High-Yield, Radical-Initiated Oxidative Functionalization of Ethane by Perfluorocarboxylic Acid Anhydrides. Role of Metal Ions in Catalytic Alkane Oxidations in the Presence of Perfluorocarboxylic Acid Anhydrides

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Abstract: Hydrogen peroxide and a trace of either ethene or propene initiated the conversion of ethane to propionic acid and its mixed anhydride ($CH_3CH_2CO_2H$ + $CH_3CH_2COOCOCF_3$) and trifluoromethyl ethyl ketone, $CH_3CH_2COCF_3$, by trifluoroacetic anhydride at 80 °C. For a fixed amount of H_2O_2, the amount of products formed increased with increasing amount of trifluoroacetic anhydride employed and was always higher than the amount of H_2O_2 added. These products were also obtained when H_2O_2 was replaced by other radical initiators: *m*-chloroperbenzoic acid, azobisisobutyronitrile, and $PbEt_4$. With $PbEt_4$, ethene or propene was not required for product formation and close to 500 equiv of products was formed for every equivalent of $PbEt_4$ employed! Longer chain perfluorocarboxylic acid anhydrides reacted analogously; however, as the R_f group increased in length, a corresponding increase in mixed anhydride to ketone selectivity was observed. Methane gave very little product under the reaction conditions whereas propane underwent simple stoichiometric oxidation to 2-propanol and acetone by H_2O_2. The addition of $(CF_3CO_2)_2Pd$ to the ethane reaction resulted in simple oxidation to ethanol and acetaldehyde in amounts lower than that corresponding to the H_2O_2 present. In complete contrast to the ethane reaction, the yield of products from methane increased significantly (although less than the H_2O_2 added) upon the addition of $(CF_3CO_2)_2Pd$, with methanol being the principal product.

The selective oxidative functionalization of primary C−H bonds of alkanes in solution under mild conditions continues to be a challenging problem.[1] Herein we report the very surprising radical-initiated conversion of ethane to, principally, propionic acid by perfluorocarboxylic acid anhydrides. An interesting feature of the reaction is that because of the nature of the steps involved, much higher conversion was observed for ethane than propane despite the presence of weaker secondary C−H bonds in the latter. It is also worth noting that while several groups have reported the metal-mediated functionalization of alkanes in trifluoroacetic acid and/or trifluoroacetic anhydride,[2] the ability of the solvent system to act as an oxidant for alkanes has never been suspected.

A second aspect of this system which merits comment is the ease with which the perfluoroalkyl radical was formed from perfluorocarboxylic acid anhydrides. Hitherto, the generation of perfluoroalkyl radicals generally necessitated the use of either ultraviolet light or high temperatures (>250 °C).[3] The current system operates at 80 °C and requires only a source of alkyl radicals and a perfluorocarboxylic acid anhydride.

Results and Discussion

In a typical reaction (reaction 1), 0.2 mL of 30% (w/w) aqueous H_2O_2 (1.8 mmol of H_2O_2) was dissolved in 3.0 mL (21.2 mmol) of $(CF_3CO)_2O$ (note that excess $(CF_3CO)_2O$ remained after mixing). The mixture was then exposed to 500 psi of C_2H_6 containing 1600 ppm of ethene and 500 psi of N_2, and heated at 75−80 °C for 1 d. At the end of this period, the products identified by ^{1}H- and ^{13}C-NMR spectroscopy (and confirmed by GC/MS and/or by comparison with authentic samples) were propionic acid and the mixed anhydride, $CH_3CH_2CO_2H$ + $CH_3CH_2COOCOCF_3$, **1** (1.85 mmol); the mixed ketone trifluoromethyl ethyl ketone, $CH_3CH_2COCF_3$, **2** (0.68 mmol); ethanol and its derivative, C_2H_5OH + $C_2H_5O_2$-CCF_3 (0.06 mmol); acetaldehyde and its derivative, CH_3CHO + $CH_3CH(O_2CCF_3)_2$ (0.09 mmol); and acetic acid and its derivative, CH_3CO_2H + $CH_3COOCOCF_3$ (0.31 mmol). GC/MS of the solution revealed the additional presence of CF_3-CO_2CF_3 and CF_3H. CF_3H and a small amount of CO_2 were found in the gas phase. Most noteworthy is that the total amount of ethane functionalized significantly *exceeded* the H_2O_2 and alkene originally present. Additionally, with the *same* amount of added H_2O_2, the amounts of **1** and **2** (but *not* the simple

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(1) General reviews on the problem of C−H activation and functionalization in solution: Olah, G. A.; Molnár, A. *Hydrocarbon Chemistry*; Wiley: New York, 1995. (b) Crabtree, R. H. *Chem. Rev.* **1995,** *95,* 987. (c) Crabtree, R. H. *Chem. Rev.* **1985,** *85,* 245. (d) Arndtsen, B. A.; Bergman, R. G.; Mobley, T. A.; Peterson, T. H. *Acc. Chem. Res.* **1995,** *28,* 154. (e) Labinger, J. A. *Fuel Process. Technol.* **1995,** *42,* 325. (f) *Selective Hydrocarbon Oxidation and Functionalization*; Davies, J. A., Watson, P. L., Greenberg, A., Liebman, J. F., Eds.; VCH: New York, 1990. (g) *Activation and Functionalization of Alkanes*; Hill, C. L., Ed.; Wiley: New York, 1989. (h) Shilov, A. E. *Activation of Saturated Hydrocarbons by Transition Metal Complexes*; D. Reidel: Dordrecht, The Netherlands, 1984.

