

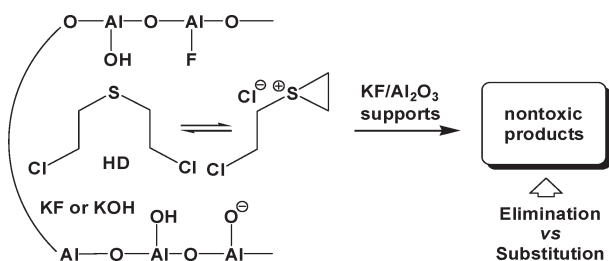
Degradation of Sulfur Mustard on KF/Al₂O₃ Supports: Insights into the Products and the Reactions Mechanisms

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Received August 6, 2009



The degradation of the warfare agent sulfur mustard (HD) adsorbed onto KF/Al₂O₃ sorbents is described. These processes were explored by MAS NMR, using ¹³C-labeled sulfur mustard (HD*) and LC-MS techniques. Our study on the detoxification of this blister agent showed the formation of nontoxic substitution and less-toxic elimination products (*t*_{1/2} = 3.5–355 h). Interestingly, the reaction rates were found to be affected by MAS conditions, i.e., by a centrifugation effect. The products and the mechanisms of these processes are discussed.

Detoxification of the chemical warfare agent (CWA) HD (sulfur mustard) is a current concern. Its copious chemistry, which includes some elementary processes such as nucleophilic displacements, eliminations, and oxidations, depends on the specific reaction conditions.¹ In spite of its high reactivity, which is largely attributed to the anchimerically assisted leaving groups, HD exhibits enhanced environmental stability (in neutral pH) because of its tendency to equilibrate with the corresponding toxic sulfonium products, such as CH-TG ((HOCH₂CH₂)₂S⁺CH₂CH₂SCH₂CH₂OH).¹ Rapid decontamination of this environmentally persistent² blister

agent from diverse surfaces is required in order to regain use of the affected area and equipment. The use of reactive sorbents that chemically destroy CWAs, rather than physically removing them, is an attractive approach to solve this problem.³ Oxidation-based decontamination of HD would form the relatively toxic products bis-2-chloroethyl sulfoxide and sulfone^{2,4} (even though they possess reduced volatility and improved water solubility). Therefore, hydrolysis processes, which lead to nontoxic products, are favored.

Recently, we reported the facile hydrolysis-based detoxification of the CWAs VX (*O*-ethyl *S*-2-(diisopropylamino)-ethyl methylphosphonothioate), GB (*O*-isopropyl methylphosphonofluoridate or sarin), and HD upon reaction with various solid-supported fluoride reagents such as KF/Al₂O₃, AgF/KF/Al₂O₃, and KF/Al₂O₃ enriched by so-called coordinatively unsaturated fluoride ions (ECUF-KF/Al₂O₃).^{3b} The difference between ECUF-KF/Al₂O₃ (prepared in dry methanol or ethanol) and regular KF/Al₂O₃ (prepared in water) is that the former contains large amounts of “free” fluoride ions, which may react as a base, while the latter sorbent mainly contains K₃AlF₆ (nonreactive) and KOH, as previously observed by ¹⁹F SS MAS NMR.^{3b} The research was focused on solvent-free degradations of the nerve agents VX and GB, which were effectively monitored and studied by a real-time solid-state magic angle spinning (SS MAS) ³¹P NMR. The reactions of HD with these active sorbents were also preliminarily investigated. It was found that HD (ca. 6.5 wt %) reacts with wetted (5% H₂O) KF/Al₂O₃ (20, H₂O, 160)⁵ or KF/Al₂O₃ (20, MeOH, 160) (defined as ECUF-KF/Al₂O₃) to form several products. The products were identified by ¹³C-MAS NMR as 2-chloroethyl vinyl sulfide (CEVS), divinyl sulfide (DVS), 2-hydroxyethyl vinyl sulfide (HOEVS), thiodiglycol (TDG), and 1,4-thioxane. These reactions were performed with unlabeled HD, resulting in low sensitivity and requiring long acquisition times for ¹³C NMR measurements, which prevent kinetics measurements and mechanistic study. To extend our insights into this process, such as, for instance, studying its products, kinetics, and mechanism as a function of the water, metal ion, and HD content or to examine the possibility of a centrifugation effect,⁶ further investigation with ¹³C-labeled mustard (HD*) was required. Herein, we wish to disclose our results on the degradation of HD* adsorbed onto alumina supported fluoride reagents with regard to all of the above-mentioned chemical applications and mechanistic aspects.

