The Journal of Organic Chemistry

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*J. Org. Chem.*, **Just Accepted Manuscript** • DOI: 10.1021/acs.joc.8b01314 • Publication Date (Web): 13 Jul 2018

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# Degradation of Sulfur Mustard (HD) on KF/$Al_2O_3$: The role of Organic Solvents and Active Species

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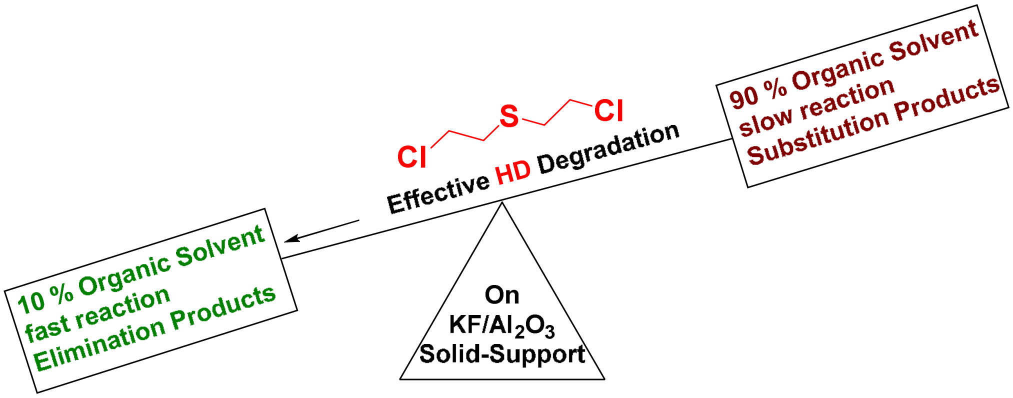


## Abstract

Solvent effects on the ability of KF/$Al_2O_3$ supports to degrade the warfare agent sulfur mustard (HD) were explored. RP-KF/$Al_2O_3$ possessing hydroxide ions and ECUF/KF/$Al_2O_3$ holding fluoride ions, were examined. Reactions on RP-KF/$Al_2O_3$ containing 10 wt % of organic solvents were faster than those on ECUF/KF/$Al_2O_3$. Additionally, RP-KF/$Al_2O_3$ led to elimination products while ECUF/KF/$Al_2O_3$ mainly to substitution derivatives. Enlarging the solvent amounts to 90 wt % resulted in decreased reaction rates. The significance of solvent identity/amount and active species are discussed.

Development of effective methods for decontamination of chemical warfare agents (CWAs)[1-4] applied in both military and homeland scenarios is most relevant as evident from recent events of CWAs use.[5] Among the array of approaches available for that purpose, reactive sorbents that physically adsorb and chemically degrade CWAs to nontoxic products seems to hold great potential. Indeed, in recent years an extensive effort has been directed towards the study of various active supports, such as nanosized MgO,[6] $Al_2O_3$,[7-10] CaO,[11] $Zr(OH)_4$,[12] and $TiO_2$,[13-15] as well as metal organic frameworks (MOFs)[16-18] that have capabilities to decontaminate CWAs. Acknowledging the attractiveness of this approach we were recently engaged with the examination of the potential of various impregnated alumina supports, i.e. RP-KF/$Al_2O_3$ (regular preparation), ECUF/KF/$Al_2O_3$ (Enriched with Coordinatively Unsaturated Fluoride)[19,20] and $R_4NF/Al_2O_3$,[21] to actively and effectively decontaminate CWAs. Indeed, we have found that the extremely toxic organo-phosphorus (OP) based CWAs VX (*O*-ethyl *S*-2-(diisopropylamino)ethyl methylphosphonothioate) and GB (*O*-isopropyl methylphosphonofluoridate, sarin) as well as the blister agent sulfur mustard (2,2'-dichloroethyl sulfide, HD) were effectively degraded on these supports with reaction half-life times ranging from few minutes to several hours.[19-21] Typically, small amount of water was added to the supports in these studies to achieve these results, while with the dry powders extremely long reaction times were obtained. However, in respect of potential application of these types of powders in the field, we envisioned that further addition of an organic solvent will be required to promote facile and effective dispersal of the sorbent as well as rapid diffusion of the CWAs towards the powder active sites. Accordingly, we have recently explored the effects organic solvents have on the fluoride-promoted heterogeneous hydrolysis and alcoholysis of various OP compounds,[22] among them the CWA VX,[23] on the surface of ECUF/KF/$Al_2O_3$. These experiments showed that not only is the identity of the solvent important in these reactions but also its quantity. It was proposed that addition of minute quantity (3-10 wt %) of the proper solvents is suffice to permit mobility of the reaction components while maintaining their very high local concentration in close proximity to the solid-support large porous surface area. Under these conditions, acceleration of reactions rates by order of magnitudes was obtained. Most importantly, leaching of fluoride ions, which were found pivotal in the mechanism of OP's hydrolysis/alcoholysis, was prevented in such small amounts of solvents.

