Comparative QSAR: Radical Reactions of Benzene Derivatives in Chemistry and Biology

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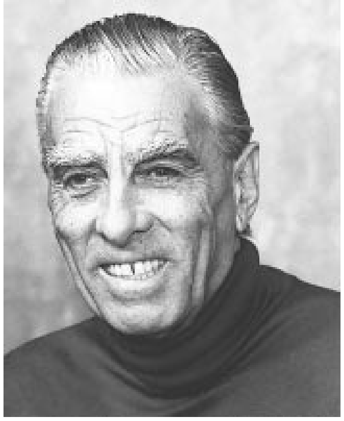
I. Introduction

The motivation for writing this review comes from our interest in using quantitative structure–activity relationships (QSAR) to understand how organic compounds effect biological systems. We are constructing a database of QSAR, for all types of reactions, which at present contains over 10 600 examples, of which 4000 are from biological systems. The others are from an extremely wide variety of studies from physical organic chemistry based largely on the Hammett equation and its extensions. Our computerized system is well suited for comparing reactions via the correlation equations.[1] Scientific hypotheses are formed by observing patterns in apparently unrelated data that give rise to new experiments to validate and extend generalizations. It is our belief that comparing QSAR from biological experiments with those from the much more firmly based work in physical organic chemistry will eventually provide a firmer foundation for work in drug and pesticide research and toxicology as well as fundamental biochemistry. Our current interest is focused on radical reactions, especially in the area of toxicology. As discussed later, we have recently found that phenols and anilines (hence presumably many other aromatic NH_2 and OH containing chemicals and drugs) display a toxicity that is characterized by terms of the Hammett parameter σ^+ with negative slopes (ρ^+).



Corwin Hansch received his undergraduate education in chemistry at the University of Illinois and his Ph.D. in organic chemistry from New York University in 1944. After working with the DuPont Company, first on the Manhattan Project and then in Wilmington, DE, he joined the Pomona College faculty in 1946. He has remained at Pomona College except for two sabbaticals—one at the Federal Institute of Technology in Zurich and the other at the University of Munich. His primary interest is in the relationship between the structure of organic compounds and their biological properties.

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The $-\rho^+$ alerted us to an unusual reaction. *Many* studies of the toxicities of these chemicals in many different systems, from organelles to animals, have shown that toxicity potency normally increases with increasing hydrophobicity and that electronic effects are much less important. Moreover, when electronic effects are present, electron-withdrawing substituents ($+\sigma$) normally favor toxicity (however see eq 12). A reason for missing this type of toxicity in the past was the poor choice of substituents studied with little variation in σ and high collinearity between σ and σ^+ (see following discussion). Comparison of the small $-\rho^+$ values for phenol and anilines with the most active radicals abstracting $H^\bullet$ suggested that radicals play a role in the toxicity. This illustrates the value of comparative studies on the widest possible scale.

Often, especially in toxicology, it is difficult to ascertain when a radical reaction is actually involved. Although ESR (electron spin resonance) technology can be used in studies with cells and even animals, we have not found published efforts to support QSAR studies with ESR.

Our main concern while producing this review was to find all possible examples of QSAR where correlation equations had been or could be derived. In searching the literature for extensive reviews of radical QSAR, we found that none have appeared since that of Afanas'ev in 1971,[2] and his update of this paper, with a short review on the use of two parameter equations for correlating radical reactions.[3]

It is relatively easy to find the radical data from organic chemistry where one normally knows when a radical process is occurring. However, the abstracting of the literature is poor. After going through several of the major journals and *Chemical Abstracts*, we found many more articles could be uncovered by checking references in the papers themselves. It is impossible to collect QSAR data for biological systems in a systematic way. Finding such examples in the last 30 years has been largely a matter of chance. One helpful approach was to consider all oxidoreductase QSAR, of which we have 404 examples. However, many of these are for inhibitors where hydrophobicity is all-important. In the end we considered all bio QSAR which contained an electronic term.[1]

In presenting our results we have been primarily interested in looking for similarity between sets of data by comparing ρ values, and hence the discussion has been organized around the parameters: σ^+, σ, σ^-, $\sigma^\bullet$, and E_R. Values for these can be found in ref 3a. Values for three types of $\sigma^\bullet$ are given in Table 10.

We realize that there is little fundamental justification for such comparative analysis. It is simply one of the very few ways of beginning to consider bio QSAR and toxicology in a general way.

It should be noted that in a number of instances, authors have reported plots of their data without supplying the actual numbers. In these examples we were precluded from deriving equations with proper statistics for comparative purposes.

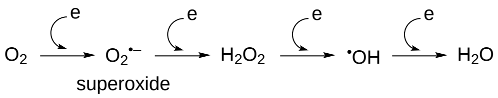
Quantitative structure–activity relationships in chemistry have been under investigation since the pioneering work of Brønsted in the early 1920s,[4] and a broad generalized approach began to evolve with Hammett's definition of σ constants in 1937[5] and Jaffé's seminal review.[5a] Other workers, notably Taft and Brown, greatly expanded our potential to rationalize structure–activity relationships in organic chemistry. The definition of σ^+ by H. C. Brown and his associates[6] was an especially important advance. Walling et al. published the first application of the Hammett equation to radicals in 1948.[7]

In biology, independent studies by Meyer and Overton[8] at the turn of the century showed that olive oil partition coefficients were related to the toxicity of organic chemicals. Although their work was not set in the form of equations, it set the stage for such studies and a general model was advanced in 1962.[9] This model, using octanol/water partition coefficients and Hammett σ constants, joined the areas of physical organic chemistry with biological studies.

Since regression analysis was first used to sort out the salient features of chemicobiological interactions,[9] thousands of such QSAR have been published.[10] Many different parameters have been devised, and all sorts of imaginative computer-assisted techniques have been employed, to enlarge our understanding of the underlying processes which accompany the perturbation of a biological system by a set of chemical congeners. What all occurs when a cell or whole organism is treated with a set of chemicals would seem to be beyond our ability to understand. The myriad enzymes, DNA, RNA, and the variety of membranes with their receptors can of course be studied as isolated independent entities. However, it remains to be seen just how much we can understand about the chemical perturbation of a living system in which all of these entities are working in concert. Nevertheless, purely empirical approaches via QSAR[10] are beginning to provide generalizations as to how organic chemicals effect whole organisms. Recent studies show that connections between physical organic chemistry and biological reactions can be made[1,11–15,15a] and that a large database of reference examples is important in expediting such research.

Earlier, the position and importance of radicals in chemistry (and much later in biology) was one of ambiguity. Although there was discussion about the existence of radicals in chemistry in the 19th century, it was not until the work of Gomberg that compelling evidence for their existence was found.[16,16a] After Gomberg's work in 1900, the concept of radicals in organic chemistry very slowly gained acceptance. Following World War II the possible importance of radicals in biochemical reactions began to attract attention. Today the subject of radicals in biological reactions has become a major area of study[17,18,18a] with constant reference to it even in newspapers and popular magazines. Stubbe[19] has reviewed the possibility of protein radicals in biological catalysis. Fridovich[20] has compiled an extensive bibliography on the superoxide radical and superoxide dismutases, and Grissom[21] has summarized the controversial evidence that radicals might be involved in the toxic effects of magnetic fields.

Although we are interested in all aspects of radical reactions, we are particularly interested in their toxicity.[14,22] One of the incredible aspects of the use of oxygen by cells is that toxic forms of oxygen occur from its reduction:



If superoxide is not controlled it can yield hydrogen peroxide which, in the reaction with ferrous ions, produces the most reactive radical $^\bullet$OH:

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^\bullet OH + OH^-$$

The extremely reactive $^\bullet$OH can react with almost any organic compound with which it comes in contact.[23] Indeed, it has been estimated that $^\bullet$OH diffuses only 5−10 molecular diameters before it reacts[24] in a cell. The damage caused by radicals in the body appears to be a primary cause of aging.[25−28] Ames has estimated[25] that the number of oxidative hits to human DNA is about 10 000 $\mathrm{cell}^{-1}/\mathrm{day}^{-1}$ while that for the rat, with a much shorter life span, is 100 000 $\mathrm{cell}^{-1}/\mathrm{day}^{-1}$. Unless these damaged sites can be repaired, they will accumulate with time and result in serious toxicity.

The formation of superoxide with the addition of one electron to O_2 opens up the possibility for the formation of $^\bullet$OH. Superoxide concentration is controlled by the enzyme superoxide dismutase (SOD):

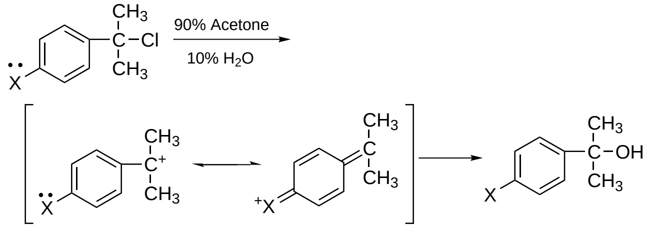
$$O_2^{\,-} + O_2^{\,-} + 2H^+ \xrightarrow{\text{SOD}} H_2O_2 + O_2$$

The enzyme catalase converts H_2O_2 to $H_2O + O_2$ and is thus an important means of protection. It has been pointed out that those animals which have the highest SOD activity also have the longest life spans.[27,28] This is related to the above fact that DNA in small animals is damaged by radicals much more than human DNA. A similar relationship appears to exist between the radical scavenger uric acid and life span.[29]

It appears that almost any organic compound that comes into contact with $^\bullet$OH will be converted into some kind of a radical. This applies to natural compounds of the body as well as xenobiotics such as drugs and the components of food. Whether or not such radicals cause cellular damage would seem to depend on the natural protection cells have. Three of the most important radical scavengers, because of their extreme log P values, tend to be localized in aqueous or hydrophobic body compartments: ascorbic acid (log P at pH 7.5 estimated to be < -4.0); uric acid (log P −2.9 at pH 7.4); and α-tocopherol (log P estimated to be > 8). The hydrophilic scavengers are well suited to neutralize hydrophilic radicals such as $^\bullet$OH and vitamin E is well suited to scavenge hydrophobic radicals. Radicals with the potential to cause harm might be those of intermediate hydrophobicity and intermediate stability. That is, radicals capable of wandering around the cells before reacting.

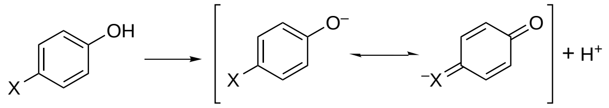
Our review is explorative in that we are concerned with uncovering processes at the enzyme or cellular level that are (may be) radical in nature. While QSAR cannot prove a radical mechanism, it can uncover leads that can be followed by other methods. Important to us is its potential for relating biological reactions to those from physical organic chemistry. Since the parameter σ^+ has been shown, from its definition in 1957,[30] to be widely useful in correlating the radical reactions of organic compounds (see Table 1), its occurrence in a bio QSAR calls for considering the possibility that a radical reaction may be involved (especially when ρ^+ is negative). To further evaluate such a possibility we can compare the bio QSAR with studies on similar compounds in physical organic chemistry, where mechanisms are on firmer ground. We can also make comparisons with other bio QSAR.

It is interesting that H. C. Brown and his associates developed σ^+ to correlate aromatic electrophilic substitution reactions according to the following scheme:



$\sigma^+ = 1/4.59 \log k_X/k_H$ where k_X is the rate of solvolysis of the substituted molecule, and k_H that of the parent compound. The scalar 1/4.59 more or less places σ^+ on the same scale as σ for substituents which have little through resonance. The fact that σ^+ is effective in correlating radical reactions implies that at some point in their formation, they must have significant polar character. Although special radical parameters have been developed,[31−41] they have been found to be generally less useful than σ^+ or σ.

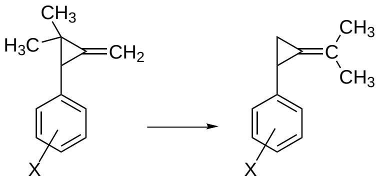
Radical reactions are also sometimes correlated by σ^- (Table 3), a parameter derived from the ionization of phenols or anilines. This parameter was also designed to deal with problems involving direct resonance between substituent and reaction center:



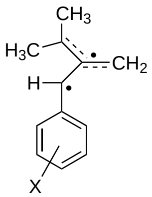
Finally, radical reactions are often correlated by σ (Table 2), which is obtained from the ionization of benzoic acids.

We have considered four radical parameters: three $\sigma^\bullet$ and E_R defined by Yamamoto and Otsu,[33] E_R is based on the abstraction of $^\bullet$H from substituted isopropylbenenes. Thus it is similar to σ^+. They proposed that it be combined with σ to account for the nonpolar aspects of radical reactions.

Creary's scale[41a] is defined by the rearrangement of methylene cyclopropanes:



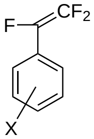
This reaction serves as a measure of the stabilizing effect of X on the benzylic radical in the transition state:



while not everyone would accept this picture of the transition state, the $\sigma^\bullet$ values appear to serve as well to correlate radical reactions as those obtained by other means (Table 10).