In the present study, two types of alumina-supported fluoride reagents, i.e., KF/Al₂O₃ (20, H₂O, 160) and KF/Al₂O₃

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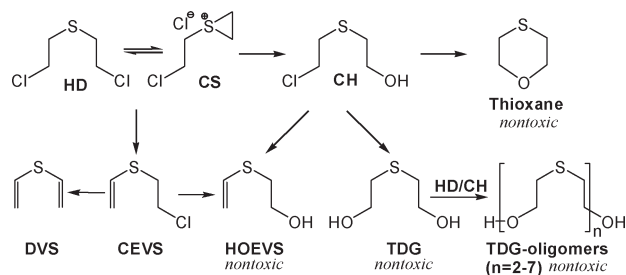
(4) Yang, Y.-C.; Baker, J. A.; Ward, R. *Chem. Rev.* **1992**, *92*, 1729.

(5) The expression KF/Al₂O₃ (20, H₂O, 160) refers to KF/Al₂O₃ that contains 20 wt % of KF, prepared in water, and finally dried overnight at 160 °C. See also ref 3b.

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SCHEME 1. Degradation Pathways for HD on KF/Al₂O₃ Sorbents


(20, EtOH, 160), were tested as simple reactive sorbents for the chemical destruction of HD. In a typical experiment, appropriate amounts of HD* were carefully added to the examined powder (ca. 100 mg, dry or wetted with 5% water, placed in the NMR rotor) without mixing or crushing. In most cases, the ¹³C MAS NMR spectra of the final reaction mixture revealed a somewhat complicated mixture of vinylic (CEVS, HOEVS, DVS), TDG, TDG-oligomers, and thioxane products, that were obtained in various ratios, depending on the sorbent and the reaction conditions used (Scheme 1). The identification of these products was based on both ¹³C SS MAS NMR and LC-MS methods (vide infra). The use of HD* enabled us to examine its degradation process even at the relatively low concentration of 1 wt %, which is somewhat more indicative for the real decontamination scenario (100:1 proportion of decontaminant/CWA).

As in other previous studies,³ the profiles of the HD* degradation processes were found to be compatible with a pseudo-first-order reaction (correlation coefficients R^2 ranged between 0.98 and 0.99) as shown in Figure 1, as well as Figures S3–S12 in the Supporting Information.

The results of the real time kinetics are summarized in Table 1. Inspection of the data revealed that both KF/Al₂O₃ (20, H₂O, 160) and KF/Al₂O₃ (20, EtOH, 160) supports react with HD* at ambient conditions. In our previous study on the reactions of VX (5 wt %) with the same solid supports, we found that the latter (a type of ECUF-KF/Al₂O₃) sorbent is more effective.^{3b} The present work shows that this phenomena is also relevant for the reactions of HD* with the above-mentioned wetted supports. Thus, the degradation rate of 6.5 wt % HD* onto wetted KF/Al₂O₃ (20, H₂O, 160) is 2-fold slower than that onto wetted KF/Al₂O₃ (20, EtOH, 160) (Table 1, runs 2 and 5). We assume that the difference in final products identity and distribution may be attributed to a competition between substitution versus elimination processes, that is strongly dependent on the reaction conditions and the sorbent type used (vide infra). In addition to the above-mentioned chemical difference, we found that these two active sorbents differ in other features, such as surface area and basicity value (Table 2). As previously reported, the impregnation of KF on alumina sorbent mostly caused a decrease in its surface area (especially with high loading

