buffer solution [30,32] to those in the solid phase from Ryu et al. [4] and Wang et al. [31] are given in Table 3.2.

MOF	Time to Reach 80% Conversion of GD		
	<i>pH 10 Buffer Solution</i>	<i>Ryu et al. [4]</i>	<i>Wang et al. [31]</i>
UiO-66	~ 10 min [32]	5-10 min	~ 1 day
UiO-66-NH ₂	~ 4 min [32]	5-10 min	~ 1 day
MOF-808	< 1 min [30]	< 5 min	-
NU-1000	< 1 min [30]	-	> 5 days

Table 3.2. GD hydrolysis rates found in the literature for UiO-66, UiO-66-NH₂, MOF-808, and NU-1000. The time to reach 80% conversion is shown for each MOF in pH 10 buffer solution versus each MOF in the solid phase at ambient humidity.

The comparisons in Table 3.2 reveal the extent to which the works by Ryu et al. [4] and Wang et al. [31] contradict one another. Ryu et al. [4] observed >80% degradation of GD by UiO-66 and UiO-66-NH₂ in under 10 min, while Wang et al. [31] did not observe >80% hydrolysis for either MOF until ~24 h. Moreover, Wang et al. [31] observed that GD hydrolysis rates for the UiO-66 series were much faster than GD hydrolysis rates for NU-1000, which has larger pore sizes, lower connectivity, and is more hydrophobic. Differing trends were also observed with respect to changes in humidity level. Results by Ryu et al. [4] suggested that the impact of increasing humidity on the initial hydrolysis rates of GD in all three Zr-MOFs was mild. In the parallel analysis conducted by Wang et al. [31] using DMNP, the results showed that increases in the content of environmental water led to moderate increases in the hydrolysis rates of NU-1000 and UiO-66-NH₂ but significant increases in the hydrolysis rate of UiO-66.

Conversion time aside, both studies observed that the hydrolysis rates of solid-phase UiO-66 and UiO-66-NH₂ (at all humidity levels) were comparable, which is not typical for these MOFs in a buffered solution. Functionalizing organic linkers in MOFs has frequently been explored for reducing reaction barriers and increasing catalytic activity [7,33,34]. In the case of UiO-66, amino functionalization of the linkers has been shown to vastly enhance nerve agent hydrolysis rates in the presence of a buffer [18] due to the ability of the amino moieties to act as proximal bases, transferring protons at crucial portions of the catalytic cycle [34,35]. When the MOF is instead added to water without a buffer, the weak acidity of the aqueous solution makes it difficult for amine groups to exhibit proton transfer abilities as Brønsted bases [4]. This conclusion is computationally supported in the work of Islamoglu et al. [36], whose DFT calculations of DMNP hydrolysis in aqueous UiO-66-NH₂ revealed that deprotonation of nearby water in step iii of the hydrated reaction mechanism was more energetically favored when promoted by -OH bound to Zr

than when promoted by a proximal amino group. This would explain why the amino functionalization of UiO-66 in an aqueous solution of neat water or the solid phase appears to have little influence on its kinetic efficiency towards nerve agent hydrolysis. Combined with the results in Table 3.2, these findings further prove that the design rules that enhance the hydrolysis rates of Zr-MOFs in aqueous solution do not necessarily apply to solid-phase decontamination [31]. However, the degree to which they may differ is unclear, given the scattered nature of the few available inquiries into the solid-phase application.

We note that research efforts have begun shifting towards addressing the dependency of efficient hydrolysis on aqueous-phase catalysts in the presence of a buffer, and current discoveries appear to be promising. In a report by Moon et al. [1], the polyethyleneimine (PEI) polymer was investigated as a heterogenous buffer for nerve agent and simulant hydrolysis in aqueous NU-1000. The results showed that dehydrated NU-1000 could hydrolyze DMNP, GD, and VX with half-lives of 1.8 min, 3.8 min, and 12.7 min, respectively, indicating a strong potential for efficient removal in heterogeneous systems. More recently, publications have advanced to investigating the feasibility of incorporating basic species into MOFs in the solid phase. An example of this was presented in the work of Ma et al. [37], who discovered that combining Zr-MOFs with crosslinked PEI-based hydrogel supplied the Lewis acidic sites, catalyst-regenerating base, and plentiful water needed for boosting near-instantaneous hydrolysis of GD and VX under ambient conditions. The use of composites was also studied by Luo et al. [38], who showed that incorporating imidazole into the pores of MOF-808 formed a material that structurally mimicked the phosphotriesterase (PTE) enzyme from soil bacteria (which is highly efficient in catalyzing the hydrolysis of organophosphorus compounds in nature), making it capable of rapid DMNP hydrolysis under high humidity conditions. Continued research efforts in this direction are encouraged, as they are

necessary for further developing MOFs that can function as intended in personal protective equipment. We point out, though, that selecting appropriate materials for future studies will likely be contingent on establishing distinct structure-property relationships for MOFs operating in the solid phase.

3.2 Sulfur Mustard Oxidation

As stated previously, oxidation is thought to be the most effective strategy for the degradation of sulfur mustard, and selective partial oxidation is necessary for achieving decomposition into a nontoxic product. Complete selective oxidation requires a mild oxidizing agent, as strong agents such as hydrogen peroxide or *tert*-butyl hydroperoxide are often observed to generate both partially and fully oxidized products [39,40]. The most desirable mild oxidant is singlet oxygen ($^1\text{O}_2$), a reactive species commonly produced from ground state O_2 using a photosensitizer [41]. Unfortunately, many prominent photosensitizers have a proclivity to aggregate in aqueous media, which diminishes their ability to absorb light and produce $^1\text{O}_2$ [39,40,42]. MOFs are an attractive potential solution to this problem, as their tunable networks allow easy incorporation and post-synthetic modification of an array of discrete photoactive moieties at their organic linkers, and their 3D structures allow those moieties to be isolated by surrounding metal nodes [43,44]. Studies of MOFs for the removal of HD and its simulant CEES are thus primarily centered around $^1\text{O}_2$ photooxidation, the proposed mechanism of which is presented in Figure 3.5.

Like nerve agent hydrolysis, the most promising and most frequently investigated MOFs for HD photooxidation are Zr-based. In addition to chemical stability, the high valence metal nodes in Zr-MOFs offer excellent thermal stability and reusability [44], making them especially

appealing supports for generating singlet oxygen [$^1\text{O}_2$] and subsequent catalytic and selective oxidation [41].

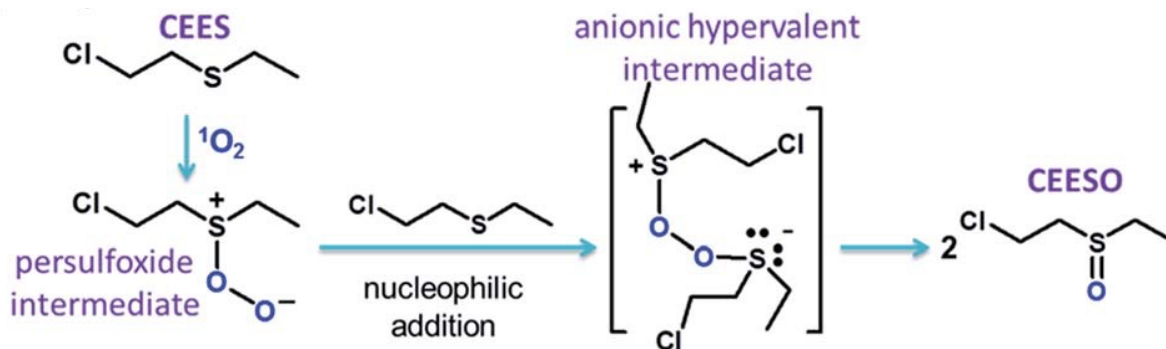


Figure 3.5. Proposed mechanism for the oxidation of CEES by singlet oxygen ($^1\text{O}_2$) [39]. Reprinted with permission from ref. [39]. Copyright 2016 Royal Chemical Society.

Many research efforts have thus been motivated to design and utilize Zr-MOFs as photocatalysts. Meaningful findings and advancements in this field are addressed in the following subsections.

3.2.1 Photooxidation in Zr-MOFs

Early reports on the impressive potential of Zr-MOFs for the photooxidation of HD can be found in a collection of papers by Liu et al., which demonstrated that the pyrene-containing NU-1000 [39] (TBAPy linkers) and the porphyrin-containing Zr-based PCN-222/MOF-545 [40] (TCPP linkers) were able to selectively oxidize the HD simulant CEES to 2-chloroethyl ethyl sulfoxide (CEESO) with half-lives of 6 and 13 min, respectively. Following these findings, research extended to a more detailed photooxidation strategy involving the photosensitizers in Zr-MOFs as nonstructural ligands [41,46]. A study by Atilgan et al. [41] examined this strategy through post-synthetic modification of NU-1000 via solvent-assisted ligand incorporation (SALI), in which aqua and hydroxo groups on Zr_6 nodes were displaced by boron-dipyrromethene (BODIPY) photoactive moieties. A schematic representation of the modified structure can be seen

in Figure 3.6. Experimental evaluations of the catalytically synthesized Br-BDP@NU-1000 shown in Figure 3.6a revealed that BODIPY-incorporated NU-1000 yielded a CEES photooxidation half-life of ~ 2.5 min, which is more than twice as efficient as that of unaltered NU-1000. While this result suggests that nonstructural ligands are far more photoactive than structural organic linkers, we note that similar photooxidation performance has been observed in MOFs whose structural linkers were strategically synthesized to have photoactive components.

As shown in a later work by Zhang et al. [47], when the porous and robust UiO-68 Zr-MOF was de novo functionalized with photoactive triazolobenzothiadiazole (TBTD)-conjugated terphenyldicarboxylate (TPDC) linkers, it could efficiently and selectively photocatalyze CEES into CEESO with a half-life as low as 3 min (nearly as fast as the post-synthetically BODIPY-modified NU-1000). Goswami et al. [48] similarly demonstrated that a version of the PNC-57 Zr-MOF partially substituted with benzoselenadiazole linkers (PCN-57-Se) was able to catalyze the photooxidation of CEES to CEESO with 100% conversion within 12 min ($t_{1/2} = 3.5$ min). It was, however, shown in comparison that PNC-57 partially substituted with benzothiadiazole linkers (PNC-57-S) took 25 min ($t_{1/2} = 7.5$ min) to selectively oxidize CEES, indicating that slight changes in the chemical structure of photosensitizers can also have a significant influence on photooxidation efficiency. As another example of this, when determining which of the two BODIPY derivatives in Figure 3.6e,d (H-BCP and Br-BDP) to incorporate into NU-1000, Atilgan et al. [41] found that homogeneous H-BDP engendered much slower conversion of CEES than homogeneous Br-BDP despite both species possessing the same chromophore. Understanding what properties contribute to higher or lower activity levels in photosensitizers is critical to selecting practical photoactive species for initial or post-synthetic functionalization into Zr-MOFs.

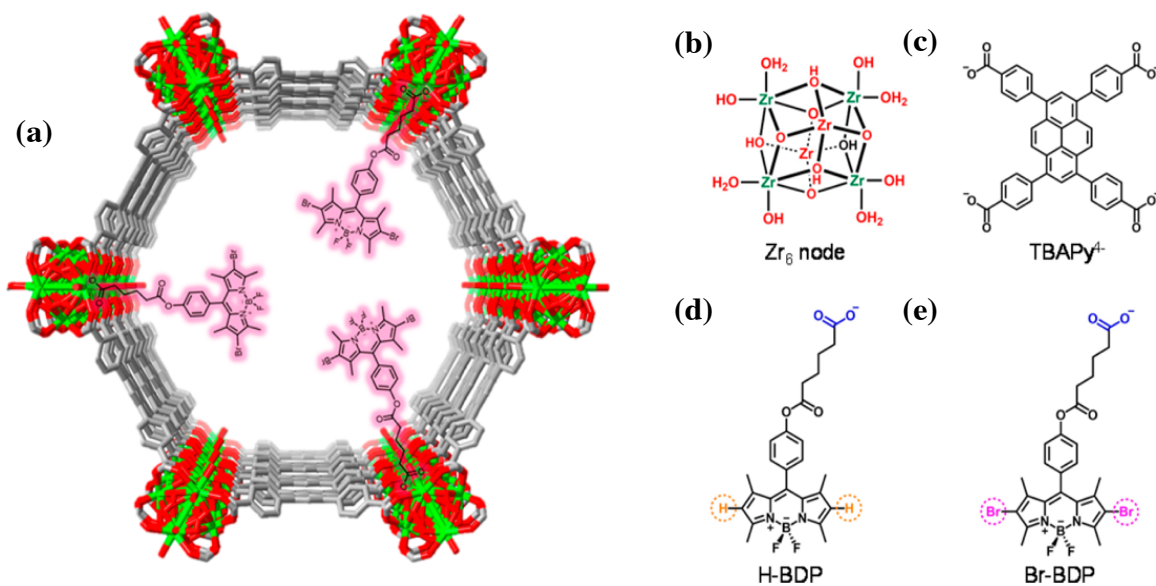


Figure 3.6. (a) Schematic representation of Br-BDP@NU-1000; (b) Zr₆ node of NU-1000, with SALI-displaceable aqua and hydroxy ligands shown in green; (c) structure of organic linker of NU-1000, (d) H- BDP, and (e) Br-BDP [41]. Reprinted with permission from ref. [41]. Copyright 2017 American Chemical Society.

In the case presented by Goswami et al. [48], time-resolved emission spectroscopy and supporting DFT calculations pointed to efficient excited-state singlet-to-triplet intersystem crossing for selenium-containing samples as a key factor in the higher catalytic activity of PCN-57-Se compared to PCN-57-S, amongst other potential contributors. We urge the increased utilization of these time-dependent DFT approaches, as they could be a highly beneficial tool for identifying ideal MOF-photosensitizer pairs.

As an alternative to complex DFT calculations, the ¹O₂ generation quantum yield (Φ_{Δ}) of a photosensitizer is a quantitative measure of its photoactive performance that can provide useful insight into its potential for promoting efficient HD photooxidation. This was demonstrated in the work of Buru et al. [45], who used singlet oxygen quantum yields of photoactive species in Zr-MOF linkers to hypothesize that UMCM-313 (perylene linkers; $\Phi_{\Delta} = 0.45$) would have a shorter

half-life for partial oxidation of CEES than the previously studied PCN-222/MOF-545 [40] (porphyrin linkers; $\Phi_{\Delta} = 0.38$) and NU-1000 [39] (pyrene linkers; $\Phi_{\Delta} = 0.40$). Experiments revealed that the rates of CEES oxidation by each MOF were indeed positively correlated to the $^1\text{O}_2$ quantum yield of each MOF's linkers, where PCN-222/MOF-545 ($t_{1/2} = 11$ min) < NU-1000 ($t_{1/2} = 6$ min) < UMCM-313 ($t_{1/2} = 4$ min) [45]. Nevertheless, certain photoactive species have operational requirements that, regardless of their $^1\text{O}_2$ generation abilities, critically hinder their practical application. For example, C_{60} -fullerene is known to be a strong singlet oxygen generator ($\Phi_{\Delta} = 1$) [49], and Howarth et al. [46] demonstrated that post-synthetic incorporation of fullerene-based photosensitizers into NU-1000 resulted in the photooxidation of CEES with a half-life of only 3.5 min (under UV-LEDs). However, the low solubility of fullerenes makes them a challenge to synthetically produce, and their low absorption efficiency across the visible spectrum limits their ability to be studied further for practical applications [41,49]. Porphyrins are also known to have excellent $^1\text{O}_2$ generating capabilities and are a prime focus in combination with MOF structures due to their ease of synthesis and exceptional chemical stability. However, they are similarly hindered by their strong absorption in the UV region and weak absorption in the visible region [50].

This drawback was displayed in the work of Wu et al. [51], who investigated HD oxidation by H_2O_2 in different Zr-based materials and found that degradation of HD in blank reaction solution under standard room lighting did not accelerate with the addition of pure H_2TCPP , the porphyrin ligand of the PCN-222 Zr-MOF. As shown in Figure 3.7, the reaction solution containing PCN-222 did achieve more enhanced catalytic activity towards HD degradation under standard room lighting than the blank solution, but this was attributed to the catalytic Zr_6 sites and three-dimensional framework contributed by the MOF rather than the presence of porphyrinic linkers

[51]. Such findings help draw attention to the fact that the reported performances of many of the photosensitizers discussed in this section rely on protic solvents and/or consistent exposure to light of specific wavelengths. While it is clear from these reports that photosensitizers can be successfully functionalized into MOFs in various ways, their intended purpose may ultimately be a challenge to realistically exercise.

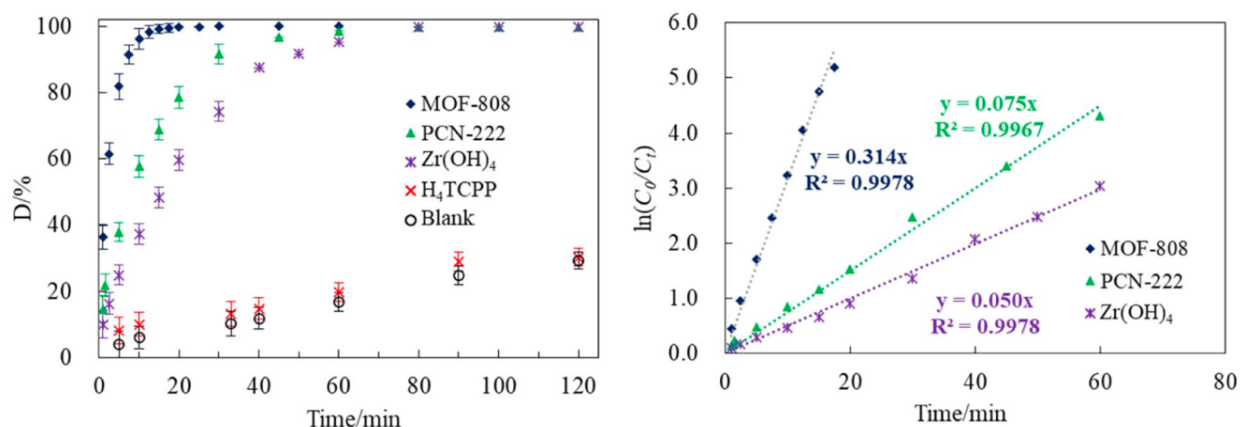


Figure 3.7. Kinetic profiles for catalytic oxidation of HD in H_2O_2 ethanol solution using different materials as catalysts under standard room lighting [51].

Although essential strides in the realm of HD photooxidation by MOFs have been made with respect to understanding different photosensitizers and methods of their implementation, most efforts have failed to provide any correlation between degradation efficiency and Zr-MOF topology. Systematic research on this issue was recently kickstarted by Hao et al. [44], who compared the efficiency and selectivity of three Zr-porphyrin MOFs with different pore shapes, sizes, and metal node connectivity for the photooxidation of CEES. The results showed that CEES reaction rates were correlated to the surface area of the MOFs, where larger surface areas and pore volumes could accommodate more reaction substrate (CEES) and enhance the diffusion of substrates and products, leading to faster oxidation [44]. This aligns with an earlier report on the

diffusion of 2-CEES through NU-1000 and UiO-66, which stated that the larger pore sizes of NU-1000 facilitated better rates and activation energies of simulant transport [52]. We also see from Figure 3.7 that in the investigations of HD oxidation by Wu et al. [51], PCN-222 and MOF-808 were found to be more efficient for H_2O_2 activation and HD degradation than $\text{Zr}(\text{OH})_4$, which was attributed to the larger surface areas of the MOFs enhancing HD adsorption and facilitating HD interactions with H_2O_2 coordinated to the Zr_6 nodes. Oddly enough, however, the results also show that MOF-808, with a measured S_{BET} of $1344 \text{ m}^2/\text{g}$ and a pore volume of $0.82 \text{ cm}^3/\text{g}$, exhibited better catalytic performance for HD oxidation than PCN-222, which had a reported specific surface area of $1625 \text{ m}^2/\text{g}$ and a pore volume of $1.22 \text{ cm}^3/\text{g}$ [51]. This suggests that the topological aspects contributing to oxidation efficiency in these materials are more complicated than surface area and pore volume alone. More thorough investigations will undoubtedly be needed to establish design rules for HD photooxidation in Zr-MOFs and determine if those rules correspond to design rules that facilitate nerve agent hydrolysis.

3.2.2 Tuning Enhanced Photocatalytic Activity

Photocatalysis in MOFs ideally occurs through the excitation of an electron from a photoactive ligand or linker, which transfers to a nearby metal node to create a redox-active center [53]. In recent years, research efforts on the use of MOFs as photocatalysts have begun exploring structural tuning in the form of linker functionalization or metal node substitutions, as these types of modifications can increase the ability of a MOF to absorb light for excitation or to transfer excited electrons from ligands to metal sites [54,55]. Evidence of this was first demonstrated by Gomes Silva et al. [56], who investigated the effects of amino-functionalization on the light absorption properties of UiO-66. While Zr-based UiO-66 is structurally well suited for photocatalysis, its practical application is hindered by its large HOCO-LUCO band gap, which

impedes excitation with light in the visible region of the spectrum [53]. Gomes Silva et al. [56] found that adding NH_2 groups to the UiO-66 framework causes a shift in its adsorption spectrum towards the visible range, improving its ability to operate as a photocatalyst. The reasoning behind this was later detailed in the work of Hendrickx et al. [57], who showed that functional groups incorporated into UiO-66 yield orbital contributions that reduce the effective band gap of the MOF, easing the excitation of linker electrons. Following this discovery, Hendrickx et al. [53] began exploring how changes to the UiO-66 metal nodes would affect its electronic properties. As elucidated in Figure 3.8, LMCT (ligand-to-metal charge transfer) in pristine UiO-66 is hindered by the lack of overlap between its empty zirconium d states and empty linker band [53]. The DOS plots indicate that substituting titanium into the metal nodes of UiO-66 introduces 3d states that are sufficiently low in energy to change the original LUCO from ligand- to metal-based while simultaneously overlapping the linker orbitals [53]. Combined experimental and TD-DFT methods confirmed that even doping with titanium gives rise to node-localized excitation peaks in the UiO-66 excitation spectrum, resulting in improved charge transfer abilities and increased photocatalytic activity.

With all this in mind, a similar study by Wu et al. [54] suggested that the electronic structure of MOFs can be specifically engineered for desired reactions using thoughtful combinations of metal node substitution and linker functionalization. DFT calculations demonstrated that UiO-66 substituted with Ce^{4+} , for example, has strong potential as a photocatalyst due to its favor towards LMCT. Support of this can be found in Figure 3.8, which shows the appearance of a broad band of empty 4f orbitals in UiO-66(Ce) that significantly lowers the LUCO state of the material, leading to a negative E_{LMCT} [53,54]. However, too negative E_{LMCT} values can prevent visible light

adsorption in MOFs [54], limiting their ability to act as photocatalysts in applications that require excitation from natural light.

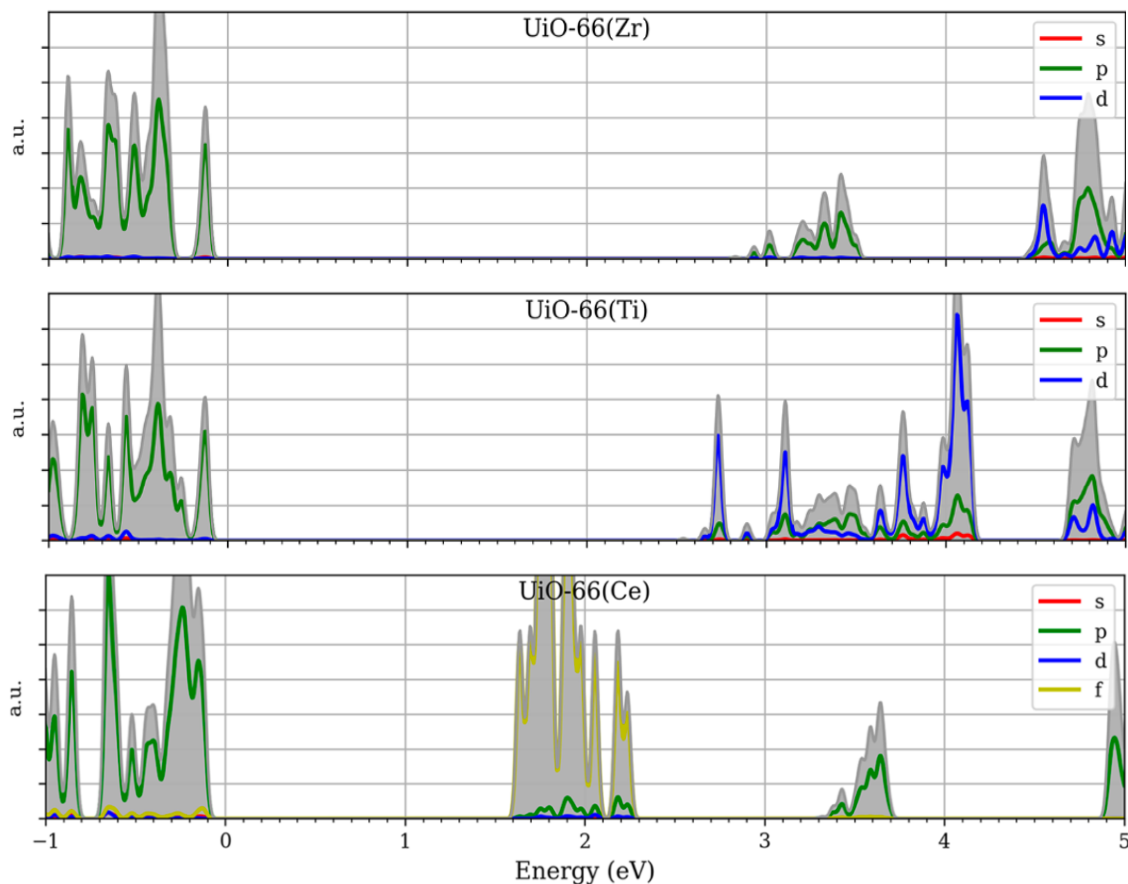


Figure 3.8. Total (gray) and projected (red, green, blue, and yellow) density of states of UiO-66(Zr), UiO-66(Ti), and UiO-66(Ce). The energy is expressed with respect to the Fermi energy ($E_F = 0$) [53]. Reprinted with permission from ref. [53]. Copyright 2018 American Chemical Society.

Subsequent evaluations by Wu et al. [54] revealed that linker functionalization of UiO-66(Ce) with electron-withdrawing groups is a procedure that can successfully raise LMCT energy while preserving favorable charge separation capability, with increasing numbers of functional groups on each linker enhancing this effect (as long as E_{LMCT} remains negative). While not centered around CWA degradation specifically, these findings suggest that combined linker

functionalization and metal substitution in MOFs is a promising research avenue for enhancing photoactive performance under realistic environmental conditions and thus for accelerating the practical implementation of MOF/photosensitizer materials as catalysts for HD photooxidation.

3.3 Outlook

Several notable approaches to improving the practical implementation of Zr-MOFs for CWA degradation have emerged in recent years. An obvious question concerning solid-state nerve agent removal is the feasibility of hydrolysis in dry environments, given that water is necessary for the reaction to proceed and for the removal of poisonous byproducts. Integrating MOFs with catalyst-regenerating bases is a promising technique for mimicking the role of high pH buffers in the solid phase, and the development of MOF composites incorporating these features is currently underway [37,38]. Composites have also been explored in sulfur mustard oxidation applications, naturally to integrate the catalytic abilities of Zr-MOFs with the photoactive abilities of materials that exhibit strong absorption in the visible range [58]. Alternatively, studies have also investigated MOF composites containing known oxidants to explore the oxidation of sulfur mustard by methods other than $^1\text{O}_2$ photooxidation [59]. Advancements in atomistic understandings of mechanisms are a challenge for hydrolysis and oxidation reactions, given that the locations and positions of active metal sites in MOFs are difficult to identify and control. Single-atom catalysts have arisen as a useful strategy in this regard, as they offer a platform for enhanced catalytic performance where the identification of reaction processes on a molecular level can be more easily realized [60-62]. We note that the proven ability of Zr-MOFs to efficiently perform both nerve agent hydrolysis and sulfur mustard oxidation has made them of principal focus in growing inquiries surrounding dual-function MOF catalysts [63-65]. That said, the emerging research efforts discussed in this

paragraph are not exclusive to zirconium-based MOFs, and recent studies on dual-function degradation suggest that Zr-MOFs are not the only materials worth considering [66].