Arnold's[40] $\sigma^\bullet$ is not kinetically determined, but is based on radical stabilizing effect of substituents ($X\text{-}C_6H_4CH_2^\bullet$) on the hyperfine coupling constants of the benzyl radical.

Jiang's[41b] $\sigma^\bullet$ is based on the relative cyclodimerization rate of



Verloop's[41c] sterimol parameters $B1$, $B5$, and L are calculated from the Corey–Pauling–Koltun assumptions for van der Waal radii and bond angles. Initially they recommended the use of five parameters $B1$, $B2$, $B4$, $B5$, and L. After several years of experimentation they concluded that little if anything was lost by the use of only three parameters. $B1$ shows considerable collinearity with E_s ($r^2 = 0.72$).

MR(molar refractivity) is defined as

$$\mathrm{MR} = \frac{n^2 - 1}{n^2 + 2}\left(\frac{\mathrm{MW}}{d}\right)$$

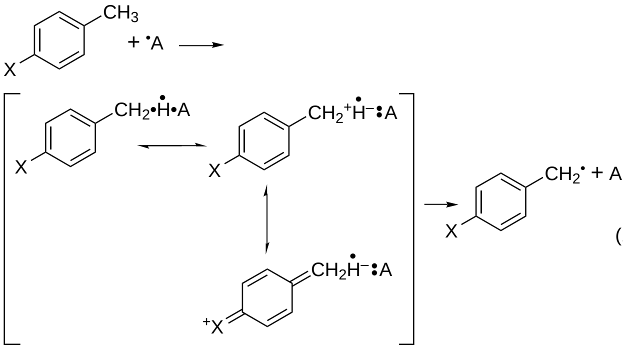
where n is the refractive index, MW is the molecular weight, and d is the density. Since the refractive index does not vary greatly for most organic fragments, MR is primarily a measure of volume with a small correction for polarizability.

log P is the octanol/water partition coefficient of the molecule and π is that of a substituent. As we have used log P it applies to the neutral form of ionized or partially ionized compounds.

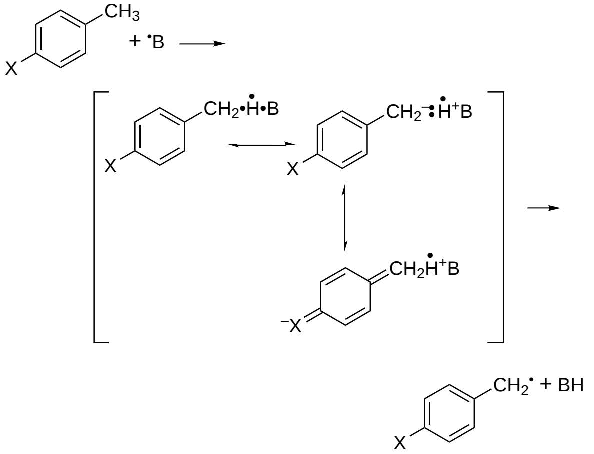
All three parameters, σ, σ^+, and σ^-, were derived to correlate polar reactions, yet they are better suited to correlate radical reactions than parameters obtained from certain radical reactions. How to explain this has been a long-standing problem. Most researchers have concluded that there must be some cationic or anionic character to radical reactions. In an extensive review of the problem, Zavitsas and Pinto[42] conclude that "polar character" in radical reactions is not a necessary concept. This point of view has been abandoned.

Assuming polar character is important, we need some guidance as to when one might expect to see any one of the three possible σ terms appear in a radical QSAR. The first step toward a better understanding is to assemble the experimental results. There has been no attempt to publish all of the radical QSAR which we now want to correct.

The following rationalizations have been offered as to why radical reactions should have polar character:[43]



(1)



(2)

In eq 1 the radical reagent $^\bullet A$ is acting as an electrophile, while in eq 2 the reagent $^\bullet B$ is acting in a nucleophilic manner. It has been generally assumed that structural changes in X are related to the stabilities of $X\text{-}C_6H_4CH^\bullet$ and its analogs where carbon in $CH^\bullet$ may be replaced by other elements. Indeed, Bordwell and his colleagues and others have in recent years provided ample evidence that bond dissociation energies of the type $AH \rightarrow H^\bullet + A^\bullet$ are well correlated by Hammett parameters.[44–47] Bordwell et al. conclude that remote substituents effect bond dissociation energies by both changing ground-state energies of HA and by stabilizing or destabilizing the radical $^\bullet A$. Mulder et al. have shown that homolytic bond dissociation energies correlate well with σ^+.[47a] Wayner[47b] has reviewed work on determining bond dissociation energies. Arnett and Ludwig have pointed out that radical reactions should correlate with ionization potentials or HOMO–LUMO gaps.[47c]

Reactions correlated by $-\rho$ can be rationalized by eq 1, and those correlated by $+\rho$ can be explained by eq 2. Possibly those correlated by σ could occur by a mixed mechanism involving both eqs 1 and 2. A shadow which hangs over all of this work is the rather high collinearity among the three σ parameters. Unless researchers choose substituents with good variation in σ^+, σ^-, and σ, it will not be possible to obtain mechanistic insight from establishing the superiority of one of them. In Table 1 we have listed r^2 for the correlation with σ for comparison with r^2 for σ^+. Also we have listed the correlation (r^2) between σ and σ^+. Clearly, with few exceptions, the collinearity between σ^+ and σ is uncomfortably high. The same situation occurs in Table 2.

In writing this review we have made a serious effort to be comprehensive. The quality of the correlations varies considerably in terms of the number of data points supporting an equation, the range in parameter values, and the reliability of the various terms. Most researchers regard five data points/parameter as the minimum to support an equation. There have been a large number, which we have included, based on only four. These results must be accepted with caution. Within the sets based on rather few data points there is the additional problem that the spread in parameter values may be narrow.

The problem of deciding on what constitutes a proper data set is very difficult. While most workers these days appear to favor a *minimum* of five data points/variable, this means little if there is not a wide spread in the parameter values. What constitutes "wide" is not easy to define. Very few studies have a spread greater than NH_2 and NO_2 and assume that linearity holds indefinitely. There are about 900 measured σ_p values and many more derived values, that is, there is a continum of values that can be used. Exactly where to set the spread for monosubstitution and say that all is well cannot be said. Disubstitution brings in additional problem of steric hinderance. Assuming that the relationship is linear *and* that it is correlated by a specific parameter, say σ, then with a OMe and an NO_2 and a high correlation a valid value for ρ could be expected. However, the problem becomes sticky when one does not know which σ is the valid parameter as is the case for the present review. Sometimes σ^+ seems best, sometimes σ or σ^-. Researchers are still not satisfied that the addition of a second parameter ($\sigma^\bullet$) is not called for. One cannot simply take a substituent with a strong σ^+ and one with a strong σ^- and assume all is well. A proper set must be built by studying the correlation matrix of parameter values to be sure of what one is attempting and that reasonable orthogonality is attained.

To be reasonably sure of one's position it is necessary to rule out nonlinearity. To do so 10−12 data points would be necessary.

In our present database of 6600 physical QSAR, 5257 are based on less than 12 data points. The poorly designed sets hamper our efforts to understand the need for a second parameter ($\sigma^\bullet$) to deal with radical reactions (see Table 8). Besides the problems of the number of data points the spread in parameter values, collinearity, and the quality of fit (confidence limits) there is another problem—the quality of the experimental work. This is particularly important in the study of radical reactions where radicals must be generated *in situ* from various precursors. Also "hot" radicals are apt to react at more than one place in the substrate where, for example, hydrogen abstraction may be possible. This calls for more than the usual quality of analytical work. In reading this review these problems must be kept in mind. It would be nice if we could point out which equations are most suspect beyond saying something about the number and spread of the data points. Because of the nature of the problems we can do no more.

One must be well aware of the collinearity problem that is even more serious in the bio QSAR (this is discussed in Chapter 13 of ref 10). Statistics (r^2, F test, confidence limits) alone do not alert one to this insidious problem that also plagues us in our daily lives.

These warnings to the reader do not mean that the studies reported here are of little value. A large range of good chemistry is illustrated in terms of both substrates and radicals. One can begin to make comparisons between and among QSAR in both areas, and we have attempted to draw some generalizations. Many first approximations have been reviewed that constitute the basis for the next round of research.

We believe that the best support for a correlation equation is lateral validation. That is, by comparing a new equation with similar published results. The radical abstraction of $^\bullet H$ from substituted toluenes by halogen provides an unusual possibility for exploring this concept. An amazing number of attempts to define ρ for this reaction have been made. In Table 1b if we drop sets **11**, **24**, **28**, **29**, **30**, **45**, **46**, **47**, **55**, **58**, **62**, **64**, **67**, **69**, **74**, and **78** (discussed below) because of poor confidence limits ($>\pm 0.20$), we are left with 18 sets. If we pick those sets with good confidence limits (<0.20) that have a good rang in σ^+ values (set **35**, **39a**, **40**, **41**, **42**, **50**, **51**, **53**, and **54**), we find a range in ρ^+ of -1.46 to -1.34 (mean -1.39), the remaining sets with confidence limits <0.20 but poor spread in σ^+ values (**33**, **36**, **38a**, **39**, **49**, **60a**, **61**, and **65**) that might be discounted as being weak because of a poor spread in σ^+ have a range of ρ^+ from -1.50 to -1.20 (mean -1.36). The results are little different from the "best" sets. That is the confidence limit is one of the best measures of reliability. Set **78** has not been included in the above discussion as it seems to be a true outlier: the confidence limits are good, there are seven data points, and the spread in σ^+ is reasonable. Without having the possibility for lateral comparisons we should not be able to single this set out with much assurance. The authors of this study term this a "slow" bromination that would seem to be a somewhat different mechanism.

We find the agreement among the ρ^+ values to be surprisingly good considering the relatively few data points/set (5 or 6) that the work was done in different laboratories by people with different levels of experience, in different solvents, at different temperatures, and with different means for generating radical halogen atoms. Of course we do not mean to imply that 5 data points/variable will produce a "gold standard" ρ value. This is a very small sample of substituent space. Most authors are all too willing to settle for four or five data points *without* giving the confidence limits and most journals put up with this.

The F test can also be employed as means for checking the reliability of terms in QSAR. We have provided F tests at the generally used 0.95 and the more stringent 0.99 level of significance for all terms in all equations. All terms except for one equation (set **122** in Table 1) pass at the 0.95 level. At the 0.99 level 487 are significant while 51 are significant somewhere between 0.95 and 0.99. For those unfamiliar with statistics the recent book by Livingston[47d] is helpful since much of the discussion is in terms of biological QSAR. Some terse guidelines have been published by the International Group for Correlation Analysis in Organic Chemistry.[47e]

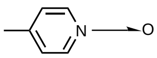
Another point that must be considered, especially in the present review, is the need for having substituents to establish the importance or lack of it in resonance interactions. An appreciation of this point was slow to arrive and even today authors fail to consider this in their design of substituent sets. For the present data one can check this by inspection of the substituents or simply by comparing r^2 for the correlation between σ and σ^+ or σ and σ^- in the tables. All data sets were evaluated to see which of these three parameters provided the best fit. High collinearity between σ and the resonance parameters is a serious shortcoming.

Many of the sets contain ortho substituents that must receive special consideration. Fujita and Nishioka[47f] have provided evidence for a general approach that we have followed in dealing with this problem. For each set with ortho substituents these were parameterized by using $\sigma_p = \sigma_o$, the F for the field/inductive effect, and the sterimol parameters $B1$ and $B5$. Sometimes F and/or the steric parameters were significant, sometimes not. For multisubstituted compounds we summed the values of σ, σ^+, or σ^- in positions conjugated with the reaction center.

Collinearity can be a problem; however, by giving some attention to substituent selection it can be greatly mitigated. For example, r^2 between σ^+ and σ for the following set of substituents is only 0.358:

	σ^+	σ
4-OMe	−0.78	−0.27
4-OC$_6$H$_5$	−0.50	−0.03
4-Cl	0.11	0.23
4-H	0.00	0.00
4-SMe	−0.60	0.00
4-OCOMe	−0.19	0.31
4-Me	−0.31	−0.17
4-CMe$_3$	−0.26	−0.20

Selecting a set of substituents for the study of a radical reaction is not as easy as one might at first think. One of the major questions we want to examine is, is σ^+ the parameter of choice as many have over the years asserted? To a considerable degree one is boxed in. Two choices to extend the range in negative values might be 4-OH (−0.92) and 4-NH$_2$ (−1.30); however, both of these are highly reactive themselves to radicals. Adding electron-accepting substituents such as 4-NO$_2$, 4-CN, and 4-SO$_2$Me is self-defeating since σ^+ and σ are almost perfectly collinear. Some further possibilities are[3a]

	σ	σ^+
NMe$_2$	−0.83	−1.70
NHCOMe	0.00	−0..60
SC$_6$H$_5$	0.07	−0.55
SeC$_6$H$_5$	0.13	−0.47
N═C═O	0.19	−0.19
SC$_6$H$_4$·4NO$_2$	0.24	−0.17
OCOMe	0.31	−0.19
OSO$_2$Me	0.39	0.16
	1.34	0.45

The first two of the above are risky because of possible radical oxidation.