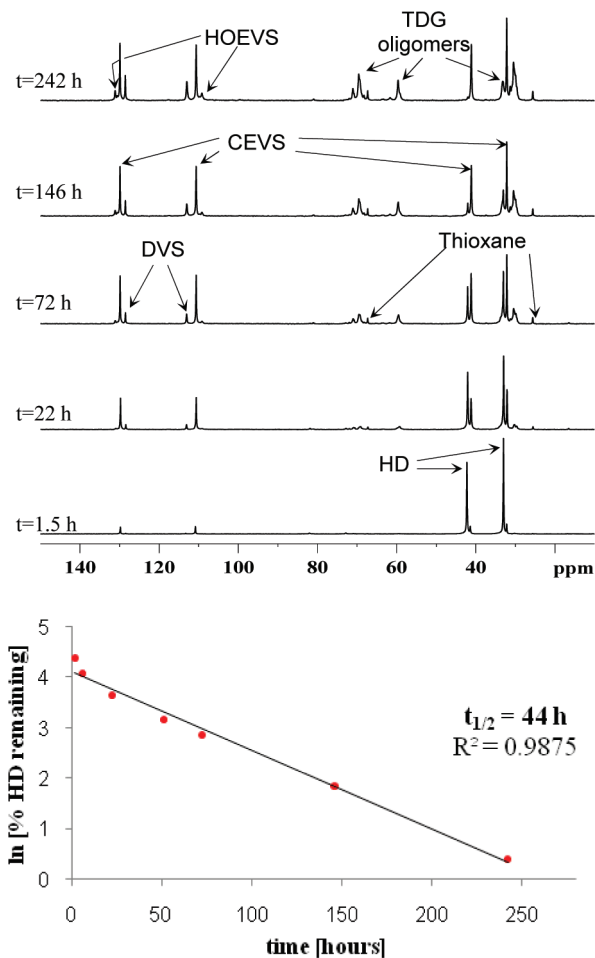


FIGURE 1. Selected ¹³C MAS NMR spectra of adsorbed HD* (6.5 wt %) on wetted KF/Al₂O₃ (20, EtOH, 160) and its degradation profile onto this sorbent.

of KF) together with a significant increase in its basicity.⁷ As is clearly shown by Table 2, the original surface area of neutral alumina was decreased to a lesser extent in ECUF-KF/Al₂O₃ supports in comparison to regular KF/Al₂O₃. The formation of K₃AlF₆ and KOH in the latter may block many of the available active sites and chemically destroy the surface area of the alumina. These compounds are barely formed when the solid support is prepared in EtOH,^{3b} and therefore, the surface area of the resulting ECUF-KF/Al₂O₃ is larger. In addition, the latter possess basicity strength similar to that of regular KF/Al₂O₃.

Consistent with our previous study on the reactions between VX and KF/Al₂O₃,^{3b} the reaction of HD* with these sorbents was found to be strongly dependent on their water content. That is, the reaction rates were slowed by either a lack (0%) or an excess (10%) of water added to both types of KF/Al₂O₃ powders prior to the addition of 6.5 wt % HD (Table 1, runs 1, 3 and 4, 6). This effect is attributed to the ability of water molecules to block the active sites of the solid catalyst or to enhance its hydrophilicity, and consequently to slow down the diffusion of HD. Even so, in dry conditions, there is no substantial difference between the two sorbents, both acting very slowly (runs 1 and 4). This observation implies that the relatively rapid degradations are largely assisted by water molecules. Interestingly, the

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TABLE 1. Degradation Rates and Products of HD* Adsorbed on Alumina-Based Powders

run	KF/Al ₂ O ₃	HD (wt %)	H ₂ O (wt %)	t _{1/2} ^a (h)	products (%) distribution ^b
1	(20, H ₂ O, 160)	6.5	0	355	14, 60, 6, 0, 20
2	(20, H ₂ O, 160)	6.5	5	87.0	5, 18, 4, 71, 3
3	(20, H ₂ O, 160)	6.5	10	138	2, 8, 8, 80, 2
4	(20, EtOH, 160)	6.5	0	319	9, 5, 9, 74, 3
5	(20, EtOH, 160)	6.5	5	44.4	8, 32, 7, 51, 2
6	(20, EtOH, 160)	6.5	10	224	1, 10, 8, 80, 1
7	(20, EtOH, 160)	1	0	22.6	7, 4, 7, 70, 12
8	(20, EtOH, 160)	1	5	3.5	28, 14, 7, 48, 3
9	(40, H ₂ O, 160)	6.5	5	59.7	36, 53, 1, 8, 2
10	(40, EtOH, 160)	6.5	5	29.0	30, 53, 2, 12, 3
11	neutral Al ₂ O ₃	6.5	0	nr	
12	neutral Al ₂ O ₃	6.5	5	315 ^d	sulfonium salts

^aHalf life times of pseudo-first-order reaction. ^bProducts distribution for DVS, CEVS (eventually degraded to DVS final product), HOEVS elimination products (in bold) and TDG-oligomers ($n = 1-7$) and thioxane, respectively. ^cBound TDG. ^dThis is the second and steady state t_{1/2} observed by the reaction profile of this reaction.