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Chapter 4

Transport Behavior of Water in the NU-1000 and UiO-66 Zr-MOFs

4.1 Introduction

An important factor in establishing design rules of MOFs for CWA degradation is understanding the influence of different structural features on the transport of particles through the porous framework. Molecular transport in microporous systems is often studied computationally using equilibrium molecular dynamics (EMD) and non-equilibrium molecular dynamics (NEMD) [1]. While EMD simulations are useful for evaluating self-diffusion, or the diffusion of particles once equilibrium has already been reached, NEMD simulations are necessary for calculating diffusion from a transport perspective, where molecules enter the system due to an external driving force such as a chemical potential gradient [2]. NEMD simulations have been successfully implemented in various applications, most commonly the evaluation of gas permeation through membranes [2,3,4]. They have even been employed to study MOFs for purposes such as water desalination [5], gas separation [6], and CO₂ capture [7]. Nevertheless, in the application of Zr-MOFs for decontamination of toxic chemicals, little computational research exists that simply explores the mass transport of guest species through the framework.

In this chapter, EMD and NEMD simulations are performed to investigate the transport diffusion properties of water in the UiO-66 and NU-1000 Zr-MOFs. By detailed analysis of the molecular flux of particles through each framework via temperature-driven chemical potential gradients, insight is gained into the dependence of water transport on ambient conditions, and on MOF features such as pore size and water affinity. The results help shed light on the design rules

of MOFs that are most likely to yield optimal functionality toward CWA decontamination under operationally relevant field conditions.

4.2 Model and Calculation Details

4.2.1 Frameworks and Simulation Cells of NU-1000 & UiO-66

The defect-free NU-1000 MOF is built up of $\text{Zr}_6(\mu_3\text{-O})_4(\mu_3\text{-OH})_4(\text{OH}_2)_4$ metal cores connected by tetratopic 1,3,6,8-tetrakis(p-benzoate)pyrene (TBAPy) linkers [8]. In this work, an NU-1000 supercell structure is used that consists of twelve Zr_6 nodes, each connected to two (total) organic linkers. The supercell forms hexagonal mesopores 31.0 Å in diameter, connected perpendicularly to smaller triangular micropores 11.0 Å in diameter. Using the PACKMOL [9] software, a rectangular prism simulation cell was constructed with the NU-1000 supercell (33.16 Å x 40.0 Å x 70.0 Å) centered at the origin, surrounded by two reservoirs 150 Å long in the z-direction on either side, as shown in Figure 4.1a. The maximum number of water molecules that can occupy a 33.16 Å x 40.0 Å x 150.0 Å space is 6633, so each reservoir was filled with 4000 water molecules, corresponding to an arbitrary per-reservoir water density of 0.601 g/cm³. This arrangement allowed for both reservoirs to be maintained once the chemical potential gradient was applied, improving computational accuracy.

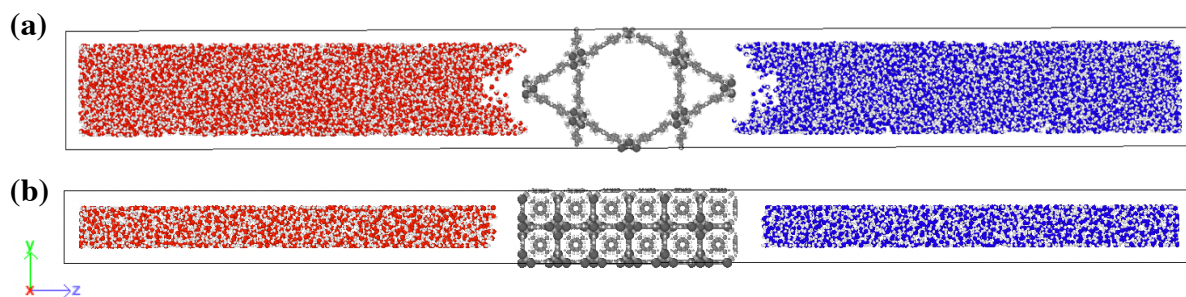


Figure 4.1. Visualization of each Zr-MOF system pre-equilibration. (a) NU-1000/water system. (b) UiO-66/water system.

The defect-free UiO-66 MOF is built up of $\text{Zr}_6(\mu_3\text{-O})_4(\mu_3\text{-OH})_4$ metal cores connected by 1,4-benzene-dicarboxylate (BDC) linkers [10]. Using the Visualization for Electronic Structural Analysis (VESTA) [11] program, a supercell of UiO-66 was constructed to have a configuration uniformly sized with that of NU-1000. This supercell has three UiO-66 primitive cells connected horizontally in the z-direction to make up twelve connected Zr_6 nodes. The framework consists of tetrahedral cages 8.0 Å in diameter, each accompanied by four octahedral cages 11.0 Å in diameter [12]. A rectangular prism simulation cell was constructed using PACKMOL [9], with the UiO-66 supercell (21.0 Å x 21.0 Å x 63.0 Å) centered at the origin and surrounded by two reservoirs 130 Å long in the z-direction on either side, as shown in Figure 4.1b. The maximum number of water molecules that can occupy a 21.0 Å x 21.0 Å x 130.0 Å space is 1910, so each reservoir was filled with 1150 water molecules, corresponding to the same per-reservoir water density of 0.601 g/cm³ used for the NU-1000 calculations.

4.2.2 Classical Molecular Dynamics Simulation

The transport properties of water in the NU-1000 and UiO-66 Zr-MOFs were investigated via EMD and NEMD simulations. Using the VMD (Visual Molecular Dynamics) [13] package, particle masses, charges, and radius sizes were assigned to each atom. Both MOF structures were made rigid, allowing for transport properties of the water molecules to be calculated when diffusing through a fixed solid region with zeroed forces. Molecular dynamics simulations were carried out using LAMMPS [14] software. Periodic boundary conditions were applied in the x and y directions, with simulated walls placed on each face of the simulation box in the xy-plane to prevent particle migration beyond the initial z-bounds. To accommodate the periodic boundaries, each simulation box was constructed so that the water molecules in the reservoirs were situated

5.0 Å from the box walls in every direction. Force field parameters used to describe the water molecules were obtained from the SPC rigid water model [15]. The potential energy for each atom in the system was assigned using the Lennard-Jones (LJ) 12/6 plus Coulomb potential. The H₂O/Zr-MOF LJ interatomic potential parameters were calculated using the Lorentz–Berthelot mixing rules [16]. Force field parameters for NU-1000 were obtained from the DREIDING [17] and UFF [18] force fields, and those for UiO-66 were obtained from the BTWFF force field [19]. A cutoff of 12.0 Å was applied to all LJ interactions [10]. Long-range electrostatic interactions were evaluated using the particle-particle particle-mesh solver (PPPM) technique [20].

EMD simulations were first run to equilibrate both systems. For these runs, the Nose-Hoover thermostat was used to generate positions and velocities from the canonical NVT ensemble, with the temperature of the water molecules in both reservoirs being set to 300 K [2,14]. The SHAKE algorithm was used to apply bond and angle constraints to the water molecules so that the timestep could be increased without forces and velocities blowing the atoms out of the boundaries [14,21]. The equations of motion were integrated using the velocity-Verlet algorithm with a time step of 1.0 fs. Each system was equilibrated for 1 ns, and equilibrated atom coordinates were used as initial configurations for subsequent NEMD calculations, as illustrated in Figure 4.2. Visualization of the water molecules throughout the simulations was performed using OVITO [22] software. NEMD simulations were run for each system for a total of 5 ns. Several simulation trials were conducted to test the most practical method for applying the chemical potential gradient. These included inserting impermeable (graphene) moving walls on the ends of the simulation box in the xy-plane and applying a constant force to them, simulating invisible walls on the ends of each reservoir in the xy-plane and applying a constant pressure to a fraction of water molecules on either side, inserting water molecules on one side of the MOF and having a vacuum region on the

other, and applying a temperature gradient to all the water molecules in the simulation cell to create a hot and cold reservoir [2,3,4,5,21].

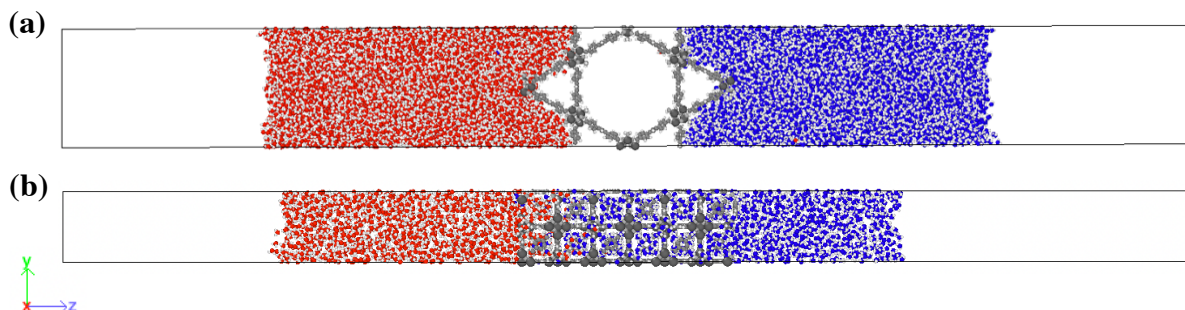


Figure 4.2. Visualization of each Zr-MOF system post-equilibration. (a) NU-1000/water system. (b) UiO-66/water system.

After investigating each method, it was determined that the most efficient simulation setup with the least computational cost was to introduce the chemical potential gradient by adjusting the temperature of each reservoir over the simulation time. The left reservoir was the designated “hot” reservoir, and the right reservoir was the designated “cold” reservoir. Using the canonical NVT ensemble, the initial temperature of the water molecules in both reservoirs was set at 300 K. The final temperature was set to 500 K for the hot reservoir and 250 K for the cold reservoir. This resulted in a chemical potential gradient between the hot and cold reservoirs which increased by 0.00005 K every timestep. Water molecules in each reservoir were assigned to separate groups for the purpose of tracking the movement of particles from one reservoir to the other over the length of the simulation.

4.3 Results and Discussion

During each NEMD simulation, the number of water molecules passing from the hot reservoir to the cold reservoir and the number of molecules inside each MOF were counted every

0.001 ns. This data was used to calculate the water number flow rate, Q , of each system, or the slope of the molecules that moved from the hot reservoir into the cold reservoir over time [3]:

$$Q = \frac{N_f^{CR} - N_i^{CR}}{t} \quad (4.1)$$

where N_i^{CR} is the initial number of water molecules in the cold reservoir, and N_f^{CR} is the final number of water molecules in the cold reservoir, at simulation time, t . The molecular flux of the water molecules, J_w , could then be extracted by dividing the water number flow rate by the cross-sectional area of the MOF, A_{xy} :

$$J_w = \frac{Q}{A_{xy}} = \frac{N_f^{CR} - N_i^{CR}}{t A_{xy}} \quad (4.2)$$

giving the total number of water molecules that passed through the MOF from left to right at any given time during the simulation [2,4]. Finally, the transport coefficient, D_t , in each MOF was calculated from the molecular flux using the following equation:

$$D_t = \frac{k_B T J_w}{\rho P A_{xy}} \quad (4.3)$$

where k_B is the Boltzmann constant, T is the temperature, ρ is the average gas density in the channel, and P is the pressure (corresponding to the given temperature and box volume) [1].

4.3.1 Transport Behavior in NU-1000

In an ideal scenario of pure water flowing through a membrane, from the view of continuum fluid dynamics, it is expected that temperature (or pressure) difference and flux will follow a direct linear relationship [21,23]. Nevertheless, it is well known that molecule transport in nanoscale pores cannot be correctly expressed by this principle [23]. The variation in the molecular flux of water across the NU-1000 MOF with respect to the temperature gradient is shown in Figure 4.3.

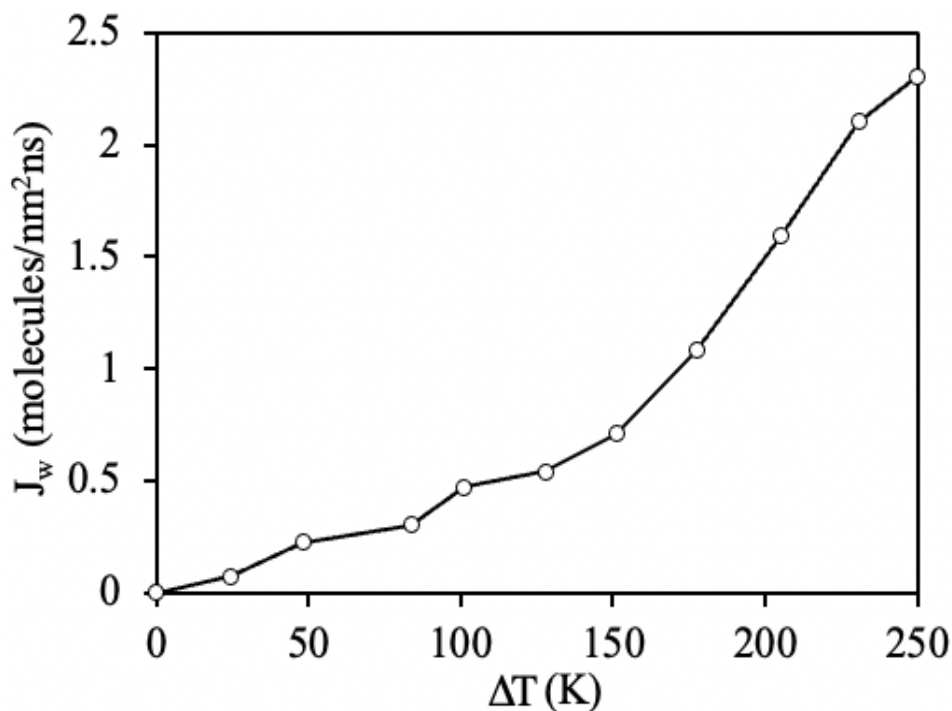


Figure 4.3. Water molecule flux from the hot reservoir to the cold reservoir in the z-direction as a function of temperature difference for the NU-1000/water system.

In the case of water in NU-1000, the molecular flux of H₂O over the range of ΔT exhibits a continuously increasing trend, but not a linear one. When temperature gradients across the MOF are between 0 K and 150 K (in the first half of the simulation), the flux does increase in a somewhat linear fashion. However, once a temperature gradient of 150 K is reached, the molecular flux exhibits more of a parabolic increase with further increases in ΔT . This continues until ΔT reaches ~230 K, at which point the rate of flux appears to slow back down. In nanoporous media, nonlinear patterns such as these are typically a result of intermolecular interactions between diffusing molecules and the solid surface [23], or restricted pore geometries interfering with the ability of molecules to navigate across the framework [24]. In general, the results are consistent with expectations according to literature, that the transport behavior of water molecules is largely dependent on the temperature contributions of the system [5,21,25].

Figure 4.4 shows visualizations of the locations of water molecules in the NU-1000 framework as the temperature gradient increases over the length of the simulation. Molecules from the hot reservoir are colored red and molecules from the cold reservoir are colored blue.

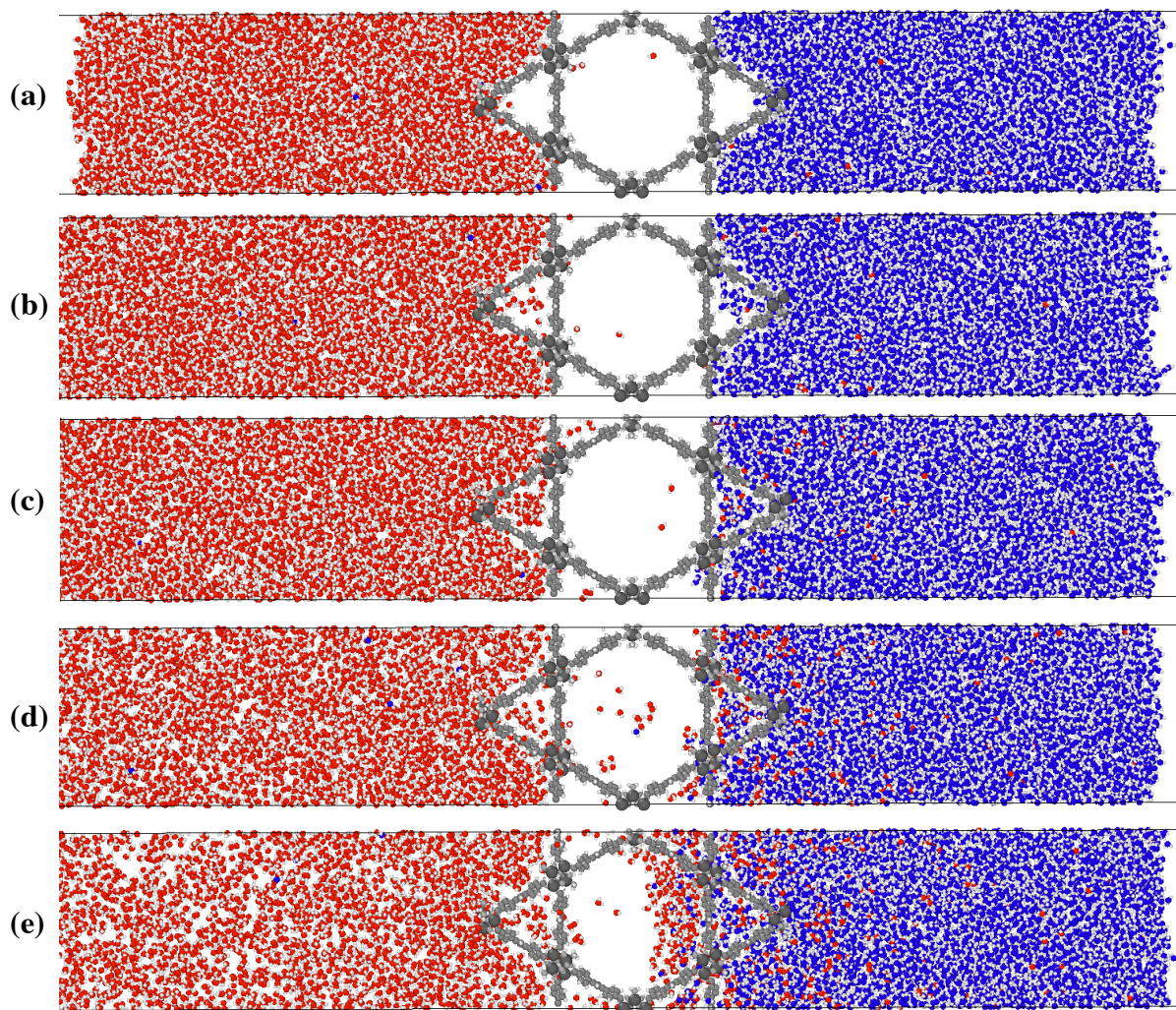


Figure 4.4. Visualization of water molecules diffusing through the NU-1000 MOF. (a) Water molecule position at 1 ns and $\Delta T = 50$ K; (b) Water molecule position at 2 ns and $\Delta T = 100$ K; (c) Water molecule position at 3 ns and $\Delta T = 150$ K. (d) Water molecule position at 4 ns and $\Delta T = 200$ K; (e) Water molecule position at 5 ns and $\Delta T = 250$ K.

From Figure 4.2a, it is observed that attractive forces between water molecules and NU-1000 during equilibration cause the molecules to be pulled towards the MOF structure, where they remain interacting on the outside surface once equilibrium is reached. Post equilibration, once the chemical potential gradient is introduced, Figure 4.4 shows that water molecules are given the motivation to push through the outside barrier of the framework. Molecules cluster in the micropores on either side of the structure, and the large NU-1000 mesopore acts as a sort of diffusion channel for molecules passing from the hot reservoir to the cold reservoir. Trajectory videos suggest that these molecules diffuse through the mesopore without any significant interferences from surface interactions.

When evaluated alongside Figure 4.4, the flux trends revealed in Figure 4.3 make sense. At low temperature gradients, water molecules must break through both the outer NU-1000 surface barrier and the barrier from micropore to mesopore to diffuse from the hot reservoir to the cold reservoir. This begins as a steady diffusion of molecules one by one across the MOF, as shown in Figure 4.4a. Figure 4.4b,c shows that as the temperature gradient continues to increase, more and more molecules break through the micropore region and diffuse through the framework, resulting in the observed linear increase in molecular flux up to a ΔT of ~ 150 K. While the transport of most water molecules appears to be limited by diffusion out of the micropore, Figure 4.4d shows that temperature gradients above 150 K are effective at influencing the separation of multiple molecules from their cluster. The expansive area of the mesopore allows groups of molecules to simultaneously transfer to the cold reservoir, resulting in rapid increases in the rate of flux. Rates continue to rise until decreasing temperatures in the cold reservoir limit the ability of hot reservoir molecules to penetrate through the packed molecules on the right side of the MOF. This leads to the clustering of transported molecules inside the mesopore, which acts as an additional barrier

against further water motion. Such behavior elucidates the increasing steepness of the flux slope observed in Figure 4.3, up until the slow down near the very end of the simulation at high ΔT . The diffusion of molecules always increases with ΔT , but the rate of this increase is clearly influenced by both surface and temperature effects.

4.3.2 Transport Behavior in UiO-66

Results from simulations of water transport in UiO-66 show much different trends than those of water transport in NU-1000. During equilibration, Figure 4.2b demonstrates that attractive forces between water molecules and the UiO-66 structure encourage the immediate diffusion of H₂O into either side of the framework. In other words, the UiO-66 structure becomes completely filled with water prior to the application of a chemical potential gradient. The NEMD simulations thus begin with the entire UiO-66 framework being occupied by fractions of molecules from the hot reservoir and the cold reservoir. Visualizations of the distribution of water molecules as the temperature gradient increases over the length of the simulation are shown in Figure 4.5.

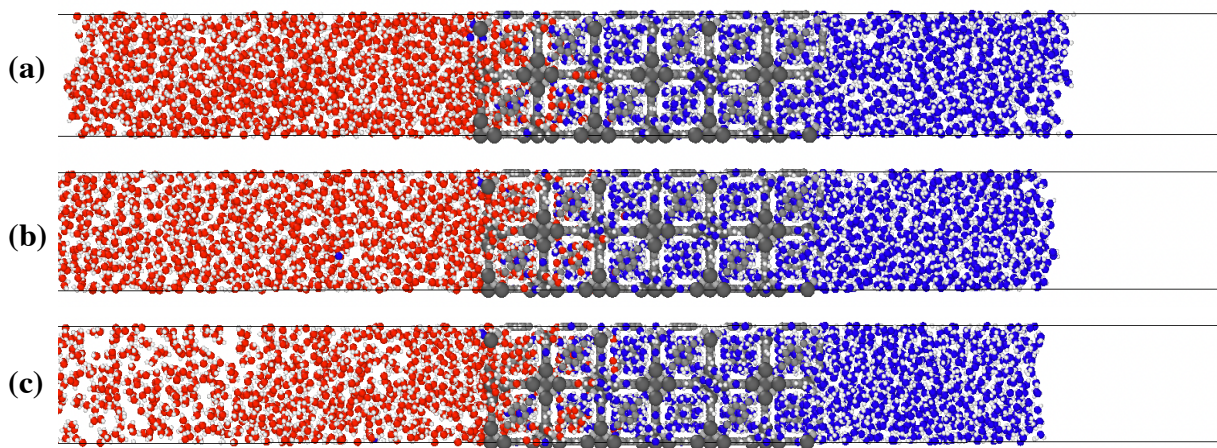


Figure 4.5. Visualization of water molecules diffusing through the UiO-66 MOF. (a). Water molecule position at 1 ns and $\Delta T = 50$ K; (b). Water molecule position at 3 ns and $\Delta T = 150$ K; (c). Water molecule position at 5 ns and $\Delta T = 250$ K.

The results in Figure 4.5 reveal that increases in the imposed temperature gradient do not result in the complete diffusion of any water molecules from the hot reservoir to the cold reservoir on the opposite side of the MOF. While water molecules in the hot reservoir are seen dispersing and exhibiting more vapor-like behavior at larger ΔT , the equilibrium position of molecules inside the framework is virtually maintained with increasing temperature gradient. A more quantitative analysis of this behavior can be found in Figure 4.6, which shows the variation in the molecular flux of water into the UiO-66 MOF with respect to temperature difference. Given that zero molecules made the complete transition from the hot reservoir region to the cold reservoir region, the water number flow rate in this system was calculated using the number of hot reservoir molecules inside the UiO-66 framework.

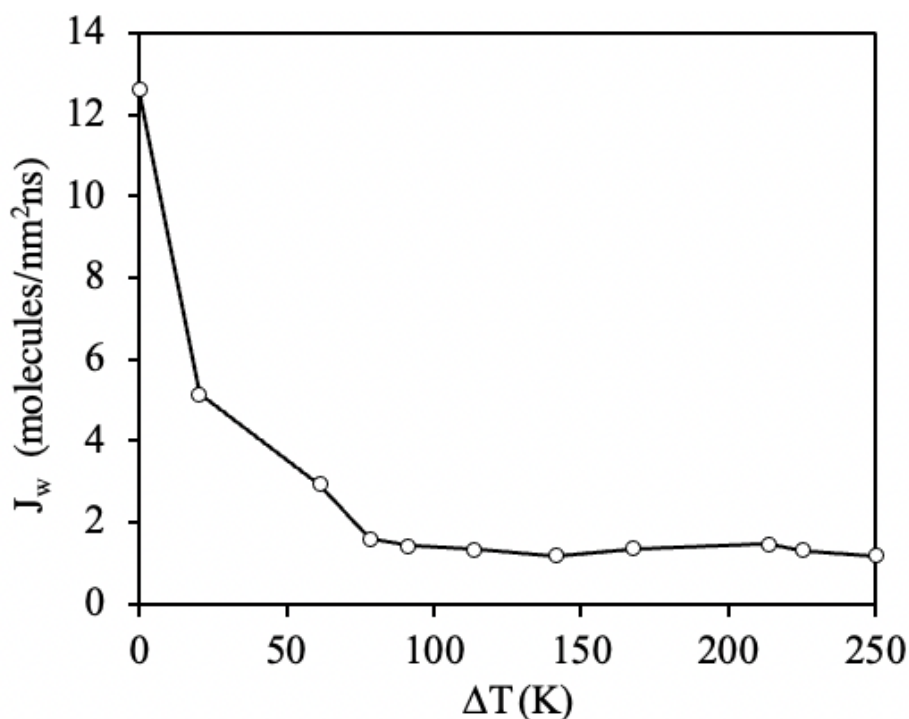


Figure 4.6. Water molecule flux into the MOF supercell in the z-direction as a function of temperature difference for the UiO-66/water system.

From the start of the NEMD simulation, the data in Figure 4.6 shows a rapid decrease in the flux of water molecules into the MOF supercell. Such a trend suggests that the number of hot reservoir molecules inside the framework stays more or less the same during the first half of the simulation. It isn't until the temperature gradient reaches ~ 100 K that more molecules begin to make their way into the structure. Still, the slope of the flux curve beyond this temperature gradient is virtually zero, indicating that increases in ΔT ultimately have little influence on molecule transport.