In light of the above discussion it is of interest that many of the small sets contain 4-OMe and 4-Cl. This is about the best spread one can get with common substituents without bringing in more collinearity. We listed r^2 for σ^+ and σ for each data set to provide some feeling for the collinearity problem.

A most useful place to start for understanding the mechanism of radical reactions is the recent publication by Leffler.[48] The results of our comparative analysis are given in Tables I-VIII.

II. Discussion of Nonbiological QSAR (Tables 1–3)

In composing Tables 1−3 we have used σ^+, σ, and σ^- to evaluate each data set, and where possible $\sigma^{\bullet}$ [40,41,41a,b] and E_R[49] were used to check the data. The decision as to where to place the data was based simply on the value of the correlation coefficient. Clearly, by this standard, σ^+ (273 examples) is the most useful parameter followed by σ (109 examples) and then σ^-. Out of 441 QSAR in all of the tables, 273 (62%) are best correlated by σ^+. In considering this figure one must bear in mind that there are many examples of data sets based on only four data points and also that substituent choices are often far from ideal; however, there is little reason that this would bias the data significantly one way or another. The results show that one cannot assume that ρ^+ means a radical reaction is occurring or vice versa that ρ means it is not. We shall be somewhat in the dark on this score until larger, better constituted data sets are studied.

The ρ values in the tables have been listed in order of increasing size. (The figures in parentheses with each term are for the 95% confidence limits.) From this it is apparent that most are negative in sign. In Table 1, 185 (81%) are negative, and in Table 2, 61 (63%) have negative signs. In Table 1, ρ^+ extends from −5.92 of set **1** (note the large confidence limit on this figure) to +3.58. In Table 2, the range is −3.05 to +5.2. The ranges are larger 9.50 for σ^+ than 8.25 for σ.

Some of the most negative ρ^+ values are associated with sterically hindered radicals abstracting $^{\bullet}$H from phenols (sets **1a**, **3**, **4**, **5**, **9**, **and 15**). The confidence limits (CI) on these sets are rather large, but the F test is significant at the highest level 0.99 for all terms. However, these are not the important points. Of most importance is that this group of sets all say the same thing about sterically hindered radicals. One expects a large negative value of ρ^+. One would worry about one set standing alone. In comparative QSAR we are most interested in trends rather than the precise value of ρ. The converse, $^{\bullet}$H abstraction from the sterically hindered phenol, does not have as large negative values of ρ (sets **23**, **52**, **71**, **and 76**). Of particular interest in this respect are sets **63** and **71**, where styrylperoxy radicals are used to abstract $^{\bullet}$H from unhindered and hindered phenols. The values of ρ^+ are essentially identical for each type of phenol.

The correlation equations of Table 1−3 have been generated over the past 50 years during which time experimental techniques have evolved considerably. Still, viewing the results it is not easy to point out which results appear to have been compromised by poor methodology. Such evaluations will have to be made on the basis of the statistics. Unfortunately there are many examples based on too few data points. If the spread in σ values is not great, little weight can be placed on these equations. This can be easily seen from the substituents which were studied. For each data set we have listed the substituents employed along with the residuals (difference between observed activity and that calculated from the correlation equation). Inspection of the residuals for various reaction types gives one an idea of which substituents are poorly behaved.

Few researchers have placed confidence limits on ρ values. We believe this is very important and have given the 95% confidence for all parameters. Hence it is relatively easy from an inspection of the *range* in σ values, the correlation coefficient and the confidence limits to identify the best work. However, one must not overlook the collinearity problem in discussing mechanisms.

1. Hydrogen Abstraction

All of the examples from Table 1 where hydrogen abstraction is from simple, unhindered phenols by unhindered radicals or radicals attached to metals are listed in Table 1a. The two examples with the largest absolute values of ρ^+ have rather wide confidence limits and a reaction temperature of 130 °C. It might be expected that a higher reaction temperature would yield a lower absolute ρ^+. In fact, set **54** in Table 2 with one of the lowest temperatures has a very low absolute ρ. (Giese has commented on temperature dependence.[49a]) Omitting the examples with the largest confidence limits and set **27**, we find a mean value of −0.90. Except for the styryl peroxide, all of the radicals are in the reactive class where the lone electron is not strongly delocalized.

Examples **2a** and **76a** in Table 1 for the oxidation of anilines by vanadium(V) and peroxydisulfate have ρ^+ values parallel to those of phenols. Although the details of aniline oxidation were not established (hydrogen abstraction or lone pair electron oxidation), the mechanism appears similar to that of the phenols.

It is difficult to draw any conclusions about the relative importance of solvents. This has been a point of concern to researchers ever since the classical study by Russell.[50] In the investigation of the photochlorination of 2,3-dimethylbutane in a large number of solvents he found that the ratio of replacement of tertiary to primary hydrogen varied by a factor of ~10. He concluded that some solvents form a complex with the radicals, making them less reactive, and hence, more selective. Russell[50] demonstrated the solvent effect on the isomer ratio with 2,3-dimethylbutane by using solvents of the type: X-C_6H_5. The ratio was found to correlate with σ_m of X. We have found a slightly better result using their data and σ_p (eq 3).

$$\log \text{ratio } t/p = -0.54(\pm 0.09)\sigma_p + 1.15 \qquad (3)$$

$$n = 16 \quad r^2 = 0.921 \quad s = 0.063$$

omitted: I, 1,2-di-CH_3

The higher the electron density on the aromatic ring of the solvent is, the more the reaction occurs at the tertiary position of the 2,3-dimethylbutane.

In recent efforts to uncover solvent effects on radical reactions, Kim et al.[51] studied $^{\bullet}H$ abstraction from phenols and thiophenols by $Me_3CO^{\bullet}$. In the case of thiophenols (sets **158**, **160**, and **163**) reacting in benzene, carbon tetrachloride and acetic acid, they obtained the same values for ρ^+ with reasonable confidence limits. For the phenols (sets **18**, **34**, and **81**) the picture is less clear. Although ρ^+ for these phenols in Table 1a varies from −1.81 to −1.02, the confidence limits on two of the values are so large that considerable doubt exists as to the true value. It is unfortunate that larger sets of phenols were not employed. Set **68** for thiophenols is interesting in that the lone electron on the radical is strongly delocalized, and ρ^+ is much more negative than the examples with $Me_3CO^{\bullet}$ (set **163**) where it is localized.

Tanner et al.[49b] have studied the effect of solvent viscosity on ρ using the reaction of X-toluenes with NBS/Br_2 to obtain the following results:

set no., Table 1	solvent	viscosity	ρ^+
29	CCl_3F/CCl_2FCClF_2	1.01	-1.56 ± 0.25
30	CCl_3F	1.11	-1.53 ± 0.22
46	CCl_2FCClF_2	1.24	-1.38 ± 0.25
64	$CCl_2FCClF_2/CCl_2FCCl_2F$	1.48	-1.20 ± 0.21
65	CCl_2FCCl_2F	1.82	-1.20 ± 0.19

The absolute value of ρ^+ decreases with increasing viscosity. Our values of ρ^+ differ somewhat from those of Tanner et al.

It is of interest that examples for phenols do not occur in Table 2 where correlation is with σ rather than σ^+. Many examples for toluene do, and two examples (sets **19** and **45**) for thiophenols are present. The absolute values of ρ are higher when σ is used in place of σ^+. This is due, at least in part, to the smaller absolute values of σ for the corresponding para substituents.

From Russell's[50] studies one might expect to see differences in ρ^+ for aliphatic and aromatic solvents; however, sets **29**, **30**, **35**, **39**, **46**, **62**, **64**, **65**, and **66** based on CCl_4 or freons have values very similar to sets **39a**, **40**−**42**, **47**, **49**−**51**, **53**, **54**, and **78**, based on benzene. In these examples $Br^{\bullet}$ is generated from *N*-bromosuccinimide (NBS). In the case of sets **107** (CCl_4) and **136** (C_6H_6), where the radical is $Me_3CO^{\bullet}$, the aliphatic solvent has the higher absolute value of ρ^+. In this case, the temperature may make the difference. Variation in solvent character is not great, but comparing sets **136**, **138**, **149**, **150**, and **154** where the $Me_3CO^{\bullet}$ radical is used, little effect is seen on ρ^+. We need better data to see if the solvent effect is a function of the type of radical used.

For some time it was thought that all hydrogen abstraction by radicals would show -ρ values in Hammett correlations. Work with alkyl radicals in Pryor's laboratory[52] changed this view (see sets **72**, **76**, and **78**, Table 2). In rationalizing abstraction

Table 1

Radical Reactions Correlated by $\sigma^{+\ a}$

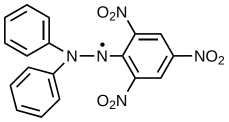
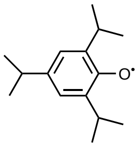
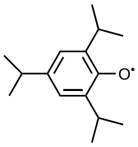
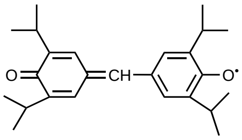
<table>
<tr><th>set</th><th>solvent</th><th>compound</th><th>radical</th><th>ρ^+</th><th>reaction, correlation</th><th>ref</th></tr>
<tr><td>1</td><td>air</td><td>X-C_6H_5</td><td>$NO_3^{\bullet}$</td><td>-5.92</td><td>react with $NO_3^{\bullet}$ radicals at 25 °C
log $k = -5.92\ (\pm1.98)\sigma^+ - 17.5\ (\pm1.52)$
$n = 11$, $s = 0.909$, $r^2 = 0.836$ (0.596),* (0.579),** $F_{1,9} = 45.84^{\S}$, omit: 1,3-Me_2 ($-1.76^{\ddagger}$), 1,3,5-Me_3 (-3.09), OMe (-2.78), CHO (5.70)</td><td>77a</td></tr>
<tr><td colspan="7">$^{\&}$1,2,3-Me_3, -1.30; 3-CH_2CH_2O-4, -1.23; tetralin, 1.13; 1-OH-4-Me, 0.99; 1-OH-2-Me, 0.98; OH, 0.63; 1-OH-3-Me, -0.57; Me, -0.51; 1,2-Me_2, -0.16; 1,2,4-Me_3, 0.11; 1,4-Me_2, -0.08</td></tr>
<tr><td>1a</td><td>CCl_4</td><td>X-C_6H_4OH</td><td> </td><td>-4.41</td><td>hydrogen abstraction 80 °C
log $k_2 = 4.41\ (\pm0.47)\sigma^+ - (0.47\ (\pm0.23)B5{,}2 - 0.83\ (\pm0.21)B5{,}6 - 2.02\ (\pm0.26)$
$n = 17$, $s = 0.198$, $r^2 = 0.970$ (0.845), (0.735), $F_{1,15} = 9.22$ (σ^+), $F_{1,14} = 30.05^{\S}$ ($B5{,}2$), $F_{1,13} = 45.84^{\S}$ ($B5{,}6$) ($B5{,}2$ and $B5{,}6$, sterimol parameter; $B5$, for 2- and 6-positions), omit: 2,4-$(CMe_3)_2$ (0.73)</td><td>78</td></tr>
<tr><td colspan="7">4-Me, -0.35; 2,4,6-Me_3, -0.33; 3,5-Me_2, 0.33; 4-$OCH_2C_6H_5$, 0.22; 2,4-Me_2-6-CMe_3, 0.21; 4-Cl, -0.19; 2,5-Me_2, 0.12; 2,3-Me_2, 0.10; H, -0.09;2 -Me, -0.08; 2,4-Me_2, 0.07; 4-Me-2,6-$(CMe_3)_2$, -0.06; 4-CMe_3, 0.05; 2,6-Me_2, -0.03; 2,4,6-$(CMe_3)_3$, 0.02; 4-OMe, -0.01; 4-Et-2,6-$(CMe_3)_2$, 0.00</td></tr>
<tr><td>2</td><td>aqueous</td><td>X-C_6H_4OH</td><td>X-$C_6H_4O^{\bullet}$</td><td>-3.53</td><td>oxidation by Cr(VI) 25 °C
log $k_2 = -3.53\ (\pm0.97)\sigma^+ - 1.39(\pm1.14)B1{,}o - 1.28(\pm2.45)$
$n = 11$, $s = 0.533$, $r^2 = 0.905$ (0.775), (0.765), $F_{1,9} = 38.91^{\S}$ (σ^+), $F_{1,8} = 7.85^{\S\S}$ ($B1{,}o$), omit; 3,4-$(OMe)_2$ (2.30), 3,5-$(OMe)_2$ (1.31) ($B1{,}o$, sterimol parameter; B1, for ortho positions)</td><td>78a</td></tr>
<tr><td colspan="7">2,6-$(OMe)_2$, -0.84; 4-OMe, 0.64; 2,4-Me_2, 0.57; H, -0.52; 2-OMe-4-CHO, -0.50; 2,6-Me_2, 0.41; 2-OMe-4-Me, 0.28; 4-Cl, -0.20; 3,4-Me_2, 0.17; 2,4,6-Me_3, -0.05; 4-Me, 0.03</td></tr>
<tr><td>2a</td><td>70% acetic acid</td><td>X-$C_6H_4NH_2$</td><td></td><td>-3.31</td><td>oxidation by vanadium(V) 35 °C
log $k_2 = -3.31\ (\pm0.79)\sigma^+ + 0.58(\pm0.41)$
$n = 7$, $s = 0.263$, $r^2 = 0.958$ (0.943), (0.977), $F_{1,5} = 115.44^{\S}$</td><td>78b</td></tr>
<tr><td colspan="7">2-NO_2, -0.44; 3-Cl, 0.30; 4-NO_2, 0.16; 3-NO_2, 0.16; H, -0.10; 2-Cl, -0.05; 4-Cl, -0.04</td></tr>
<tr><td>3</td><td>C_6H_5Cl</td><td>X-C_6H_4OH</td><td> </td><td>-3.27</td><td>hydrogen abstraction 60 °C
log $k = -3.27(\pm1.13)\sigma^+ + 1.16(\pm0.51)$
$n = 4$, $s = 0.219$, $r^2 = 0.987$ (0.787), (0.735), $F_{1,2} = 156^{\S}$</td><td>79</td></tr>
<tr><td colspan="7">H, -0.25; 3-COOEt, 0.16; 4-OMe, 0.07; 4-CMe_3, 0.03</td></tr>
<tr><td>4</td><td>benzene</td><td>X-C_6H_4OH</td><td> </td><td>-3.20</td><td>hydrogen abstraction 24 °C
log $k = -3.20(\pm0.35)\sigma^+ + 1.13(\pm0.15)$
$n = 10$, $s = 0.199$, $r^2 = 0.0.982$ (0.839), (0.899), $F_{1,8} = 447.04$,§ omit: 4-C_6H_5 (0.695)</td><td>80</td></tr>
<tr><td colspan="7">H, -0.340; 4-Br, 0.290; 4-CN, 0.170; 4-OMe, 0.157; 3-COOEt, 0.133; 3-CN, -0.130; 3-CMe_3, -0.129; 3,5-Me_2, -0.087; 4-COOMe, -0.072; 4-CMe_3, 0.009</td></tr>
<tr><td>5</td><td>CCl_4</td><td>X-C_6H_4OH</td><td> </td><td>-3.18</td><td>hydrogen abstraction 25 °C
log $k_2 = -3.18(\pm0.36)\sigma^+ + 0.013(\pm0.207)$
$n = 8$, $s = 0.238$, $r^2 = 0.987$ (0.896), (0.942), $F_{1,6} = 462$,§ omit: 4-COOMe (-1.98)</td><td>81</td></tr>
<tr><td colspan="7">H, -0.38; 4-Br, 0.34; 4-OMe, 0.20; 4-Me, -0.17; 4-F, -0.07; 4-CN, 0.05; 4-NO_2, 0.03; 4-OH, 0.01</td></tr>
<tr><td>6</td><td>aqueous 50% CH_3CN</td><td>X-$C_6H_4CH_2COOH$</td><td>Ce^{4+}</td><td>-3.10</td><td>oxidation room temperature
log $k_{rel} = -3.10(\pm0.98)\sigma^+ + 0.42(\pm0.25)$
$n = 4$, $s = 0.114$, $r^2 = 0.989$ (0.970), (0.939), $F_{1,2} = 183$,§ omit: H (-0.42)</td><td>82</td></tr>
<tr><td colspan="7">3-Me, 0.14; 4-Me, -0.08; 4-Cl, -0.03; 3-Cl, -0.03</td></tr>
<tr><td>7</td><td>aqueous 30% CH_3CN</td><td>X-$C_6H_4CH_2COOH$</td><td>Ce^{4+}</td><td>-2.96</td><td>oxidation room temperature
log $k_{rel} = -2.96(\pm0.58)\sigma^+ + 0.52(\pm0.24)$
$n = 8$, $s = 0.243$, $r^2 = 0.963$ (0.962), (0.982), $F_{1,6} = 157$,§ omit: H (-0.52)</td><td>82</td></tr>
<tr><td colspan="7">4-F, -0.38; 4-NO_2, 0.26; 3-Me, 0.20; 3-Cl, -0.19; 4-Me, 0.19; 3-NO_2, -0.13; 4-Br, 0.08; 4-Cl, -0.02</td></tr>
</table>