(2) (a) Sen, A. *Platinum Metals Rev.* **1991,** *35,* 126. (b) Kao, L.-C.; Hutson, A. C.; Sen, A. *J. Am. Chem. Soc.* **1991,** *113,* 700. (c) Kao, L.-C.; Sen, A. *New J. Chem.* **1991,** *15,* 575. (d) Vargaftik, M. N.; Stolarov, I. P.; Moiseev, I. I. *J. Chem. Soc., Chem. Commun.* **1990,** 1049. (e) Nakata, K.; Yamaoka, Y.; Miyata, T.; Taniguchi, Y.; Takaki, K.; Y. Fujiwara, Y. *J. Organomet. Chem.* **1994,** *473,* 329. (f) Nakata, K.; Miyata, T.; Jintoku, T.; A. Kitani, A.; Taniguchi, Y.; Takaki, K.; Fujiwara, Y. *Bull. Chem. Soc. Jpn.* **1993,** *66,* 3755. (g) Yamanaka, I.; Soma, M.; Otsuka, K. *Chem. Lett.* **1996,** 565. (h) Nomura, K.; Uemura, S. *J. Chem. Soc., Chem. Commun.* **1994,** 129.

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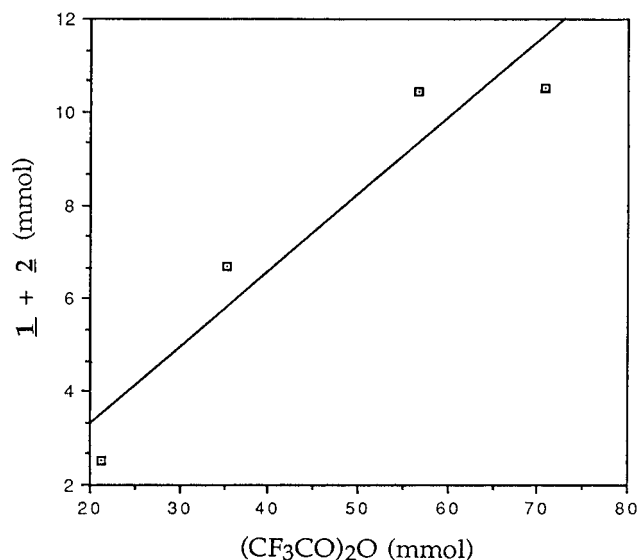
Oxidative Functionalization of Ethane

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Figure 1. Sum of the amounts of $CH_3CH_2CO_2H$ + derivative, **1**, and $CH_3CH_2COCF_3$, **2**, formed as a function of the amount of $(CF_3CO)_2O$ present in the reaction mixture. Reaction conditions: H_2O_2 (1.8 mmol); $(CF_3CO)_2O$; C_2H_6 containing 1600 ppm of C_2H_4, 500 psi; N_2, 500 psi; 80 °C, 1 d.

A	- Capillary (DMSO/D_2O)
B	- $CH_3CH_2COOCOCF_3$
C	- $CH_3CH_2COCF_3$
D	- CH_3CHO + Derivatives
E	- CH_3CH_3

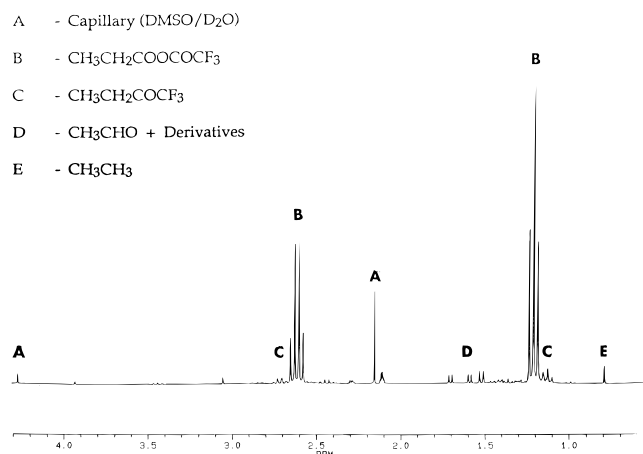**Figure 2.** ^{1}H-NMR spectrum obtained after the following reaction conditions: 0.2 mL of 30% (w/w) aqueous H_2O_2; 24 mL of $(CF_3CO)_2O$; C_2H_6 containing 1600 ppm of C_2H_4, 100 psi, N_2, 900 psi; 80 °C, 1d.

oxidation products) formed *increased* with *increasing* amount of $(CF_3CO)_2O$ (Figure 1)! For example, when 10.0 mL (70.7 mmol) of $(CF_3CO)_2O$ was used in reaction 1, 8.06 mmol of $CH_3CH_2COOCOCF_3$, **1**, and 2.45 mmol of $CH_3CH_2COCF_3$, **2**, were formed. Figure 2 shows an NMR spectrum obtained with an even higher amount of $(CF_3CO)_2O$ (24 mL, 169.7 mmol). Significantly, in the absence of ethene (using 99.997% C_2H_6 in reaction 1) *only* simple oxidation products were formed: ethanol and ethyl trifluoroactetate, C_2H_5OH + $C_2H_5O_2CCF_3$ (0.35 mmol); acetaldehyde and its derivative, CH_3CHO + $CH_3CH(O_2CCF_3)_2$ (1.26 mmol); and acetic acid and its mixed anhydride, CH_3CO_2H + $CH_3COOCOCF_3$ (0.28 mmol). The addition of propene (0.08 mmol) to reaction 1 along with 99.997% C_2H_6 again formed **1** (2.48 mmol) and **2** (1.56 mmol). Interestingly, the product composition varied significantly with even small changes in propene concentration (Figure 3).