In order to develop a universal decontamination sorbent, namely, one that will effectively detoxify OP CWA's as well as HD type of agents, it was of interest for us to complete and examine whether the above notions on solvents effects could also be implemented for the effective decontamination of the more hydrophobic agent HD on such matrices. To the best of our knowledge, solvent effects on HD decontamination reactions on solid-supports were not explored before. A study on the reactions of an HD simulant, 2-chloroethylethyl sulfide (2-CEES), in the presence of MgO (~150 mg) and large amounts (10 mL) of pentane, methanol and THF was however reported.[24] Using GC-MS as their method of analysis, the authors showed that surprisingly the most hydrophobic and inert solvent pentane led to the fastest reactions. Accordingly, we envisioned that degradation studies of HD itself on KF impregnated alumina supports wetted with different amounts (minute to large) of organic solvents and monitored by NMR would provide significant information. The results of these studies are described herein with specific attention to products identity and volume of solvents used.

For this study, methanol and ethanol were chosen as representatives of polar protic solvents, acetonitrile as an example of a polar aprotic solvent and heptane as a hydrophobic solvent. On the basis of previous kinetic data, we have decided to perform the solvent effect study on

HD decontamination with two of our leading supports, namely, RP-KF/$Al_2O_3$ and ECUF/KF/$Al_2O_3$ (Table 1).[19-21]

**Table 1. Kinetics and product distribution of HD degradation reactions on RP-KF/$Al_2O_3$ and ECUF/ KF/$Al_2O_3$ in the presence of solvents.[a]**

| Run | Solid support | Sol. | Sol. % | $t_{1/2}$ (h) | Elimination[d] vs Substitution[e,f,g] Products(%) | |
|---|---|---|---|---|---|---|
| **1** | RP-KF/$Al_2O_3$ | - | - | 355[b] | 80 | 20[e] |
| **2** | ECUF/KF/$Al_2O_3$ | - | - | 319[b] | 23 | 77[e] |
| **3** | RP-KF/$Al_2O_3$ | Water | 10 | 138[b] | 18 | 82[e] |
| **4** | ECUF/KF/$Al_2O_3$ | Water | 10 | 224[b] | 19 | 81[e] |
| **5** | RP-KF/$Al_2O_3$ | MeOH | 10 | 18.5[c] | 97 | 3[f] |
| **6** | RP-KF/$Al_2O_3$ | MeOH | 90 | 102[c] | 3 | 97[f] |
| **7** | None | MeOH | 100 | 347[c] | 0 | 100[f] |
| **8** | ECUF/KF/$Al_2O_3$ | MeOH | 10 | 30.1[c] | 91 | 9[f] |
| **9** | RP-KF/$Al_2O_3$ | EtOH | 10 | 21.1[c] | 93 | 7[g] |
| **10** | ECUF/KF/$Al_2O_3$ | EtOH | 10 | 578[c] | 39 | 61[e,g] |
| **11** | RP-KF/$Al_2O_3$ | Hep | 10 | 42.0[c] | 93 | 7[e] |
| **12** | RP-KF/$Al_2O_3$ | Hep | 90 | 105[c] | 93 | 7[e] |
| **13** | ECUF/KF/$Al_2O_3$ | Hep | 10 | 996[c] | 81 | 19[e] |
| **14** | RP-KF/$Al_2O_3$ | MeCN | 10 | 50.6[c] | 95 | 5[e] |
| **15** | ECUF/KF/$Al_2O_3$ | MeCN | 10 | 1751[c] | 14 | 86[e] |