Table 1 (Continued)

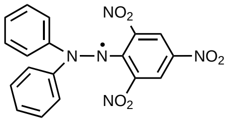
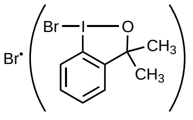
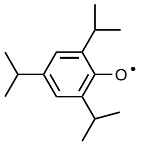
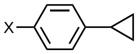
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
8	CCl_4	$C_6H_5CH_2X$	$Br^\bullet$(NBS)	−2.70	side-chain bromination 77 °C $\log k_{rel} = -2.70(\pm0.63)\sigma^+ + 0.25(\pm0.27)$ $n = 10$, $s = 0.374$, $r^2 = 0.924$ (0.956), (0.883), $F_{1,8} = 97.32$,§ omit: SC_6H_5 (1.51), CN (0.87)	83
	Br, −0.58; C_6H_5, 0.52; COOMe, 0.48; Me, 0.32; Cl, −0.29; H, −0.25; OMe, −0.15; OCOMe, −0.11; OC_6H_5, 0.06; NO_2, −0.01					
9	benzene	X-C_6H_4OH		−2.68	hydrogen abstraction 30 °C $\log k = -2.68(\pm0.37)\sigma^+ - 1.21(\pm0.32)B1{,}2 + 3.19(\pm0.45)$ $n = 18$, $s = 0.291$, $r^2 = 0.940$ (0.815), (0.957), $F_{1,16} = 35.3$§ (σ^+), $F_{1,15} = 61.3$§ ($B1{,}2$) ($B1{,}2$, sterimol parameter; $B1$, for position 2), omit; H (−0.64), 3-OMe (0.46), 2,3,4,5,6-Cl_5 (2.63)	84
	4-C_6H_5, 0.50; 4-OMe, 0.39; 2-C_6H_5, 0.37; 3-Me, −0.34; 4-NO_2, 0.31; 3-Cl, −0.30; 2-Cl, 0.30; 2,6-Me_2, −0.25; 4-Me, −0.24; 2,6-$(CHMe_2)_2$, 0.23; 4-F, −0.21; 2,6-$(CMe_3)_2$, −0.20; 4-Me-2,6-$(CMe_3)_2$, −0.18; 4-CMe_3, −0.16; 4-COMe, −0.10; 4-Cl, −0.09; 3-NO_2, −0.08; 2-Me, 0.06					
10	aqueous	X-C_6H_4OH	X-$C_6H_4O^\bullet$	−2.60	oxidation with Mn(III) 25 °C $\log k = -2.60(\pm0.68)\sigma^+ -6.48(\pm0.19)$ $n = 7$, $s = 0.190$, $r^2 = 0.950$ (0.849), (0.953), $F_{1,5} = 95.4$,§ omit: 4-COMe (−1.07)	84a
	4-Cl, 0.36; H, −0.17; 4-COOH, −0.14; 3-Me, −0.05; 3-Cl, 0.03; 4-Me, −0.01; 4-Et, −0.01					
11[b]	benzene	X-C_6H_4Me		−2.53	halogenation 50 °C with bromoarylalkoxyiodinane $\log k_{rel} = -2.53(\pm1.67)\sigma^+ + 0.26(\pm0.50)$ $n = 4$, $s = 0.220$, $r^2 = 0.955$ (0.879), (0.981), $F_{1,2} = 42.1$§§	85
	H, −0.26; 4-OMe, 0.14; 3-Br, 0.09; 3-F, 0.03					
12	acetic acid	X-$C_6H_4CH{=}CHMe$	Co^{3+}	−2.35	oxidation 60 °C $\log k_{rel} = -2.35(\pm0.63)\sigma^+ + 0.06(\pm0.26)$ $n = 5$, $s = 0.173$, $r^2 = 0.979$ (0.815), (0.887), $F_{1,3} = 143$§	86
	3-Cl, 0.19; 4-Me, −0.14; 4-OMe, 0.13; 4-Cl, −0.12; H, −0.06					
13	CH_3CN	X-C_6H_5	$Me_2CHOCOO^\bullet$	−2.12	substitution 60 °C $\log F = -2.12(\pm0.37)\sigma^+ + 0.04(\pm0.13)$ $n = 8$, $s = 0.152$, $r^2 = 0.970$ (0.866), (0.899), $F_{1,6} =$ 195§ (F, partial rate factors for meta and para positions)	87
	4-F, −0.27; 3-OMe, −0.15; 4-Cl, 0.15; 4-Me, 0.10; 3-Cl, 0.07; 3-Me, 0.04; 4-OMe, 0.04; 3-F, 0.02					
14	CH_2Cl_2	X-$C_6H_4CH_3$	(Cl)(TPP)Cr=O (TPP, tetraphenylporphyrin)	−2.08	hydrogen abstraction 27 °C $\log k_{rel} = -2.08(\pm1.26)\sigma^+ + (0.24(\pm0.52)$ $n = 5$, $s = 0.351$, $r^2 = 0.902$ (0.710), (0.927), $F_{1,3} = 27.5$§§	88
	3-Cl, 0.42; 4-Cl, −0.29; H, −0.24; 4-OMe, 0.20; 4-Me, −0.09					
15	C_6H_5Cl	X-C_6H_4OH		−2.05	hydrogen abstraction 30 °C $\log k_1 = -2.05(\pm1.21)\sigma^+ + 1.06(\pm0.28)$ $n = 4$, $s = 0.131$, $r^2 = 0.964$ (0.857), (0.948), $F_{1,2} = 53.8$,§§ omit: 3-COC_2H_5 (−0.67)	89
	3,5-Me_2, −0.14; 4-CMe_3, 0.12; 2,4,6-Cl_3, 0.05; 4-Br, −0.03					
16	aqueous 85% acetic acid	X-$C_6H_5CH(OH)CH_2C_6H_4$-X	Ce^{4+}	−1.99	oxidation room temperature $\log k_{rel} = -1.99(\pm0.05)\sigma^+ + 0.01(\pm0.02)$ $n = 4$, $s = 0.010$, $r^2 = 1.00$ (0.979), (0.981), $F_{1,2} > 1000$§	90
	4-Cl, 0.01; H, −0.01; 4-Me, −0.00; 4-NO_2, −0.00					
17	carbon disulfide		$Br^\bullet$	−1.85	bromination photochemical 20 °C $\log k_{rel} = -1.85(\pm0.17)\sigma^+ + 0.56(\pm0.07)$ $n = 8$, $s = 0.060$, $r^2 = 0.992$ (0.978), (0.973), $F_{1,6} = 717.8$§	91
	4-Br, −0.09; 4-Cl, −0.08; H, 0.06; 4-C_6H_5, 0.05; 3-Br, 0.03; 4-NO_2, 0.03; 4-I, 0.01; 4-CN, −0.00					
18	CCl_4	X-C_6H_4OH	$Me_3CO^\bullet$	−1.81	hydrogen abstraction 130 °C $\log k_{rel} = -1.81(\pm0.77)\sigma^+ + 0.11(\pm0.32)$ $n = 4$, $s = 0.123$, $r^2 = 0.981$ (0.819), (0.821), $F_{1,2} = 105$§	51
	4-Me, 0.13; H, −0.11; 4-OMe, −0.05; 4-Cl, 0.02					

Table 1 (Continued)