Comparison of the transport diffusion coefficients for water molecules in each MOF further emphasizes the mass transport limitations in UiO-66. In NU-1000, the transport diffusion coefficient calculated for water molecules present inside the MOF at the highest temperature gradient was $1.12 \times 10^{-11} \text{ m}^2/\text{s}$. On the other hand, the transport diffusion coefficient calculated for water molecules in UiO-66 at the highest temperature gradient was $1.60 \times 10^{-12} \text{ m}^2/\text{s}$, an order of magnitude lower than that of NU-1000. Such mitigated diffusion can be attributed in part to the small pore sizes of UiO-66. The largest cages (octahedral) in UiO-66 are about three times smaller in diameter than that of the NU-1000 mesopore. Consequently, the diffusion of guest species through the UiO-66 framework is much more confined. EMD simulation research has revealed that water does in fact demonstrate a generally confined diffusion nature in UiO-66, with the formation of water clusters via hydrogen bonding in both the tetrahedral and octahedral cages [12]. Given this information, it is appropriate to assume that the small pores of UiO-66 limit the ability of molecules to transport completely through the supercell upon application of the chemical potential gradient, especially under circumstances where water molecules have already aggregated in the available space in the framework.

We note that despite its small pore sizes, faster transport through UiO-66 could potentially have occurred had the framework not been immediately filled by water molecules. In the NU-1000

system, water molecules do not penetrate the framework until the chemical potential gradient is applied. This leaves much more framework space available for diffusion. Studies have shown that NU-1000 is an internally hydrophobic MOF [26], which limits the adsorption of water molecules into the framework at low pressures and limits strong interactions between adsorbed water molecules and active sites. UiO-66 is alternatively known to be a hydrophilic MOF [27], allowing quick adsorption of water molecules which disperse to available active sites to participate in adsorbate-adsorbent interactions. The results ultimately suggest that in addition to its confined channels, the hydrophilicity of UiO-66 may seriously hinder the mass transport of any guest species through its framework in the presence of atmospheric moisture.

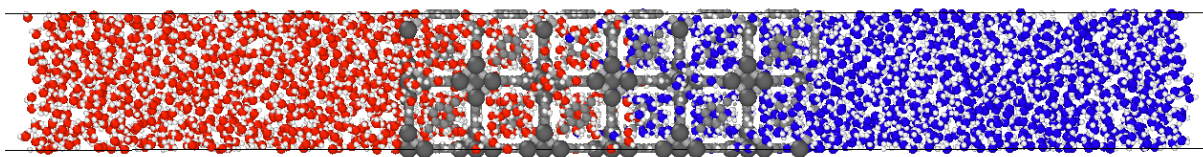


Figure 4.7. Visualization of water molecules diffusing through the UiO-66 MOF at equilibrium when QuickFF force field parameters are applied to the framework atoms.

It must be taken into consideration that variables like the simulation box design, force field parameters, application of walls, etc., can all have a relevant influence on the calculation results [28]. In an attempt to evaluate the trustworthiness of this data, simulations for the UiO-66 system were run a second time using the QuickFF [10,29] force field model for the UiO-66 framework atoms. As illustrated in Figure 4.7, while the QuickFF parameters yield slightly less filling of the framework by cold reservoir molecules, transport in UiO-66 for this design and setup still follows the same general trend of complete pore filling by water.

4.4 Conclusion

The influence of structural features on guest species transport through Zr-MOFs has been investigated by simulating temperature-driven water diffusion through NU-1000 and UiO-66. A combination of EMD and NEMD techniques were used to compute the molecular flux and transport diffusion of water molecules in each system at varying temperature gradients. Results showed that the number of water molecules fully permeating through the NU-1000 framework increased as temperature difference increased, but in a nonlinear fashion. Trajectory videos from NEMD simulations revealed that the rate of molecule flux may have been enhanced by the expansive volume of the NU-1000 mesopores. Alternatively, water molecule flux in the UiO-66 MOF was found to be constricted by the small size of the pores and the high water loading. Surface interactions of water molecules with the framework led to the total filling of the MOF cages during the process of equilibration. In combination with the confined space of the channels, this resulted in the inability of hot reservoir water molecules to make their way through the framework, with zero molecules achieving complete diffusion to the cold reservoir region. The mass transport limitations of UiO-66 were further confirmed by diffusion calculations, which showed the transport diffusion coefficient of water at the highest temperature gradient in UiO-66 as being an order of magnitude lower than that in NU-1000. These results ultimately suggest that the structure and water affinity of NU-1000 make it far better equipped than UiO-66 for chemical reaction operations in humid environments.

4.5 References

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Chapter 5

Vapor-Like Water in the NU-1000 Zr-MOF: A Molecular Level Understanding of Balanced Hydrophobicity in Humid Conditions*

5.1 Abstract

While the structural features and tunability of metal-organic frameworks (MOFs) make them promising materials for chemical warfare agent (CWA) hydrolysis, their stability and performance in conditions of varying humidity is an unsolved challenge. Understanding what design rules enable lasting hydrolytic functionality in evolving field conditions is consequently essential to developing practical MOFs for such applications. In this work, molecular dynamics simulations are carried out to examine the behavior of water at various loadings in the Zr-based MOF NU-1000. With its strong node-linker bonds, expansive pores, and balanced hydrophobicity, pristine NU-1000 possesses the characteristic attributes for structural stability and hydrolytic efficiency in the presence of environmental water. Adsorption and residence time results reveal that while NU-1000 is hydrophilic enough to allow water to adsorb, internal hydrophobicity discourages the distribution of H₂O molecules to active sites at the metal nodes. Water-water interactions take precedence in NU-1000, forming a water cluster that grows with loading and distracts individual molecules from diffusing throughout the framework. On the other hand, self-diffusion coefficients and radial distribution function patterns suggest a lack of hydrogen bonding, with the clustered molecules having faster diffusion and less ordering than that of liquid-phase water. The limited interactions between water and the metal nodes indicate a lower likelihood of competition for sites impeding target species hydrolysis in NU-1000. Additionally, the partially vapor structural state

of the aggregated water molecules in the expansive NU-1000 channels indicates a lower likelihood of pore filling by water that interferes with target species adsorption and diffusion. Such results evidence a strong potential of the NU-1000 Zr-MOF for superior performance in hydrolysis applications like toxic chemical decomposition.

5.2 Introduction

With the evolution of toxic chemicals continuing to progress, developing methods for the destruction of chemical warfare agents (CWAs) has become an increasingly important research topic. Advancements in the engineering of filtration media that can protect individuals from CWAs are needed, as complications including low adsorption capacities, deactivation of active sites, and slow reaction kinetics have hindered the practical use of existing degradation materials [1–3]. Focus has thus shifted to the design of adsorbents, particularly nanoporous materials, with the capability to efficiently hydrolyze CWAs under operationally relevant field conditions [4]. Metal-organic frameworks (MOFs) are a class of porous crystalline solids that have sparked interest in this area. With tunable networks that provide customizable chemical functionalities, MOFs are adjustable to dynamic environments, making them useful in a wide variety of practical applications [5,6]. Furthermore, the exceptional porosities and large surface areas of MOFs create an ideal setting for selective capture and hydrolytic destruction of target species like CWAs [1,2,7].

When evaluating MOFs for operation in realistic environmental conditions, a principal quality to consider is their stability and reactivity toward water. Many MOFs show limitations of weak mechanical and chemical stability in the presence of humidity that stems from a combination of hydrophilic functional groups and water-susceptible linkages between metal nodes and ligands [8]. Exposure to water invites adsorbate attack on the metal nodes, which breaks weak bonds

between the nodes and ligands, resulting in framework collapse. In hydrolysis applications, this strong affinity for water leads to additional problems like competition between H₂O and target molecules for active sites [9,10] and facilitation of hydrogen bonding and pore filling of adsorbed water [11,12]. Interactions with water often take precedence over target species interactions, reducing the accessibility of active sites and decreasing the probability of target species hydrolysis. These obstacles make hydrophilic MOFs a poor choice for hydrolysis applications, particularly in settings where varying levels of humidity are present. As an alternative, highly connected MOFs with high oxidation state metals (such as Cr³⁺, Fe³⁺, Al³⁺, and Zr⁴⁺) and organic carboxylate ligands have been widely considered [8,13,14]. Steric hindrances around active sites and strong node-linker coordination bonds in materials of this type make them well-equipped for avoiding framework attack and breakdown by water. Of course, high connectivity and small pore openings can also limit the accessibility and abundance of potential binding sites to target species [3], especially those larger in molecular size than H₂O. Hydrophobic MOFs show promise in this regard, as their resistance to chemical degradation by water [15] makes them chemically stable in humid conditions and unrestricted by competitive adsorption upon water exposure [16]. That said, strong hydrophobicity tends to discourage the adsorption of water into MOF pores. While prevention of water-framework interactions is essential for target molecule site accessibility, the hydrolytic activity of MOFs towards target adsorbates has been shown to substantially decrease in the absence of atmospheric moisture [17]. Consequently, the ability of water to enter MOF channels along with target species is an important attribute for optimal hydrolytic efficiency.

Based on these understandings, we speculate that an ideal MOF for hydrolysis applications in fluctuating field conditions would be tuned with three combined features: (1) strong linkages between metal nodes and ligands to provide structural stability in water; (2) low node connectivity

and large pore sizes to enable efficient diffusion and reaction kinetics; and (3) a balanced hydrophobicity to prevent water from occupying all the available sites while still allowing water to enter and participate in target species hydrolysis. In this work, we demonstrate that the NU-1000 Zr-MOF is equipped with these attributes and has the potential to exhibit the desired functionality. Zirconium-based MOFs like NU-1000 are known to possess unprecedented stability in humid environments [6,13,18] due to strong bonds between their negatively charged linkers and highly oxophilic Zr^{IV} centers [19]. While many Zr-MOFs also possess high node connectivity, NU-1000 has a low-coordination network of ultrawide pores (11-31 Å), thus offering both stability in water and broad guest species site accessibility [3]. Most importantly, the water adsorption in NU-1000 resembles a type V isotherm [20,21], as shown in Figure 5.1a [22]. Type V adsorption of water in nanoporous materials follows the trend of the middle curve in Figure 5.1b, with low adsorption in the low-pressure region, followed by quick filling of the material to saturated adsorption capacity [20]. This behavior in MOFs has been associated with water-water interactions that are preferred over the distribution of water to widely separated active sites [20,23], and is characteristic of materials that are not strongly hydrophilic nor strongly hydrophobic, but somewhere in between [21].

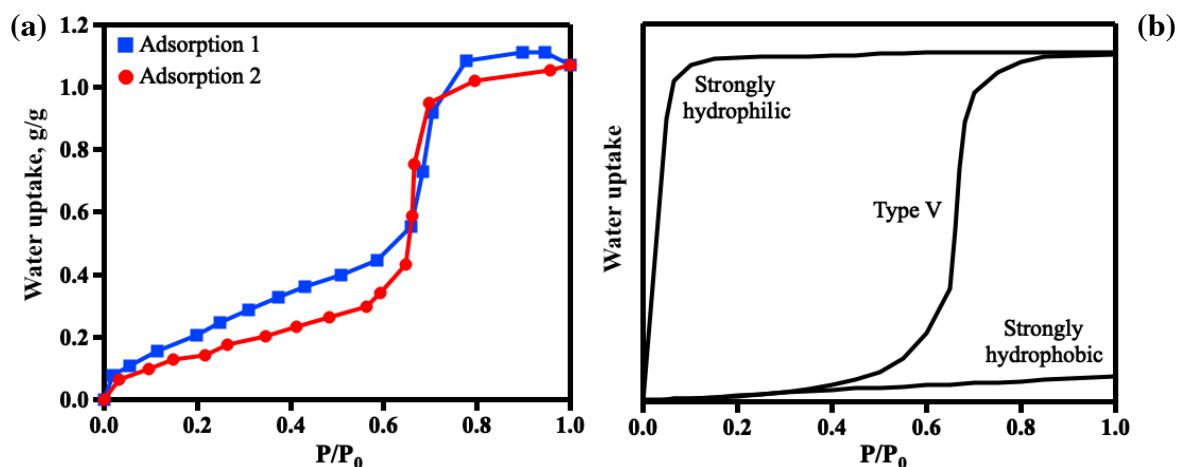


Figure 5.1. Characterization of water adsorption in NU-1000. (a) Experimental adsorption isotherms for single-step (blue) and multi-step (red) adsorption of water in the NU-1000 primitive cell at 300 K and 1 atm [22]. (b) Adsorption isotherms for water in different types of nanoporous adsorbents near room temperature. Reprinted with permission from ref [20], Copyright 2014 American Chemical Society, and from ref [21], Copyright 2008, with permission from Elsevier.

Combined with its topological features, reports suggest that the hydrophobic nature of NU-1000 promotes enhanced target species removal efficiency compared to other Zr-MOFs [24,25]. However, as systematic studies on atmospheric moisture and MOFs are rare, there is little understanding of how water exposure at different levels realistically impacts the functionality of NU-1000 for hydrolysis applications. In this work, by a series of molecular dynamics (MD) simulations, we have evaluated the effect of pore structure and hydrophobicity on the self-diffusion, distribution, and structural phase of environmental water at various loadings ($\sim 0.5\%$ to $\sim 85\%$ RH) in pristine NU-1000. Our findings suggest that NU-1000 exhibits the ideal interaction with water for efficient hydrolytic performance in realistic environmental conditions, making it a promising material to consider for the capture and degradation of toxic chemicals. This result serves as evidence that the discussed combination of features should be considered in the future design of MOFs for such applications.

5.3 Model and Calculation Details

5.3.1 Topology and Adsorption Capacity of NU-1000

The pristine NU-1000 MOF is composed of $\text{Zr}_6(\mu_3\text{-O})_8(\text{O})_8(\text{H})_{16}$ metal cores connected by tetratopic 1,3,6,8-tetrakis(*p*-benzoic acid)pyrene (TBAPy⁴⁺) linkers. In this work, a supercell model of NU-1000 [26] is used that connects twelve of these Zr_6 -nodes with twenty-four organic linkers, see Figure 5.2a. The supercell forms large hexagonal mesopores connected

perpendicularly to smaller triangular micropores [27], as illustrated in Figure 5.2b. Passageways exist throughout the framework that allow direct access between pores of the same or different types. This feature gives guest species the ability to maintain residency in their preferred pore environment while moving between active sites.

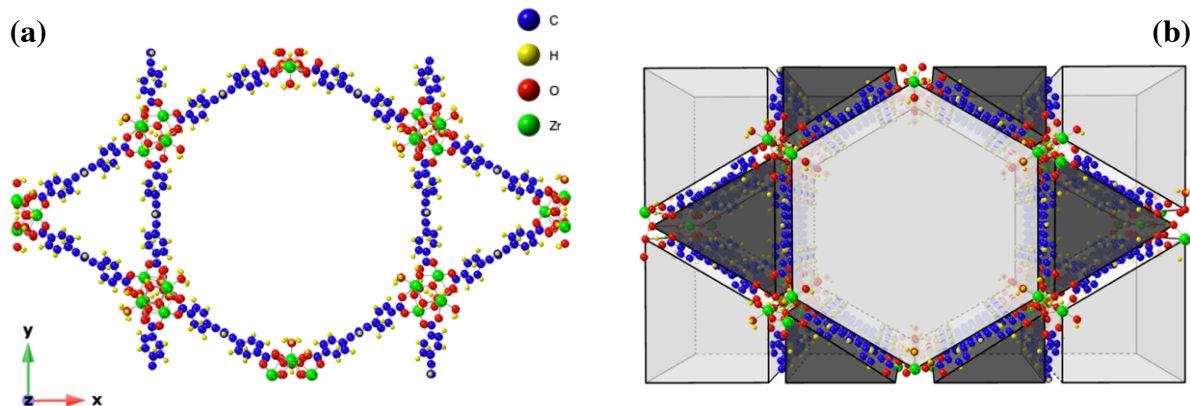


Figure 5.2. Supercell of NU-1000 in the z-direction. (a) This supercell of NU-1000 combines twelve Zr metal cores with twenty-four TBAPy linkers. (b) Visualization of two types of NU-1000 pores: light gray regions are mesopores (31 Å diameter), dark gray regions are micropores (11 Å diameter) [26].

Several proposed models exist for the experimentally synthesized NU-1000 metal core, but the precise topology of the 16 charge-balancing protons is difficult to assign and is not well understood [28]. It has been suggested that mixed-ligand MOFs can have superior chemical and thermal stability [29], and studies of NU-1000 have reported mixed-node topology as the most thermodynamically stable configuration of the existing protons [28]. As demonstrated in Figure 5.3, the metal core used in this work has a mixed-node proton topology for the Zr_6 nodes consisting of eight-coordinated zirconium atoms and three distinct hydrogen-containing groups. Half of the μ_3 -O groups in the metal core are protonated, forming μ_3 -OH groups. The twelve remaining

protons are distributed evenly to each pair of single-bonded oxygens on the four outer zirconium atoms, resulting in a combination of one water ligand and one hydroxide ligand per zirconium.

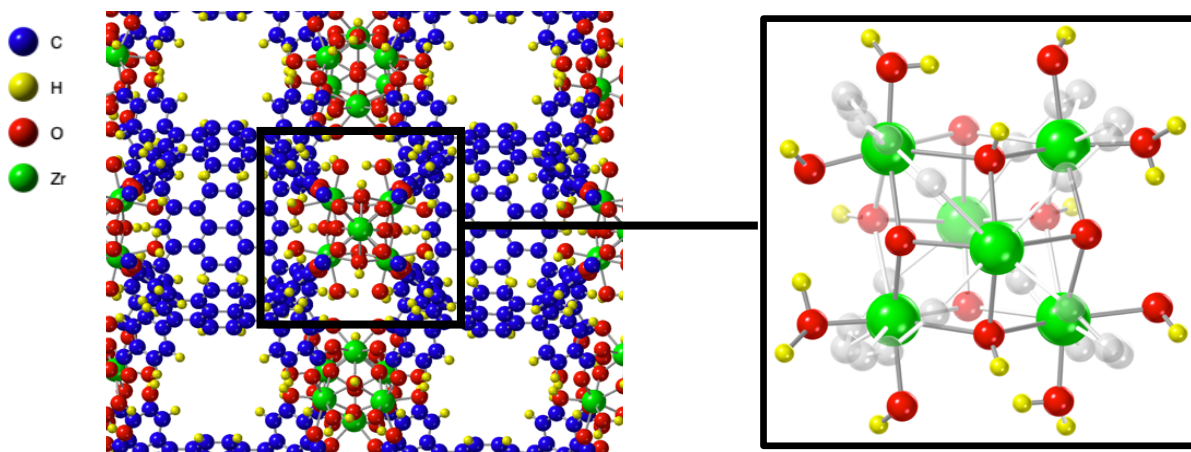


Figure 5.3. NU-1000 metal core structure composed of $\text{Zr}_6(\mu_3\text{-O})_4(\mu_3\text{-OH})_4(\text{OH})_4(\text{OH}_2)_4$ nodes connected to 1,3,6,8-tetrakis(*p*-benzoate)pyrene (TBAPy⁴⁻) linkers [26–28,30].

Each metal core has four open faces of $\mu_3\text{-O}$, $\mu_3\text{-OH}$, Zr-OH , and $\text{Zr-H}_2\text{O}$ sites directed into two different environments. Half of the faces point in the direction normal to a mesopore while the other half point in parallel with the *z*-direction, occupying a transition region between pores. Therefore, the configuration of the Zr_6 mixed node enables access of guest molecules to certain protonated NU-1000 sites from both pore types. In contrast, other protonated sites can only be reached from the mesopores. Enhanced visualization of these environments can be seen in Figure 5.4. Another important topological feature of NU-1000 is that it does not exhibit a uniform three-dimensional structure, as shown in Figure 5.5. Molecules diffuse from one pore to another through two-dimensional passageways that are 7.0 Å to 12.0 Å in size and only allow pore crossover in the *x* and *y* directions.

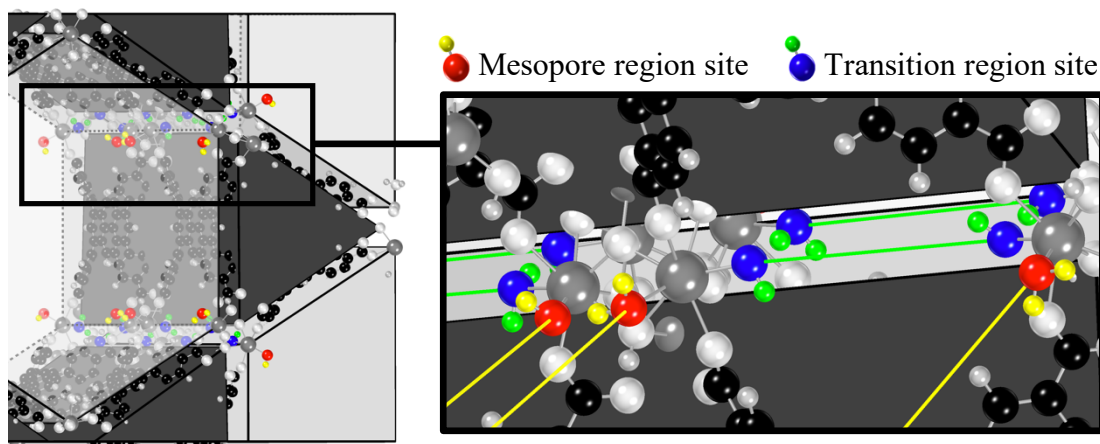


Figure 5.4. Demonstration of NU-1000 metal core site configuration. Each outer zirconium atom has one protonated group that points into a mesopore and one protonated group that points into a transition region. The result is four sets of Zr-OH and Zr-H₂O pairs per metal core, half of which can only be accessed from a mesopore.

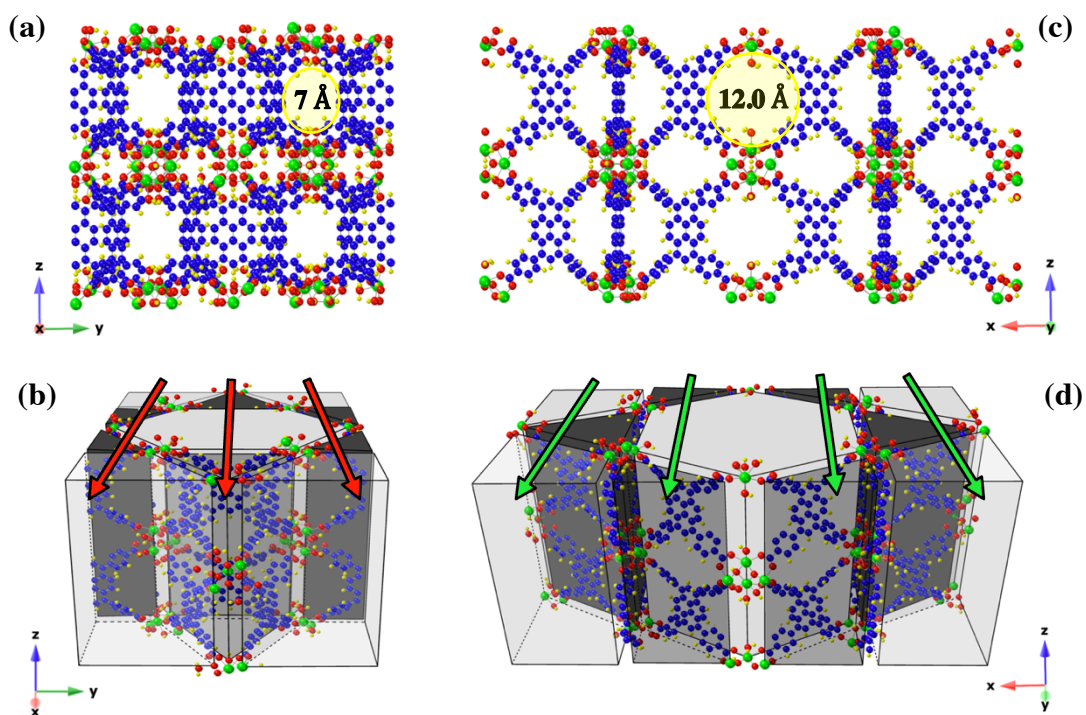


Figure 5.5. Demonstration of NU-1000 nonuniformity. (a) NU-1000 passageways in the x-direction. (b) View of NU-1000 pores from the x-direction. (c) NU-1000 passageways in the y-direction. (d) View of NU-1000 pores from the y-direction.

Consequently, while diffusion in the x and y directions is complicated by framework obstacles and enhanced site access, diffusion in the z-direction is pore-exclusive and unobstructed. Given these variations in directional topology, it is not appropriate to calculate diffusion behavior in the NU-1000 MOF as an average over the three dimensions. In addition to water loading, we must treat the direction of movement as an independent variable.

Loading levels for the five systems tested in this work were chosen based on the experimental determination of water adsorption in NU-1000, as shown in Figure 5.1a. Water uptake was tested with two different loading processes, both yielding a saturated adsorption capacity of ~ 130 H₂O in the NU-1000 primitive cell. The NU-1000 supercell used in this work is made up of 12 primitive cells. Adjusting to account for the increased volume of the NU-1000 supercell, systems in this study were modeled with loadings of 24 ($\sim 0.5\%$ RH), 120 ($\sim 5\%$ RH), 360 ($\sim 35\%$ RH), 840 ($\sim 65\%$ RH), and 1560 ($\sim 85\%$ RH) water molecules, with 1560 H₂O ($130 \text{ H}_2\text{O} \times 12$) being the saturated adsorption capacity of the supercell.

5.3.2 Classical Molecular Dynamics Simulation

The mean-squared displacement (MSD), radial distribution function (RDF), and residence time behavior of water in NU-1000 were investigated using classical molecular dynamics simulations via the LAMMPS software [31]. The framework was treated as rigid, restricting atoms in the NU-1000 supercell from changing position throughout the simulation. While flexible models can be more accurate for simulating diffusion in MOFs with small pore windows, large pore channels in MOFs like NU-1000 allow diffusion to be reasonably modeled using rigid geometries [32,33]. Non-bonded water-framework interactions were modeled using the Lennard-Jones (LJ) 12/6 plus Coulomb potential with parameters obtained from the DREIDING [34] and UFF [35]

forcefields [32,36–38], as this combination of force field parameters has already been successfully used to simulate water and gas adsorption in MOF materials [39–41]. The partial charges on the framework atoms were calculated using the EQeq method [42], a semiempirical technique that has been shown to provide reliable atomic charges for various MOFs [42,43], commonly used for its computationally inexpensive iterative calculations compared to charge assignments based on electronic structure calculations [44,45]. The water molecules for bulk water and water in NU-1000 were modeled using the SPC water model with the SHAKE algorithm [46–48]. A cutoff radius of 12 Å was applied for LJ interactions, and a cutoff of 10 Å was applied for Coulombic interactions. The H₂O/NU-1000 LJ interatomic potential parameters were calculated using the Lorentz-Berthelot mixing rules [49]. The particle-particle particle-mesh solver technique [50] was used to handle long-range electrostatic interactions (beyond the 12 Å cutoff).

A series of MD simulations were performed for water at the five different loadings. Using PACKMOL software [51], water molecules were randomly inserted into the NU-1000 supercell constructed as a 33.16 Å x 40.0 Å x 69.23 Å rectangular prism simulation box. Particle masses and charges were then assigned to each atom using the Visual Molecular Dynamics (VMD) software package [52]. Each system was equilibrated in the NVT ensemble for 50 ns at a constant temperature of 300 K. Following equilibration, a series of identical 20 ns production runs were performed for each water loading. Production runs were differentiated by changing the velocity random number seed, ensuring diversity in the spatial distribution of water molecules from one run to the next. The prolonged equilibration length eliminated any history of each system's initial configuration from subsequent production runs, thus minimizing the effects of PACKMOL-generated molecule arrangements on the results of the simulations. LAMMPS integrated the

equations of motion using the velocity-Verlet algorithm. A timestep of 1.0 fs was used for all calculations.