The products **1** and **2** were not formed in the presence of molecules capable of trapping alkyl radicals.[4] Thus, when either O_2 (100 psi) or I_2 (0.1 mmol) was added to reaction 1, only simple oxidation products of ethane, such as alcohol and aldehyde, were formed in yields *lower* than that corresponding
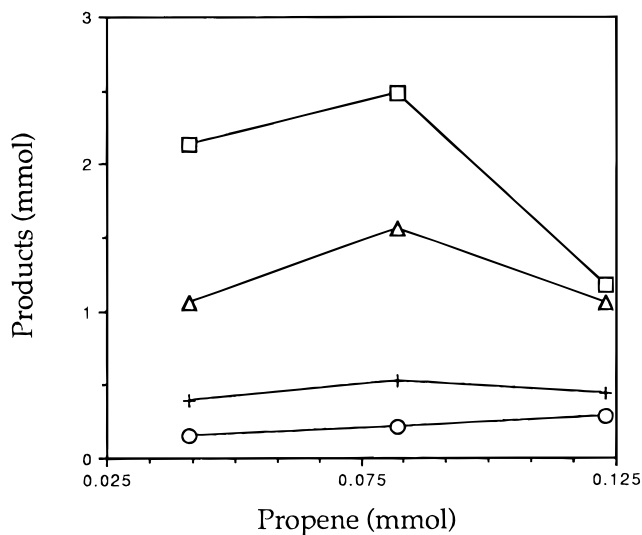

Figure 3. Amount of products formed versus amount of propene added. Reaction conditions: propene, 30% H_2O_2 (0.2 mL, 1.8 mmol); $(CF_3CO)_2O$ (5 mL, 35.3 mmol); C_2H_6, 500 psi; N_2, 500 psi; 80 °C, 1 d. Key: $CH_3CH_2CO_2H$ and derivative, (□); $CH_3CH_2COCF_3$, (△); CH_3CH_2OH and derivative, (○); CH_3CHO and $CH_3CH(O_2CCF_3)_2$ (+).

to the H_2O_2 present (O_2: $C_2H_5O_2CCF_3$ + C_2H_5OH (0.25 mmol), $CH_3CH(O_2CCF_3)_2$ + CH_3CHO (0.56 mmol); I_2: $C_2H_5O_2CCF_3$ + C_2H_5OH + C_2H_5I (0.70 mmol), $CH_3CH(O_2CCF_3)_2$ + CH_3CHO (0.23 mmol)).

Several other features of the reaction merit comment. First, the reaction was quite rapid. For example, while the reactions were routinely run for 1 d, running reaction 1 for only 1 h resulted in yields that were approximately half of that obtained normally. Second, the products **1** and **2**, were *only* formed when $(CF_3CO)_2O$ was present; the addition of H_2O_2 in amounts sufficient to convert all the $(CF_3CO)_2O$ to the acid resulted in the formation of only simple oxidation products of ethane,[5] principally CH_3CO_2H, in yields *lower* than that corresponding to the H_2O_2 present (Figure 4). Third, in order to establish the origin of the carbonyl group in products **1** and **2**, reaction 1 was rerun in the presence of ^{13}CO (100 psi). Two interesting observations were made: very little of **2** was formed and ^{13}CO was incorporated in only ~25% of the propionic acid derivative **1** formed (total yield, 1.12 mmol). While ^{13}CO is certainly capable of trapping an ethyl radical (cf. the rate constant in water for trapping of methyl radical:[6] 2×10^6 L mol^{-1} s^{-1} at 25 °C), its concentration in the reaction mixture was much lower than that of the solvent $(CF_3CO)_2O$. Therefore, it is not suprising that only 25% of the product is ^{13}C-labeled. Finally, in the absence of ethane, propionic acid itself was efficiently decarboxylated to an ethanol derivative. For example, when reaction 1 was rerun with 1.34 mmol of $CH_3CH_2CO_2H$ replacing ethane, 1.09 mmol of $C_2H_5O_2CCF_3$ + C_2H_5OH was formed in 24 h. The addition of 500 psi of CO to the reaction mixture had no effect on the rate of decarboxylation.

The products **1** and **2** were also formed when H_2O_2 was replaced with other radical initiators: *m*-chloroperbenzoic acid

(4) (a) Trapping of alkyl radicals with halogens: Poutsma, M. L. In *Free Radicals*; Kochi, J. K., Ed.; Wliey: New York, 1973; Vol. II, p 159. (b) Trapping of alkyl radicals with dioxygen: Howard, J. A. In *Free Radicals*; Kochi, J. K., Ed.; Wliey: New York, 1973; Vol. II, p 3.