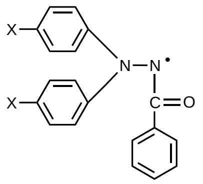
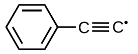
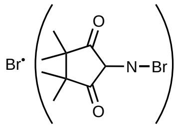
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
19	toluene	X,X′-$(C_6H_4)_2NNCOC_6H_5$		−1.79	dimerization −18 °C $\log k = -1.79(\pm 0.22)\sigma^+ - 3.41(\pm 0.16)$ $n = 8$, $s = 0.186$, $r^2 = 0.984$ (0.949), (0.967), $F_{1,6} = 379$§	92
		4-Br-4′-Br, −0.29; 4-Br, −0.24; 4-NO_2-4′-NO_2, 0.17; 4-Me-4′-Me, 0.13; 4-Me, 0.10; H, 0.07; 4-OMe, 0.05; 4-NO_2, 0.01				
20	acetic acid	X-C_6H_5	$O_2NCH_2^{\bullet}$	−1.76	nitromethylation catalyzed by $Ce(NH_4)_2(NO_3)_6$ unknown temperature $\log F = -1.76(\pm 0.45)\sigma^+ + 0.05(\pm 0.17)$ $n = 6$, $s = 0.146$, $r^2 = 0.967$(0.959), (0.866), $F_{1,4} = 119$,§ (*F*, partial rate factor for meta and para positions)	93
		3-Me, 0.16; 4-Me, 0.15; 4-OMe, −0.13; 3-Cl, −0.010; 4-Cl, −0.08; 3-OMe, 0.00				
21	CH_2Cl_2	X-C_6H_4Me	(Cl)(TPP)Fe═O (TPP: tetraphenylporphyrin)	−1.71	hydrogen abstraction 27 °C $\log k_{rel} = -1.71(\pm 0.06)\sigma^+ + 0.04(\pm 0.03)$ $n = 6$, $s = 0.025$, $r^2 = 0.999$ (0.922), (0.927), $F_{1,4} = 8610$§	88
		H, −0.04; 4-Me, 0.03; 4-NO_2, 0.01; 4-Cl, 0.01; 3-Cl, −0.01; 4-OMe, 0.00				
22[b]	CCl_3F	4-X-C_6H_4Me	Br_2/ethylene oxide	−1.69	bromination 23 °C $\log k = -1.69(\pm 0.72)\sigma^+ - 0.02(\pm 0.19)$ $n = 5$, $s = 0.126$, $r^2 = 0.948$ (0.918), (0.953), $F_{1,3} = 54.8$,§ omit: 4-F (−0.33)	49b
		3-F, 0.17; 3-Cl, −0.12; 4-Cl, −0.06; 4-Me, 0.03; H, −0.02				
23	methanol	4-X-2,6-di-*tert*-butylphenol	singlet oxygen	−1.68	photooxidation, quenching of singlet oxygen $\log k = -1.68(\pm 0.28)\sigma^+ + 6.12(\pm 0.07)$ $n = 7$, $s = 0.076$, $r^2 = 0.979$ (0.897), (0.953), $F_{1,5} = 237$,§ omit: 4-C_6H_5(0.48)	94
		H, −0.12; 4-Me, 0.10; 4-Br, 0.05; 4-CMe_3, −0.03; 4-COOEt, 0.03; 4-CH_2OH, −0.02; 4-$CH_2C_6H_5$, −0.01				
24[b]	CCl_3F	X-C_6H_4Me	$Br^{\bullet}$ (Br^2)	−1.66	bromination 23 °C $\log k = -1.66(\pm 0.49)\sigma^+ - 0.08(\pm 0.12)$ $n = 6$, $s = 0.101$, $r^2 = 0.958$ (0.927), (0.947), $F_{1,4} = 89.9$§	49b
		4-F, −0.15; 4-Cl, 0.10; H, 0.08; 3-F, −0.05; 4-Me, 0.01; 3-Cl, −0.01				
25	acetic acid	X-C_6H_5	$O_2NCH_2^{\bullet}$	−1.63	nitromethylation catalyzed by $Ce(OAc)_4$ at unknown temperature $\log F = -1.63(\pm 0.43)\sigma^+ + 0.07(\pm 0.16)$ $n = 6$, $s = 0.140$, $r^2 = 0.965$ (0.950), (0.866), $F_{1,4} = 111$,§ (*F*, partial rate factor for meta and para positions)	93
		3-Cl, −0.17; 3-OMe, 0.13; 3-Me, 0.12; 4-OMe, −0.11; 4-Me, 0.08; 4-Cl, −0.05				
26	reactants	X-C_6H_5		−1.62	substitution at unknown temperature $\log k_{rel} = -1.62(\pm 0.43)\sigma^+ - 0.21(\pm 010)$ $n = 7$, $s = 0.082$, $r^2 = 0.949$ (0.920), (0.973), $F_{1,5} = 92.9$§	95
		F, −0.15; Cl, 0.09; Me, 0.06; Et, 0.02; $CHMe_2$, −0.01; CMe_3, −0.01; Br, 0.00				
27	styrene	X-C_6H_4OH	styrylperoxy radicals	−1.60	hydrogen abstraction at 65 °C $\log k = -1.60(\pm 0.08)\sigma^+ + 3.47(\pm 0.04)$ $n = 11$, $s = 0.052$, $r^2 = 0.996$ (0.876), (0.892), $F_{1,9} = 1959$§	96
		3-Me, −0.09; 3-Cl, −0.08; 4-C(Me_2)CH_2CMe_3, 0.06; 4-CN, 0.05; 4-Cl, 0.04; 4-OMe, −0.04; 4-OH, 0.03; 3-OMe, 0.02; 4-C(Me)$_2$Et, −0.01; H, −0.01; 4-Me, 0.00				
27a	acetonitrile	X-C_6H_5	$C_6H_4COO^{\bullet}$	−1.58	substitution at 60 °C $\log F = -1.58(\pm 0.22)\sigma^+ + 0.08(\pm 0.09)$ $n = 5$, $s = 0.061$, $r^2 = 0.994$ (0.850), (0.874), $F_{1,3} = 542$,§ (*F*, partial rate constant for meta and para positions)	96a
		4-Cl, 0.09; 3-Cl, −0.05; 3-Me, −0.04; 4-OMe, −0.01; 4-Me, 0.00				
28[b]	benzene	4-X-$C_6H_4CH_3$		−1.58	bromination 19 °C $\log k_{rel} = -1.58(\pm 0.35)\sigma^+ - 0.04(\pm 0.14)$ $n = 5$, $s = 0.097$, $r^2 = 0.986$ (0.930), (0.904), $F_{1,3} = 213$§	97
		3-Br, −0.10; Me, 0.09; OMe, −0.08; Cl, 0.05; H, 0.04				

Table 1 (Continued)

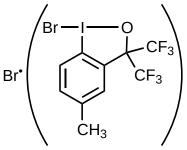
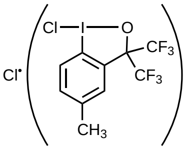
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
29[b]	CCl_3F and CCl_2CClF_2	4-X-C_6H_4Me	$Br^{\bullet}$ (NBS/Br_2)	−1.56	bromination at 23 °C $\log k = -1.56(\pm0.25)\sigma^+ - 0.010(\pm0.09)$ $n = 7$, $s = 0.98$, $r^2 = 0.980$ (0.867), (0.908), $F_{1,5} = 244^{\S}$	49b
		4-Me, −0.13; 4-F, −0.11; H, 0.10; 4-Cl, 0.08; 4-OMe, 0.07; 3-Cl, −0.01; 3-F, 0.01				
30[b]	CCl_3F	4-X-C_6H_4Me	$Br^{\bullet}$ (NBS/Br_2)	−1.53	bromination 23 °C $\log k = -1.53(\pm0.22)\sigma^+ - 0.11(\pm0.08)$ $n = 7$, $s = 0.085$, $r^2 = 0.984$ (0.900), (0.908), $F_{1,5} = 311^{\S}$	
		4-F, −0.12; H, 0.11; 4-Cl, 0.08; 4-Me, −0.04; 3-Cl, −0.04; 4-OMe, 0.01; 3-F, −0.01				
31	toluene	$(4\text{-X-}C_6H_4(C_6H_5)N\text{-})_2$		−1.52	dissociation 65 °C $\log k = -1.52(\pm0.79)\sigma^+ - 3.02(\pm0.37)$ $n = 6$, $s = 0.273$, $r^2 = 0.876$ (0.558), (0.871), $F_{1,4} = 28.3^{\S}$	98
		Me, −0.34; H, −0.27; Cl, 0.23; Br, 0.18; OEt, 0.13; OMe, 0.07				
32	aqueous	X-$C_6H_4O^-$	X-$C_6H_4O^{\bullet}$	1.51	oxidation by peroxy disulfate 30 °C $\log k = -1.51(\pm0.18)\sigma^+ + 0.18(\pm0.07)$ $n = 35$, $s = 0.198$, $r^2 = 0.895$ (0.825), (0.931), $F_{1,33} = 281$,§ omit: 2-COOH (0.85)	98a
		4-CMe_3, −0.52; 2-CMe_3, 0.42; 3-OMe, 0.41; 4-COOH, −0.35; 3-CMe_3, −0.34; 2-F, −0.30; 2-C_6H_5, 0.30; 4-C_6H_5, 0.30; 3-F, 0.21; 3-NO_2, 0.17; 2-I, 0.13; 3-Me, −0.12; H, −0.12; 4-Me, 0.10; 3-COOH, −0.10; 4-F, 0.10; 3-Cl, −0.08; 2-OMe, −0.08; 2-$CONH_2$, −0.07; 4-Cl, 0.06; 4-I, 0.05; 2-Me, 0.05; 3-I, −0.05; 4-OMe, −0.05; 4-Br, 0.04; 2-CHO, −0.03; 2-Cl, −0.03; 4-CN, −0.03; 2-CN, −0.03; 3-CN, 0.02; 2-Br, 0.02; 2-NO_2, −0.01; 3-CHO, −0.01; 3-Br, −0.01; 3-OC_6H_5, 0.00				
33[b]	benzene	X-C_6H_4Me		−1.50	halogenation 50 °C $\log k_{rel} = -1.50(\pm0.04)\sigma^+ - 0.01(\pm0.01)$ $n = 6$, $s = 0.008$, $r^2 = 1.000$ (0.945), (0.949), $F_{1,4} > 1000^{\S}$	85
		4-CMe_3, −0.01; 3-F, −0.01; H, 0.01; 4-Me, 0.01; 4-Cl, 0.00; 4-Br, 0.00				
33a	acetonitrile	X-C_6H_5	$MeC_6H_4COO^{\bullet}$	−1.48	substitution 60 °C $\log F = -1.48(\pm0.21)\sigma^+ + 0.15(\pm0.09)$ $n = 7$, $s = 0.091$, $r^2 = 0.985$ (0.844), (0.916), $F_{1,5} = 332^{\S}$ (F, partial rate constant for meta and para positions)	96a
		3-Me, −0.12; 4-Me, −0.10; 4-OMe, 0.09; 4-Cl, 0.08; 3-COMe, 0.05; 3-Cl, 0.02; 4-COMe, −0.01				
34	benzene	X-C_6H_4OH	$Me_3CO^{\bullet}$	−1.47	hydrogen abstraction 130 °C $\log k_{rel} = -1.47(\pm0.37)\sigma^+ + 0.03(\pm0.16)$ $n = 4$, $s = 0.060$, $r^2 = 0.993$ (0.845), (0.821), $F_{1,2} = 229^{\S}$	51
		4-Me, 0.07; H, −0.03; 4-OMe, −0.03; 4-Cl, −0.01				
35	CCl_4	X-C_6H_4Me	$Br^{\bullet}$ (NBS)	−1.46	hydrogen abstraction 80 °C $\log k_{rel} = -1.46(\pm0.17)\sigma^+ - 0.04(\pm0.07)$ $n = 16$, $s = 0.127$, $r^2 = 0.962$ (0.918), (0.937), $F_{1,14} = 353^{\S}$	99
		4-F, −0.30; 4-Br, 0.23; 4-CN, 0.16; 3-Me, 0.12; 4-NO_2, −0.10; 4-Cl, 0.10; 3-CN, −0.010; 3-NO_2, −0.08; H, 0.04; 4-CMe_3, −0.04; 4-OMe, −0.03; 3-COOH, −0.01; 3-Br, 0.01; 3-OMe, 0.00; 4-COOH, 0.00; 4-Me, 0.00				
36[b]	benzene	X-C_6H_4Me		1.45	halogenation 50 °C $\log k_{rel} = -1.45\ (\pm0.09)\sigma^+ + 0.01(\pm0.03)$ $n = 9$, $s = 0.038$, $r^2 = 0.995$ (0.888), (0.876), $F_{1,7} = 1578^{\S}$	
		3-OMe, 0.09; 3-F, −0.03; 4-Cl, −0.02; 4-Br, −0.02; 3-Br, −0.01; H, −0.01; 4-OMe, −0.01; 4-CMe_3, 0.01; 4-Me, 0.00				
37	toluene, X-toluene, chlorobenzene	X-C_6H_4Me	$Cl_3C^{\bullet}$	−1.45	hydrogen abstraction 50 °C $\log k_{rel} = -1.45(\pm0.11)\sigma^+ + 0.02(\pm0.04)$ $n = 8$, $s = 0.043$, $r^2 = 0.994$ (0.864), (0.857), $F_{1,6} = 1016^{\S}$	100
		3-Me, 0.06; 4-Br, 0.05; 3-Br, −0.04; 4-Me, −0.03; H, −0.02; 3-OMe, −0.01; 4-OMe, −0.01; 4-Cl, 0.00				
38	γ-picoline	X-C_6H_4Me	$Me_3COO^{\bullet}$	−1.44	hydrogen abstraction 110 °C $\log k_{rel} = -1.44(\pm0.62)\sigma^+ + 0.04(\pm0.10)$ $n = 5$, $s = 0.069$, $r^2 = 0.948$(0.794), (0.868), $F_{1,3} = 55.1$,§ omit: 3-Cl (0.34)	101
		4-Cl, 0.07; 4-C_6H_5, −0.06; 4-$CHMe_2$, 0.06; H, −0.04; 2-Cl, −0.02				
38a	CH_2Cl_4	X-C_6H_4Me	$Br^{\bullet}$ (NBS)	−1.43	bromination 80 °C $\log k_{rel} = -1.43(\pm0.15)\sigma^+ + 0.04(\pm0.05)$ $n = 8$, $s = 0.056$, $r^2 = 0.990$ (0.876), (0.870), $F_{1,6} = 591^{\S}$	56
		3-Cl, −0.09; 4-F, −0.07; 4-Cl, 0.06; 3-F, 0.05; H, 0.04; 3-Me, 0.02; 4-OMe, −0.01; 4-Me, 0.00				