We note that a recent paper by Wardzala et al. on modeling diffusion in Zr-MOFs found that the Lennard-Jones diameter in DREIDING for the hydrogen atom of μ_3 -OH metal node groups is too large, prohibiting guest molecules from getting close enough to form hydrogen bonds with these sites [33]. They propose using the TRAPPE isopropanol potential in place of DREIDING for μ_3 -OH cross-interactions with adsorbate molecules as a solution to this problem. After testing simulations of NU-1000 with the suggested modified potential for the μ_3 -OH active sites, it was concluded that the use of typical UFF and DREIDING parameters is sufficient for the systems modeled in this work. However, we strongly recommend the consideration of this modified potential in studies of Zr-MOFs for guest species hydrolysis, particularly those involving the identification of primary binding sites or detailed analyses of the hydrolysis reaction mechanism. More details on this can be seen in Figure 5.6.

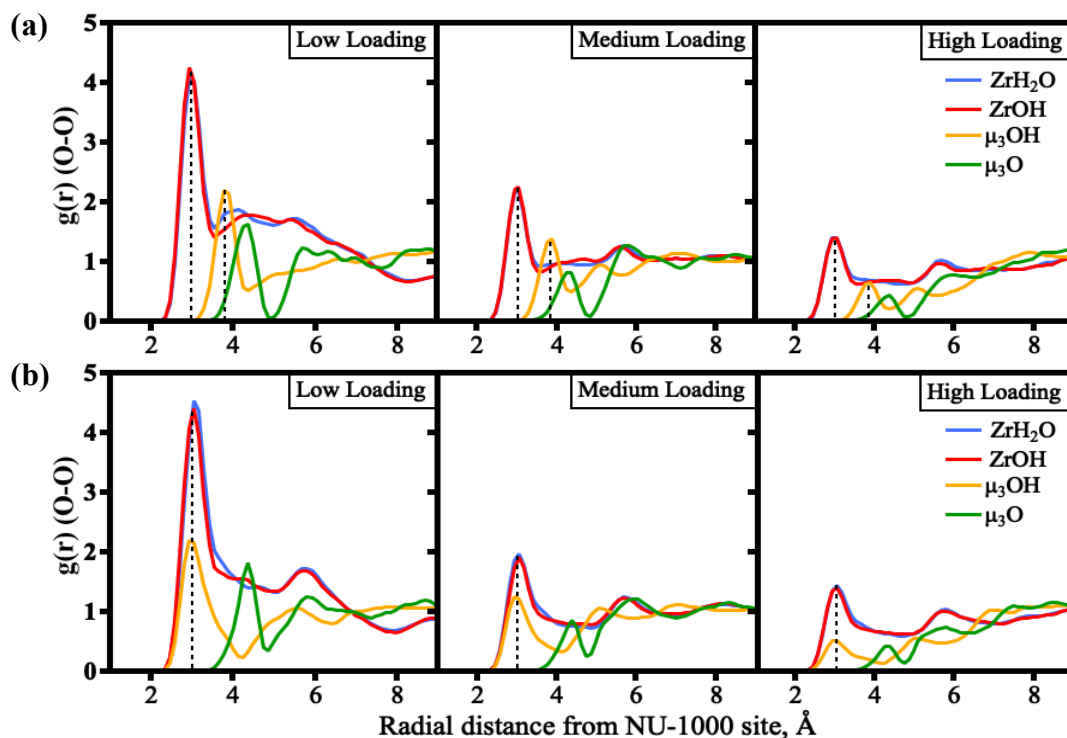


Figure 5.6. Radial distribution functions for the oxygen atoms of water to the oxygen atoms of the four metal core groups of NU-1000 with respect to loading. (a) DRIEDING potential used for μ_3 -OH active sites. (b) TraPPE isopropanol potential used for μ_3 -OH active sites.

Use of the TRAPPE potential results in water molecules interacting with μ_3 -OH sites at a closer radial distance, but not close enough to suggest the formation of hydrogen bonds. Aside from this shift in peak position, TRAPPE parameters have no significant effect on the results shown in this work (residence times, self-diffusion coefficients, or structural phase of water in NU-1000). Nevertheless, these findings do indicate that TRAPPE parameters may be important to consider in studies of other guest species in NU-1000, or studies of water in more hydrophilic MOFs, where strong interactions at binding sites are anticipated.

5.3.3 Mean-Squared Displacements and Diffusion Mode Calculation

Mean-squared displacements for each water loading were estimated using multiple time origins averaged over ten production runs. Self-diffusion coefficients for each direction of movement at each water loading were then extracted from the following equation for one-dimensional particle motion [53]:

$$\lim_{n \rightarrow \infty} \langle [z(t) - z(0)]^2 \rangle = 2Dt^\alpha \quad (5.1)$$

where the left-hand side is the MSD or the ensemble average of the displacement of fluid molecules over time. This value is directly proportional to the self-diffusion coefficient (D), which is calculated as the slope of the averaged MSD data versus time. The diffusion mode (α) is a quantitative measure of the level of restriction present in the motion of interacting particles. Our

calculations of the self-diffusion coefficient assume Fickian diffusion mode ($\alpha = 1$), which describes the typical diffusion process of bulk systems or systems with large pores where molecules can diffuse in three dimensions and MSD increases linearly with time [53,54]. The emergence of anomalous (non-Fickian) diffusion modes such as single-file diffusion has been frequently discussed in studies of nanoporous materials due to the potential for constrained fluid motion in pores of such small diameters [55]. More specifically, evidence of this confined diffusion has been reportedly observed for guest species in certain MOFs, including the Zr-based MOF UiO-66 [36]. The actual diffusion modes for our systems were determined from the following equation by disregarding the self-diffusion coefficient:

$$\log(MSD) = \alpha \log(t) + \log(2D) \quad (5.2)$$

where α becomes the slope of the log of MSD versus the log of time.

5.3.4 Residence Time and Distribution Analysis Calculation

As shown in Figure 5.2b, the NU-1000 supercell contains distinct micropore regions and mesopore regions. Given that the pores of NU-1000 are not interchangeable in the z-direction, the geometric parameters of these regions can be treated as two-dimensional, making it very simple to identify and quantify the precise location of guest species. Information on the location of water molecules in the NU-1000 framework was extracted from LAMMPS output files containing the coordinates of each water molecule in each system every 10,000 timesteps. Using MATLAB R2021b [56] and Python 3 [57] software, the pore location of every water molecule at every timestep interval was identified for each of the ten production runs at each of the five water loadings. Subsequent evaluation of this data was performed to determine the average occupation

of individual pores by water and the average residence times of water in the micropore and mesopore regions. Averages were taken over all molecules in the system for all production runs. A cutoff value of 0.02 ns was set as the minimum amount of time a molecule must have spent in a region for its residence time to be contributed to the overall average. This was done to reduce computational cost and eliminate the contribution of less relevant data to the average residence time. A pooled variance of individual molecule errors was used to calculate the final error reported in averaged residence time outputs.

5.3.5 Radial Distribution Function Calculation for Heterogeneous Structures

While radial distribution function is a property that can be calculated directly in LAMMPS, the LAMMPS definition of RDF is only appropriate for characterizing uniformly distributed atoms throughout a simulation cell [58]. As shown in the Results and Discussion section of this work, the distributions of water molecules at various loadings in NU-1000 do not meet this criterion. Consequently, RDF calculations for these systems could not be accurately performed in LAMMPS. Instead, LAMMPS output files containing the coordinates of each atom in each system every 10,000 timesteps were used to extract RDF curves for water-water interactions and water-NU-1000 interactions via Python 3 software. Step-by-step details of the code operation are as follows:

1. The code uses two criteria to filter out metal core sites or water molecules not participating in relevant interactions: distance to the nearest neighbor and total number of surrounding neighbors. At every time step, the oxygen-oxygen radial distance of each site or water molecule in the system to the remaining H₂O in the system is calculated. A cutoff is applied so that H₂O neighbors farther than a 12 Å distance from the main oxygen atom in any

direction are not considered. The area within the cutoff region is treated as a sphere with the main oxygen atom as its center point. If the nearest H₂O to the central oxygen is sufficiently far away, or the number of surrounding H₂O in the sphere is a small fraction of the total H₂O in the system, the data for that site or water molecule (when used as a central point) is not included in the RDF analysis.

2. For each site or water molecule found to be relevant, the code divides the spherical region around its oxygen into 100 bins of equal thickness. Using the oxygen-oxygen distances calculated in Step 1, the code detects the position of each surrounding H₂O oxygen and the specific bin its midpoint resides in. An applied oxygen radius of 0.12 Å allows the code to then determine the exact fraction of the atom residing in that bin and the adjacent bins. This is repeated for every water molecule within the cutoff distance. If fractions from multiple oxygen atoms are found within the same bin, their values are summed together, giving the total number of water molecules in each of the 100 bins.
3. The RDF is calculated as the ratio of the local density of atoms in a specific bin to the bulk density of atoms in the sphere. To find the local density of atoms in a bin, the code takes the total number of bin atoms calculated in Step 2 and divides it by the shell volume of that bin. The bulk density is not calculated as a function of all the water molecules in the system, but as the sum of the water molecules existing in all the bins divided by the total volume of the 12 Å sphere (which can vary based on central atom location and simulation timestep). The process is repeated for every individual metal core site or water molecule used as a center point. The overall RDF is then found by averaging over the RDFs for each individual center point atom at every time interval over the entire length of the simulation.

The accuracy of this code was tested by running the calculation for a system of bulk water and comparing the results to those produced for the same system by LAMMPS.

5.4 Results and Discussion

5.4.1 Self-Diffusion and Diffusion Mode of Water in NU-1000

The self-diffusion coefficient of water in NU-1000 has been calculated as a function of loading and direction, as shown in Figure 5.7. The reliability of SPC parameters for modeling water molecules in our system was tested by performing MD simulations of bulk water at 300 K with the SPC water model and comparing calculated self-diffusion coefficients to those found in the literature [48,59,60].

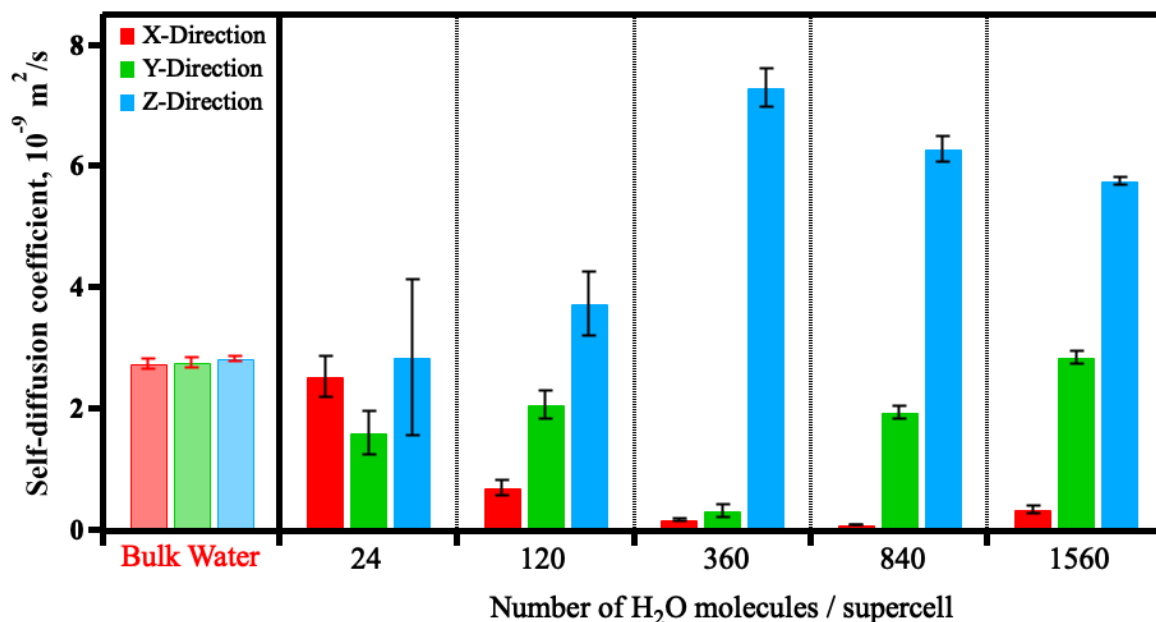


Figure 5.7. Self-diffusion coefficients of water in NU-1000 with respect to loading. Separate self-diffusion coefficients were calculated for movement in the x, y, and z directions. For comparison purposes, the three-dimensional self-diffusion coefficients of bulk water are shown in the far-left column.

The self-diffusion coefficient values shown in Figure 5.7 for water in NU-1000 are on the order of 10^{-9} m²/s for all loadings in all three dimensions. When compared to values on the order of 10^{-11} m²/s reported for guest species in UiO-66 [33,36] (a Zr-MOF with different topology and pores of 8.0-11.0 Å), the results support claims that the large pore apertures of NU-1000 give rise to faster diffusion of reactants and products [3,27]. This is especially evident in the z-direction, where self-diffusion coefficients take on values even greater than that of bulk water. Similar behavior has been previously reported for adsorbate self-diffusion in MOFs of large pore diameter [38], and might suggest that water molecules in NU-1000 are moving more freely than liquid-phase H₂O.

As suspected, the nonuniform topology of NU-1000 results in anisotropic self-diffusion behavior, with x- and y-direction coefficients consistently lower than those in the z-direction. Special attention should be paid to the 360 H₂O case, which has a noticeable drop in x- and y-direction diffusion when compared to the lower loadings. As movement through passageways can only occur in these two directions, such small values indicate that water molecules at medium loading are neglecting to diffuse between pores. Lack of diffusion can be indicative of water molecule immobility at active sites, as attractive dispersion interactions between adsorbates and the framework have been known to significantly hinder diffusion in MOF materials [61]. That said, the results also show an extreme spike in z-direction self-diffusion at this loading. In general, the large z-direction self-diffusion coefficients observed at all five loadings provide evidence of a balanced hydrophobicity in NU-1000, where water molecules are allowed to adsorb and diffuse in the pores without occupying and reacting at open metal core sites [20]. Consequently, a better explanation for the observed dip in x and y self-diffusion is preferential interactions between water molecules that lead to cluster formation and limit or discourage inter-pore diffusion [11].

The formation of clusters and their behavior in MOF materials can be indicated by the presence of certain observable phenomena. For instance, studies of water exposure in MOFs have attributed linker hydrolysis effects to the clustering of H₂O molecules near the Zr₆-based nodes [62]. Alternatively, water in nanoporous materials has been shown to exhibit confinement effects as a product of the formation of stable clusters which act and diffuse as single entities [63]. As the ratio of guest species to host pore diameter largely determines the diffusion mechanism [54], the wide pores of NU-1000 make confinement effects unlikely. In such a case, if single-file diffusion mode was observed for water in NU-1000, it would point towards configurational space restrictions for whole clusters attempting to pass one another. To investigate further, logarithmic plots of MSD vs. time were used to calculate the diffusion mode of water in each direction at low, medium, and high loadings, as shown in Figure 5.8.

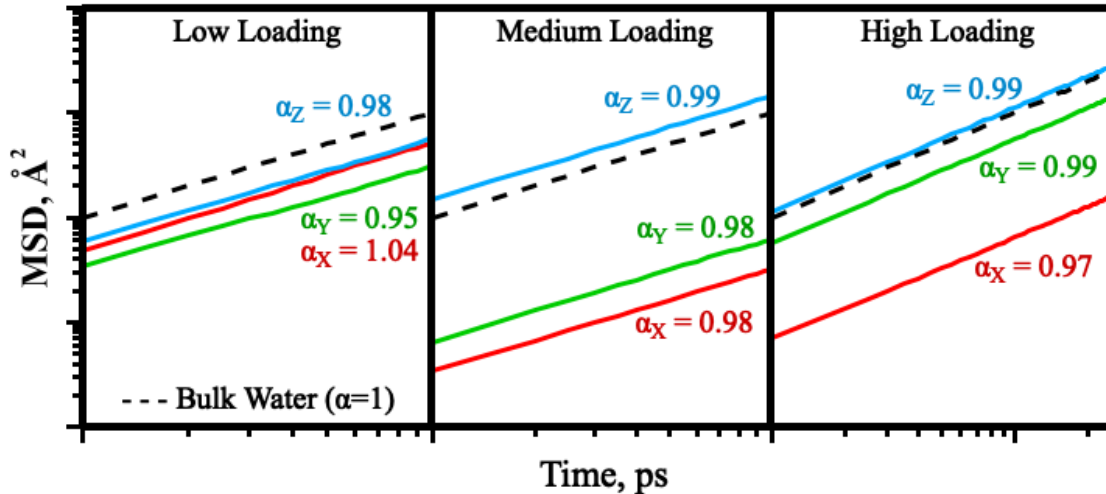
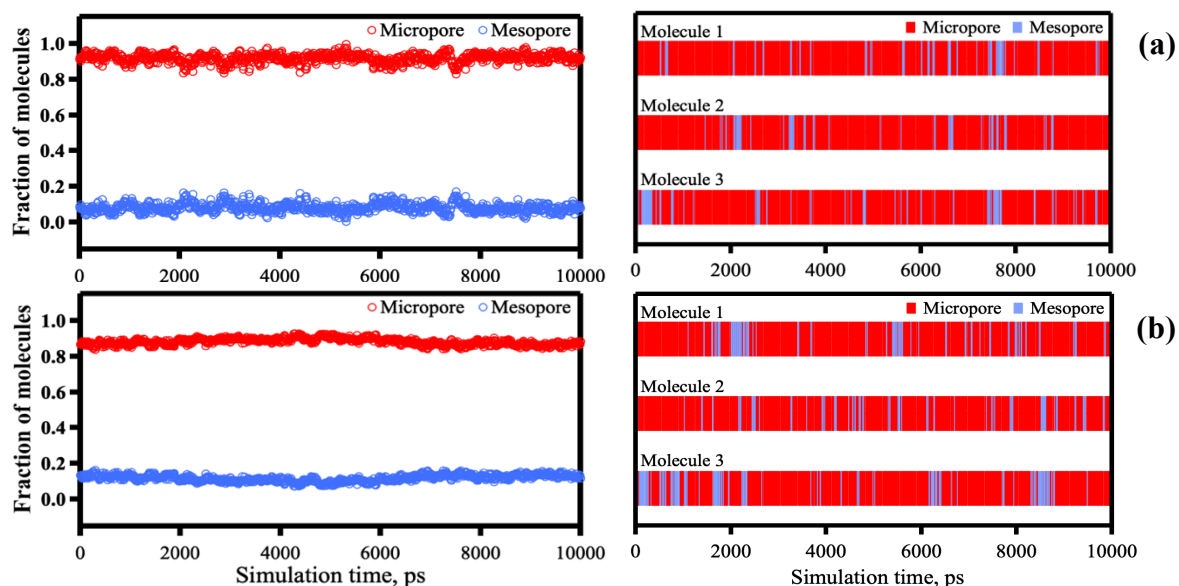


Figure 5.8. Logarithmic plots of MSD vs. time showing the diffusion mode of water in NU-1000 with respect to loading. Separate calculations were done for diffusion in the x, y, and z directions. Results are shown for 20 ns of simulation time at the low and medium loadings and 50 ns of simulation time at the high loading, which required more time to fully converge in the x-direction.

The results show no evidence of a confinement effect, with Fickian diffusion mode for all loadings in all directions. If water clusters are indeed present, this outcome could indicate that the intermolecular interactions between the H₂O adsorbates exceed water-framework interactions, causing the clusters to stay put rather than diffuse to empty framework regions [64].

5.4.2 Water Distribution in NU-1000

Studies of loading dependence on adsorbate diffusivities in MOFs have reported that nonmonotonic diffusivity-loading relationships can be explained by the spatial distribution of adsorbates at different loadings [61]. To better understand our self-diffusion observations, distribution analyses of water in NU-1000 were performed. The location of water molecules in NU-1000 as a function of simulation time is shown in Figure 5.9. The bars show how residence time, dominant region of occupation, and movement between pore types vary with respect to loading.



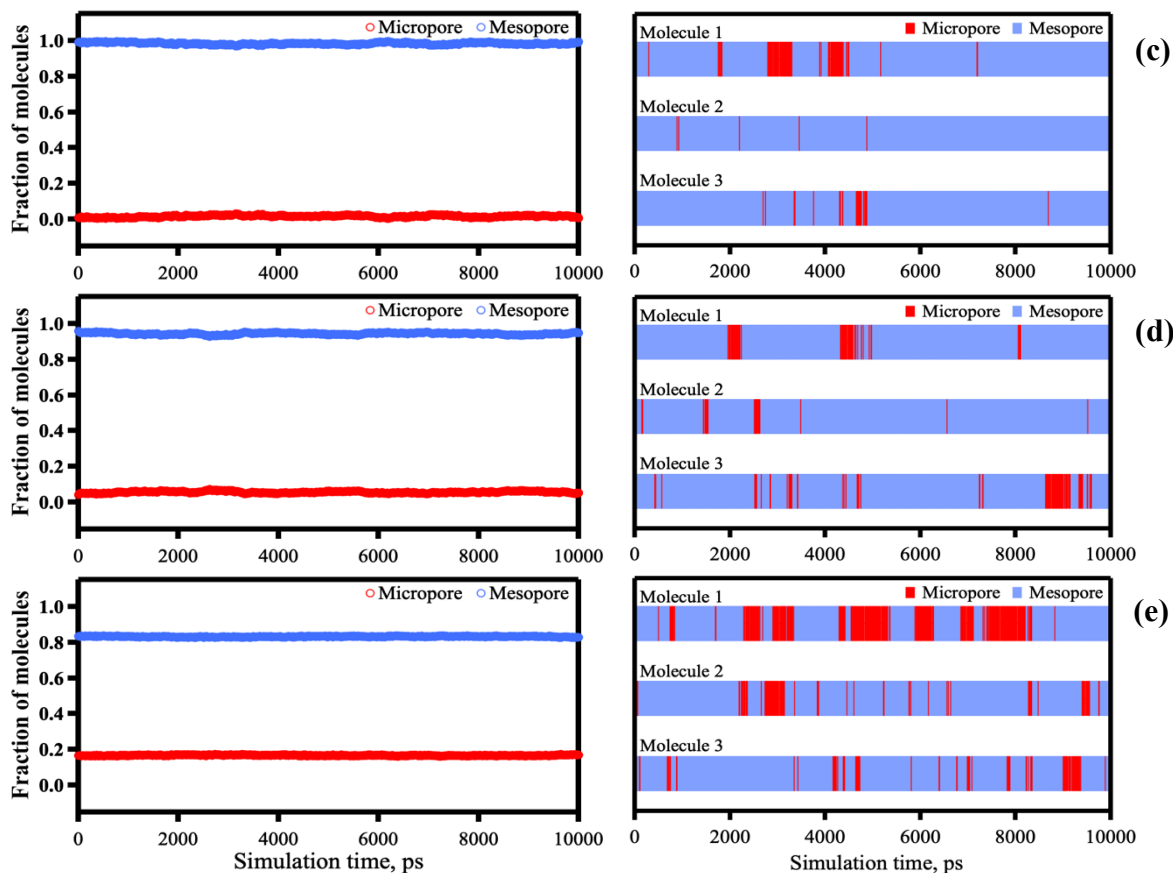


Figure 5.9. Fraction of water molecules in micropore and mesopore regions of NU-1000 and trajectory of individual water molecules in NU-1000 as a function of simulation time. The pore location of each H₂O molecule was recorded every 10,000 timesteps for each production run of each loading. Figures on the left show the fraction of molecules in the micropores and mesopores as an average value taken over all ten production runs for each timestep interval. Figures on the right demonstrate the movement of several individual water molecules from micropore to mesopore (and vice versa) over the length of the simulation. (a) 24 H₂O loading. (b) 120 H₂O loading. (c) 360 H₂O loading. (d) 840 H₂O loading. (e) 1560 H₂O loading.

Figure 5.9 demonstrates that the distribution behavior of water in NU-1000 is highly loading-dependent. At low loadings, a preference seems to exist for water molecules in the micropore regions of the framework. Previous studies of adsorption in NU-1000 agree with this result, reporting almost exclusive residence of adsorbates in the micropores at low loadings

[32,61]. Nevertheless, self-diffusion results indicate that the molecules are moving relatively quickly, and their trajectories exhibit frequent hops from pore to pore. With an increase in loading, a shift occurs, and water resides most often in the mesopores. A substantial decrease in the frequency of pore hops is also observed. The lack of switches from micropore to mesopore is especially distinct in the 360 H₂O system, providing strong evidence to support that decreases in x- and y-direction diffusion at this loading are linked to a decrease in the passage between pores. In fact, the hopping frequencies at every loading appear to compliment the x- and y-direction self-diffusion coefficients observed in Figure 5.7. A more in-depth evaluation of the observed distribution patterns was achieved through quantitative analysis of residence time data, as shown in Figure 5.10. The results were found by recording the location of each individual molecule every 10,000 timesteps, summing the number of timesteps spent in micropores and mesopores, then averaging over every molecule in the system and every production run.

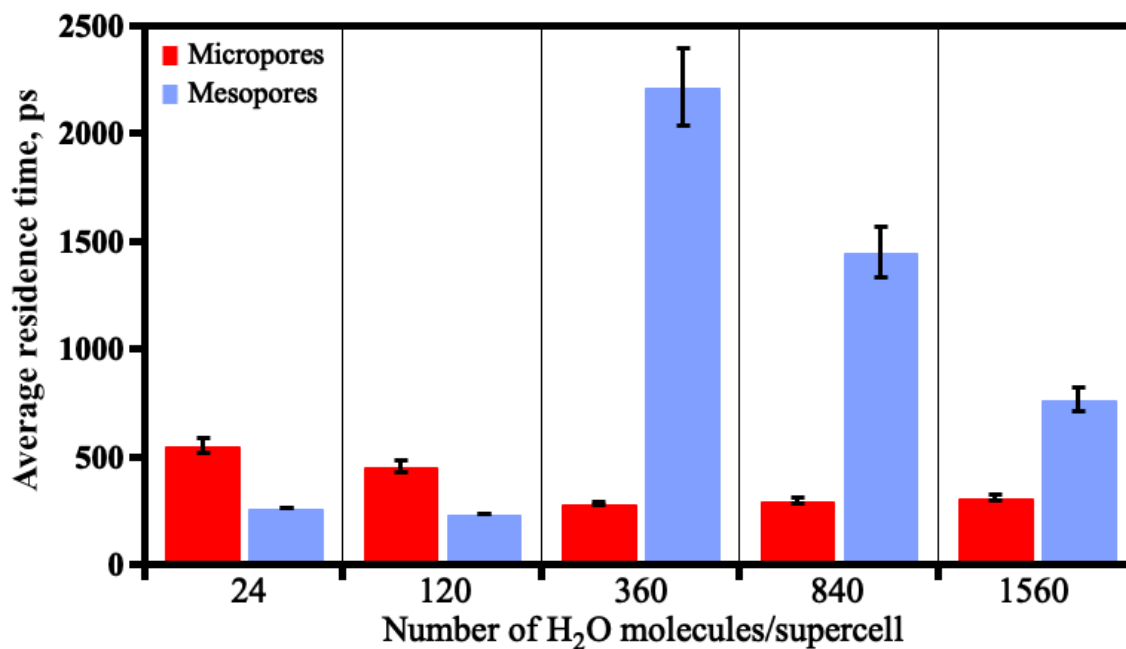
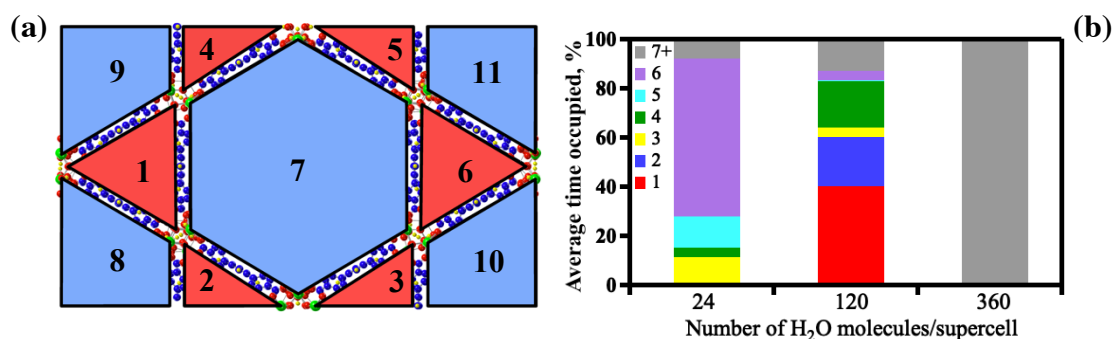


Figure 5.10. Average residence time of water molecules in each pore type with respect to loading.