(5) Uncatalyzed alkane oxidation by H_2O_2 in CF_3CO_2H: (a) Deno, N. C.; Jedziniak, E. J.; Messer, L. A.; Meyer, M. D.; Stroud, S. G.; Tomezsko, E. S. *Tetreahedron* **1977**, *33*, 2503. (b) Hamilton, G. A.; Giacin, J. R.; Hellman, T. M.; Snook, M. E.; Weller, J. W. *Ann. N.Y. Acad. Sci.* **1973**, *212*, 4.

(6) Bakac, A.; Espenson, J. H. *J. Chem. Soc., Chem. Commun.* **1991**, 1497.
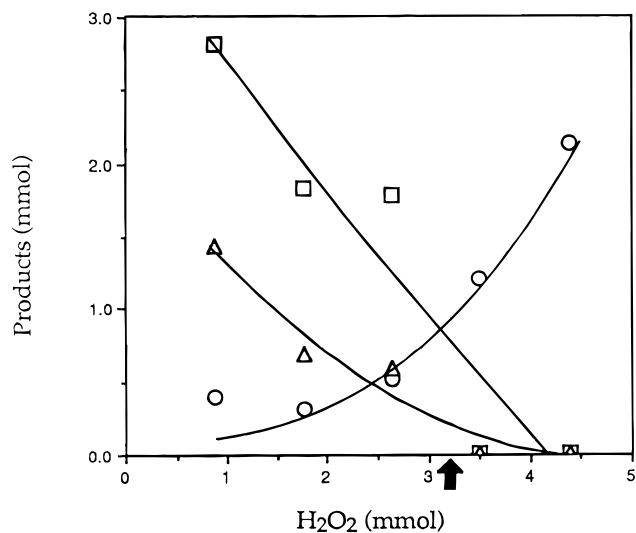
Figure 4. Amount of products formed versus amount of H_2O_2 added. Reaction conditions: H_2O_2; $(CF_3CO)_2O$ (3 mL, 21.2 mmol); C_2H_6 containing 1600 ppm of C_2H_4, 500 psi; N_2, 500 psi; 80 °C, 1 d. Key: $CH_3CH_2CO_2H$ and derivative, (□); $CH_3CH_2COCF_3$, (△); CH_3CO_2H and derivative, (○). The arrow represents the point where the amount of aqueous H_2O_2 added becomes sufficient to convert all the anhydride to the acid.

Table 1. Product Distributions Obtained Using Various Initiators (+ Ethene)[a]

initiator	amt (mmol)	amt of **1** (mmol)	amt of **2** (mmol)	amt of EtO_2CCF_3 (mmol)
H_2O_2[b]	1.80	1.85	0.68	0.33
m-CPBA[b]	1.80	0.76	0.56	0.01
AIBN[b]	0.29	0.32	0.12	0.32
$PbEt_4$	0.005	1.51	0.80	0.15

[a] Reaction conditions: 500 psi of C_2H_6; 500 psi of N_2; 3 mL of $(CF_3CO)_2O$; initiator; 90 °C, 1 d. [b] 1600 ppm of C_2H_4 was present in the C_2H_6 employed.

(*m*-CPBA), azobisisobutyronitrile (AIBN), and $PbEt_4$ (Table 1). With $PbEt_4$, an alkene (ethene or propene) was *not* required for product formation, and as Table 1 indicates, *close to 500 equivs of products were formed for every equivalent of $PbEt_4$ employed!* Furthermore, as with the H_2O_2/alkene-initiated reaction, for a fixed amount of added $PbEt_4$, the amounts of **1** and **2** (but not the simple oxidation products) formed increased with increasing amounts of $(CF_3CO)_2O$ (Figure 5).

Besides ethane, other alkanes were briefly investigated. Under typical reaction conditions (cf. reaction 1), methane (1000 psi, no N_2) was converted to $CH_3O_2CCF_3$ + CH_3OH in quite low yields (0.16 mmol) after 18 h. Propane (150 psi + 550 psi N_2) was converted to $(CH_3)_2CHO_2CCF_3$ + $(CH_3)_2CHOH$ (1.32 mmol) and CH_3COCH_3 (0.39 mmol) in 1 d; i.e., the reaction was a simple stoichiometric oxidation by the H_2O_2 (1.8 mmol used).

A working mechanism that is consistent with these observations is shown in Scheme 1. A primary alkyl radical is formed either directly (e.g., from $PbEt_4$) or by the addition of the initiating radical (e.g., $HO^\bullet$) to an alkene. This radical then abstracts a hydrogen from ethane to generate the $C_2H_5^\bullet$ radical which in turn attacks $(CF_3CO)_2O$ at the carbonyl carbon to form an alkoxy radical. The attack by the $C_2H_5^\bullet$ radical occurs at the most electron deficient site because of the alkyl radical's nucleophilic nature,[7] (for example, kinetic studies have shown that cyclohexyl radicals react 8500 times faster with acrolein