[a] Products ratio at the end of the reactions. [b] On the basis of our previous study, loading of 6.5% of HD.[20] [c] Loading of 5% HD. [d] CEVS (**1**), DVS (**3**), traces of HOEVS (**2**). [e] TDG (**4**), TDG oligomers (**5**), Thioxane (**6**). [f] methoxyethyl chloroethylsulfide (**7**), bis(2-methoxyethyl)sulfide (**8**). [g] ethoxyethyl chloroethylsulfide (**9**), bis(2-ethoxyethyl)sulfide (**10**).

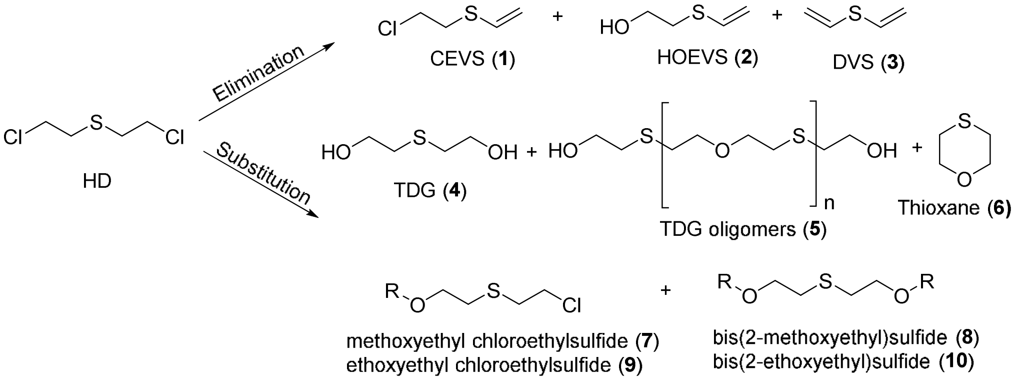
Although prepared from the same materials, i.e. alumina and KF, due to variation in their protocol of preparation these supports differ in the nature of their active species. Specifically, in the case of RP-KF/$Al_2O_3$ which is prepared in water, the fluoride ions are mainly consumed for the formation of inactive water-insoluble $K_3AlF_6$ and the support active species are hydroxide ions.[25] In the case of ECUF/KF/$Al_2O_3$, which is prepared in methanol or ethanol, the fluoride ions are "free" and available for reactions, as the formation of $K_3AlF_6$ is prevented in these solvents (eq. 1-2).[19-21]

$$12KF + Al_2O_3 \xrightarrow{3H_2O} 2K_3AlF_6 + \underset{\text{"Free" hydroxide}}{6KOH} \qquad \textbf{RP-KF/Al}_2\textbf{O}_3 \tag{1}$$

$$KF + Al_2O_3 \xrightarrow{ROH} Al_2O_3 + \underset{\text{"Free" fluoride}}{KF} \qquad \textbf{ECUF/KF/Al}_2\textbf{O}_3 \tag{2}$$