TABLE 2. Physical/Chemical Properties of the Alumina Powders

KF/Al ₂ O ₃	surface area (m ² /g) ^a	pH ^b	fluoride group	¹⁹ F MAS NMR (ppm) ^c
neutral Al ₂ O ₃	148.7	8.4		
(20, EtOH, 160)	100.7	10.6	F ⁻	-132
(20, H ₂ O, 160)	57.7	10.9	K ₃ AlF ₆	-158
(40, EtOH, 160)	72.5	11.4	F ⁻	-132
(40, H ₂ O, 160)	10.9	11.8	K ₃ AlF ₆	-158

^aMultipoint surface areas measured by BET technique. ^bMeasured as a slurry of 0.5 g of powder in 10 mL of double distilled water. ^cChemical shifts of fluoride groups of the dry powders (see also ref^{3b}).

reaction of HD* with dry KF/Al₂O₃ (20, EtOH, 160) resulted in bound TDG as a major product, as can be shown by its exceptionally broad signals in the NMR spectrum, which are attributed to its immobility feature (Table 1, runs 4 and 7 and Figures S7 and S9 in the Supporting Information). This product implies that the dominant active group in dry KF/Al₂O₃ (20, EtOH, 160) is the [Al-O⁻], which directly reacts with the chloromethylene functions of HD (vide infra). On the other hand, the reaction of HD* (6.5 wt %) with dry KF/Al₂O₃ (20, H₂O, 160) gave the appropriate vinylic sulfides as major products together with thioxane (run 1). The dominant active group in this regular KF/Al₂O₃ is [OH⁻],⁷ which reacts as a strong base in a dehydrochlorination process.

The reaction studies indicate that 40% KF loading (compared to 20%) results in slightly faster rates with both regular- and ECUF-KF/Al₂O₃, but with a higher percentage of vinylic products (runs 9 and 10). In addition, the reactions of 1 wt % of HD*, with both dried and wetted KF/Al₂O₃ (20, EtOH, 160), are considerably faster than those of 6.5 wt % (runs 4, 5 and 7, 8). These results are in agreement with the fact that the reaction rate is diffusion dependent, and may be explained by a faster dispersion of the reactant toward the active sites when the bulk of the drop is smaller.^{3a}

When compared to neutral alumina,⁸ these results are impressive in terms of both products and kinetics (runs 11 and 12). Thus, adsorption of HD* onto the surface of dry neutral alumina did not yield any products, but did strongly physisorb to the support, according to the signal broadening

(8) Taking into account that commercial neutral alumina powders may differ from batch to batch, we used a sample of alumina that was dried at the same condition (160 °C, overnight) for all experiments.

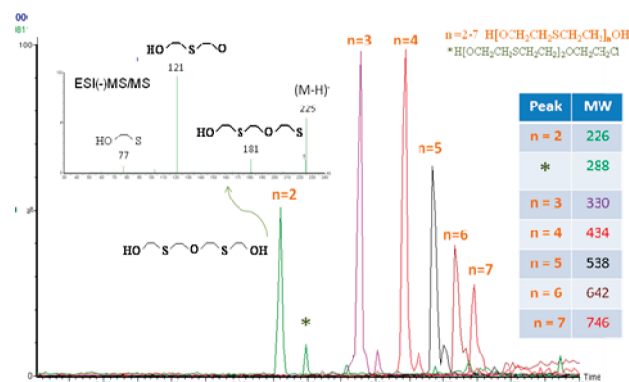


FIGURE 2. Overlaid LC-ESI(-)/RSIM-MS scan chromatograms of TDG-oligomers ($n = 2-7$) and daughter scan spectrum of the dimer ($n = 2$, an example for structure elucidation).

in the NMR spectrum. On the other hand, the reaction of HD* with wetted (5 wt %) neutral alumina mainly produced the toxic sulfonium salts CH-TG and H-2TG,^{1,9,10} resulting from a nucleophilic attack on HD or CH intermediate by TDG (see Figure S12, Supporting Information).