(7) Motherwell, W. B.; Crich, D. *Free Radical Chain Reactions in Organic Synthesis*; Academic Press: London, 1992; p 4.
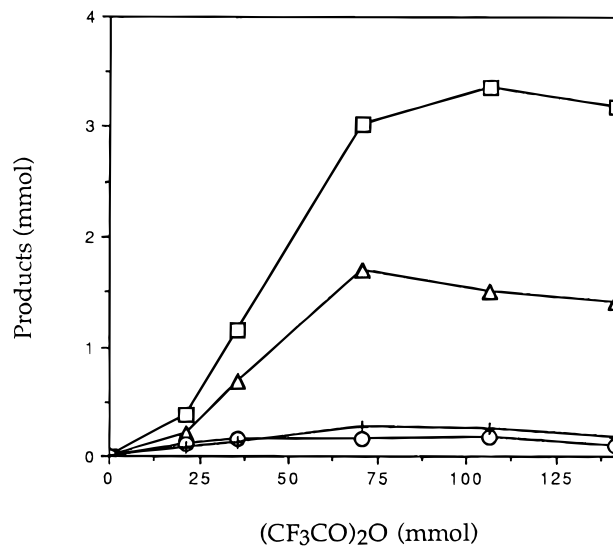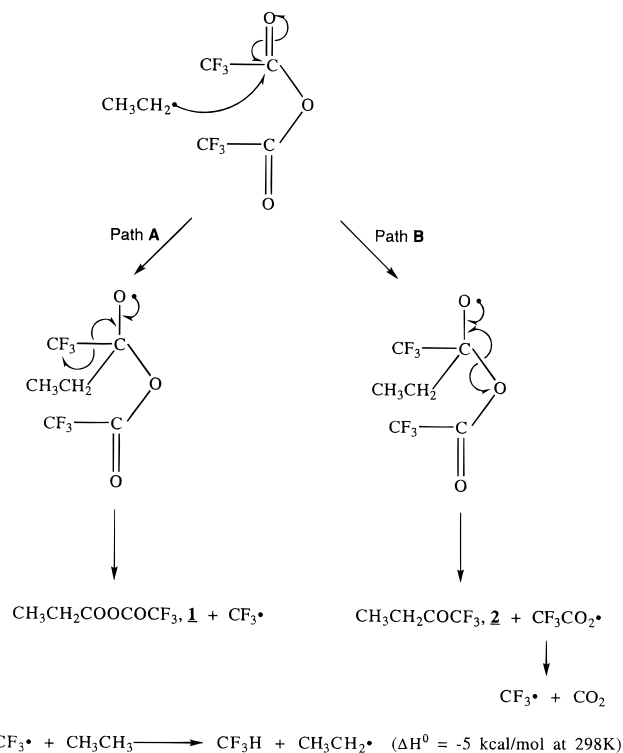

Figure 5. Amount of products formed as a function of the amount of $(CF_3CO)_2O$ present in the reaction mixture. Reaction conditions: $PbEt_4$ (1 µL, 0.005 mmol); $(CF_3CO)_2O$; C_2H_6, 500 psi; N_2, 500 psi; 80 °C, 1 d. Key: $CH_3CH_2CO_2H$ and derivative, (□); $CH_3CH_2COCF_3$, (△); CH_3CH_2OH and derivative, (○); CH_3CHO and $CH_3CH(O_2CCF_3)_2$ (+).

Scheme 1

than with 1-hexene[8]). The alkoxy radical formed undergoes the well-known β-bond cleavage reaction.[9] If the F_3C-C bond is cleaved, the product is **1** (path A). On the other hand, if the $C-O$ bond is broken, **2** is produced (path B). Both pathways produce the $CF_3^\bullet$ radical: path A directly, path B by formation and subsequent decarboxylation of the $CF_3CO_2^\bullet$ radical. The $CF_3^\bullet$ radical then continues the chain reaction by abstracting a

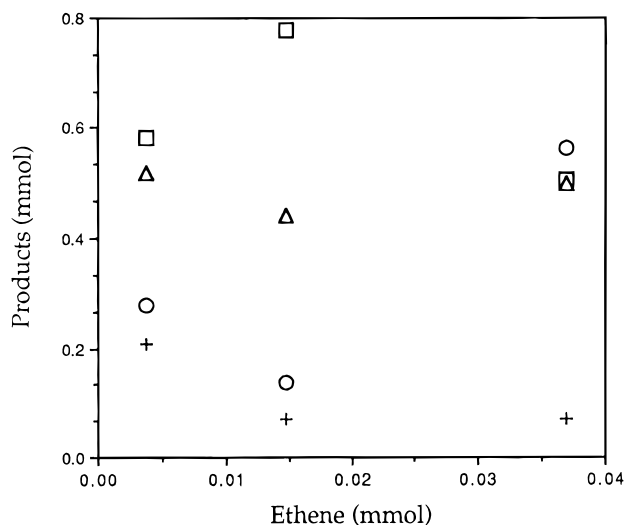(8) Giese, B.; Kretzschmar, G. *Chem. Ber.* **1983**, *116*, 3267.

Figure 6. Amount of products formed versus amout of ethene added. Reaction conditions: ethene; AIBN (10 mg, 0.07 mmol); $(CF_3CO)_2O$ (5 mL, 35.3 mmol); C_2H_6 containing 1600 ppm of C_2H_4, 500 psi; N_2, 500 psi; 80 °C, 1 d. Key: $CH_3CH_2CO_2H$ and derivative, (□); $CH_3CH_2COCF_3$, (△); CH_3CH_2OH and derivative, (○); CH_3CHO and $CH_3CH(O_2CCF_3)_2$ (+).

hydrogen from C_2H_6, forming the $C_2H_5^•$ radical and CF_3H. The direct initiation of the chain reaction by $CF_3^•$ may also occur following reaction of the radical derived from the initiator (+ alkene) with $(CF_3CO)_2O$.