This difference was previously shown to have marked effect on the kinetics of OP CWAs decontamination reactions on these dry or water wetted matrices, i.e. reactions on ECUF/KF/$Al_2O_3$ were found to be much faster and effective than those on RP-KF/$Al_2O_3$, presumably due to the major role the fluoride ion has in the hydrolysis mechanism of OPs.[19,26] As can be seen in table 1, this pattern also exists in the case of HD reactions (5 wt %) on these matrices in the presence of 10 wt % of organic solvents, however in an opposite direction. Namely, RP-KF/$Al_2O_3$ appears superior than ECUF/KF/$Al_2O_3$ for these reactions in all solvents. In the case of ethanol, heptane and acetonitrile this behavior is most pronounced with degradation reactions up to ~20-30 times faster on RP-KF/$Al_2O_3$ than on ECUF/KF/$Al_2O_3$ (runs 9, 11, and 14 versus 10, 13 and 15 respectively). In the case of methanol, however, the reaction on the former was only ~1.5 times faster than that on the latter (run 5 versus 8). Interestingly, reactions on RP-KF/$Al_2O_3$ in the presence of all organic solvent examined resulted in improved kinetics as compared to reactions on the dry or water wetted supports. For example, reaction in the presence of 10 wt % methanol (run 5) was found to be ~7 times faster than that in the presence of 10 wt % of water (run 3). However, in the case of ECUF/KF/$Al_2O_3$, only methanol (run 8) led to a faster reaction, ~ 7 times, than that obtained in the presence of water (run 4). All other solvents led to extremely slow transformation rates, even much slower than that observed on the dry support. Apart of the different kinetics, the reactions on the two supports differed also in the identity of the products obtained as well as their ratio (Table 1). It should be noted that hydrolysis[27] or elimination pathways are favored over oxidation for this environmentally persistent and hydrophobic CWA, as some of its oxidation products are toxic.[28] Reactions on RP-KF/$Al_2O_3$ in the presence of all solvents led almost exclusively (93-97%) to the elimination products, 2-chloroethyl vinyl sulfide (CEVS, **1**) and divinyl sulfide (DVS, **3**), while only small amount (3-7%) of substitution products were observed (Scheme 1 and Figure 1). However, on

ECUF/KF/$Al_2O_3$ the product identity and distribution varied contingent on the solvent used. In the case of methanol and heptane, elimination products were mostly obtained, while in the case of ethanol and acetonitrile substitution products were predominant. Significantly, all products obtained in these experiments are relatively of non-toxic nature.[28]



**Scheme 1. Optional HD degradation products on KF alumina supports.**

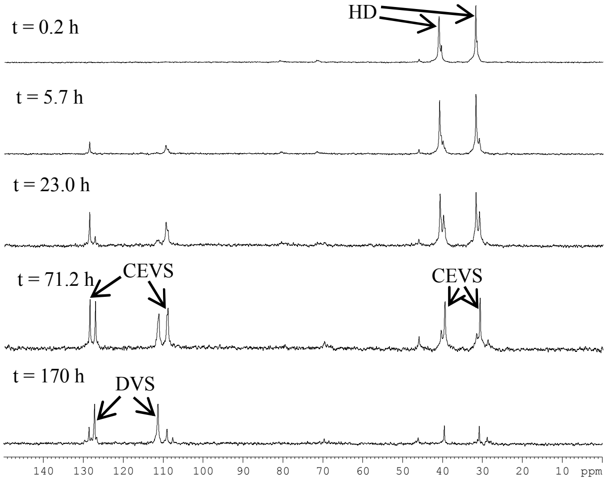


**Figure 1.** Selected $^{13}$C-NMR spectra of HD degradation reactions on RP-KF/$Al_2O_3$ in the presence of 10 wt % of methanol. See scheme 1 for structures.