In view of the complexity of the products mixture obtained from the above-mentioned processes, especially those that were derived from TDG, we decided to confirm their identity by LC-MS methods. To obtain simpler LC-MS data for structure elucidation, unlabeled HD was reacted with wetted KF/Al₂O₃ (20, EtOH, 160), and the products mixture was extracted by chloroform. In this analysis, TDG was detected by LC-MS, using positive ESI. The mass spectrum exhibited low intensity peaks corresponding to TDG ions at m/z 123 ($M + H$)⁺ and 145 ($M + Na$)⁺ and a significant fragment ion at m/z 105 due to loss of H₂O. This identification was confirmed by comparative analysis of a reference material. TDG-oligomers ($n = 2-7$) were detected by LC-MS, using negative ESI (Figure 2). They eluted from the LC column consecutively as expected from their increasing hydrophobicity. The dimer, the most polar oligomer, eluted after 7 min while the heptamer eluted after 13 min. Their mass spectra contained only the ($M - H$)⁻ ions with the expected isotopic ratios typical for sulfur-containing compounds. Structure elucidations of these compounds were performed following MS-MS experiments, where typical sequential losses of -18 (-H₂O), -44 (-CH₂CH₂O), -60 (-CH₂CH₂S), -62 (-CH₂CH₂O-H₂O), and -104 (-OCH₂CH₂S-CH₂CH₂) were observed.

In light of these results, the significant variety in the observed products leads to the conclusion that the degradation of HD onto the surface of alumina-supported fluoride sorbents may proceed by few plausible mechanisms, as shown in Figure 3. Clearly, it is influenced by the chemical differences between the above-mentioned four possible active sorbents, i. e., wetted vs. dried and regular- vs. ECUF-KF/Al₂O₃. It seems that the nature of the final products is strongly dependent on the water content of the sorbents, which determines the competition between the substitution vs. elimination processes. The substitution processes may be carried out by an S_N1-type mechanism that occurs via a CS (cyclic sulfonium)

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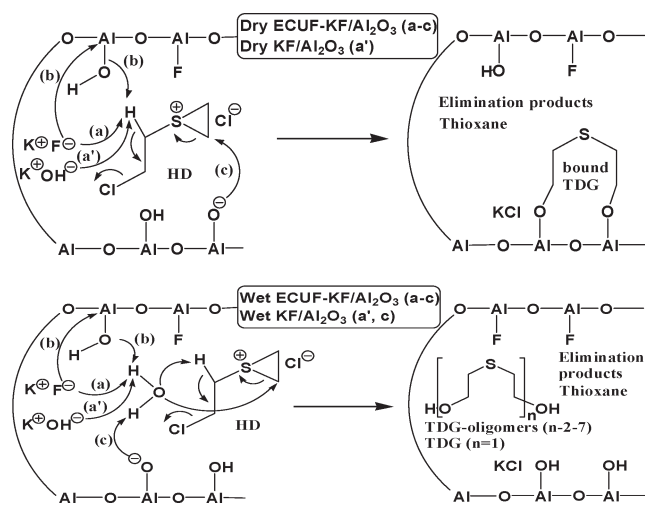


FIGURE 3. Proposed mechanisms of the degradation of HD onto the surface of regular- and ECUF-KF/Al₂O₃.

intermediate,¹¹ which is solvated and stabilized by water (strong ionization power). The elimination process probably proceeds by both E1- and E2-type mechanisms via CS or neutral HD starting material. The presence of water encourages the formation of CS, and therefore, the major products in the wetted sorbents, both regular and ECUF-KF/Al₂O₃, are TDG and TDG-oligomers, which originate from nucleophilic substitutions. On the other hand, in the absence of water, the dominant equilibrium form is that of the neutral HD, but not a solvated CS, and therefore, the major products in its reaction with regular KF/Al₂O₃ (enriched with the relatively strong base, KOH) are vinylic sulfides, via an E2 pathway. On dry ECUF-KF/Al₂O₃ the major product is bound-TDG obtained through a substitution of chloride by Al-O⁻ (a relatively weak base). This substitution, as expected, is much slower than its S_N1 counterpart, in which CS acts as an active intermediate. The fact that adsorption of HD onto the surface of both wetted KF/Al₂O₃ (40, H₂O, 160) and KF/Al₂O₃ (40, EtOH, 160) leads to vinylic sulfides as major products may be attributed to the high loading (40%) of KOH or KF, respectively, which are highly solvated by water molecules, therefore consuming the water available for CS solvation.