The mechanism shown in Scheme 1 encompasses several key observations. First, the alkene's purpose was to generate a reactive primary alkyl radical. While addition to propene to form a secondary radical is favored thermodynamically, Hammond[10] has shown by ESR that both primary and secondary radicals are produced from the addition of $HO^•$ to propene. Only primary alkyl radicals are sufficiently reactive to attack ethane and/or $(CF_3CO)_2O$. This reasoning also explains why an alkene was not required when $PbEt_4$ was employed since it decomposes directly to a primary alkyl radical. Second, the carbonyl group was *directly* transferred from $(CF_3CO)_2O$ to the $C_2H_5^•$ radical, and free CO was not involved in a significant way. Third, secondary alkyl radicals, while formed more easily (e.g., from propane), were too stable to participate in the chain reaction and underwent simple stoichiometric oxidation by H_2O_2. On the other hand, the C–H bond of methane was too strong to undergo significant hydrogen atom abstraction (the reaction of $CF_3^•$ radical with CH_4 is, at best, thermoneutral) although $CH_3^•$, if formed, can in principle take part in the chain reaction.

An examination of the effect of ethene on the AIBN-initiated conversion of ethane by trifluoroacetic anhydride showed that, as with H_2O_2/propene (see Figure 3), the product concentration depended on the ethene concentration (Figure 6). The ethene concentration was determined for a solution of trifluoroacetic anhydride saturated with ethene, and aliquots of this solution were added to produce varying concentrations of ethene in the reaction mixture. Figures 3 and 6 are consistent with the hypothesis that the initiator and alkene were reacting to form an initiating species. Too much alkene would compete with ethane, with the products being derived preferentially from the former.

We have examined other carboxylic acid anhydrides for similar reactivity (Table 2). Acetic anhydride and trichloroacetic

Table 2. Effect of the Carboxylic Acid Anhydride Employed on Product Distribution[a]

anhydride	amt of EtC(O)OCOR$_f$ (mmol)	amt of EtCOR$_f$ (mmol)	amt of CH$_3$CHO (mmol)	amt of R$_f$CO$_2$Et (mmol)
$(CF_3CO)_2O$	1.15	0.69	0.13	0.16
$(CF_3CF_2CO)_2O$	2.97	0.22	0.31	0.33
$(CF_3CF_2CF_2CO)_2O$	3.59	–	0.13	0.24
$(CCl_3CO)_2O$	–	–	–	–
$(CH_3CO)_2O$	–	–	–	–

[a] Reaction conditions: $PbEt_4$, 0.005 mmol; anhydride, 5 mL; C_2H_6 (99.997%), 600 psi; N_2, 400 psi; 80–90 °C, 1 d.

anhydride failed to react. However, longer chain perfluorocarboxylic acid anhydrides did react to form $CH_3CH_2COOCOR_f$ and $CH_3CH_2COR_f$ ($R_f = CF_3$, CF_2CF_3, and $CF_2CF_2CF_3$). In a typical reaction, 1 μL of $PbEt_4$ (0.005 mmol) was dissolved in 3.0 mL (15.2 mmol) of $(CF_3CF_2CO)_2O$. The mixture was then exposed to 500 psi of 99.997% C_2H_6 and 500 psi of N_2 and heated at 75–80 °C for 1 d. The products, as detected by ^{1}H-NMR spectroscopy, included propionic acid and the mixed anhydride, $CH_3CH_2CO_2H$ + $CH_3CH_2COOCOCF_2CF_3$ (2.97 mmol); the mixed ketone trifluoromethyl ethyl ketone, $CH_3CH_2COCF_2CF_3$ (0.22 mmol); ethanol and its derivative, C_2H_5OH + $C_2H_5O_2CCF_2CF_3$ (0.33 mmol); acetaldehyde and its derivative, CH_3CHO + $CH_3CH(O_2CCF_2CF_3)_2$ (0.31 mmol); and pentafluoroethane, HCF_2CF_3 (0.10 mmol). As the R_f group increased in length, a corresponding increase in mixed anhydride to ketone selectivity was observed. This change in selectivity presumably arose from the weakening of the R_f–CO bond with increasing length of the R_f group. While the corresponding bond strengths have not been determined for the anhydrides in question, the general trend can be seen from perfluoroalkyl iodides: CF_3–I, 53.2 ± 1.0 kcal/mol; CF_3CF_2–I, 51.2 ± 1.0 kcal/mol; $CF_3CF_2CF_2$–I, 49.8 ± 1.0 kcal/mol.[11] Thus, with the progressive weakening of the R_f–CO bond, path A in Scheme 1 became more favored, leading to an increase in the mixed anhydride to ketone ratio in the product mixture.

Our observations make it critically important to reassess the reported metal-mediated alkane functionalizations in trifluoroacetic acid and/or trifluoroacetic anhydride.[2] The addition of certain metal species appears to have a profound influence on the reactions described above. Thus, the addition of either B_2O_3 (0.5 mmol), a presumed radical trap,[12] or more importantly $(CF_3CO_2)_2Pd$ (0.1 mmol) to reaction 1 with ethane resulted in the suppression of the products **1** and **2**; mostly simple oxidation products of ethane, such as alcohol and aldehyde, were formed in yields *lower* than that corresponding to the H_2O_2 present (B_2O_3: $C_2H_5O_2CCF_3$ + C_2H_5OH (0.61 mmol), $CH_3CH(O_2CCF_3)_2$ + CH_3CHO (0.16 mmol) plus unidentified products; $(CF_3CO_2)_2Pd$: $C_2H_5O_2CCF_3$ + C_2H_5OH (0.27 mmol); $CH_3CH(O_2CCF_3)_2$ + CH_3CHO (0.26 mmol); $CH_3COOCOCF_3$ + CH_3CO_2H (0.10 mmol). Therefore, for ethane the addition of the metal species resulted in a significant *decrease* in product yields; presumably, they interrupted the radical-chain reaction pathway.