Table 1 (Continued)

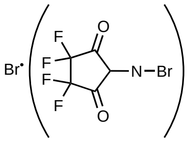
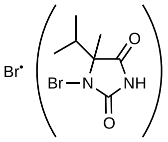
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
39	CCl_4	X-C_6H_4Me	Br• (NBS)	−1.43	bromination 80 °C log $k_{rel} = -1.43(\pm 0.14)\sigma^+ + 0.04(\pm 0.05)$ $n = 8$, $s = 0.056$, $r^2 = 0.991$ (0.869), (0.870), $F_{1,6} = 622$[§]	
		3-Cl, −0.08; 4-F, −0.06; 4-Cl, 0.06; 3-F, 0.05; H, 0.04; 4-Me, 0.01; 3-Me, −0.01; 4-OMe, 0.01				
39a[b]	benzene	3-CN-4-X-C_6H_3Me	Br• (NBS)	−1.43	bromination 80 °C log $k_{rel} = -1.43(\pm 0.02)\sigma^+ - 0.01(\pm 0.01)$ $n = 11$, $s = 0.015$, $r^2 = 1.000$ (0.947), (0.944), $F_{1,9} = 18540$,[§] omit: N=NC_6H_5(0.47)	102
		4-Cl, 0.02; 4-Me, −0.02; 4-NO_2, −0.02; 4-OMe, −0.02; 4-F, 0.01; 4-I, 0.0; 4-C_6H_5, 0.01; 4-CN, −0.01; H, 0.01; 4-Br, 0.00; 4-COMe, 0.00				
40[b]	benzene	4-X-C_6H_4Me	Br• (NBS)	−1.43	bromination 80 °C log $k_{rel} = -1.43(\pm 0.13)\sigma^+ + 0.01(\pm 0.06)$ $n = 6$, $s = 0.049$, $r^2 = 0.996$ (0.907), (0.888), $F_{1,4} = 1056$[§]	97
		CMe_3, 0.08; Me, −0.03; OMe, −0.03; CN, −0.02; H, −0.01; Cl, 0.00				
41[b]	benzene	X-C_6H_4Me	Br• (NBS)	−1.43	bromination 80 °C log $k_{rel} = -1.42(\pm 0.16)\sigma^+ + 0.01(\pm 0.08)$ $n = 5$, $s = 0.054$, $r^2 = 0.996$ (0.931), (0.911), $F_{1,3} = 778$[§]	103
		4-CMe_3, 0.08; 4-Me, −0.03; 4-OMe, −0.03; 4-CN, −0.02; 4-Cl, 0.01				
42[b]	benzene	4-X-C_6H_4Me		−1.41	bromination 80 °C log $k_{rel} = -1.41(\pm 0.17)\sigma^+ + 0.06(\pm 0.06)$ $n = 5$, $s = 0.040$, $r^2 = 0.996$ (0.963), (0.888), $F_{1,3} = 717$[§]	97
		H, −0.06; CMe_3, 0.03; Cl, 0.01; CN, 0.01; Me, 0.00				
42a	air	X-C_6H_5	HO•	−1.40	react with HO• radicals 25 °C log $k = -1.40(\pm 0.24)\sigma^+ - 11.65(\pm 0.13)$ $n = 19$, $s = 0.257$, $r^2 = 0.903$ (0.878), (0.930), $F_{1,17} = 158$,[§] omit: F (−0.72)	103a
		naphthalene, 0.59; Cl, −0.37; 1-OH, 3-Me, −0.33; Br, −0.30; 1,4-Me_2, 0.29; 1,2-Me_2, 0.28; H, −0.24; C_6H_5, 0.24; I, −0.19; 1,3-Cl_2, −0.19; 1,3-Me_2, 0.16; 1-OH,2-Me, −0.14; Et, 0.10; 1-OH, 4-Me, −0.10; CN, 0.09; NO_2, 0.08; $CHMe_2$, 0.07; 1,2-Cl_2, −0.06; Me, 0.0				
43	CCl_4	X-$C_6H_4CHMe_2$	Br• (NBS)	−1.40	hydrogen abstraction 80 °C log $k = -1.40(\pm 0.13)\sigma^+ - 0.09(\pm 0.07)$ $n = 10$, $s = 0.084$, $r^2 = 0.987$ (0.954), (0.947), $F_{1,8} = 590$[§]	104
		4-CN, 0.17; 4-NO_2, −0.10; 3-CN, −0.08; 3-NO_2, −0.07; 4-OMe, −0.05; 3-OMe, 0.04; 3-Br, 0.03; 4-CMe_3, 0.03; 4-COOH, 0.02; 3-COOH, 0.02				
43a	air	X-C_6H_5	HO•	−1.40	react with HO• radicals 300 K log $k = -1.40(\pm 0.16) - 11.8(\pm 0.11)$ $n = 31$, $s = 0.253$, $r^2 = 0.916$ (0.891), (0.907), $F_{1,29} = 319$,[§] omit: F_6 (−1.44)	104a
		3-C_4H_4-4, 0.62; F, −0.56; 1-OH, 2-NO_2, −0.43; 1,4-Cl_2, −0.37; C_6H_5, 0.31; 1-OH, 2-Me, −0.31; 1,3-Me_2, 0.27; Et, 0.27; 1,2-Cl_2, −0.27; CN, 0.24; $CHMe_2$, 0.24; NO_2, 0.23; 1,3,5-Me_3, 0.22; Cl, −0.22; 1-OH, 4-Me, −0.20; C_3H_7, 0.16; Me, 0.16; H, −0.14; Br, −0.13; 1-OH, 3-Me, −0.09; 1,2,3-Me_3, −0.07; 1,2-Me_2, 0.06; 1,3-Cl_2, −0.05; 1-NH_2, 4-Cl, 0.05; 1,2,4-Me_3, 0.04; 1,2,4-Cl_3, −0.04; NH_2, 0.04; I, −0.03; OH, −0.03; 1,4-Me_2, 0.03; OMe, 0.01				
44	1,2-dichloro-benzene	X-C_6H_4NHMe	tetralin hydroperoxy radicals	−1.39	hydrogen abstraction 65 °C log $k = -1.39(\pm 0.21)\sigma^+ + 3.66(\pm 0.06)$ $n = 4$, $s = 0.029$, $r^2 = 0.997$ (0.955), (0.974), $F_{1,2} = 653$[§]	105
		4-Me, 0.03; 3-Me, −0.02; H, −0.02; 4-COOMe, 0.01				
45[b]	CCl_4	X-C_6H_4Me		−1.39	bromination 80 °C log $k_{rel} = -1.39(\pm 0.43)\sigma^+ - 0.02(\pm 0.14)$ $n = 8$, $s = 0.162$, $r^2 = 0.911$ (0.804), (0.872), $F_{1,6} = 61.7$[§]	106
		4-F, −0.33; 3-Me, 0.18; 4-Br, 0.07; 4-Cl, 0.06; 4-OMe, 0.04; 4-Me, −0.04; H, 0.02; 3-Cl, −0.02				
46[b]	CCl_2CClF_2	4-X-C_6H_4Me	Br• (NBS/Br_2)	−1.38	bromination 23 °C log $k = -1.39(\pm 0.25)\sigma^+ - 0.10(\pm 0.09)$ $n = 7$, $s = 0.096$, $r^2 = 0.975$ (0.860), (0.908), $F_{1,5} = 199$[§]	49b
		4-Me, −0.15; H, 0.10; 4-OMe, 0.08; 4-F, −0.08; 3-F, 0.04; F-Cl, −0.01; 3-Cl, 0.00				

Table 1 (Continued)

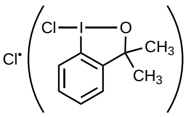
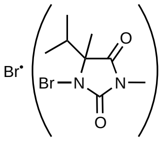
set	solvent	compound	radical	ρ^+	reaction, correlation	
47[b]	benzene	4-X-C_6H_4Me	$Br^•$ (Br_2)	−1.37	bromination 19 °C $\log k_{rel} = -1.37(\pm0.61)\sigma^+ - 0.07(\pm0.25)$ $n = 5$, $s = 0.170$, $r^2 = 0.945$ (0.938), (0.904), $F_{1,3} = 51.9$[§]	97
			3-Br, −0.18; Me, 0.15; OMe, −0.14; Cl, 0.10; H, 0.07			
48	CH_2Cl_2	X-C_6H_4Me	(Cl)(TPP)Mn═O (TPP: tetraphenylporphyrin)	−1.37	hydrogen abstraction 27 °C $\log k_{rel} = -1.37(\pm0.11)\sigma^+ + 0.06(\pm0.06)$ $n = 6$, $s = 0.049$, $r^2 = 0.997$ (0.922), (0.927), $F_{1,4} = 1216$[§]	88
			3-Cl, 0.07; H, −0.06; 4-NO_2, −0.03; 4-Me, 0.02; 4-OMe, 0.00; 4-Cl, 0.00			
49[b]	benzene	X-C_6H_4Me		−1.35	halogenation 50 °C $\log k_{rel} = -1.35(\pm0.03)\sigma^+ - 0.00(\pm0.01)$ $n = 5$, $s = 0.007$, $r^2 = 1.000$ (0.984), (0.983), $F_{1,3} > 1000$[§]	85
			3-Br, −0.01; 3-F, 0.01; 4-CMe_3, 0.00; H, 0.00; 4-Me, 0.00			
50[b]	benzene	4-X-C_6H_4Me	$Br^•$ (Br_2)	−1.35	bromination 80 °C $\log k_{rel} = -1.35(\pm0.14)\sigma^+ - 0.03(\pm0.06)$ $n = 7$, $s = 0.065$, $r^2 = 0.992$ (0.927), (0.904), $F_{1,5} = 588$[§]	97
			3-Br, −0.09; CMe3, 0.08; OMe, −0.06; Cl, 0.04; H, 0.03; CN, 0.01; Me, 0.00			
51[b]	benzene	X-C_6H_4Me	$Br^•$ (Br_2)	−1.34	bromination 80 °C $\log k_{rel} = -1.34(\pm0.15)\sigma^+ - 0.04(\pm0.07)$ $n = 6$, $s = 0.064$, $r^2 = 0.993$ (0.938), (0.922), $F_{1,4} = 581$[§]	103
			3-Br, −0.08; 4-CMe_3, 0.08; 4-OMe, −0.05; 4-Cl, 0.04; 4-CN, 0.01; 4-Me, 0.00			
52	reactants	4-X-2,6-di-*tert*-butylphenols	tetralin peroxide radical	−1.34	hydrogen abstraction 65 °C $\log k_{rel} = -1.34(\pm0.23)\sigma^+ + 0.09(\pm0.12)$ $n = 7$, $s = 0.119$, $r^2 = 0.979$ (0.928), (0.928), $F_{1,5} = 235$[§]	107
			4-NO_2, −0.14; 4-CMe_3, 0.12; 4-CN, 0.11; 4-Cl, 0.10; H, −0.09; 4-OMe, −0.07; 4-Me, −0.01			
53[b]	benzene	X-C_6H_4Me	$Br^•$ (NBS)	−1.34	bromination 80 °C $\log k_{rel} = -1.34(\pm0.15)\sigma^+ - 0.00(\pm0.06)$ $n = 7$, $s = 0.066$, $r^2 = 0.991$ (0.924), (0.904), $F_{1,5} = 555$[§]	97
			3-Br, −0.09; Me, 0.07; OMe, −0.06; CMe_3, 0.06; CN, 0.04; Cl, −0.02; H, 0.00			
54[b]	benzene	X-C_6H_4Me	$Br^•$ (NBS)	−1.33	bromination 80 °C $\log k_{rel} = -1.33(\pm0.17)\sigma^+ - 0.00(\pm0.08)$ $n = 6$, $s = 0.072$, $r^2 = 0.992$ (0.941), (0.922), $F_{1,4} = 465$[§]	103
			3-Br, −0.09; Me, 0.07; OMe, −0.06; CMe_3, 0.06; CN, 0.04; Cl, −0.02; H, 0.00			
55[b]	CCl_4	4-X-C_6H_4Me	$Br^•$ (NBS)	−1.32	halogenation 80 °C $\log k = -1.32(\pm0.16)\sigma^+ + 0.01(\pm0.06)$ $n = 9$, $s = 0.075$, $r^2 = 0.982$ (0.823), (0.879), $F_{1,7} = 384$[§] omit: C_6H_5 (0.25)	108
			4-CH_2Cl, 0.15; 4-CH_2CN, −0.11; 4-CMe_3, −0.04; 4-OMe, 0.02; 4-Me, −0.01; H, −0.01; 4-CN, 0.01; 4-Br, −0.01; 4-Cl, 0.00			
56	benzene	X-$C_6H_4OCH_2COC_6H_5$	X-$C_6H_4O^•$ and $^•CH_2COC_6H_5$	−1.32	photochemical cleavage $\log k_{rel} = -1.32(\pm0.31)\sigma^+ + 8.07(\pm0.16)$ $n = 9$, $s = 0.197$, $r^2 = 0.934$ (0.830), (0.907), $F_{1,7} = 99.4$,[§] omit: 3-Cl (−0.58)	109
			4-COOMe, −0.32; 4-CN, 0.25; 3-OH, 0.25; 4-OH, 0.14; 4-OMe, −0.11; 4-Cl, −0.010; 3-Me, −0.07; 4-Me, −0.02; H, −0.01			
57	reactants	X-C_6H_5	ground-state atomic oxygen	−1.31	hydroxylation 30 °C $\log k = -1.32(\pm0.20)\sigma^+ + 0.14(\pm0.06)$ $n = 14$, $s = 0.101$, $r^2 = 0.945$ (0.827), (0.844), $F_{1,12} = 204$,[§] (*F*, partial rate factors for meta and para positions), omit: 3,4-Me_2 (−0.32), 4-CF_3 (0.38)	110
			4-F, −0.19; 3-Et, 0.15; H, −0.14; 4-Me, 0.13; 3,4,5-Me_3, −0.12; 3-Me, 0.07; 4-Et, 0.06; 3-F, 0.04; 3-CF_3, −0.03; 3-CMe_3, 0.03; 3,5-Me_2, −0.02; 3-OMe, 0.02; 4-CMe_3, 0.01; 4-OMe, −0.01			
58[b]	CCl_4	X-C_6H_4Me		−1.31	bromination 80 °C $\log k_{rel} = -1.31(\pm0.26)\sigma^+ - 0.14(\pm0.9)$ $n = 9$, $s = 0.113$, $r^2 = 0.952$ (0.899), (0.877), $F_{1,7} = 138$,[§] omit: 3,4-OMe (0.24)	106
			3-Br, −0.18; H, 0.14; 3-Me, 0.12; 4-Cl, 0.11; 4-F, −0.07; 4-Me, −0.07; 4-OMe, −0.05; 4-Br, 0.00; 3-Cl, 0.00			