The results in Figure 5.10 further detail the degree of locational bias of water molecules at various loadings. For the low-loading systems, residence times are indeed longer in the micropores than the mesopores, but the difference is quite minimal relative to higher-loading systems. Despite the apparent micropore preference, the averaged micropore residence time values around 500 ps reveal that the typical stretch of time for water in the micropores amounts to only ~5% of the 10 ns simulation time. Therefore, the combined mesopore and micropore averages indicate some 10-15 one-way hops over the length of the production run. These results give evidence that while water-framework interactions exist more favorably in the micropores, they are not favored enough to cause excessive occupation of water molecules at micropore-localized active sites. It also suggests that the expansive pore structure of NU-1000 allows easy transport of guest species to empty framework regions.

Moving to medium loading, the anticipated spike in mesopore residence time yields a single mesopore stay averaging to ~18% of the simulation time. The driving force promoting the initial micropore preference is no longer evident in the system, with a complete shift in primary pore residence and significantly minimized inter-pore diffusion. To investigate the potential presence of water clusters as the underlying cause of this behavior, water inhabitation in each pore was analyzed, as shown in Figure 5.11.



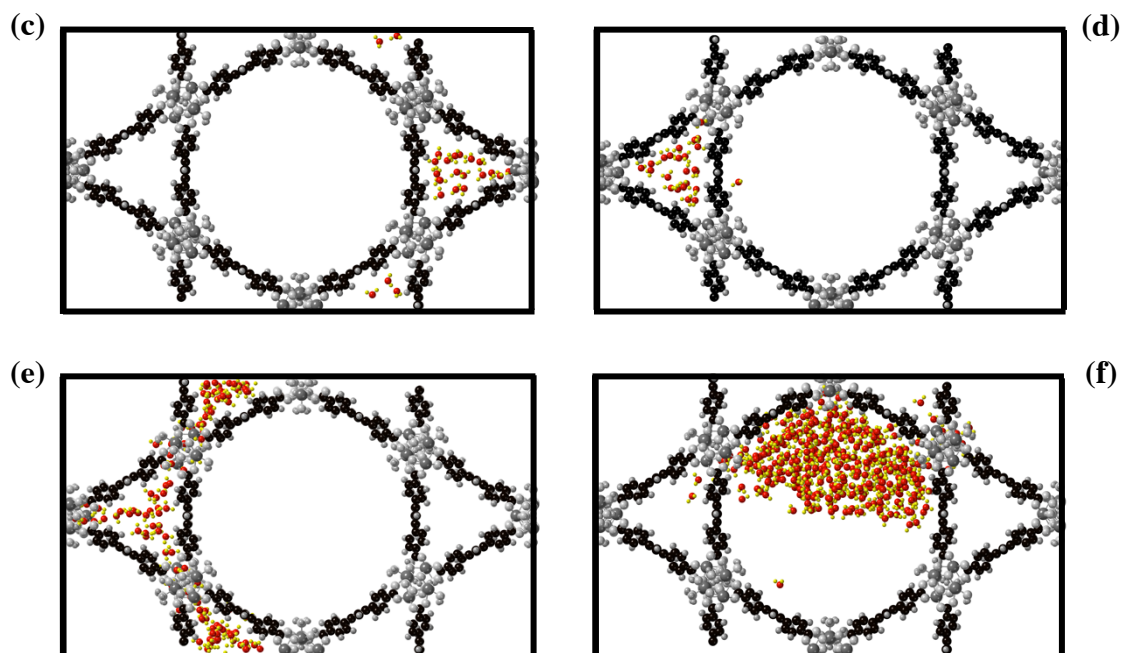


Figure 5.11. Clustering behavior of water molecules in NU-1000 pores at low and medium loadings. (a) Micropore and mesopore regions of NU-1000 are labeled 1-6 and 7-11, respectively. (b) The average percentage of simulation time that each NU-1000 pore region was occupied by water molecules with respect to loading. (c) Visualization of water clustering in micropore region 6 at the 24-molecule loading. (d) Visualization of water clustering in micropore region 1 at the 24-molecule loading (at a different timestep in the simulation). (e) Visualization of water clustering in micropore regions at the 120-molecule loading. (f) Visualization of water clustering occurring in the center mesopore at the 360-molecule loading.

Clustering is indicated by an uneven distribution of water molecules throughout individual pores, regardless of their status as a micropore or mesopore. The results in Figure 5.11 were found by recording the location of each individual molecule every 10,000 timesteps, summing the number of timesteps spent in each specific pore, then averaging over every molecule in the system and every production run. The classification of the various pore regions is demonstrated in Figure 5.11a.

It is observed from Figure 5.11b that the distribution of molecules throughout the NU-1000 pores is indeed nonuniform. At the 24 H₂O loading, primary residence takes place in micropore 6, which is occupied by water molecules for an average of 64% of the simulation time. The 120 H₂O loading shows similar large percentages of simulation time spent in micropores 1, 2, and 4. This is followed by results at the 360 H₂O loading, which show an almost exclusive inhabitation of a single mesopore region. Water occupation in region 7 averages 99% of the simulation time, signifying that the lack of inter-pore diffusion is not just between pores of a different type. It is worth noting that the specific micropore or mesopore region in which molecules mainly reside is trivial. Trajectory images of water at the 24 H₂O loading in Figures 5.11c,d show that while molecules at this humidity level do not always maintain their stay in a specific micropore, they do tend to maintain their proximity to one other. This clustering behavior becomes increasingly apparent with increased loading, as shown in Figures 5.11e,f. At the 120 H₂O loading, water molecules interact with metal core sites from the micropores, but the available space is becoming crowded. The expected transfer occurs at the 360 H₂O loading, where a large group of molecules now resides in the center mesopore. The shift does not appear to be related to enhanced site access or strong water-framework interactions, as the trajectory videos show minimal diffusion of individual molecules to the available sites throughout the framework. It seems more likely, in this case, that water migrates to the mesopore because of the larger volume available for aggregation. Such clustering behavior elucidates both the long mesopore residence times and the decrease in x- and y-direction self-diffusion coefficients observed at the medium loading.

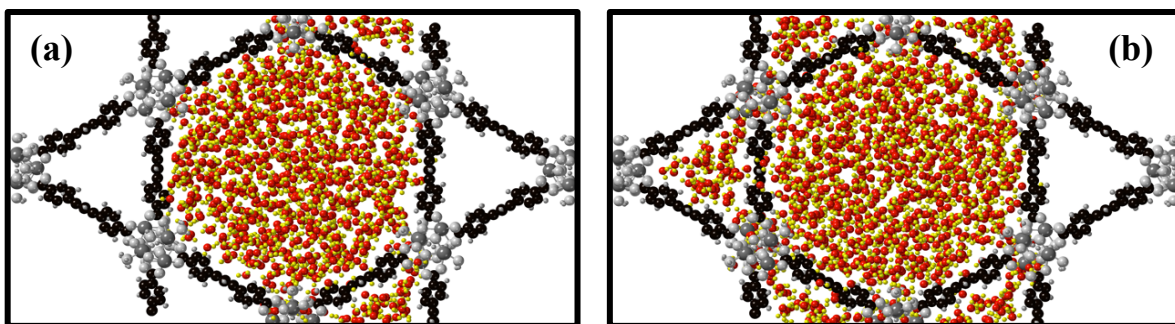


Figure 5.12. Clustering behavior of water molecules in NU-1000 pores at high loadings. (a) Visualization of cluster extension to neighboring pores for the 840 H₂O loading. (b) Visualization of micropore preference upon increase in loading to 1080 H₂O.

Results for the 840 and 1560 H₂O systems agree with the discussed trends. As the amount of water in NU-1000 increases, available space in the pores decreases. Trajectory videos at the higher loadings show that water molecules will continue to cluster in region 7 until the maximum occupancy is reached. When this occurs, the excess particles begin to form clusters in the surrounding pores. The increase in y-direction self-diffusion coefficients and hopping between pore types seen at the higher loadings can likely be explained by the diffusion of molecules from one water cluster to another. The decrease in mesopore residence times corresponds, as the overall average incorporates particles that do not have primary occupancy in the center cluster. Visualization of this behavior as loading approaches saturation is provided in Figure 5.12.

5.4.3 Interactions of Water in NU-1000

As stated previously, the metal core sites of NU-1000 are oriented in either a transition region or a mesopore region of the framework. Given that mesopore region sites can only be accessed from a mesopore, it is possible that the primary pore occupancies observed for water molecules in NU-1000 at different loadings are a product of differing interaction strengths with or accessibilities to the active sites in each framework region. To further evaluate this, radial

distribution function calculations for water oxygens with metal core site oxygens in the two different environments were performed, as shown in Figure 5.13.

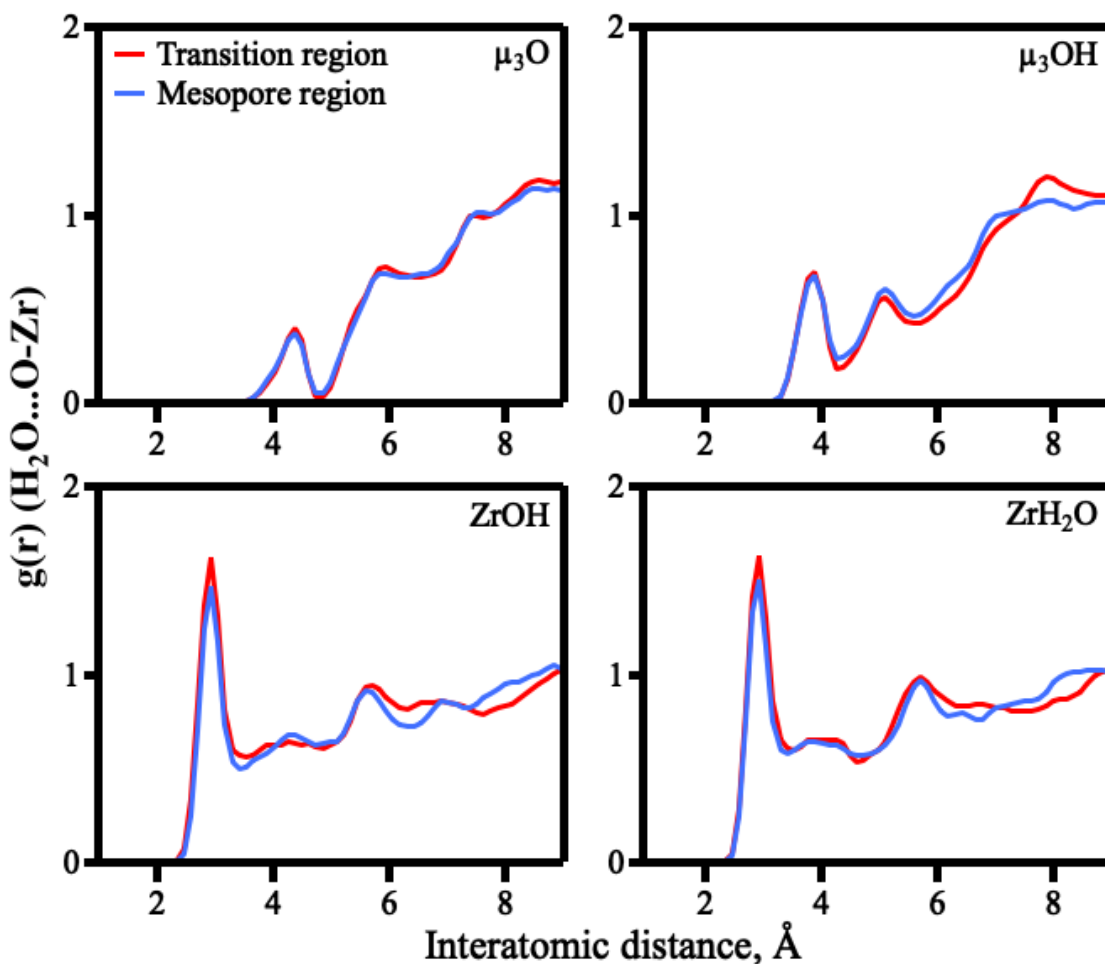


Figure 5.13. Radial distribution functions for the oxygen atoms of water to the oxygen atoms of each NU-1000 metal core group at saturated loading. The figure shows the average data found for sites located in transition regions compared to sites located in mesopore regions.

In comparing the site-specific interactions of water molecules with the Zr₆ nodes, Figure 5.13 shows closer proximities and higher peak intensities for H₂O with the Zr-OH and Zr-H₂O sites than for H₂O with the μ_3 -O and μ_3 -OH sites. This suggests that if the pore preference of

water molecules in NU-1000 is influenced by stronger site interactions or easier site access, that influence likely comes from the Zr-OH and Zr-H₂O sites. However, the results show nearly indistinguishable RDFs for water with sites in the transition regions versus the mesopore regions of NU-1000. For each site region, there are consistently negligible differences in the locations of the first peaks with only mild dissimilarity in peak intensity. Based on this data, there is no evidence that metal core site accessibility or interaction strength between water and the NU-1000 nodes is variable with respect to framework region. These findings put further emphasis on the idea that the pore preference observed for water molecules in NU-1000 is governed more by ease of cluster formation than ease of adsorbate-framework interaction. Still, we note the presence of potential contributing factors to the observed pore preferences that are outside the scope of this work and could benefit from further investigation.

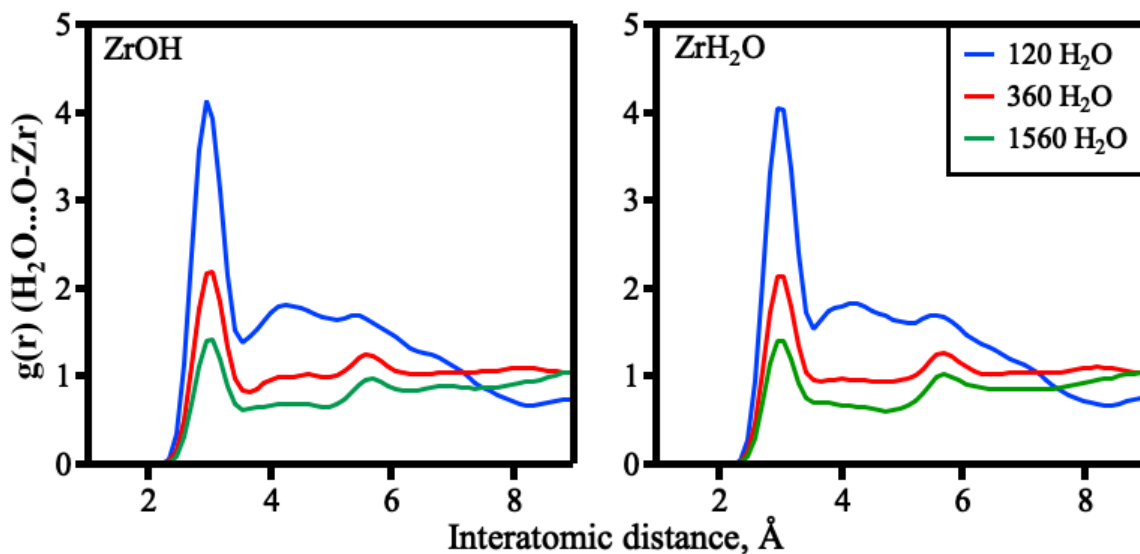


Figure 5.14. Radial distribution functions for the oxygen atoms of water to the oxygen atom of the Zr-OH and Zr-H₂O metal core groups of NU-1000 with respect to loading.

To better understand the role of humidity level on the self-diffusion and distribution behaviors of water in NU-1000, RDF calculations were performed for water-framework activity with respect to the Zr-OH and Zr-H₂O metal core sites of NU-1000 at low, medium, and high loadings, as shown in Figure 5.14. The results demonstrate that changes in loading do not seem to have any impact on the radial distance of the nearest water molecule to the metal core sites. Comparison of the RDFs for the two separate NU-1000 sites also suggests that there is no obvious preference for one site over the other. On the other hand, both figures show that water loading has a clear effect on the distribution of molecules within the vicinity of the Zr₆ nodes, with the RDFs becoming more structured for each NU-1000 site as the humidity level increases. All three loadings demonstrate a peak at ~2.9 Å and ~5.6 Å, but the low loading case shows an additional peak at ~4.4 Å that disappears as loading increases. While observations of micropore preference at low loadings are indicative of relevant water-framework intermolecular interactions, strong interactions are typically more capable of holding the water molecules at fixed distances from one another [65]. Stronger binding energies would also have been made evident by decreases in water-framework interatomic distances [66]. Like the previous results, this trend suggests relatively weak interactions between water and the framework at low loading. The similarity between RDFs going from medium to high loading also matches the expected behavior of molecules aggregating in the spacious MOF channels instead of dispersing to various active sites.

Weak attraction of water to the NU-1000 framework is a positive feature for hydrolysis applications, as it lowers the likelihood of issues like competitive adsorption. That said, the rapid clustering of adsorbed water in the NU-1000 is cause for concern. In high-humidity environments, a large, tightly bound water cluster could effectively block the adsorption of target species. If target molecules could manage to adsorb and diffuse to active sites, hydrogen-bonded water would be

less likely to leave its cluster to participate in the hydrolysis reaction. Figure 5.15 shows the RDF analyses for water-water interactions in NU-1000 at low, medium, and high loadings, revealing the ordering that takes place as water aggregates in the MOF.

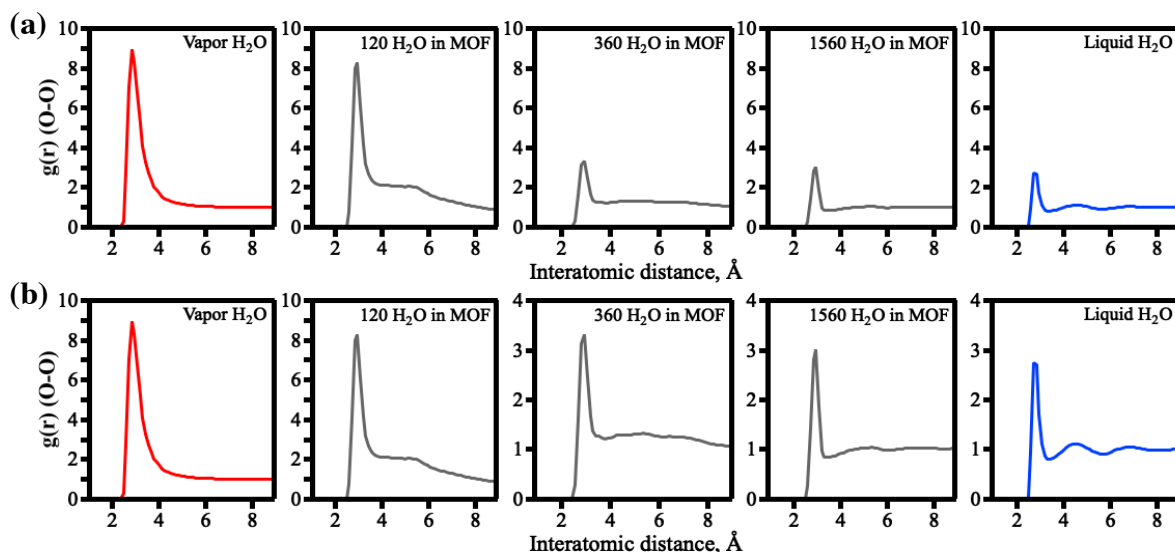


Figure 5.15. Radial distribution functions for water-water oxygen interactions of vapor-phase H₂O, liquid-phase H₂O, and H₂O in NU-1000 at low, medium, and high loadings. (a) Curves are all shown on the same scale. (b) Y-axis range varied on each curve to better demonstrate RDF peak detail.

In liquid-phase water, intermolecular interactions between molecules yield a high ordering of oxygen atoms, resulting in three distinct RDF peaks at ~ 2.8 Å, ~ 4.5 Å, and ~ 6.8 Å. Vapor-phase water exhibits only a single peak at ~ 2.8 Å, representing interactions between molecules that happen to encounter one another in motion. This peak is much higher in intensity than the first peak for liquid water, as the bulk density of molecules in the RDF vicinity is significantly lower in the gas phase. While both the micropores and mesopores of NU-1000 have more than enough room for the aggregation of molecules in all three liquid-phase shells, Figure 5.15 shows that the water clusters observed in the MOF have a structural phase somewhere in between liquid and gas.

At 120 loading (~5% RH), the intensity of the first RDF peak suggests that water is behaving much like that of vapor-phase H₂O. However, water at this loading shows an additional peak around 5.5 Å, beyond which the RDF curve steadily declines. While the second peak occurs at a farther intermolecular distance than what is seen in liquid water, its existence provides clear evidence of NU-1000's hydrophobic nature. At low loading, persistent clustering and interaction takes place among adsorbed water, as opposed to the scattered distribution of molecules to various active sites.

As expected, the behavior of water continues to approach that of the liquid phase with increased loading. Figure 5.15a shows that the first peak intensity for water at low loading in NU-1000 is around three times that of water at medium and high loading, indicating an increase in the ordered filling of water molecules throughout the RDF bins as the humidity level rises. On the other hand, scaled versions of these curves in Figure 5.15b reveal distinct inconsistencies in the ordering of molecules between bulk water and water adsorbed in the MOF. At 360 loading (~35% RH), the outer-neighbor peaks present beyond 4.0 Å are indiscrete. Despite the apparent unwillingness of water to diffuse between pores at this loading, the weak intensity of the RDF peaks reveals that the large mesopore cluster seen in Figure 5.11 has a much less ordered structure [67] than liquid water. Further support of this comes from the extremely high z-direction self-diffusion of molecules relative to that of bulk water at medium and high loading. Once saturation is reached (~85% RH), the available space for molecules to enter and diffuse is minimized, but the spacious pores of NU-1000 allow diffusion in the z-direction to be maintained at nearly double the magnitude of H₂O in the bulk phase. While the appearance of more distinct second and third peaks in the RDF curve implies an increase in hydrogen bonding, coordination number results show an average of ~28.3 molecules at a 6.0 Å distance, compared to ~30.5 molecules for liquid water. Even at saturated loading, the ordering of water molecules in NU-1000 does not resemble a fully

condensed phase. The absence of liquid-level interactions in the clustered water suggests that target species will have a better chance at adsorption and diffusion in conditions of high humidity. It also suggests that environmental water molecules adsorbed in the MOF will be more readily available to participate in target species hydrolysis.

5.4.4 Overview of Theory

Based on our understandings from literature, we have hypothesized that the combined attributes of (1) strong linkages between metal nodes and ligands to provide structural stability in water; (2) low node connectivity and large pore sizes to provide broad guest species site accessibility; and (3) partial hydrophobicity to prevent atmospheric moisture from hindering reaction kinetics; would yield a promising MOF for hydrolysis operations under conditions of varying humidity. Zr-based MOFs are our primary focus because of the impressive strength of their node-linker bonds, which fulfill criteria (1). The 3 main classes of Zr-MOFs are UiO-66, MOF-808, and NU-1000, all of which have significant topological differences and show very dissimilar hydrolytic activity. While guest species interactions in pristine UiO-66 are known to be limited by its topology, MOF-808 and NU-1000 both possess large pores and low linker connectivity, thus fulfilling criteria (2). This is not to say that MOF-808 and NU-1000 are similar. In fact, NU-1000 has a different metal node configuration, different organic linkers, fully interconnected channels, larger pores, higher coordination, and a larger surface area than MOF-808. Most importantly, NU-1000 adsorbs water with a type V isotherm, indicating internal hydrophobicity and fulfilling criteria (3). Given that NU-1000 is the best example of all three criteria, we have used it to test whether our proposed design rules make up a potentially suitable MOF for hydrolysis in humid conditions. This evaluation has allowed us to reach a conclusion on

whether such design rules should be considered in the selection or tuning MOFs for CWA degradation.

5.5 Conclusion

In summary, a series of MD simulations were performed to evaluate the behavior of environmental water at various humidity levels (0.5-85% RH) in the pristine NU-1000 Zr-MOF. The results give insight into how combined features of strong node-likers bonds, large pore volumes, and semi-hydrophobic functional groups impact the performance potential of NU-1000 for hydrolysis applications in realistic environmental conditions. Simulation trajectories demonstrated that aggregation of adsorbed water was immediately present at low loadings, with molecules diffusing in clusters throughout the NU-1000 micropores. Despite interactions between H₂O adsorbates being clearly favored over framework interactions, self-diffusion coefficients and water-water RDFs revealed that the observed water clusters were not highly ordered. Even at saturated water loading, clustered molecules in NU-1000 exhibited an ordered arrangement somewhere in between vapor and liquid. These observations suggest that while interactions with NU-1000 are not strong enough to cause water molecules to uniformly distribute to available active sites and exist fully in the vapor phase, interactions between water molecules are not strong enough to cause hydrogen bonded clusters that fully condense into the liquid phase. The discussed combination of topological features has therefore yielded a MOF that, under humid conditions, can allow water molecules to enter and potentially participate in target species hydrolysis without competing for adsorption on active sites or threatening structural stability. We anticipate that these design rules will be important to consider in the future study of feasible MOFs for hydrolytic destruction of toxic species.

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Chapter 6

A Computational Analysis of Sarin, Soman, and Their Mixtures with Water in NU-1000: Interactions, Distributions, and the Pairing Effect*

6.1 Abstract

Due to their extraordinary structural stability under humid conditions, zirconium-based metal-organic frameworks (Zr-MOFs) have been widely investigated for the hydrolytic degradation of nerve agents. That said, mechanisms of hydrolysis in the solid state and the participation of environmental water are not well understood. This work utilizes computational techniques to evaluate the behavior of water and two organophosphorus nerve agents (sarin and soman) in NU-1000, a Zr-MOF with the characteristic attributes for hydrolytic efficiency under humid conditions. Density functional theory (DFT) calculations reveal that soman binds more favorably to NU-1000 active sites than sarin, resulting in different preferential locations of each nerve agent within the framework. The strength of nerve agent binding is also found to vary depending on the site environment, with more favorable binding of both nerve agents occurring in the c-pores of NU-1000 than in the mesopores. Molecular dynamics (MD) simulation results further illustrate that free water molecules in NU-1000 prioritize interactions with nerve agents. Given the variation in their affinity for active site interactions, the introduction of different nerve agents to the framework results in substantial differences in water distribution and behavior. The results give insight into potential variances in the functionality of NU-1000 towards the hydrolysis of each nerve agent. More importantly, they emphasize the significance of considering the role of environmental water

in hydrolysis, and the possibility of diverse reaction variables based on the type of nerve agent and the properties of the MOF.

6.2 Introduction

Owing to their excellent adsorption, reactivity, and catalytic abilities [1], metal-organic frameworks (MOFs) have been identified as favorable materials for the capture and degradation of chemical warfare agents (CWAs). While progress has been made in the design and tuning of MOFs for this purpose [2], their implementation under operationally relevant field conditions is an unsolved challenge. A major setback for many classes of MOFs stems from water-susceptible node-ligand linkages [3] which can lead to structural instability and framework collapse upon exposure to humidity [4]. This is especially concerning in the application of CWA degradation via hydrolysis, where water is required for the reaction to proceed [5]. MOFs with high oxidation state metals and organic carboxylate ligands have sparked interest in operations involving humidity [3,6–8], as the strong binding that occurs between hard acids and hard bases [9] (in this case, the metal atoms and the oxygen atoms terminating the linkers, respectively) reduces the sensitivity of these materials to framework hydrolysis. Zirconium-based MOFs are known to exhibit particularly extraordinary stability in the presence of water [6,10,11] and have thus become a widely adopted focus of experimental and computational studies on CWA degradation.