Recently, we reported that solid supported reaction rates, measured by SS MAS NMR, may be affected by a centrifugation effect (or possibly by a heat friction) caused by the high spinning rate of the sample (ca. 5–8 kHz).⁶ This effect is attributed to the fact that in such processes the diffusion of reactants toward the active sites of the solid support plays a significant role in the reaction kinetics. In the context of decontamination it is important to know whether the real time reaction rates onto KF/Al₂O₃ measurements are affected by MAS. It was found that in contrast to the case with VX, which reacts with similar rates with and without spinning,^{3b} the degradation kinetics of HD were indeed affected (ca. 3-fold faster) by the high spinning rate during the measurement (Figure 4). To examine this effect, we performed an experiment

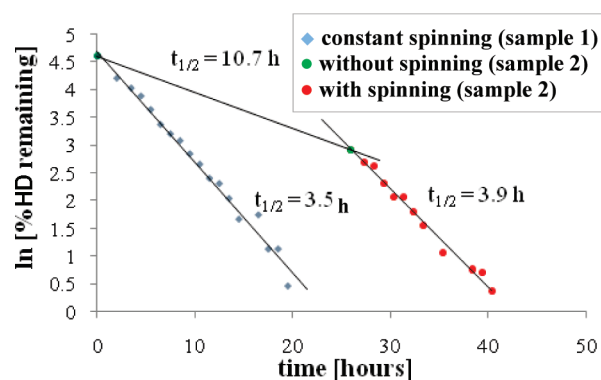


FIGURE 4. A centrifugation effect on degradation rates of HD* (1 wt %) onto the surface of wetted (5%) KF/Al₂O₃ (20, EtOH, 160).

in which the reaction rates were tested onto a sample of wetted (5%) KF/Al₂O₃ (20, EtOH, 160) under MAS NMR conditions (5 kHz) and onto another duplicate sample that was left aside (samples 1 and 2, respectively). Once the concentration of HD of the first sample was totally decayed under spinning conditions, the second duplicate sample was subjected to MAS NMR measurement. The reaction rate continuously measured by MAS NMR was found to be higher than its still counterpart. Thus, the degradation rates of HD by KF/Al₂O₃ measured by the MAS NMR technique are not the intrinsic rates, and the contribution of the spinning should be taken into account when comparing sets of data. It seems that this effect is correlated to the relationship between the hydrophilicity/hydrophobicity of both reactant and sorbent. Namely, in reactions occurring between hydrophobic reactants and inorganic solids, in which the repulsive interactions are dominant, the spinning effect would be more significant.

In conclusion, this work shed light on the products and the mechanisms of the degradation of HD adsorbed onto KF/Al₂O₃, using ¹³C-labeled HD and both SS MAS NMR and LC-MS techniques. The significant variety in the observed nontoxic products (schematically divided into elimination and substitution products) stems from the chemical differences between the possibilities of wetted versus dried and regular- versus ECUF-KF/Al₂O₃. The fact that the degradation rate of HD onto the wetted KF/Al₂O₃ (20, EtOH, 160) sorbent was affected by the high spinning rate of the sample (a centrifugation effect), contrary to VX, should be considered in every study related to this topic. This phenomenon is now specifically under further extensive study.

Experimental section

Sample Preparation. *Caution:* These experiments should only be performed by trained personnel, using applicable safety procedures. Samples of the appropriate powder (ca. 100 mg) were added to the 0.4 cm ZrO₂ rotor. A 0.8–5 μL sample of HD* was applied via a 5 μL syringe to the center of the sample. The rotor was sealed with a fitted Kel-F cap. ¹³C MAS NMR spectra were measured periodically to determine the remaining starting material and identify degradation products.

Supporting Information Available: General experimental details and Figures S3–S12 giving ¹³C MAS NMR spectra and reaction profiles of adsorbed HD* onto selected KF/Al₂O₃ powders. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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