In complete contrast to the ethane reaction, the yield of products from methane *increased* significantly upon the addition of an appropriate Pd(II) salt. Thus, confirming our earlier report,[2a,b] when methane (1000 psi, no N_2) was allowed to react under typical reaction conditions for 18 h (cf. reaction 1) in the presence of $(CF_3CO_2)_2Pd$ (0.1 mmol), the products formed were $CH_3O_2CCF_3$ + CH_3OH (0.40 mmol) and $CH_3COOCOCF_3$ +

(9) Review: Kochi, J. K. In *Free Radicals*; Kochi, J. K., Ed.; Wiley: New York, 1973; Vol. II, p 665.

(10) Hefter, H. J.; Hecht, T. A.; Hammond, G. S. *J. Am. Chem. Soc.* **1972**, *94*, 2793.

(11) *Handbook of Chemistry and Physics,* 61st ed.; Chemical CRC Press: Boca Raton, FL, 1980; p F-243.

(12) Effect of added B_2O_3 on free radical oxidation of alkanes: Sheldon, R. A.; Kochi, J. K. *Metal-Catalyzed Oxidations of Organic Compounds*; Academic: New York, 1981; p 343.

Table 3. Table of ^{1}H- and ^{13}C-NMR Data for Selected Reaction Products.

compound	^{1}H NMR[a] (ppm)	^{13}C NMR[b] (ppm)
CF$_3$CO$_2$COCH$_2$CH$_3$	1.22 (3H, t, $J = 7.45$ Hz), 2.62 (2H, q, $J = 7.45$ Hz)	7.5 (s), 29.1 (s), 114.5 (q, $J = 284.0$ Hz), 151.1 (q, $J = 47.8$ Hz), 169.2 (s)
CF$_3$COCH$_2$CH$_3$	1.13 (3H, t, $J = 7.03$ Hz), 2.72 (2H, q, $J = 7.03$ Hz)	5.9 (s), 30.7 (s), 115.0 (q, $J = 284.6$ Hz), 154.4 (q, $J = 45.5$ Hz)
CF$_3$CO$_2$CH$_2$CH$_3$	1.36 (3H, t, $J = 7.16$ Hz), 4.38 (2H, q, $J = 7.16$ Hz)	13.2 (s), 66.2 (s)
(CF$_3$CO$_2$)$_2$CHCH$_3$	1.72 (3 H, d, $J = 5.47$ Hz), 7.05 (1 H, q, $J = 5.47$ Hz)	18.3 (s), 93.0 (s)
CF$_3$H	6.42 (1H, q, $J = 79.32$ Hz)	
CF$_3$CF$_2$H	5.80 (1H, tq, $J = 52.31, 2.55$ Hz)	
CF$_3$CF$_2$CF$_2$H	5.92 (1H, tt, $J = 51.94, 4.57$ Hz)	

[a] Referenced to ethane at 0.8 ppm. [b] Referenced to an external capillary tube containing 1 μL of DMSO in 60 μL of D$_2$O.

CH$_3$CO$_2$H (0.12 mmol); i.e., the yield was *3 times* that obtained in the absence of the Pd(II) salt. Enhanced yield of products was not obtained when (CF$_3$CO$_2$)$_2$Pd was replaced by B$_2$O$_3$ (0.5 mmol). It is evident from the data that the Pd(II) ion catalyzes the oxidation of methane by H$_2$O$_2$ in this solvent system through a different (electrophilic) mechanism.[2a,b]

In conclusion, our results clearly indicate that studies of metal-catalyzed alkane oxidations in such solvent systems should be approached with caution (preliminary investigations have revealed a broadly similar pattern in the H$_2$S$_2$O$_7$ + H$_2$SO$_4$ solvent system).[13] The solvent cannot be assumed to be an innocent spectator in all cases. Furthermore, as the reaction of methane (no involvement of (CF$_3$CO)$_2$O) versus ethane (oxidation by (CF$_3$CO)$_2$O) versus propane (no involvement of (CF$_3$CO)$_2$O) illustrates, the participation of the solvent in the reaction does *not* follow simple trends, e.g., substrate C—H bond energy.

Experimental Section

Materials and Equipment. The following chemicals were used as received: tetraethyllead, perfluorocarboxylic acid anhydrides, 30% (w/w) hydrogen peroxide, azobisisobutyronitrile, peracetic acid, *m*-chloroperbenzoic acid, iodine, propionic acid, and boric oxide (Aldrich); methane, ethane, propane, ethene, propene, carbon monoxide, oxygen, and nitrogen (Matheson); and deuterium oxide, and [^{13}C]carbon monoxide (Isotech, Inc.). Reactions under pressure were carried out in Parr general purpose bombs using glass liners. Reaction products were identified by their ^{1}H- and ^{13}C-NMR spectra recorded on a Bruker AM 300 FT-NMR spectrometer using solvent resonance at appropriate frequency or an external standard consisting of a capillary tube containing 1 μL of DMSO in 60 μL of D$_2$O for lock and reference and as an integration standard. The ^{1}H- and ^{13}C-NMR data for selected compounds are given in Table 3. The identity of the products was further confirmed by GC/MS and/or by comparison with authentic samples.