Regarding the hydrolytic degradation of organophosphorus nerve agents, Zr-MOFs with displaceable -OH and -OH₂ ligands at the metal nodes, such as UiO-66, NU-1000, and MOF-808, are among the most promising heterogeneous catalysts reported to date [12–18]. That said, many unanswered questions still exist surrounding the hydrolysis reaction mechanism and the effectiveness of these materials towards CWA removal under ambient conditions. Until now, most

of the CWA decontamination kinetics reported in the literature have been for MOFs operating in a buffered solution rather than in a solid state [18,19]. Furthermore, current understandings of the hydrolysis mechanism seem to depend heavily on a range of questionable assumptions and exhibit a lack of consideration for variables that are relevant to the practical application. One of the most apparent examples of this is that suggested schemes often neglect to account for the potential role of environmental water. Figure 6.1 [18] shows the two main mechanisms commonly proposed for CWA decontamination reactions at Zr-MOFs, which proceed by the following elementary steps: (i) binding of the organophosphorus compound to an open metal site; (ii) nucleophilic attack at phosphorus by displaced -OH_2 (Figure 6.1a) or by an adjacent ligand (Figure 6.1b); (iii) elimination of the leaving group from the organophosphorus compound; and (iv) removal of the monodentate (Figure 6.1a) or bidentate (Figure 6.1b) product from the active site [15,20–22].

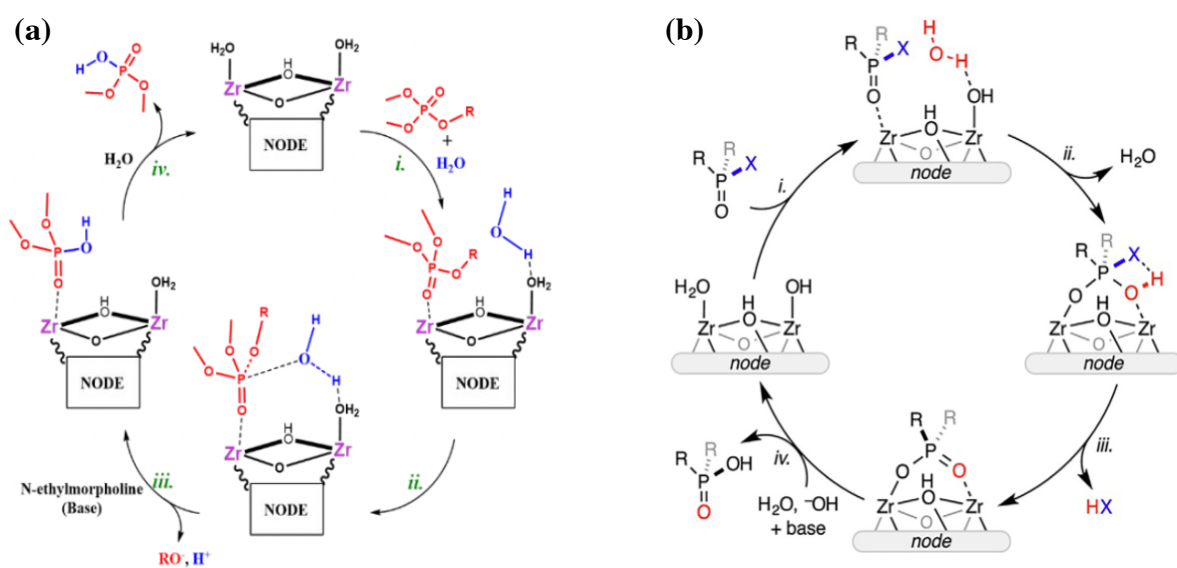


Figure 6.1. Mechanistic schemes for hydrolysis of organophosphorus nerve agents and their simulants on Zr^{IV} -MOFs. (a) Reaction with nucleophilic attack by displaced -OH_2 and monodentate product binding on metal nodes [21]. (b) Reaction with nucleophilic attack by adjacent -OH and bidentate product binding on metal nodes [15]. Reprinted with permission from

ref. [21] (left) and ref. [15] (right). Copyright 2021 Royal Society of Chemistry and 2020 American Chemical Society, respectively.

In step (i), both mechanisms assume that the -OH_2 group on the hydrated metal node will repeatedly be displaced by a nerve agent molecule. The presence of environmental water in the vicinity of the nodes is not considered, even though competing interactions between CWAs and external water have been experimentally shown to interfere with toxic gas adsorption in MOFs [5,23].

In contrast to reports of water hindering reaction kinetics, multiple studies on nerve agent removal have shown the presence of external water increasing catalytic activity in Zr-MOFs [14,24]. This has been attributed in part to the increased availability of water for hydrolysis and the ability of liquid water to ease the displacement of reaction products [14]. Such findings suggest that if environmental water is adsorbed in a MOF, it will likely contribute in different ways to each elementary reaction step. As shown in Figure 6.1, proposed mechanisms generally follow one of two scenarios, mainly differentiated by the participation of the displaced water molecule from the metal site and the resulting mode of nerve agent binding to the node. While these scenarios provide an idea of how the presence of water will influence the rate of hydrolysis, the potential role of water at different humidity levels in each reaction step remains unclear.

Moreover, the structure-property relationships governing the behaviors of nerve agents and environmental water in the framework are essentially ignored. Apart from framework stability, attributes such as pore size, connectivity, and water affinity can have a significant impact on the interactions of guest species in different types of MOFs [16,22,25–27]. For instance, while all Zr-MOFs are known to be water-stable, they do not all exhibit the same levels of hydrophilicity [16,28]. This feature can dictate the ability of the MOF to adsorb water and the interaction between

adsorbed water and the MOF SBUs [18,29]. The binding strengths of guest molecules at Zr-MOF nodes have also been shown to vary depending on the structure and topology of the pore environment in which they reside [20,22]. We note that in addition to material attributes, experimental reports have evidenced that decontamination conversions in Zr-MOFs are variable with respect to the specific organophosphorus compound [24]. It is thus essential to begin exploring the possibility of diverse hydrolysis mechanisms based on both the type of Zr-MOF and the type of nerve agent.

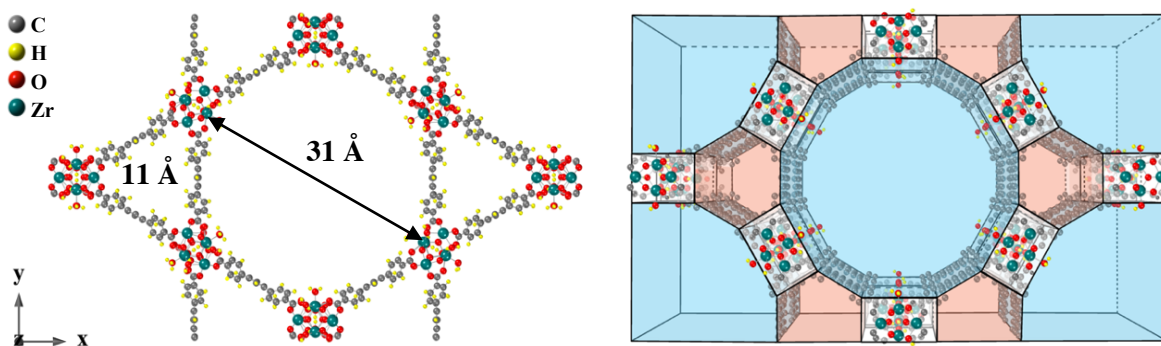
From our previous study on water at various loadings in the NU-1000 Zr-MOF [30], it was concluded that the combined attributes of (1) strong linkages between metal nodes and ligands to provide structural stability in water; (2) low node connectivity and large pore sizes to provide broad guest species site accessibility; and (3) partial hydrophobicity to prevent atmospheric moisture from hindering reaction kinetics, make NU-1000 a well-equipped candidate for hydrolysis operations under humid conditions. The main objective of this work is to further explore whether NU-1000 would exhibit consistent functionality toward the solid-state hydrolysis of different nerve agents. By a series of molecular dynamics (MD) simulations and density functional theory (DFT) calculations, we have investigated the behavior of the organophosphorus agents, sarin (GB) and soman (GD), in NU-1000. Self-diffusion coefficients, distributions, and binding energies of each nerve agent are compared, both in their pure form and in mixtures with water. Our findings reveal that variances in the affinities of each nerve agent for NU-1000 lead to significant differences in their interactions and preferential pore locations within the framework, leading to significant differences in the behavior of water within the framework. The results provide evidence that nerve agent hydrolysis in Zr-MOFs cannot be described by a universal

mechanism. Even within a single MOF, future studies must begin considering how hydrolysis may be influenced by diverse nerve agent interactions and the dynamic role of environmental water.

6.3 Model and Calculation Details

6.3.1 Structure and Topology of NU-1000

This work uses a supercell model of the pristine NU-1000 MOF, which connects twelve $\text{Zr}_6(\mu_3\text{-O})_8(\text{O})_8(\text{H})_{16}$ metal cores with twenty-four tetratopic 1,3,6,8-tetrakis(p-benzoic acid)pyrene (TBAPy^{4-}) organic linkers. NU-1000 has a low coordination environment relative to other Zr-MOFs, with nodes consisting of 8-connected zirconium atoms [12]. Each metal core in this model is assigned a mixed-node proton topology adopted from the work of Planas et al. [31]. More structural details can be found in our previous study on water at various loadings in the same NU-1000 supercell [30]. The framework structure yields large mesopores (diameter, 31 Å) connected perpendicularly to smaller micropores (diameter, 11 Å), as illustrated by the blue and orange shaded regions in Figure 6.2. Micropores and mesopores are interconnected with rectangular passageways ~ 8 Å long, as illustrated by the gray-shaded regions in Figure 6.2. These passageways, also known as “c-pores” [32], allow unrestricted transfer of molecules between the other two pore types.



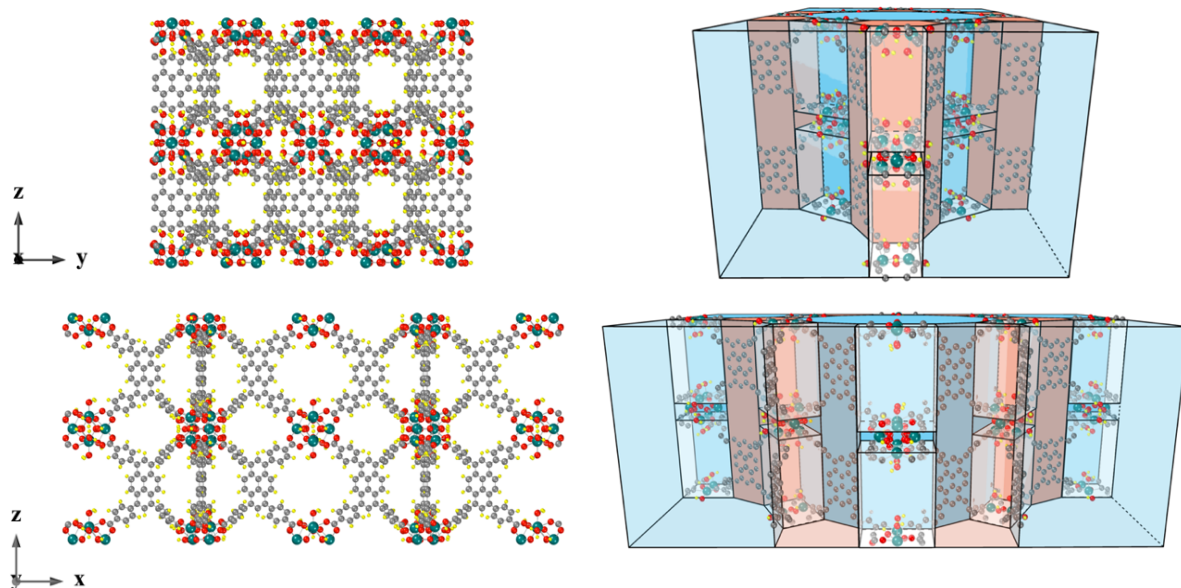


Figure 6.2. NU-1000 supercell pore structure in the z-direction (top), x-direction (middle), and y-direction (bottom). Blue-shaded regions represent the mesopores, orange-shaded regions represent the micropores, and gray-shaded regions represent the interconnecting channels (the c-pores).

The nodes of NU-1000 have four open faces of μ_3 -O, μ_3 -OH, Zr-OH, and Zr-H₂O sites. As shown in Figure 6.2, two of these open faces are directed horizontally into opposite mesopores, while the other two faces are directed vertically into adjacent c-pores. Therefore, the configuration of the Zr₆ node enables access of guest molecules to two different types of active sites, mesopore sites and c-pore sites. While no active sites are present in the NU-1000 micropores, the interconnectivity of the framework allows c-pore sites to be accessed by guest species initially positioned in either a mesopore or a micropore. Alternatively, mesopore sites can only be accessed by guest species residing within that mesopore.

Five systems are tested in this work, each containing a 30-molecule loading of pure species (water, sarin, or soman), or a 30/30 molecule loading mixture of water with each CWA. These loading levels were chosen based on GCMC simulated uptakes of sarin and soman in NU-1000

[33] and experimental adsorption isotherms of water in NU-1000 [30,34] found in the literature. Saturated adsorption capacities of sarin and soman were reported as ~11 mmol/g and ~8 mmol/g, respectively, corresponding to maximum loadings of ~300 GB and ~210 GD in the NU-1000 supercell. The saturated adsorption capacity of water was reported as ~6 mmol/g, corresponding to a maximum loading of ~1560 H₂O in the supercell from Figure 6.2. The loadings of 30 pure molecules and 60 mixed molecules simulated in this study are thus considered realistic, as they are far below the maximum capacity of NU-1000.

6.3.2 Classical Molecular Dynamics Simulations

The mean-squared displacements (MSD), radial distribution functions (RDF), and pore locations of water, sarin, and soman molecules in NU-1000 were investigated using classical molecular dynamics simulations via LAMMPS [35] software. Non-bonded guest-framework interactions were modeled using 12/6 Lennard-Jones (LJ) plus Coulomb potentials. Water molecules were described using the SPC water model in combination with the SHAKE algorithm [36–38]. The force field parameters employed for sarin and soman molecules were adopted from the work of Emelianova et al. [39], which proposes the use of the TraPPE united-atom force field [40] with corrected angle bending potentials for the O=P-F and O-P-F angles [41], and the addition of harmonic bond constants [42]. Given the large pore channels of NU-1000, properties of guest species could be reasonably modeled with the framework treated as rigid [43,44]. A combination of DREIDING [45] and UFF [46] force field parameters has commonly been used to simulate water and gas adsorption in NU-1000 [30,43,47] and other Zr-MOFs [48,49]; however, a recent study by Wardzala et al. [44] showed that the Lennard-Jones diameter for hydrogen atoms from DREIDING is too large to allow guest molecules to form hydrogen bonds with μ_3 -OH metal node groups, and instead proposes the use of the TraPPE isopropanol potential [50] for μ_3 -OH cross-

interactions with adsorbate molecules. After testing simulations of NU-1000 using both potentials for the H atoms of μ_3 -OH active sites, as shown in Figure 6.3, it was concluded that a combination of DREIDING, UFF, and TraPPE parameters was best suited for the systems modeled in this work.

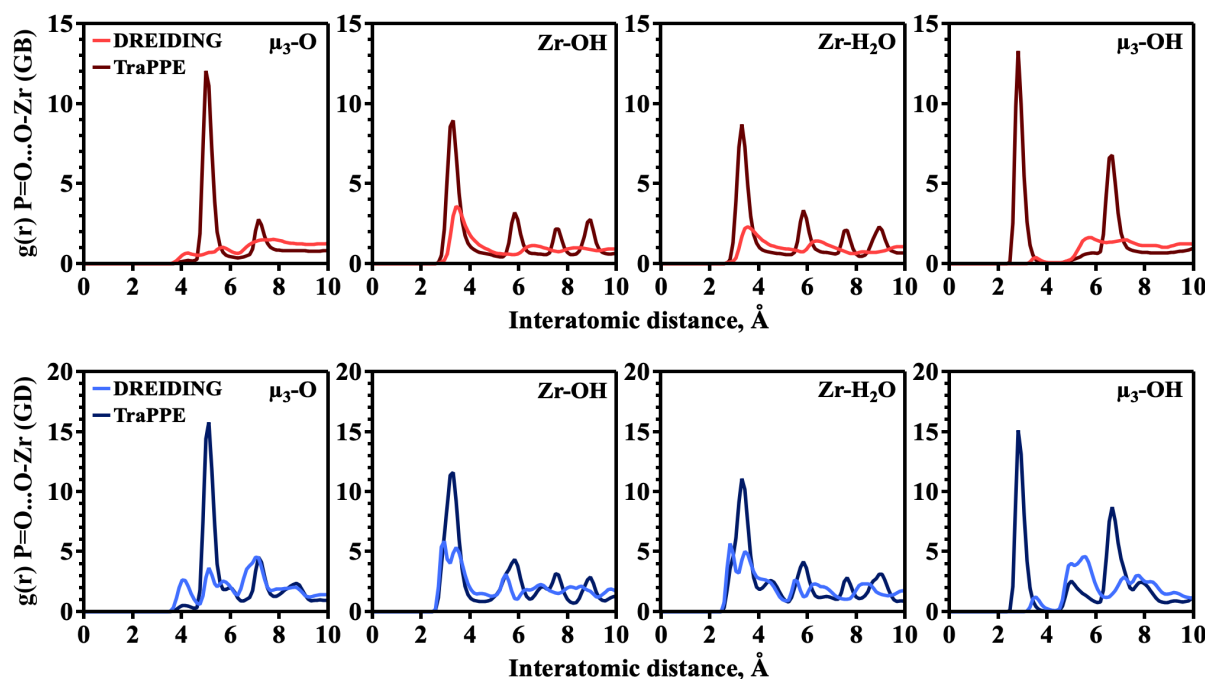


Figure 6.3. Comparison of RDFs for the P=O oxygen atoms of sarin (top) and soman (bottom) to the oxygen atoms of NU-1000 active sites using DREIDING versus TraPPE parameters for hydrogen atoms of μ_3 -OH groups. Use of the TraPPE potential results in a higher peak intensity of CWA molecules around all four active sites, and a decrease in the radial distance of CWA molecules around μ_3 -OH sites by ~ 1 Å.

All non-bonded and bonded force field parameters used in this study are listed in Table 6.1. Partial charges on the framework atoms were calculated using the EQeq method [51]. A cutoff radius of 12 Å was applied for LJ interactions. A cutoff of 10 Å was applied for Coulombic interactions, beyond which the particle-particle particle-mesh solver technique [52] was used to handle long-

range electrostatic interactions. The LJ interatomic potential parameters between guest species and NU-1000 were calculated using the Lorentz-Berthelot mixing rules.

Non-Bonded Parameters				
Force Field		Element	ϵ (kcal/mol)	σ (Å)
NU-1000	UFF [46]	Zr	0.0689	2.783
	DREIDING [45]	O	0.0956	3.033
		C	0.0950	3.473
		H (C-H, Zr-OH, Zr-H ₂ O)	0.0152	2.846
	TRAPPE [50]	H (μ_3 -OH)	0.0000	0.000
Water SPC [38]		O	0.1553	3.166
		H	0.0000	0.000
Sarin/Soman TraPPE [40]		P	0.1709	4.000
		O-	0.1093	2.800
		O=	0.1570	3.050
		C	0.0010	6.400
		F	0.0531	2.950
		CH	0.0199	4.330
		CH ₃	0.1947	3.750
Bonded Parameters				
Force Field	Bond Stretch	K (kcal/mol-Å ²)		r _o (Å)
Water SPC [38]	O-H	-		1.000
Sarin/Soman TraPPE [40] + harmonic bonds [39,42]	C-CH _x	501.910		1.540
	CH _x -CH _y	501.910		1.540
	CH _x -O	501.910		1.410
	CH _x -P	501.910		1.790
	F-P	501.910		1.580
	O-P	501.910		1.580
	O=P	1003.82		1.458
Force Field	Angle Bend	K (kcal/mol-rad ²)		θ_o (deg)
Water SPC [38]	H-O-H	-		109.47
Sarin/Soman TraPPE [40] + corrected bending	CH _x -(P)=O	160.140		116.30
	O=(P)-F	160.140		111.42
	O=(P)-O	200.300		116.50
	O-P-F	81.2600		101.20
	CH _x -(P)-F	81.2600		104.30

potentials [39,41]	CH _x -(P)-O	81.2600				104.30
	CH _x -(O)-P	160.140				121.00
	CH _x -(CH _y)-O	124.200				106.00
	CH _x -(C)-CH ₃	124.200				109.40
	CH ₃ -(CH _x)-CH ₃	124.200				114.00
Force Field	Dihedral Torsion	K (kcal/mol)				f (deg)
		K₁	K₂	K₃	K₄	
<i>Sarin/Soman</i> TraPPE [40]	CH _x -(CH)-(O)-P	2.069	-1.496	0.858	0.451	2
	C-(CH)-(O)-P	2.069	-1.496	0.858	0.451	2
	CH _x -(O)-(P)-CH _y	0.114	2.933	0.366	0.000	0
	CH-(O)-(P)-F	0.000	0.000	0.000	0.000	0
	CH _x -(O)-(P)=O	5.954	-2.915	0.427	-0.063	0
	CH ₃ -(C)-(CH)-CH ₃	0.000	0.705	-0.136	-1.572	0
	CH ₃ -(C)-(CH)-O	0.000	0.351	-0.106	1.530	0

Table 6.1. Non-bonded and bonded force field parameters for water, sarin, soman, and NU-1000.

A series of MD simulations were performed for the following five systems of guest species in NU-1000: pure H₂O (30 molecules), pure GB (30 molecules), pure GD (30 molecules), H₂O/GB mixture (30 H₂O/30 GB), and H₂O/GD mixture (30 H₂O/30 GD). Guest molecules were randomly inserted into the NU-1000 supercell using PACKMOL software [53]. Particle masses and charges were then assigned to each atom using the Visual Molecular Dynamics (VMD) software package [54]. Simulations were equilibrated in the NVT ensemble for 100 ns at a constant temperature of 300 K. Following equilibration, a series of 15 parallel production runs 50 ns long were performed for each system. The prolonged equilibration length ensured that any history of each system's initial configuration was eliminated from subsequent production runs. Diversity in the special distribution of molecules between production runs was achieved by changing the random number seeds for initial velocities. The equations of motion were integrated using the velocity-Verlet algorithm with a timestep of 1.0 fs. Periodic boundary conditions were applied to the simulation box in the x, y, and z directions. All results from MD simulations were averaged over the 15

production runs for each system. Self-diffusion coefficients for guest molecules were estimated as follows from calculations of MSD by the Einstein relation:

$$D = \frac{1}{2d} \lim_{t \rightarrow \infty} \frac{\langle [z(t) - z(0)]^2 \rangle}{t^\alpha} \quad (6.1)$$

where d is the dimensionality of the particle displacement, t is the simulation time, $z(t)$ is the position of the particle at time t , and α represents the level of restriction present in the motion of interacting particles. Self-diffusion coefficients reported in this work are three-dimensional ($d = 3$) and were obtained using multiple time origins. RDFs were computed between guest molecules and each of the four NU-1000 active sites (μ_3 -O, μ_3 -OH, Zr-OH, Zr-H₂O) by the following relation:

$$g(r) = \frac{\langle \rho(r) \rangle}{\rho} \quad (6.2)$$

where $\rho(r)$ is the local density of guest particles at a distance r from an active site, and ρ is the bulk density of guest particles (of a given type) in the system. MSD and RDF results were both taken on a time-average basis and sampled separately for each guest species.

6.3.3 Density Functional Theory Calculations

The binding energies of CWA molecules in NU-1000 were determined using DFT calculations via CP2K [55] software. Calculations were performed for systems of individual sarin and soman molecules in different regions of the NU-1000 framework. The DZVP-MOLOPT-SR basis set [56] with core-electron pseudopotentials according to the Geodecker-Teter-Hutter formulation [57] was used for all MOF and CWA atoms, and the PBE functional [58] with

Grimme's DFT-D3 dispersion correction [59] was applied. The plane-wave cutoff and relative cutoff were set to 400 and 50 Ry, respectively. SCF convergences were assigned a value of 10^{-6} . The DIIS orbital transformation minimizer [60] and LBFGS optimizer [61] were used. These settings were adopted from the work of Ruffley et al. [62], where they were successfully implemented to calculate the binding energies of DMMP (a simulant of sarin) in the UiO-67 Zr-MOF. Zirconium and oxygen atoms of NU-1000 were held fixed during geometry optimizations, while carbon and hydrogen atoms were allowed to relax. Separate systems were considered to differentiate between interactions in the c-pore, micropore, and mesopore regions of the framework. Stable structures obtained from geometry optimizations were used to calculate the energetics of sarin and soman in NU-1000. The binding energies were then calculated as follows:

$$\Delta E_{bind} = E_{CWA+MOF} - (E_{MOF} + E_{CWA}) \quad (6.3)$$

where $E_{CWA+MOF}$ is the total energy for the CWA molecule adsorbed inside NU-1000, E_{MOF} is the total energy of the NU-1000 structure, and E_{CWA} is the total energy of an isolated CWA molecule, in the simulation box of an equivalent volume of NU-1000. Favorable binding is indicated when the total binding energy, ΔE_{bind} , holds a negative value.

6.4 Results and Discussion

6.4.1 Interactions of Pure Molecules in NU-1000

For the hydrated model of NU-1000 used in this work, Lewis acidic metal sites, where nerve agent hydrolysis will take place, are initially occupied by individual water molecules (Zr-H₂O sites). Under these circumstances, the advancement of the hydrolysis reaction is contingent

on the displacement of the -OH_2 group from the zirconium site by the CWA. As illustrated in Figure 6.2, ligand displacement and binding of the nerve agent to the empty zirconium site (through its phosphoryl oxygen) is widely accepted as the likely first step of the hydrolysis mechanism; however, the interactions leading up to coordination of the CWA to the SBU are not well understood. For instance, some studies present -OH_2 displacement and nerve agent coordination as taking place immediately and simultaneously at the $\text{Zr-H}_2\text{O}$ sites [15,21]. Alternatively, it has been proposed that nerve agent molecules will initially interact with $\mu_3\text{-OH}$ sites before proceeding with -OH_2 displacement and binding at the node [22]. To determine the most favorable binding sites for sarin and soman molecules in NU-1000, RDF analyses were conducted for the P=O oxygens of the CWAs to the oxygen atoms of each of the four NU-1000 active sites, as shown in Figure 6.4.

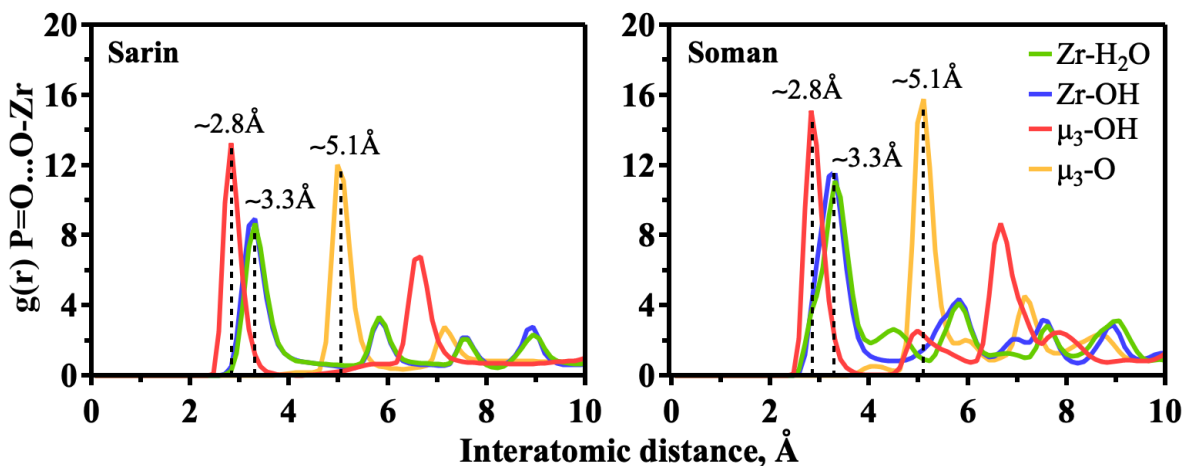


Figure 6.4. RDFs for the P=O oxygen atoms of sarin (left) and soman (right) to the oxygen atoms of NU-1000 active sites. The data shows that both CWA molecules interact most favorably with the $\mu_3\text{-OH}$ sites of NU-1000.