In order to understand the above results, the solubility/mobility of HD in the organic solvents and the relative activity of the powders active species towards this substrate should be considered. Although only minute amounts, i.e. 10 wt %, of solvents were added, such that the supports maintained their solid nature, this volume is in principal suffice, as we recently showed for the degradation of OP-based CWA and simulants,[22,23] to afford effective mobility of all reaction components. Since in a specific solvent HD is mobile on the two supports to the same extent, the different reactions kinetics obtained on them must arise from the fact that KOH is a stronger base than KF. Accordingly, it probably better activates the RP-KF/$Al_2O_3$ support towards reaction with HD and makes it superior than ECUF/KF/$Al_2O_3$, although the surface area of the former matrix is lower than the latter.[20] The different kinetics obtained on a specific support in the presence of the various solvents may stem from the different solubility of HD as well as of the active species KOH or KF in them. Interestingly, in the case of RP-KF/$Al_2O_3$ these differences somewhat compensated each other such that all four solvents (although different in nature) led to similar kinetics with $t_{1/2}$ times ranging from 18.5h to 50.6h. Specifically, due to the rather high solubility of KOH in methanol and ethanol (Table S1 in the supporting information) these solvents led to 2-3 times faster reaction rates (runs 5 and 9) than those obtained in heptane and acetonitrile (runs 11 and 14). The latter solvents managed to mediate relatively fast reactions, albeit the negligible solubility of KOH in them, due to their ability to promote effective diffusion of HD to the support active pores. In the case of ECUF/KF/$Al_2O_3$ experiments, however, a large difference in reaction times was obtained (~30 to 1750h) among these solvents. The substantial reactions rate difference between the two polar protic solvents methanol and ethanol (runs 8 and 10) stems from the large difference of KF solubility's in these solvents (MeOH- 10.3g/100g solvent, EtOH- 0.1g/100g solvent, see Table S1 in the supporting information). A similar reaction rate difference phenomena in the presence of these solvents was also observed by us in the case of an organo-phosphorous compound.[22] Heptane and acetonitrile which negligibly solubilize KF mediated even much slower reactions than ethanol (runs 13 and 15). In respect to the products obtained and their ratio, the activity of KOH and KF in elimination or substitution reactions should be examined. Evidently, once strong bases like KOH are present on the support and are accessible in the presence of organic solvents, elimination reactions are favored over substitution. For example, in the RP-KF/$Al_2O_3$ experiments the elimination products CEVS (**1**) and DVS (**3**) were almost the sole products obtained while substitution products were obtained only in trace amounts. Since KF is a weaker base than KOH and in addition it exhibits lower solubility in the examined solvents (Table S1 in the supporting information),[29-33] reactions on ECUF/KF/$Al_2O_3$ apart of slower kinetics typically provided a much more complex mixture of products. In general, as longer the reactions became, the ratio between elimination and substitution products shifted towards the latter. Apparently, elimination reactions of HD are quicker, however, if not occurring, slow hydrolysis promoted by surface hydroxyl group or residual amounts of water present in the solvents is obtained.

In order to evaluate the effect large amounts of solvents promote, experiments in the presence of 90 wt % of solvents were next performed. Specifically, RP-KF/$Al_2O_3$ was mixed with 90 wt % of methanol or heptane holding 5 wt % of HD, and the mixtures were examined periodically, after vigorous shaking, using solution NMR. The results showed that enlarging the solvent amounts led to decreased reactions rates, i.e. ~5 times for methanol (run 6) and ~2.5 times for heptane (run 12), as compared to reactions in the presence of 10 wt % of solvents (runs 5 and 11). Most interestingly was the fact that the increased amount of methanol led solely to the methanol-based substitution products methoxyethyl chloroethylsulfide (**7**) and bis (2-methoxyethyl)sulfide (**8**),[34] while in the presence of 10 wt % of methanol elimination products were predominantly obtained (Figure S2 in the Supporting Information). Evidently, the relatively large amount of methanol afforded effective leaching of both KOH and HD from the $KF/Al_2O_3$ support, such that the decontamination reactions practically occurred in the solution phase in the presence of active methoxide ions. The fact that the pH of the solution at the end of the experiment was found to be 11 further supports this notion. Under heterogeneous conditions, i.e. once a minute amount of solvent is added, KOH leaching is prevented and elimination reactions of HD, which probably forms specific interactions with the RP-$KF/Al_2O_3$ support, are promoted on the basic solid media.

To further substantiate that the reactions in the presence of 90 wt % of methanol occurs mainly due to KOH leaching from the RP-$KF/Al_2O_3$ support and not only from methanol intrinsic nucleophilic activity, a control solvolysis experiment in which only methanol and HD were mixed, was performed. Indeed, it was found, that although not inert, methanol itself led to a solvolysis reaction ~3 times slower (run 7) than that obtained in the presence of 10 wt % of the powder (run 6). In the case of heptane, since KOH has negligible solubility in it, even large amount of this hydrophobic solvent did not mediate leaching of the salt, as was also evident from the neutral pH the solution exhibited at the end of the experiment. In accord, reactions of HD must have occurred only after its diffusion and adsorption to the RP/$KF/Al_2O_3$ matrix. Once adsorbed, the support mediated the formation of the elimination product CEVS (**1**) which was also the major product obtained under heterogeneous conditions in the presence of 10 wt % of solvent.