Table 1 (Continued)

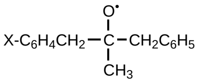
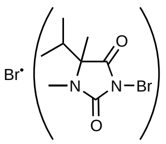
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
59[b]	CCl_4	$X\text{-}C_6H_4CH_2Cl$	$Br^\bullet$ (NBS)	−1.30	halogenation 80 °C $\log k = -1.30(\pm 0.14)\sigma^+ - 0.01(\pm 0.03)$ $n = 8$, $s = 0.036$, $r^2 = 0.988$ (0.910), (0.911), $F_{1,6} = 485^§$	107
		4-F, −0.08; 4-C_6H_5, 0.03; 4-CMe_3, 0.01; 4-Cl, 0.01; H, 0.01; 3-Cl, 0.01; 4-CH_2Cl, 0.01; 3-F, −0.01				
60	CCl_4		 $X\text{-}C_6H_4CH_2\text{-}\overset{O^\bullet}{\underset{CH_3}{C}}\text{-}CH_2C_6H_5$	−1.29	β-scission (elimination of $X\text{-}C_6H_4CH_2^\bullet$) 30 °C $\log k_{rel} = -1.29(\pm 0.87)\sigma^+ - 0.12(\pm 0.37)$ $n = 4$, $s = 0.140$, $r^2 = 0.953$ (0.946), (0.821), $F_{1,2} = 40.5^§$	111
		3-Cl, −0.14; H, 0.12; 4-Me, 0.06; 4-OMe, −0.04				
60a	CCl_4	$X\text{-}C_6H_4Me$	$Br^\bullet$ (NBS)	−1.28	hydrogen abstraction 40 °C $\log k_{rel} = -1.28(\pm 0.15)\sigma^+ - 0.05(\pm 0.05)$ $n = 8$, $s = 0.061$, $r^2 = 0.986$ (0.842), (0.870), $F_{1,6} = 430^§$	56
		3-Me, 0.07; 4-CMe3, 0.06; 4-OMe, −0.04; 3-OMe, −0.03; 4-Br, −0.02; 3-Br, −0.02; 4-Me, −0.01; H, 0.01; 4-Cl, 0.00				
61[b]	reactants	$X\text{-}C_6H_4Me$	$Br^\bullet$ ($BrCCl_3$)	−1.24	bromination 50 °C $\log k_{rel} = -1.24(\pm 0.10)\sigma^+ - 0.01(\pm 0.03)$ $n = 9$, $s = 0.042$, $r^2 = 0.991$ (0.882), (0.838), $F_{1,7} = 827^§$	112
		3-Me, 0.07; 4-CMe_3, 0.06; 4-OMe, −0.04; 3-OMe, −0.03; 4-Br, −0.02; 3-Br, −0.02; 4-Me, −0.01; H, 0.01; 4-Cl, 0.00				
62[b]	CCl_4	$X\text{-}C_6H_4Me$		−1.23	bromination 80 °C $\log k_{rel} = -1.23(\pm 0.24)\sigma^+ - 0.19(\pm 0.08)$ $n = 9$, $s = 0.102$, $r^2 = 0.956$ (0.921), (0.877), $F_{1,7} = 151^§$	106
		H, 0.19; 3-Me, 0.13; 4-F, −0.11; 4-Me, −0.07; 3-Br, −0.05; 4-Br, −0.05; 4-OMe, −0.02; 3-Cl, −0.01; 4-Cl, −0.01				
63	styrene	$X\text{-}C_6H_4OH$	styrylperoxy radical	−1.23	hydrogen abstraction 65 °C $\log k = -1.23(\pm 0.11)\sigma^+ - 0.40(\pm 0.05)B1{,}6 - 2.07(\pm 0.11)$ $n = 38$, $s = 0.108$, $r^2 = 0.957$ (0.870), (0.901), $F_{1,36} = 66.0^§$ (σ^+), $F_{1,35} = 250^§$ ($B1{,}6$) ($B1{,}6$, sterimol parameter; $B1$, for position 6)	113
		2-CMe_3, 4-OMe, 0.22; 2,6-$(CMe_3)_2$, −0.18; 2,6-$(C(Me_2)CH_2CMe_3)_2$, 4-Me, −0.18; 2,6-$(CHMe_2)_2$, 4-Me, 0.17; 2-CMe_3, 6-Me, −0.17; 2,6-$(CMe_3)_2$, 4-CN, 0.17; 2,6-Me_2, 4-CN, −0.16; 2-CMe_3, 4-Me, 0.15; 2,6-Me_2, −0.14; 2,3,5,6-Me_4, −0.13; 2,6-$(CEt_3)_2$, 4-Me, 0.12; 2,6-$(CMe_3)_2$, 4-NO_2, 0.12; 2,6$(CHMe_2)_2$, 0.12; 2,6-$(CMe_3)_2$, 4-Cl, 0.11; 2,6-Me_2, 4-Cl, 0.11; 2-CMe_3, 5-Me, 0.10; 2-CMe_3, 4-CN, −0.10; 2-CMe_3, 5,6-Me_2, 0.10; 2-CMe_3, 4-Me, 6-$C(Me_2)CH_2CMe_3$, −0.08; 2,6-Et_2, −0.07; 2,3,4,5,6-Me_5, −0.06; 2,6-$(CMe_3)_2$, 4-CHO, −0.05; 2-$C(Me_2)Et$, 4-Me, 0.05; 2,4,5-Me_3, −0.05; 2-CEt_3, 4-Me, −0.04; 2,3-Me_2, −0.03; 2,6-$(C(Me_2)Et_2$, 4-Me, −0.03; 2,6-$(CMe_3)_2$, 4-$C(Me_2)Et$, 0.03; 2,4-Me_2, 0.03; 2,4,6-Me_3, −0.02; 2-CMe_3, 0.02; 2,6-$(CMe_3)_2$, 4-$C(Me_2)CH_2CMe_3$, −0.02; 2,6-$(CMe_3)_2$, 4-Me, −0.02; 2-$CHMe_2$, 4-Me, −0.02; 2,6-$(CMe_3)_2$, 4-$C(Me_2)C_6H_5$, −0.01; 2,4,6-$(CMe_3)_3$, 0.01; 2-$C(Me_2)CH_2CMe_3$, 4-Me, 0.00; 2,6-$(CMe_3)_2$, 4-OMe, 0.00				
64[b]	CCl_2FCCl_2F and CCl_2FCClF_2	4-X-C_6H_4Me	$Br^\bullet$ (NBS/Br_2)	−1.20	bromination 23 °C $\log k = -1.20(\pm 0.21)\ \sigma^+ - 0.12(\pm 0.08)$ $n = 7$, $s = 0.081$, $r^2 = 0.977$ (0.951), (0.908), $F_{1,5} = 210^§$	49b
		H, 0.12; 3-F, −0.08; 4-OMe, −0.06; 4-Me, 0.06; 4-F, −0.05; 4-Cl, 0.04; 3-Cl, −0.03				
65[b]	CCl_2FCCl_2F	4-X-C_6H_4Me	$Br^\bullet$ (NBS/Br_2)	−1.20	bromination 23 °C $\log k = -1.20(\pm 0.19)\ \sigma^+ - 0.11(\pm 0.07)$ $n = 7$, $s = 0.071$, $r^2 = 0.982$ (0.921), (0.908), $F_{1,5} = 274^§$	49b
		H, 0.11; 4-Cl, 0.07; 3-F, −0.05; 3-Cl, −0.05; 4-F, −0.04; 4-OMe, −0.02; 4-Me, −0.02				
66	CCl_4	$X\text{-}C_6H_4Me$	$Br^\bullet$ (NBS)	−1.19	hydrogen abstraction 10 °C $\log k = -1.19(\pm 0.21)\ \sigma^+ - 0.06(\pm 0.07)$ $n = 8$, $s = 0.085$, $r^2 = 0.969$ (0.806), (0.870), $F_{1,6} = 184^§$	56
		3-F, 0.12; 4-F, −0.08; 4-OMe, 0.08; 4-Cl, −0.07; 3-Me, −0.06; H, 0.06; 4-Me, −0.05; 3-Cl, 0.01				
67	CH_2Cl_2	$X\text{-}C_6H_4Me$	$Br^\bullet$ (NBS)	−1.19	hydrogen abstraction 10 °C $\log k = -1.19(\pm 0.21)\sigma^+ - 0.05(\pm 0.08)$ $n = 8$, $s = 0.086$, $r^2 = 0.968$ (0.804), (0.870), $F_{1,6} = 184^§$	56
		3-F, 0.12; 4-F, −0.09; 4-OMe, 0.09; 4-Cl, −0.07; 3-Me, −0.06; 4-Me, −0.06; H, 0.05; 3-Cl, 0.01				

Table 1 (Continued)