CAUTION: Appropriate precautions should be taken while working with gases under high pressures. Particular attention should be paid to flammability limits of gas mixtures.

General Procedures. To 3.0 mL (21.2 mmol) of (CF$_3$CO)$_2$O was added 0.2 mL of 30% (w/w) aqueous H$_2$O$_2$ (1.8 mmol of H$_2$O$_2$) (note that excess (CF$_3$CO)$_2$O remained after mixing). The mixture was placed

(13) Basickes, N.; Hogan, T. E.; Sen, A. *J. Am. Chem. Soc.* **1996**, *118*, 13111.

in a glass liner inside a 125 mL Parr bomb, which was subsequently pressurized with 500 psi of C$_2$H$_6$ containing 1600 ppm of C$_2$H$_4$, and 500 psi of N$_2$, and heated at 75−80 °C for 1 d. At the end of this period, the products identified by ^{1}H- and ^{13}C-NMR spectroscopy (and confirmed by GC/MS and/or by comparison with authentic samples) were propionic acid and the mixed anhydride, CH$_3$CH$_2$CO$_2$H + CH$_3$CH$_2$COOCOCF$_3$, **1** (1.85 mmol); the mixed ketone trifluoromethyl ethyl ketone, CH$_3$CH$_2$COCF$_3$, **2** (0.68 mmol); ethanol and its derivative, C$_2$H$_5$OH + C$_2$H$_5$O$_2$CCF$_3$ (0.06 mmol); acetaldehyde and its derivative, CH$_3$CHO + CH$_3$CH(O$_2$CCF$_3$)$_2$ (0.09 mmol); and acetic acid and its derivative, CH$_3$CO$_2$H + CH$_3$COOCOCF$_3$ (0.31 mmol). A GC/MS of the solution revealed the additional presence of CF$_3$CO$_2$CF$_3$ and CF$_3$H. CF$_3$H and a small amount of CO$_2$ were found in the gas phase.

Reaction in Pentafluoropropionic Anhydride. The general procedure was followed replacing 30% H$_2$O$_2$ with PbEt$_4$ (1 μL, 0.005 mmol), (CF$_3$CO)$_2$O with (CF$_3$CF$_2$CO)$_2$O (3 mL, 15.2 mmol), and C$_2$H$_6$ containing 1600 ppm of C$_2$H$_4$ with pure C$_2$H$_6$ (99.997%). The products identified by ^{1}H- and ^{13}C-NMR spectroscopy at the end of 17 h were propionic acid and the mixed anhydride, CH$_3$CH$_2$CO$_2$H + CH$_3$CH$_2$COOCOCF$_2$CF$_3$ (2.97 mmol); the mixed ketone pentafluoroethyl ethyl ketone, CH$_3$CH$_2$COCF$_2$CF$_3$ (0.22 mmol); ethanol and its derivative, C$_2$H$_5$OH + C$_2$H$_5$O$_2$CCF$_2$CF$_3$ (0.33 mmol); acetaldehyde and its derivative, CH$_3$CHO + CH$_3$CH(O$_2$CCF$_2$CF$_3$)$_2$ (0.31 mmol); acetic acid and its derivative, CH$_3$CO$_2$H + CH$_3$COOCOCF$_2$CF$_3$ (0.31 mmol); and pentafluoroethane, CF$_3$CF$_2$H (0.1 mmol) [^{1}H NMR: 5.80 ppm (1 H, tq, $J = 52.31, 2.55$ Hz)].

Reaction in Heptafluorobutyric Anhydride. The general procedure was followed replacing 30% H$_2$O$_2$ with PbEt$_4$ (1 μL, 0.005 mmol), (CF$_3$CO)$_2$O with (CF$_3$CF$_2$CF$_2$CO)$_2$O (3 mL, 12.18 mmol), and C$_2$H$_6$ containing 1600 ppm of C$_2$H$_4$ with pure C$_2$H$_6$ (99.997%). The products identified by ^{1}H- and ^{13}C-NMR spectroscopy at the end of 16 h were propionic acid and the mixed anhydride, CH$_3$CH$_2$CO$_2$H + CH$_3$CH$_2$COOCOCF$_2$CF$_2$CF$_3$ (3.59 mmol); ethanol and its derivative, C$_2$H$_5$OH + C$_2$H$_5$O$_2$CCF$_2$CF$_2$CF$_3$ (0.24 mmol); acetaldehyde and its derivative, CH$_3$CHO + CH$_3$CH(O$_2$CCF$_2$CF$_2$CF$_3$)$_2$ (0.31 mmol); acetic acid and its derivative, CH$_3$CO$_2$H + CH$_3$COOCOCF$_2$CF$_2$CF$_3$ (0.02 mmol); and heptafluoropropane, CF$_3$CF$_2$CF$_2$H (1.13 mmol) [^{1}H NMR: 5.92 ppm (1 H, tt, $J = 51.94, 4.57$ Hz)].