The data revealed that both types of nerve agent molecules exhibit the closest radial distance to the $\mu_3\text{-OH}$ sites in the framework, suggesting that $\mu_3\text{-OH}$ is the preferred site for initial binding

and interactions of sarin and soman at the NU-1000 SBUs. Given this result, binding energies for sarin and soman in the c-pore and mesopore regions of the framework were calculated with the molecules positioned at a μ_3 -OH active site. These binding energies, along with the preferential pore locations of molecules in systems of pure sarin and pure soman, are shown in Figure 6.5.

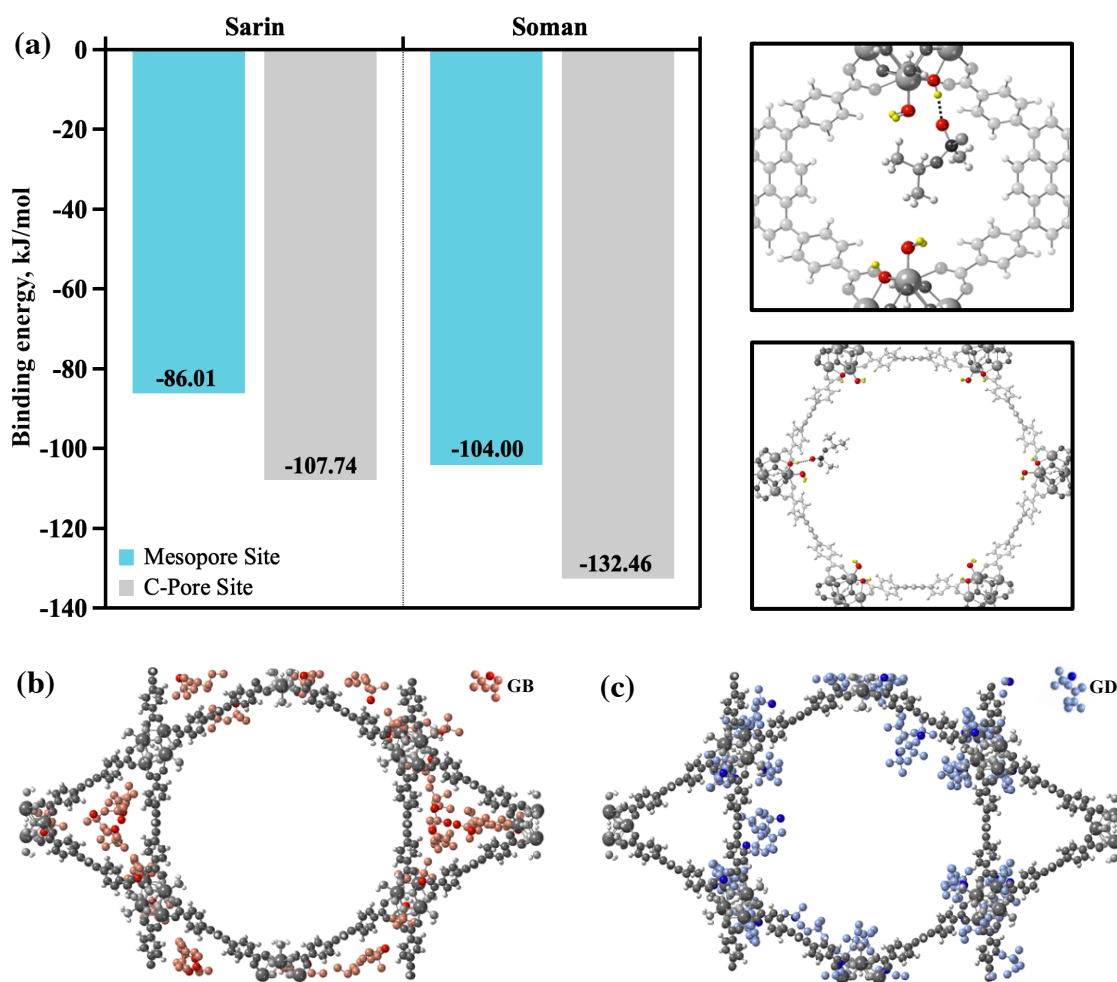


Figure 6.5. Pore locations and binding energies of pure sarin (GB) and pure soman (GD) in NU-1000. (a) Comparison of CWA binding energies at μ_3 -OH active sites in the mesopores and c-pores. Visualizations on the right illustrate initial configurations used for DFT binding energy calculations in the c-pore (top) and the mesopore (bottom). Dashed lines denote binding between the O=P oxygen of the nerve agent and the hydrogen of the μ_3 -OH site. (b) Preferential location of sarin molecules in the framework. (c) Preferential location of soman molecules in the framework.

Upon comparison of the binding energies for the two nerve agents in Figure 6.5a, it is apparent that soman has more favorable binding at NU-1000 μ_3 -OH sites than sarin, with energies ~ 18 kJ/mol stronger at sites in the mesopore regions and ~ 25 kJ/mol stronger at sites in the c-pore regions. Trajectory images in Figures 6.5b,c further reveal that soman molecules have a tendency to reside in the mesopore and c-pore regions of the framework, while sarin molecules prefer to reside in the micropores. CWA-MOF interactions are evidently a lower priority for sarin molecules than for soman molecules, especially given the fact that NU-1000 active sites are not present in the micropores. While binding strengths at the nodes do not entirely dictate the pore locations of each nerve agent in NU-1000, the results evidence that differences in their active site affinities lead to differences in the framework regions in which they primarily reside. We note that preferential distribution and binding of guest species in spatially confined framework regions have been previously observed in NU-1000 and other MOFs [30,43,63,64], despite the availability of binding sites in less sterically demanding positions [65]. Certain cases suggest that such behavior can be attributed to greater dispersion interactions between guest species and the MOF in these regions [65,66]. To further investigate this, the binding energies of each nerve agent located inside a micropore and a mesopore, but not bound to any active sites, were calculated and compared. As illustrated in Figure 6.6, the results show that the binding energy of sarin is ~ 13 kJ/mol stronger in the micropore versus the mesopore, elucidating the favorability of sarin molecules towards residing in the micropores when not interacting with active sites.

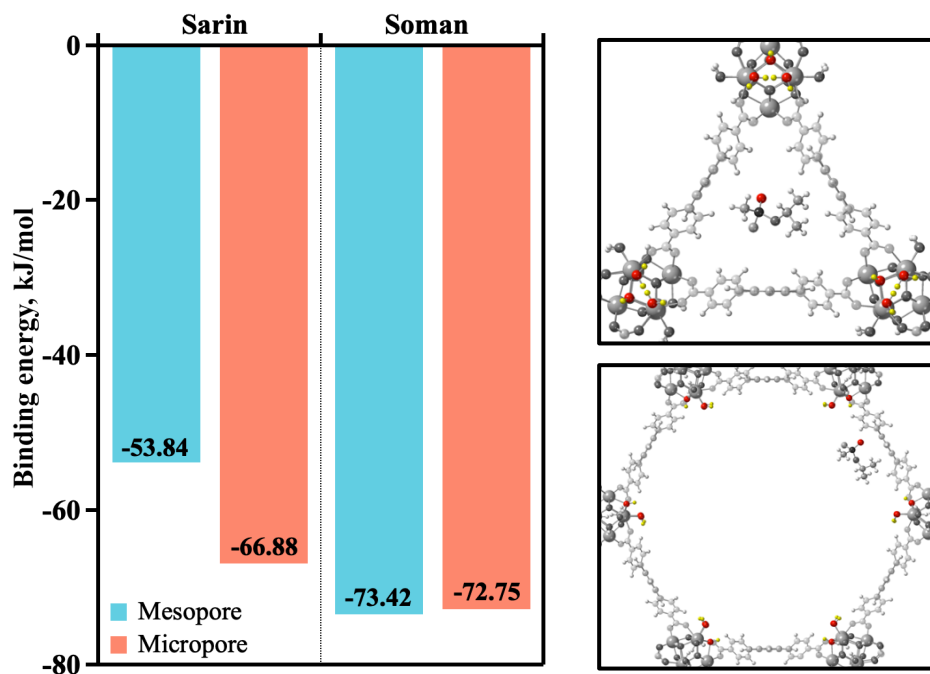


Figure 6.6. Comparison of binding energies of pure sarin (GB) and pure soman (GD) in the micropores and mesopores of NU-1000. Visualizations on the right illustrate initial configurations used for DFT binding energy calculations in the micropore (top) and the mesopore (bottom).

Analysis of the binding energies for the two metal core site regions in Figure 6.5a reveals that sarin and soman molecules both exhibit more favorable binding at μ_3 -OH sites in the c-pores of NU-1000 than in the mesopores. The preferential location of sarin molecules in the NU-1000 micropores in Figure 6.5b suggests that sarin may be far more likely to interact with c-pore active sites than mesopore active sites, considering that c-pore sites are directly accessible from the micropores (while mesopore sites are not). On the other hand, Figure 6.5c shows that soman molecules, which interact more readily with the framework, may choose to occupy sites in either the c-pores or the mesopores. Support for this hypothesis can be found in Figure 6.7, which shows the RDFs of sarin and soman molecules at μ_3 -OH sites in each framework region.

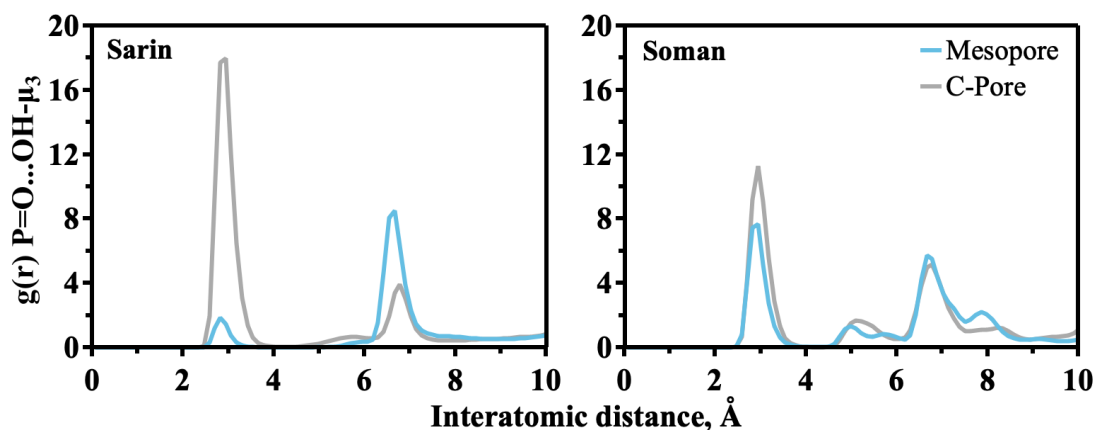


Figure 6.7. Comparison of oxygen-oxygen RDFs for CWA molecules (P=O oxygens) at μ_3 -OH active sites in the mesopore regions and c-pore regions of NU-1000.

The RDF curves in Figure 6.7 (left) reveal a profound difference in the intensities of the first peaks for sarin molecules at μ_3 -OH sites in the two regions. The significant peak intensity at the c-pore sites indicates the expected behavior, that much higher densities of sarin molecules occupy the c-pore regions than the mesopore regions when interacting with active sites in the framework. Alternatively, Figure 6.7 (right) shows more comparable peak intensities for soman molecules at μ_3 -OH sites in the two regions. The peak intensities for each region level out at normalized values in between those observed for sarin, suggesting a relatively even distribution of soman molecules between sites in the mesopores and the c-pores. Coupled with the results of Figure 6.5, it can be reasonably assumed that the affinity of the nerve agents for the active sites, which appears to impact their preferential pore location in the framework, will accordingly impact the type of active site (mesopore or c-pore) where the reaction will take place. This will, in turn, dictate the strength of binding at the node. We note that $-\text{OH}_2$ displacement during nerve agent coordination to the metal node is often considered to be a rate-limiting step in hydrolysis because oxygen, a hard base, tends to bind strongly to zirconium, a hard acid [9]. However, studies have shown that the binding of water to zirconium atoms varies in MOFs based on their pore size and

linker connectivity [20,22]. In NU-1000 specifically, it has been reported that the binding free energy of water molecules at the SBUs is also weaker in the mesopores than in the c-pores [20]. Consequently, it is anticipated that the pore location of nerve agent molecules may additionally dictate their ability to displace $-OH_2$ groups from hydrated Zr-MOF nodes. These combined findings suggest that the species of nerve agent occupying the framework will likely influence the rate of the hydrolysis reaction.

We note that current understandings of the nerve agent hydrolysis reaction mechanism depend largely on a range of assumptions, one being that CWA molecules will have no competition with atmospheric water when attempting to adsorb at open metal sites [18]. With respect to several factors, including MOF structure, topology, and water affinity, studies have presented scattered reports on whether the presence of external water will accelerate, interfere with, or have no effect on the ability of nerve agents to repeatedly adsorb, react, and desorb at MOF nodes [5,14,23,67]. To evaluate the likelihood of competitive adsorption between nerve agents and atmospheric water in NU-1000, self-diffusion and RDF calculations for systems of pure water, pure sarin, and pure soman in the framework were performed, as shown in Figure 6.8.

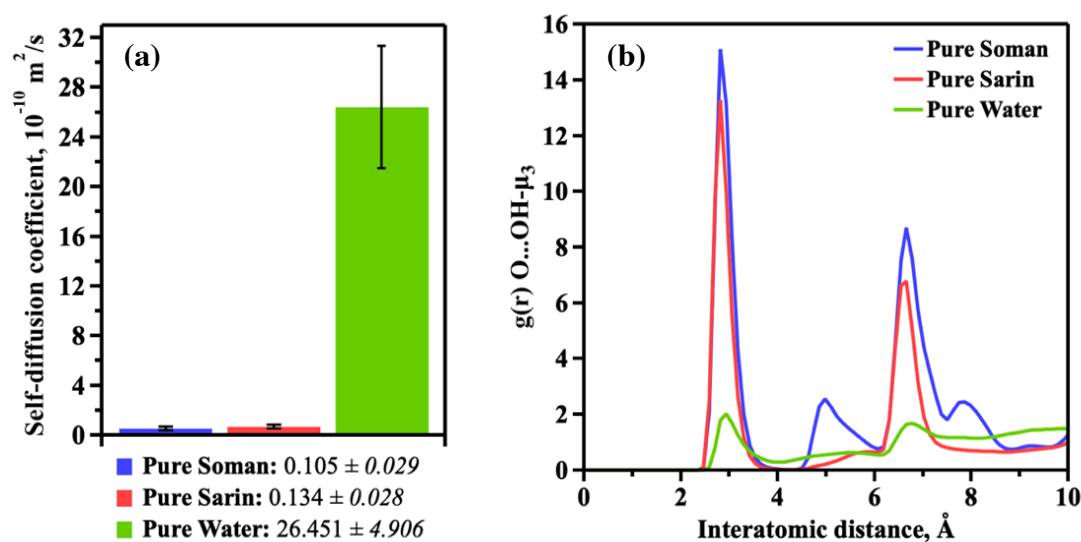


Figure 6.8. Diffusion and distribution behavior of pure sarin, pure soman, and pure water molecules in NU-1000. (a) Comparison of guest species self-diffusion coefficients. (b) Comparison of oxygen-oxygen RDFs for CWA molecules (P=O oxygens) and water molecules at μ_3 -OH active sites.

The self-diffusion data in Figure 6.8a reveals that pure water has a self-diffusion coefficient in NU-1000 two orders of magnitude larger than that of pure sarin and pure soman. This result is in some ways anticipated, as the smaller molecular size of water has been previously shown to result in faster diffusion of water molecules in MOFs compared to CWAs or their simulants [68]. That said, the RDF data in Figure 6.8b also demonstrates a considerably lower peak intensity for water molecules at the μ_3 -OH sites of the MOF than for nerve agent molecules. This indicates that the uniform distribution of guest molecules across the NU-1000 SBUs is far less apparent in systems of pure water than in systems of pure sarin and pure soman. In our previous study on water behavior at different humidity levels in NU-1000 [30], it was determined that the balanced hydrophobicity of this Zr-MOF allows water molecules to adsorb into the framework while preventing them from distributing to and occupying all the available active sites. This attribute is expected to decrease the likelihood of competitive adsorption issues during CWA hydrolysis under realistic environmental conditions. The results of Figure 6.8 suggest that pure sarin and pure soman have a much stronger affinity for active site interactions in NU-1000 than pure water, providing supporting evidence that these nerve agents would be unlikely to have to compete for adsorption at active sites when in the presence of atmospheric water.

6.4.2 Interactions of Mixed Molecules in NU-1000

At a low loading of 30 H₂O (< 1% RH), trajectory images show that pure water molecules exhibit clustering behavior in NU-1000, aggregating and diffusing in groups throughout the micropore regions of the framework, as shown in Figure 6.9.

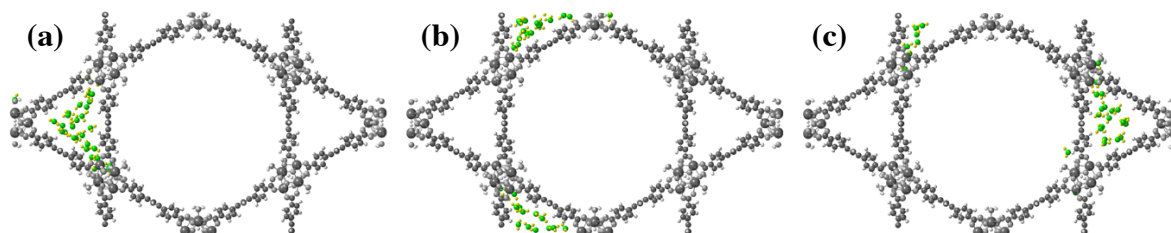


Figure 6.9. Trajectory images of pure water molecules diffusing in clusters throughout the micropore regions of NU-1000. (a) Timestep = 0.9 ns. (b) Timestep = 18.75 ns. (c) Timestep = 45.25 ns.

From investigations of this behavior in our previous work [30], it was discovered that water assemblies in NU-1000 are not highly ordered, exhibiting a structural arrangement somewhere between vapor and liquid. Such results suggest that interactions between aggregated water molecules in this MOF are not strong enough to form hydrogen-bonded clusters that fully condense into the liquid phase. In other words, individual water molecules may have the potential to break off from their groups to participate in more preferred interactions in the presence of other guest species. To further evaluate this possibility, simulations were performed for water/sarin and water/soman mixtures in NU-1000. Pore locations of pure water in NU-1000 compared to water in a mixture with sarin and water in a mixture with soman are illustrated in Figure 6.10.

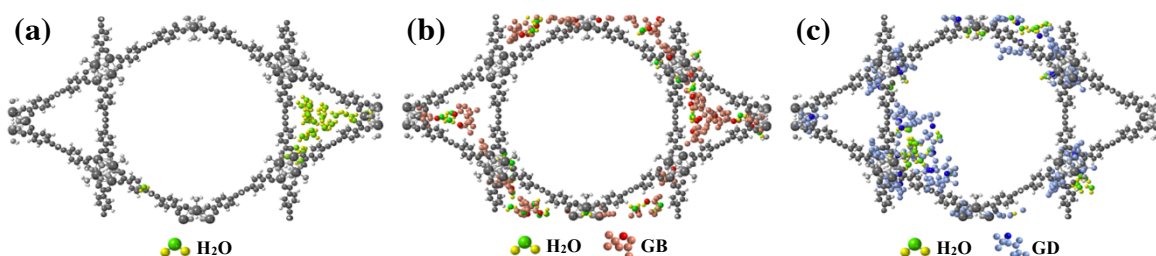


Figure 6.10. Pore locations of guest molecules in the NU-1000 framework. (a) Pure water. (b) Sarin and water mixture. (c) Soman and water mixture. Darker colored atoms represent the O=P oxygens in each type of nerve agent.

The influence of mixing on the distribution of individual species throughout the NU-1000 framework was quantified by calculating the average percentage of simulation time spent by each adsorbate in each pore region. Results for systems of pure sarin, pure soman, and pure water compared to their respective mixtures are presented in Figure 6.11. When comparing pure CWAs to CWAs in mixtures with water, Figure 6.11a shows negligible differences in the division of time between the micropores, mesopores, and c-pores. It is understood from this result that the addition of water to the framework does not have a significant effect on the behavior of these nerve agents with respect to their locational preferences. On the other hand, Figure 6.11b shows that the locational preference of water molecules is relevantly impacted by the presence of each nerve agent. In a mixture with sarin, water molecules still spend most of their time in the micropore regions of the framework, but the amount of time spent outside of the micropores increases by ~10%. In a mixture with soman, significant changes in the pore preferences of the water molecules are observed, with ~60% of the simulation time now being spent in the NU-1000 mesopores.

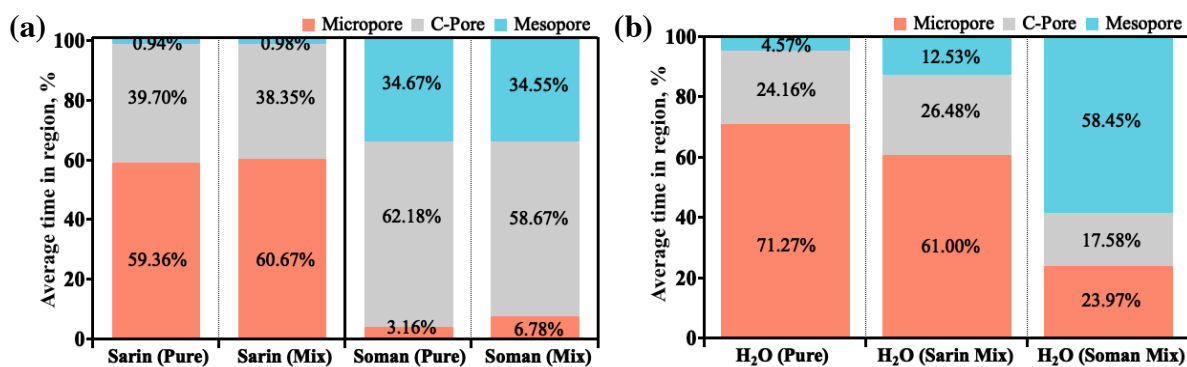


Figure 6.11. Average percentage of simulation time spent by guest species in each framework region. Charts illustrate differences in the framework distribution for (a) pure CWA molecules

compared to CWA molecules in a mixture with water and (b) pure water molecules compared to water molecules in a mixture with CWAs.

Looking at the trajectory images in Figure 6.10, it becomes apparent that water molecules in mixtures with both sarin and soman do not behave like pure water, which aggregates into clusters that diffuse together from micropore to micropore. Instead, water molecules appear to be distributing to the pore locations of each nerve agent. This observation supports the hypothesis that adsorbed water molecules in NU-1000 are capable of dispersing out from their clusters and indicates that they are likely to do so to participate in interactions with these two nerve agents. Water-CWA interactions were also evidenced in diffusion results, which showed that the total self-diffusion coefficients of water decreased by ~30-40% in mixtures with the CWAs, as shown in Figure 6.12.

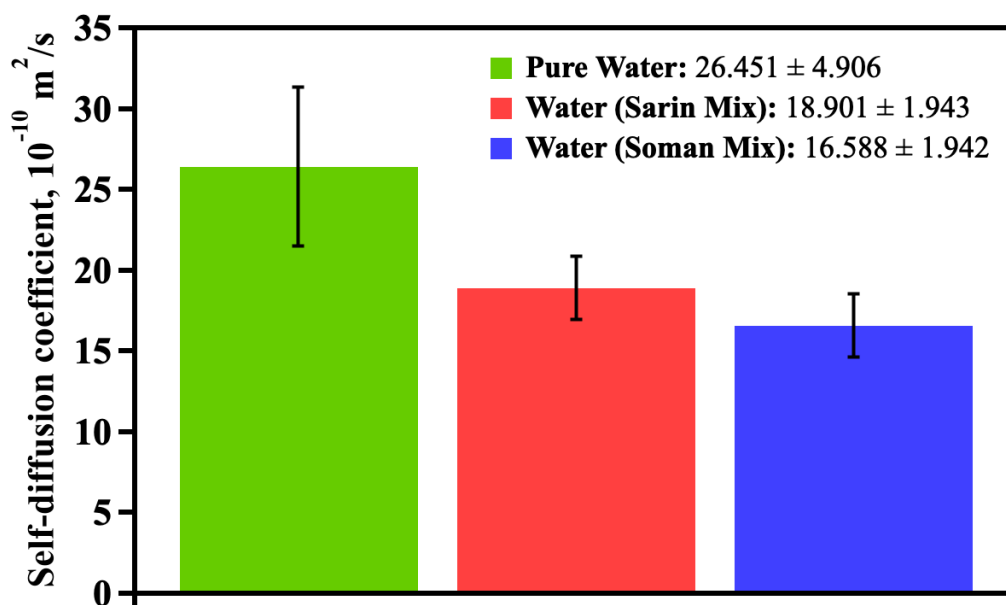


Figure 6.12. Comparison of self-diffusion coefficients for pure water, water in a mixture with sarin, and water in a mixture with soman in NU-1000.

The results in Figure 6.11a confirm that sarin molecules prefer to reside mainly in the NU-1000 micropores, spending, on average, ~60% of simulation time in those regions. With only ~1% of simulation time being spent in the mesopore regions of the framework, it is further proven that sarin molecules interact preferentially with c-pore sites over mesopore sites, only choosing to gain access to c-pore sites from the micropores. The data also confirms that soman molecules prefer to divide their time between the c-pore and mesopore site regions, spending very little time on average in the micropores. With ~60% of simulation time being spent in the c-pore regions and only ~35% being spent in the mesopore regions, it is probable that soman molecules only opt for interactions with mesopore sites when c-pore sites are not readily available. These results ultimately reveal that hydrolysis of both nerve agent types is most likely to take place at the c-pore sites of NU-1000. Nevertheless, the preference of soman molecules to gain access to c-pore sites through the mesopores suggests that binding at mesopore sites is one possibility for soman that is alternatively very unlikely for sarin.

We note that the data in Figure 6.11 shows that in both water/sarin and water/soman mixtures, the nerve agent molecules occupy specific regions of the framework for more simulation time than the water molecules. Visualizations of molecule residence times in each pore region demonstrate that sarin and soman molecules positioned in a region tend to maintain their residency in that region for very long portions of the simulation, while water molecules tend to hop frequently from one region to another, as illustrated in Figures 6.13 and 6.14.