Solvent effects on the degradation reactions of HD were explored. Our results demonstrated that organic solvent wetted supports mediated much quicker reactions than those obtained on the dry or water wetted matrices, seemingly due to the improved diffusion HD exhibits under these conditions. Reactions of HD on RP-$KF/Al_2O_3$ were found to be much faster than those on ECUF/$KF/Al_2O_3$. It seems reasonable to assume that the increased RP-$KF/Al_2O_3$ activity is derived from hydroxide ion being a stronger base than fluoride ion. Small amounts of solvents were found beneficial for such reactions as leaching of active species was avoided while effective mobility of the reaction components and high concentration reactions were still maintained. Usage of small amounts of solvent is of course also mostly desired from environmental and economical considerations. We believe, that the fact that this pattern was observed in our studies might suggest that using minute amounts of the appropriate solvent is advantageous in general.

## Experimental section

*Caution: These experiments should only be performed by trained personnel using applicable safety procedures.*

**Materials and chemicals**. HD labeled with $^{13}C$ (HD*) was prepared (>99% purity) according to a literature procedure.[35] The $^{13}C$ label was distributed evenly among the carbons. KF (≥99%), $Al_2O_3$ (activated, neutral, 150 mesh 58Å), Methanol (HPLC grade), Heptane (HPLC grade) and acetonitrile (HPLC grade) were purchased from commercial suppliers. Deionized water was obtained from a laboratory water purification system. RP-KF/$Al_2O_3$ (regular preparation) and ECUF/KF/$Al_2O_3$ (Enriched with Coordinatively Unsaturated Fluoride) powders were prepared as previously described.[20,23]

**Preparation of powders wetted with 10% solvent:** Dry powders (0.45 g) were placed in glass vials and solvents (0.05 g) were added on top. The mixtures were vortexed and ground thoroughly, using a glass rod, until homogenous powders were obtained (typically two or three cycles).

**Preparation of powder wetted with 90% solvent:** dry powder, 0.03g, were placed in Teflon NMR tubes, and 0.27 g of solvent (which contained 1.2 µl of HD) was added.

**Sample preparation.** Samples of the appropriate powders (40 mg) were added to the 0.4 cm $ZrO_2$ rotor and 1.6 µL HD, 5 wt %, were applied via syringe to the center of the sample. The rotor was then sealed with a fitted Kel-F cap. For the 90 wt %: 1.2 µl of HD was added to the solvent as described above. For the 100 % methanol (control experiment): 1.2 µl of HD was added to 340 µL of methanol and the mixture was placed in a Teflon NMR tube.

**Kinetic studies using MAS NMR:** To obtain clear NMR data, $^{13}$C-labeled HD (HD*) was used. $^{13}$C spectra were obtained at 125 MHz on a 11.7 T (500 MHz) spectrometer, equipped with a 0.4 cm standard CP-MAS probe, using direct polarization (i.e., no cross polarization (CP) was used). Typical spinning rates were 5 kHz. Chemical shifts for $^{13}$C were referenced to external TMS as 0.0 ppm. The number of transients per spectrum varied between 100 and 2000. For comparison purposes, spectra were recorded under identical conditions. Spectra were measured periodically to determine remaining starting material and identify degradation products. In all cases, the reactions profiles fitted a pseudo-first-order seemingly due to the large excess of hydroxide or fluoride ions and a rate-determining step, such as diffusion of the reactants.

## Supporting Information

NMR spectra and kinetic profiles of all reactions. The supporting information is available free of charge on the ACS Publications website at DOI.

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## Notes

The authors declare no competing financial interest.

## Acknowledgments

This work was internally funded by the Israeli Prime Minister's office.

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34. Products **7** and **8** were identified by NMR (Figure S2 in the supporting information), albeit the methyl ether peak originating from methanol was not conclusively

observed, as the methanol was not $^{13}$C labeled. Product's **8** identity was further verified using GC-MS, $(M+H)^+$, 152.

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