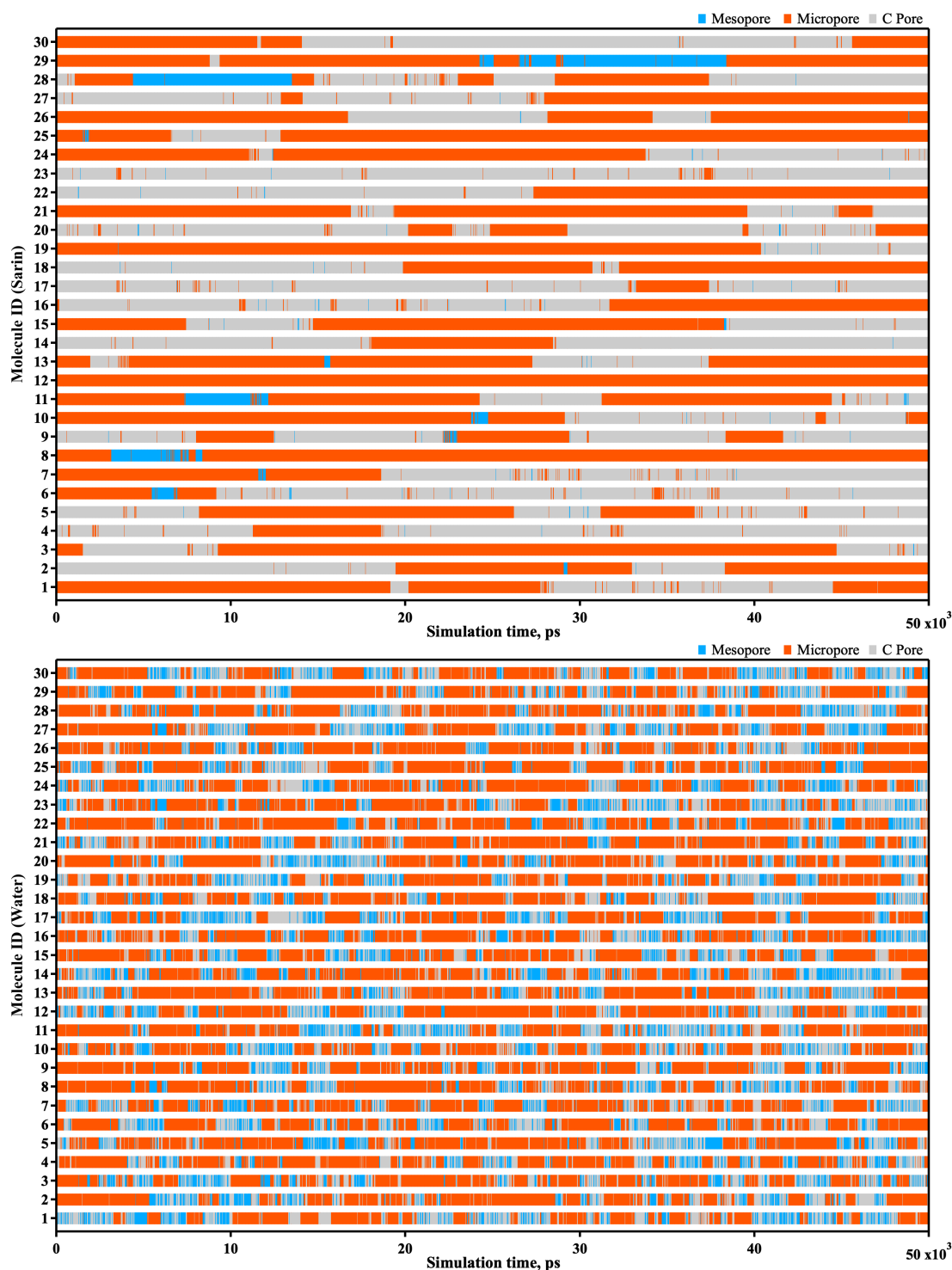


Figure 6.13. Pore location of guest molecules in NU-1000 as a function of simulation time. Figures illustrate differences in the movement of individual sarin molecules (top) and water molecules (bottom) between micropore, mesopore, and c-pore regions of NU-1000 when sarin and water are present in a mixture.

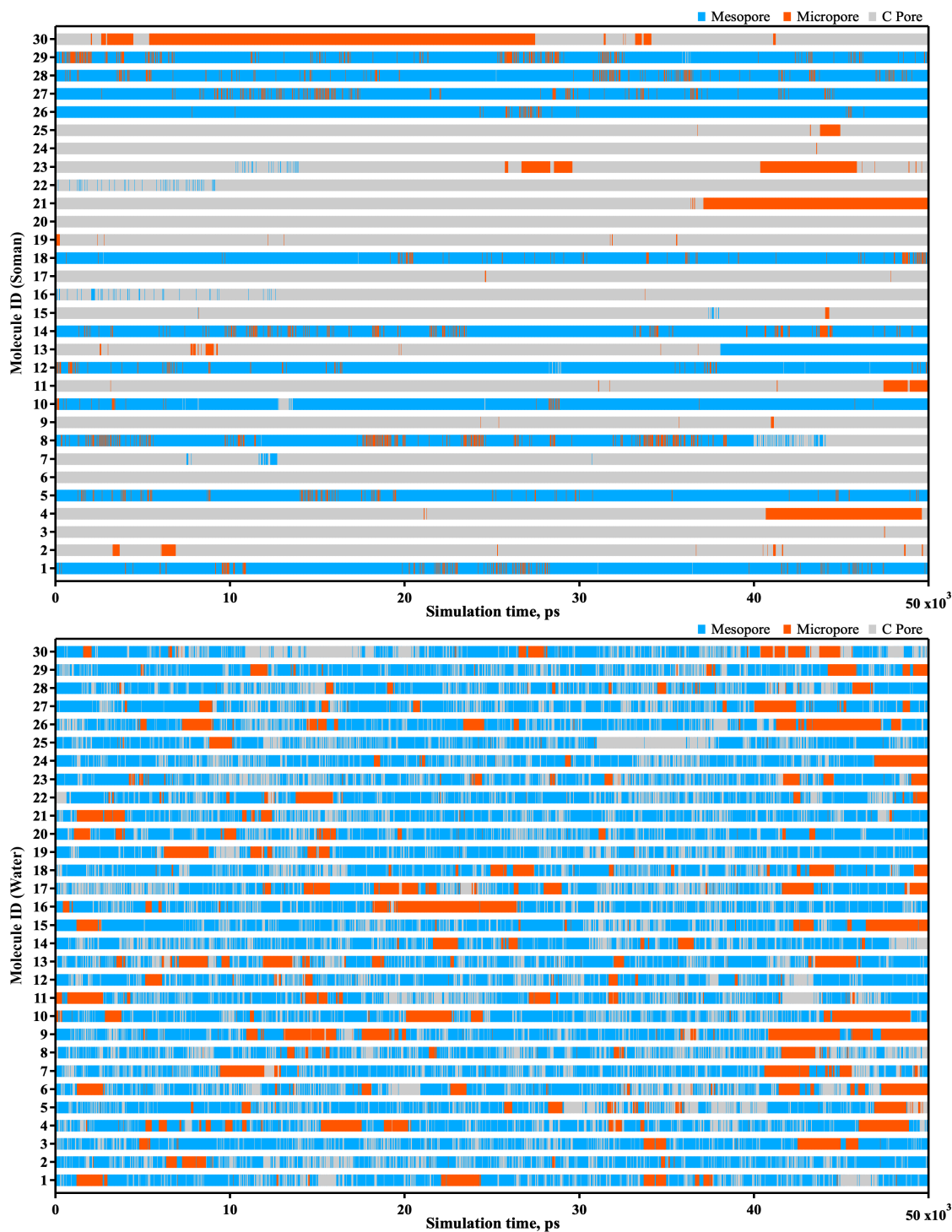


Figure 6.14. Pore location of guest molecules in NU-1000 as a function of simulation time. Figures illustrate differences in the movement of individual soman molecules (top) and water molecules (bottom) between micropore, mesopore, and c-pore regions of NU-1000 when soman and water are present in a mixture.

In the case of water/soman mixtures, the data mainly shows each water molecule hopping consistently between mesopores and c-pores but spending most of the time occupying mesopores. Meanwhile, the majority of soman molecules spend nearly the entire length of the simulation occupying a specific c-pore. In the case of water/sarin mixtures, water molecules similarly hop back and forth from region to region, but both guest species spend most of their time occupying the micropores. This begs the question, even though water molecules are dispersing throughout the framework to interact with CWA molecules, are they really making themselves available to participate in the hydrolysis reaction? Are they in the vicinity of the active sites for long enough to aid in the reaction? Are they even in the vicinity of the active sites at all, or are they interacting more with CWA molecules that aren't bound to a metal node? To further investigate this, RDF analyses were conducted for H₂O molecules at each of the four NU-1000 active sites. Results for pure water compared to water in a mixture with each nerve agent are demonstrated in Figure 6.15.

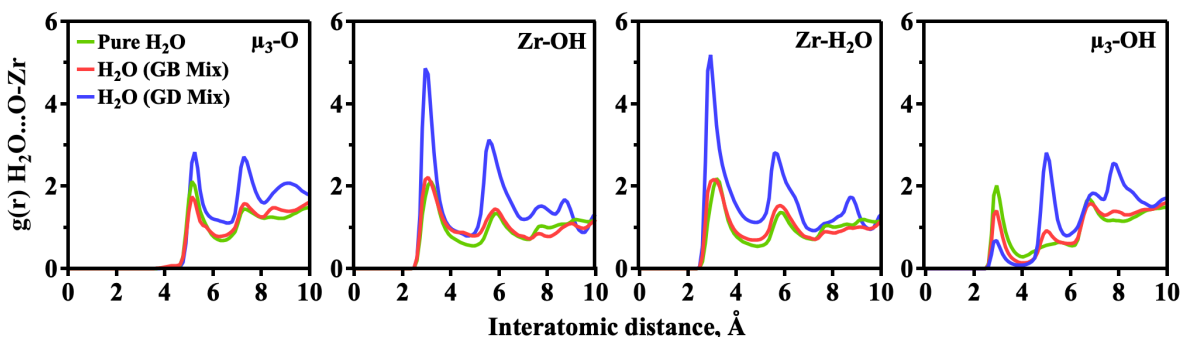


Figure 6.15. RDFs for the oxygen atoms of water to the oxygen atoms of NU-1000 active sites. Figures illustrate differences in the RDF patterns for pure water molecules compared to water molecules in a mixture with sarin (GB) and to water molecules in a mixture with soman (GD).

When comparing the RDFs of pure water to water in a mixture with sarin, the results show virtually no difference in the density of molecules around the nodes. Especially at the $\mu_3\text{-O}$, Zr-

OH, and Zr-H₂O sites, the RDF curves for water mixed with sarin almost perfectly overlap those for pure water in the MOF. This lack of influence by the addition of sarin suggests that water dispersing throughout the framework is not being drawn more toward the metal nodes. Water molecules simply diffuse from region to region to interact with sarin molecules, which mainly exist as free particles preferentially taking residence in the micropores. This is not the case for water in a mixture with soman. As illustrated by the blue curves in Figure 6.15, the peak intensities of water molecules at the μ_3 -O, Zr-OH, and Zr-H₂O sites of NU-1000 increase quite drastically when soman is introduced into the framework. Even more interesting is the trend of the curves at the μ_3 -OH sites, which alternatively demonstrates a decrease in the intensity of the first peak from pure water to water mixed with soman, followed by the appearance of a sharp second peak at a radial distance of ~ 5 Å. While this behavior is also mildly present for water mixed with sarin, it is far more apparent in a mixture with soman and further emphasizes the degree of variances between these nerve agents with respect to priority for site interactions. A more detailed look at the distribution behaviors of guest molecules in NU-1000, when water and soman are present in a mixture, is provided in Figure 6.16.

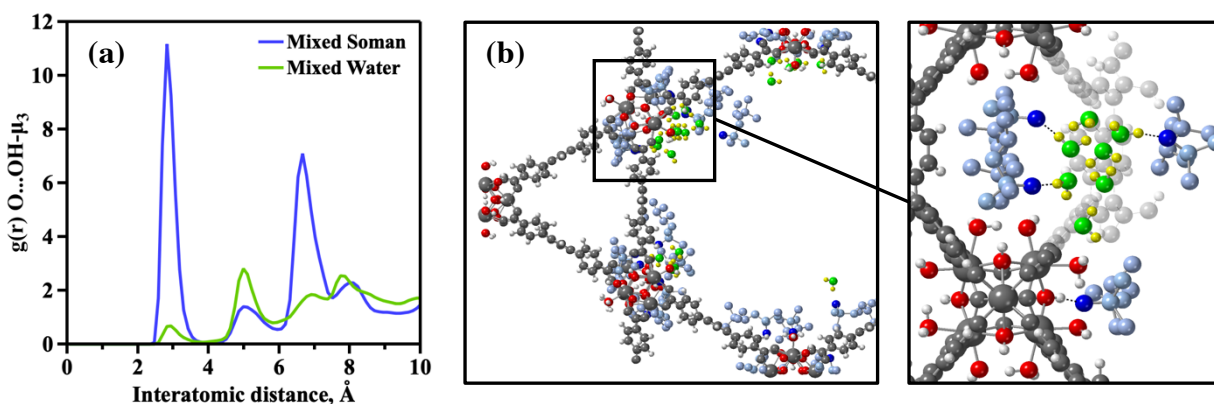


Figure 6.16. Distribution behaviors of soman and water molecules in NU-1000 when soman and water are present in a mixture. (a) Comparison of oxygen-oxygen RDFs for soman molecules (P=O

oxygens) and water molecules at μ_3 -OH active sites. (b) Zoomed-in trajectory image of guest molecules around metal nodes. Darker blue atoms represent the O=P oxygens in each soman molecule.

The RDF results in Figure 6.16a demonstrate that in a water/soman mixture, soman molecules are far more present in close proximity to the μ_3 -OH active sites of the framework than water molecules. For soman, intense peaks appear at the closest radial distance of ~ 3 Å and the farthest radial distance of ~ 7 Å, with a weak peak in between at ~ 5 Å. In contrast, water molecules exhibit weak peaks at ~ 3 Å and ~ 7 Å with a more intense peak at ~ 5 Å overlapping that of soman, suggesting possible layering of water and soman molecules around the metal nodes. Trajectory videos confirm that there is no room for H₂O to closely interact with the μ_3 -OH active sites in NU-1000, as these sites become immediately occupied by soman. As shown in Figure 6.16b, soman molecules tend to block access to active sites by residing in groups of two or three in the c-pores or otherwise interacting μ_3 -OH sites accessible from the mesopores. Nevertheless, the preferential binding of the majority of soman molecules to these sites means that as water disperses throughout the framework to interact with soman, more water molecules happen to be present near the metal nodes. Figure 6.16b reveals that water molecules mostly occupy framework regions that act as a boundary between the mesopores and the c-pores, simultaneously interacting with the soman molecules present in each region. This elucidates the layering patterns around the μ_3 -OH sites seen in Figure 6.16a, as well as the frequent hops between the mesopores and c-pores observed for each H₂O over the length of the simulation (see Figure 6.14 of the Supporting Information). Water molecules even exhibit clustering patterns in these regions, forming separate groups around the various NU-1000 nodes. Such behavior also explains the spikes in peak intensities observed for water molecules at the μ_3 -O, Zr-OH, and Zr-H₂O active sites seen in Figure 6.15. In short, the

results reveal a tendency of water molecules to aggregate around the metal nodes in a mixture with soman, versus disperse to more insignificant framework regions in a mixture with sarin.

6.5 Conclusion

In this work, a series of MD simulations and DFT calculations have been performed to evaluate the behaviors of sarin, soman, and their mixtures with water in the NU-1000 Zr-MOF. The results give insight into how interactions of different nerve agents in NU-1000 influence its functionality towards hydrolysis and the role played by environmental water in the reaction. Simulation trajectories demonstrate that sarin molecules prefer to reside in the micropore regions of NU-1000, while soman molecules take residence in the mesopores and c-pores where active sites are located. Binding energies further reveal that soman molecules bind more favorably to NU-1000 active sites than sarin molecules, suggesting that the affinity of each nerve agent for site interactions impacts their preferential location within the framework. RDF analyses show that the density of sarin molecules around mesopore sites is almost negligible, providing evidence that binding in the mesopores is a possibility for soman that is unlikely for sarin. Given that the binding energies observed at c-pore active sites are stronger than those at mesopore active sites, it is anticipated that these diverse binding locations will lead to variations in the hydrolysis kinetics of each nerve agent.

Pure water demonstrates clustering behavior at low loadings in NU-1000, signifying a preference for water-water interactions over water-MOF interactions. Diffusion calculations also show that the self-diffusion coefficient of water in NU-1000 is two orders of magnitude larger than that of sarin and soman. Combined with comparably low water-site RDF peak intensities, it is apparent that nerve agent hydrolysis in this MOF would not be limited by competitive adsorption

with environmental water. While pure water molecules are more inclined to interact with each other than with the NU-1000 framework, simulation results from water/CWA systems indicate that aggregated molecules are not strongly bound. In mixtures with sarin and soman, water molecules separate from their clusters and disperse to the pore locations of each nerve agent. These observations support the notion that interactions with environmental water are relevant and necessary to consider when investigating nerve agent hydrolysis. However, the observed interactions are not necessarily indicative of water's availability to participate in the reaction itself. Further analyses illustrate that mixing with sarin has virtually no effect on the interactions of water molecules with the MOF, whereas water-framework interactions change drastically in a mixture with soman. While sarin's weaker affinity for NU-1000 leads to a majority residence of both water and sarin molecules in the micropores, soman's stronger affinity for NU-1000 incites the layering of both species at μ_3 -OH sites, and the general aggregation of both species around the metal nodes. Despite previous evidence that water displays the ideal relationship with NU-1000 for aiding in hydrolysis, such contrasting behaviors suggest that the degree of participation by environmental water in the degradation of each nerve agent will not be the same. These discoveries strongly support the conclusion that the hydrolysis mechanism, and specifically the role of water in the hydrolysis mechanism, will depend greatly on the reacting species and its interactions with the MOF.

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Chapter 7

Conclusions & Recommendations for Future Work*

7.1 Conclusions

In this dissertation, combined atomistic and quantum mechanical computational approaches have been applied to gain insight into the role of structure and topology in the adsorption, molecular accessibility, mass transport, and kinetics of water and nerve agents in Zr-based MOFs. Structure-property relationships of Zr-MOFs with guest species have been characterized, with the goal of identifying key design rules that will lead to effective CWA degradation under relevant environmental conditions of humidity. The results can be summarized as follows:

- ◆ **Chapter 3:** A comprehensive literature survey was conducted on recent advancements in the computational and experimental studies of MOFs for the degradation of nerve agents, blister agents, and their simulants, with a primary focus on degradation via hydrolysis and oxidation strategies in Zr-based MOFs. Key design considerations for efficient degradation concerning CWA type and reaction mechanism were summarized, and insight was given into the gaps present in current understandings.
- ◆ **Chapter 4:** The influence of pore structure and water affinity on the performance potential of Zr-MOFs under realistic environmental conditions was evaluated. Equilibrium and non-equilibrium MD simulations were carried out to examine the mass transport behavior of water in UiO-66 and NU-1000, two types of Zr-MOFs with significant differences in topology and hydrolytic activity. Trends in molecule transport were investigated using temperature-induced chemical potential gradients. The simulation results showed that the rate of water molecule

flux in both MOFs follows a nonlinear pattern with increasing temperature difference. In the NU-1000 framework, expansive pore volumes allow for unobstructed molecule permeation that is enhanced at larger temperature gradients. Alternatively, water molecule flux in UiO-66 is restricted by its small pore sizes and hydrophilicity. Trajectory images illustrated that confinement and surface interactions in the UiO-66 framework yield total filling of the pores by water, preventing diffusion of water molecules through the structure upon application of a temperature difference. Variations in the mass transport properties of the two MOFs were quantified with diffusion calculations, which revealed that transport diffusion coefficients of water in UiO-66 are at least an order of magnitude lower than those in NU-1000. Such results suggest that the structure and water affinity of NU-1000 make it far better equipped than UiO-66 for chemical reaction operations in humid environments.

- ◆ **Chapter 5:** The influence of pore structure and water affinity on the performance potential of Zr-MOFs under realistic environmental conditions was further evaluated. It was proposed that the combined attributes of strong node-linker bonds, expansive pores, and internal hydrophobicity could yield a promising MOF for hydrolysis applications in the presence of humidity. MD simulations were carried out to examine the behavior of water at various loadings in NU-1000, a Zr-MOF equipped with these three characteristic attributes. Simulation trajectories showed that water molecule aggregation is apparent at all loadings in NU-1000, with molecules diffusing in clusters throughout the framework. To adequately quantify the distribution behavior of the molecules, a code was developed for calculating radial distribution functions in systems where guest particles are not uniformly distributed. Analyses of self-diffusion coefficients, residence times, and radial distribution functions revealed that these water clusters are not tightly bound, exhibiting ordered arrangements somewhere in between

vapor and liquid. While water-framework interactions are not strong enough to cause the uniform distribution of water molecules to all the available MOF active sites, interactions between water molecules are not strong enough to cause hydrogen-bonded clusters that fully condense into the liquid phase. Such results support the hypothesis that Zr-MOFs like NU-1000 may be well suited for CWA hydrolysis, as they can allow water molecules to enter and be available to participate in hydrolysis without competing for adsorption or threatening structural stability.

- ◆ **Chapter 6:** Reaction sites and reaction mechanisms for nerve agent hydrolysis in Zr-MOFs, including the role of water, were investigated. MD simulations and DFT calculations were carried out to examine the behavior of the organophosphorus nerve agents, sarin and soman, in NU-1000, both in pure form and in mixtures with water. Evaluation of CWA radial distribution functions revealed preferential interactions with μ_3 -OH active sites, giving insight into the likely mechanism of nerve agent binding to the metal node. CWA binding energies showed more favorable binding in the c-pores of NU-1000 than in the mesopores, providing evidence that hydrolysis kinetics may vary in a MOF with multiple site environments. Simulation trajectories demonstrated that soman molecules prefer to reside in the mesopores and c-pores of NU-1000, while sarin molecules take residence in the micropore regions of the framework. Binding energies further revealed that soman molecules bind more favorably to NU-1000 active sites than sarin molecules, suggesting that differences in the affinities of each nerve agent for site interactions lead to differences in their preferential locations within the framework. Evaluation of water/CWA mixtures confirmed that the structural features of NU-1000 facilitate the dispersion of water molecules across the framework to participate in interactions with the CWAs and potentially participate in hydrolysis. However, while soman's

stronger affinity for NU-1000 incites the aggregation of both species around the metal nodes, sarin's weaker affinity for NU-1000 leads to a majority residence of both water and sarin molecules in the micropores where no active sites are located. These discoveries strongly support the conclusion that the hydrolysis mechanism, and specifically the role of water in the hydrolysis mechanism, will depend greatly on the reacting species and its interactions with the MOF.

7.2 Recommendations for Future Work

In Chapter 4 and Chapter 5 of this dissertation, we show that Zr-MOFs with additional features of wide channels, low linker coordination, and internal hydrophobicity present as strong candidates for hydrolysis applications, given the large volume available for guest species adsorption and diffusion, the enhanced accessibility of the metal nodes, and the ability of environmental water to adsorb in the pores without competing for active sites. Water adsorption isotherms are a popular method for characterizing overall water affinity, providing insight into whether water will adsorb in and interact with a given MOF. However, they do not offer much insight into local water interactions at the linkers, at the nodes, and in different pore environments. Developing computational approaches to identify and assign these local regions of hydrophilicity and hydrophobicity could be a major step forward in designing MOFs with the perfect balance of water affinity for efficient nerve agent hydrolysis.

While high-valence Zr metal nodes are ideal for creating strong and stable bonds with carboxylate organic linkers, they also tend to create strong bonds with guest molecules and nonstructural ligands. For this reason, displacement of aqua ligands and strongly bound reaction products present as rate-limiting hydrolysis steps in many Zr-MOFs. Combined experimental and

computational studies have uncovered that certain structural and topological attributes can significantly reduce the influence of these variables on hydrolytic efficiency. There is a positive correlation between linker coordination and Zr-H₂O bond strength, where the binding of water ligands to Zr atoms is weaker in MOFs with lower connectivity. Guest-host bond strengths and transition state structures have also been shown to vary in MOFs with different pore sizes. In Chapter 6, we reveal that guest species binding energies can even vary in different pore regions within the same MOF. Future studies would therefore benefit from considering nerve agent location when evaluating hydrolysis rates in MOFs, especially those with sites accessible from multiple pore environments.

In terms of structural tuning, linker functionalization and SBU dehydration have frequently been presented as promising strategies for improving hydrolysis kinetics. Unfortunately, these design rules stem primarily from implementing MOFs in aqueous buffer solutions, which facilitate the reaction and do not account for environmental variables relevant to the solid-phase application. Studies have shown that functionalizing proximal bases only reduces reaction barriers and enhances catalytic activity in a high pH environment. Convincing arguments have also been made that displaced water in the vicinity of the metal nodes is crucial in the solid state for preventing bidentate product binding and promoting product displacement, both of which are necessary to avoid catalyst inhibition. Evidence suggests that this effect would be accelerated with the addition of external water molecules from the atmosphere; however, well-developed understandings of the role of environmental water (at different loadings) in the hydrolysis mechanism are lacking. The proposed mechanisms appear to carry the assumption that all nerve agents and Zr-MOFs have an equal affinity for water, often failing to incorporate the participation of external water altogether. These mechanisms also neglect to consider the level of interaction between a nerve agent and

MOF, suggesting that the degradation of all nerve agents in all Zr-MOFs will proceed by the same reaction steps. In Chapter 6, we uncovered that the interactions of different nerve agents in the same Zr-MOF are varied, as is the behavior of environmental water in the presence of each nerve agent. More thorough ab initio calculations are undeniably needed to accurately characterize the role of environmental water at critical steps of the hydrolysis process and to begin exploring the possibility of diverse reaction mechanisms based on the type of nerve agent and the type of MOF.

As discussed in Chapter 3, the structural stability, thermal stability, and reusability of Zr-MOFs make them stand out as appealing supports and catalysts for sulfur mustard degradation via $^1\text{O}_2$ photooxidation. While many Zr-MOFs contain photoactive species in the form of structural organic linkers, studies have shown that enhanced photocatalytic activity can sometimes be achieved by post-synthetic incorporation of photoactive species in the form of nonstructural ligands. Whether or not the method of incorporation improves photooxidation efficiency depends on several factors, including the chemical structure of the photosensitizer and the MOF-photosensitizer pair. Evaluating singlet oxygen generation quantum yields of photoactive species is a useful first step to take when determining which MOF to use (or which photosensitizer to incorporate into a given MOF), as this property has proven to be a reasonable indicator of the partial oxidation efficiency a material will likely achieve. However, determining truly ideal MOF-photosensitizer pairs requires a more in-depth evaluation of chemical properties from the quantum scale. Time-dependent density functional theory (TD-DFT) is an evolving technique that can shed light on these properties, alleviating the troublesome task of hypothesizing favorable materials and comparing their performances experimentally. Advancements in TD-DFT approaches are expected to be instrumental in elucidating the key factors that determine whether a certain photosensitizer or incorporation method will improve a MOF's photocatalytic capabilities. Improved

characterizations of structure-property relationships are also needed, as MOFs' structural and topological design rules governing effective sulfur mustard removal are not currently well understood.

Lastly, insights into optimizing photooxidation in Zr-MOFs are far less developed than those for optimizing hydrolysis, and significant efforts in many areas will be needed to advance with the practical application. Current studies reporting efficient MOF performance are almost exclusively from operation in protic solvents and under LED lights, used to improve selectivity and enhance light absorption and excitation, respectively. Many high-functioning photosensitizers realistically exhibit weak absorption in the visible spectrum region, severely challenging their practical use under standard room lighting or in the dark. Investigations on MOFs for alternative photocatalysis applications have exhibited a breakthrough in this area, revealing that linker functionalization and metal node substitution are methods of structural tuning that can enhance photocatalytic activity without any external stimuli. Such modifications have been shown to alter the electronic properties of Zr-MOFs, increasing their ability to absorb light for excitation and/or transfer excited electrons from ligands to metal sites. Further development in this area could vastly reduce the barriers preventing photosensitizer excitation in relevant field conditions, which is essential to the realistic employment of Zr-MOFs for sulfur mustard photooxidation.

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