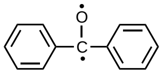
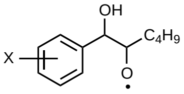
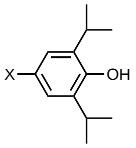
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
68	C_6H_5Cl	X-C_6H_4SH	$C_6H_4COO^•$	−1.18	hydrogen abstraction 100 °C $\log k_{rel} = -1.18(\pm 0.10)\sigma^+ + 0.02(\pm 0.04)$ $n = 5, s = 0.023, r^2 = 0.998$ (0.795), (0.830), $F_{1,3} = 1042^§$	114
					4-Me, −0.03; H, −0.02; 4-Cl, 0.02; 4-F, 0.02; 4-OMe, 0.01	
69[b]	CCl_2FCCl_2F	4-X-C_6H_4Me	$Br^•$ (Br_2)	−1.17	bromination 23 °C $\log k = -1.17(\pm 0.49)\ \sigma^+ - 0.13(\pm 0.12)$ $n = 6, s = 0.102, r^2 = 0.916$ (0.913), (0.947), $F_{1,4} = 43.8^§$	49b
					H, 0.13; 3-Cl, −0.09; 4-Cl, 0.08; 4-F, −0.08; 4-Me, −0.05; 3-F, 0.01	
70	benzene	X-C_6H_4Me		−1.17	hydrogen abstraction 22 °C $\log k_{rel} = -1.17(\pm 0.24)\ \sigma^+ + 0.05(\pm 0.08)$ $n = 7, s = 0.068, r^2 = 0.968$ (0.646), (0.699), $F_{1,5} = 155^§$	115
					4-Me, −0.09; 4-Cl, 0.07; 3,5-Me_2, 0.06; 4-F, −0.05; H, −0.05; 4-OMe, 0.03; 3-Me, 0.03	
71	reactants	4-X-2,6-di-*tert*-butylphenols	styrylperoxy radical	−1.15	hydrogen abstraction 65 °C $\log k_{rel} = -1.15(\pm 0.22)\ \sigma^+ + 0.21(\pm 0.11)$ $n = 7, s = 0.114, r^2 = 0.974$ (0.846), (0928), $F_{1,5} = 186^§$	108
					H, −0.21; 4-OMe, 0.09; 4-CN, 0.08; 4-Cl, 0.06; 4-Me, −0.03; 4-NO_2, 0.00; 4-CMe_3, 0.00	
72	CCl_4	X-C_6H_4OH	$Me_3CO^•$	−1.13	hydrogen 120 °C $\log k = -1.13(\pm 0.18)\sigma^+ + 1.39(\pm 0.06)$ $n = 11, s = 0.082, r^2 = 0.959$ (0.915), (0972), $F_{1,9} = 210^§$	116
					3-Me, −0.19; 4-Me, 0.12; 3,4,5-Me3, −0.06; 4-CMe3, 0.05; 3-Cl, 0.05; H, 0.04; 3-OMe, −0.03; 4-Cl, 0.02; 3,5-Me_2, 0.01; 3-F, −0.01; 4-CN, 0.00	
73[b]	CCl_4	X-$C_6H_4CH_2CH_2Cl$	$Br^•$ (NBS)	−1.12	bromination 80 °C $\log k = -1.12(\pm 0.17)\sigma^+ - 0.03(\pm 0.04)$ $n = 8, s = 0.047, r^2 = 0.977$ (0.832), (0.901), $F_{1,6} = 270^§$	117
					4-F, −0.09; 4-CMe_3, 0.06; H, 0.03; 4-Br, 0.03; 4-Me, −0.02; 3-F, 0.01; 4-Cl, 0.01; 3-Cl, 0.00	
74[b]	CCl_4	X-C_6H_4Me	$Br^•$ ($CH_3CONHBr$)	−1.11	bromination 80 °C $\log k_{rel} = -1.11(\pm 0.41)\sigma^+ - 0.09(\pm 0.15)$ $n = 7, s = 0.147, r^2 = 0.908$ (0.738), (0.877), $F_{1,5} = 49.3^§$	106
					4-F, −0.18; 4-Me, −0.17; 4-OMe, 0.14; 3-Br, 0.11; H, 0.09; 4-Cl, 0.07; 4-Br, −0.05	
75	CH_3CN			−1.09	decay of radicals 25 °C $\log k_{rel} = -1.09(\pm 0.24)\sigma^+ - 0.16(\pm 0.12)$ $n = 12, s = 0.169, r^2 = 0.910$ (0.860), (0.937), $F_{1,10} = 101,^§$ omit: 3-OMe (0.54)	118
					4-CF_3, 0.24; 4-CN, −0.24; 4-Br, −0.23; 3-Cl, 0.22; H, 0.16; 3-Br, −0.11; 3-NO_2, 0.09; 4-OMe, 0.08; 4-Me, −0.07; 3-Me, −0.07; 4-Cl, −0.05; 4-NO_2, −0.02	
76	isopentane		$Me_3COO^•$	−1.09	hydrogen abstraction −37 °C $\log k_2 = -1.09(\pm 0.0312)\sigma^+ - 0.54(\pm 0.15)$ $n = 8, s = 0.166, r^2 = 0.922$ (0.825), (0.918), $F_{1,6} = 71.0,^§$ omit: 4-Cl (0.36)	119
					4-CN, 0.26; 4-$COOCMe_3$, −0.21; 4-COOH, −0.16; 4-CMe_3, 0.10; 4-Me, −0.10; H, 0.07; 4-OMe, 0.05; 4-CHO, −0.02	
76a	40% *tert*-butyl alcohol	X-$C_6H_4NH_2$		−1.07	oxidation by peroxy disulfate 45 °C $\log k_2 = -1.07(\pm 0.15)\sigma^+ - 1.26(\pm 0.29)$F, 2 − 0.18(±0.14)Mr, 6 − 0.08 (0.10) $n = 15, s = 0.093, r^2 = 0.984$ (0.953), (0.914), $F_{1,13} = 74.1^§$ (σ^+), $F_{1,12} = 57.9^§$ (F,2), $F_{1,11} = 7.41^{§§}$ (Mr,6)	119a
					2-OMe, 0.17; H, 0.15; 2-I, −0.12; 2-$CHMe_2$, −0.11; 2-OEt, −0.07; 2-Et, −0.06; 2-COMe, 0.06; 2-Br, −0.04; 2-NO_2, 0.04; 2-Me, 0.03; 2-Me, 6-Et, −0.03; 2-COO^-, −0.03; 2-Cl, −0.02; 2,6-$(CHMe_2)_2$, 0.02; 2-F, 0.01	
77	methanol	X-$C_6H_4CH{=}CH_2$	$(^-OOC)_2CH^•$	−1.06	addition 20 °C $\log k_{rel} = -1.06(\pm 0.15)\sigma^+ - 0.02(\pm 0.06)$ $n = 5, s = 0.037, r^2 = 0.994$ (0.971), (0.977), $F_{1,3} = 501^§$	120
					3-Cl, −0.05; 3-NO_2, 0.03; H, 0.02; 4-Cl, −0.01; 4-Me, 0.01	
78[b]	benzene	4-X-C_6H_4Me	$Br^•$ (Br_2)	−1.06	bromination 80 °C $\log k_{rel} = -1.06(\pm 0.15)\sigma^+ - 0.02(\pm 0.07)$ $n = 7, s = 0.068, r^2 = 0.985$ (0.907), (0.904), $F_{1,5} = 332^§$	97
					3-Br, −0.11; CMe_3, 0.08; CN, 0.06; OMe, −0.03; H, −0.02; Cl, 0.01; Me, 0.01	

Table 1 (Continued)

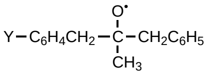
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
79	CCl_4	X-$C_6H_4CHMe_2$	$Br^\bullet$ (Br_2)	−1.05	hydrogen abstraction 80 °C $\log k = -1.05(\pm0.13)\sigma^+ - 0.05(\pm0.08)$ $n = 6$, $s = 0.066$, $r^2 = 0.992$ (0.936), (0.947), $F_{1,4} = 513^{\S}$	104
		4-CN, 0.08; 4-NO_2, −0.08; 4-CMe_3, −0.04; 3-Br, 0.04; 3-NO_2, −0.02; 4-OMe, 0.01				
80	methanol	X-$C_6H_4CH{=}CH_2$	$(^-OOC)_2CH^\bullet$	−1.05	addition 20 °C $\log k_{rel} = -1.05(\pm0.27)\ \sigma^+ - 0.18(\pm0.13)$ $n = 6$, $s = 0.118$, $r^2 = 0.967$ (0.917), (0.927), $F_{1,4} = 115^{\S}$	120
		H, 0.19; 4-Me, −0.10; 4-Cl, −0.10; 4-OMe, 0.03; 3-Cl, −0.03; 4-NO_2, 0.00				
81	CH_3CN	X-C_6H_4OH	$Me_3CO^\bullet$	−1.02	hydrogen abstraction 130 °C $\log k_{rel} = -1.02(\pm0.16)\sigma^+ - 0.02(\pm0.07)$ $n = 4$, $s = 0.026$, $r^2 = 0.997$ (0.857), (0.821), $F_{1,2} > 1000^{\S}$	51
		4-Cl, −0.03; H, 0.02; 4-Me, 0.01; 4-OMe, −0.01				
82	benzene	X-$C_6H_4CH{=}CH_2$	$MeCOOO^\bullet$	−1.02	photoepoxidation 25 °C $\log k_{rel} = -1.02(\pm0.33)\sigma^+ - 0.07(\pm0.14)$ $n = 5$, $s = 0.092$, $r^2 = 0.969$ (0.828), (0.887), $F_{1,3} = 93.4^{\S}$	121
		4-Me, −0.13; H, 0.07; 4-Cl, 0.04; 4-OMe, 0.04; 3-Cl, −0.03				
83	benzene	X-$C_6H_4CH{=}CH_2$	$C_6H_5COOO^\bullet$	−1.00	photoepoxidation 25 °C $\log k_{rel} = -1.00(\pm0.16)\sigma^+ - 0.05(\pm0.06)$ $n = 5$, $s = 0.043$, $r^2 = 0.993$ (0.918), (0.887), $F_{1,3} = 386^{\S}$	121
		H, 0.05; 4-Cl, −0.05; 4-OMe, −0.01; 3-Cl, 0.00; 4-Me, 0.00				
84	benzene	X-$C_6H_4CH{=}NC_6H_5$	$Me_3COO^\bullet$	−0.99	hydrogen abstraction 130 °C $\log k_{rel} = -0.99(\pm0.16)\sigma^+ - 0.059(\pm0.05)$ $n = 6$, $s = 0.038$, $r^2 = 0.986$ (0.924), (0.957), $F_{1,4} = 269,^{\S}$ omit: 4-OMe (−1.04), 4-F (−0.28)	122
		4-Me, 0.05; H, −0.03; 3-CN, 0.03; 4-Cl, −0.03; 3-Me, −0.01; 4-Br, −0.01				
84a	benzene	X-C_6H_4SMe	singlet oxygen	−0.96	oxidation 35 °C $\log k = -0.96(\pm0.58)\sigma^+ + 5.95(\pm0.57)$ $n = 4$, $s = 0.175$, $r^2 = 0.962$ (0.905), (0.986), $F_{1,2} = 50.3,^{\S}$ omit: 4-OMe (−0.39)	122a
		4-OH, 0.21; 4-NMe_2, −0.10; 4-Me, −0.07; H, −0.04				
85	benzene	X-$C_6H_4CH{=}CH_2$	$C_6H_4COOO^\bullet$	−0.96	epoxidation $\log k_{rel} = -0.96(\pm0.28)\sigma^+ - 0.09(\pm0.112)$ $n = 5$, $s = 0.079$, $r^2 = 0.975$ (0.879), (0.887), $F_{1,3} = 386^{\S}$	121
		H, 0.09; 4-Me-, −0.07; 3-Cl, −0.06; 4-Cl, 0.04; 4-OMe, 0.00				
86	CCl_4	 $Y{-}C_6H_4CH_2{-}\overset{O^\bullet}{\underset{CH_3}{C}}{-}CH_2C_6H_5$		−0.91	β-scission (elimination of Y-$C_6H_4CH_2^\bullet$) 25 °C $\log k_{rel} = -0.91(\pm0.28)\sigma^+ - 0.04(\pm0.03)$ $n = 6$, $s = 0.026$, $r^2 = 0.996$ (0.890), (0.888), $F_{1,4} = 860^{\S}$	123
		H, 0.04; 4-Me, −0.03; 3-Cl, −0.01; 4-OMe, 0.01; 4-Cl, 0.00; 4-F, 0.00				
87	benzene	X-$C_6H_4CH_2C_6H_5$	$Br^\bullet$ (NBS)	−0.90	bromination 40 °C $\log k_{rel} = -0.90(\pm0.07)\sigma^+ - 0.04(\pm0.02)$ $n = 8$, $s = 0.026$, $r^2 = 0.993$ (0.842), (0.797), $F_{1,6} = 860,^{\S}$ omit: 4-F (−0.13)	124
		H, 0.04; 4-Cl, −0.04; 4-CMe_3, 0.02; 4-OC_6H_5, −0.02; 4-Br, −0.01; 3-F, 0.01; 3-Cl, 0.00; 3-Br, 0.00				
88	CCl_4	X-$C_6H_4CH_2CMe_3$	$Cl_3C^\bullet$	−0.89	hydrogen abstraction 70 °C $\log k_{rel} = -0.89(\pm0.16)\sigma^+ - 0.07(\pm0.07)$ $n = 9$, $s = 0.092$, $r^2 = 0.960$ (0.926), (0.908), $F_{1,7} = 169^{\S}$	125
		4-NO_2, −0.15; 4-CMe_3, −0.11; 4-Me, 0.09; 4-OMe, −0.07; 3-Cl, 0.07; 3-CF_3, 0.06; 3-Me, 0.03; 4-Cl, 0.02				
89	50% methanol	X-$C_6H_4NMe_2$	singlet oxygen	−0.81	quenching of singlet oxygen 25 °C $\log k = -0.81(\pm0.24)\sigma^+ + 7.75(\pm0.22)$ $n = 10$, $s = 0.184$, $r^2 = 0.921$ (0.843), (0.961), $F_{1,8} = 58.7,^{\S}$ omit: 3,4-$(OMe)_2$ (0.86), 3-NMe_2 (0.77) (B1,2, sterimol parameter for ortho position)	126
		H, −0.32; 3-OMe, 0.22; 2-OMe, 0.25; 4-OMe, 0.39; 2,4,6-Me_3, −0.42; 4-Cl, 0.01; 2-NMe_2, −0.01; 2,4-Me_2, −0.24; 4-NMe_2, 0.21; 4-Me, −0.08				

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
90	mesitylene	X-$C_6H_4CH_2CH_2Br$	$Cl_3C^\bullet$	−0.84	hydrogen abstraction 70 °C $\log k_{rel} = -0.84(\pm 0.07)\ \sigma^+ + 0.00(\pm 0.03)$ $n = 8$, $s = 0.032$, $r^2 = 0.993$ (0.913), (0.897), $F_{1,6} = 850^§$	127
					3-CF_3, −0.04; 4-CMe_3, 0.04; 4-F, −0.03; 3-Cl, 0.03; 4-OMe, −0.03; 4-Cl, 0.02; 4-Me, 0.01; H, 0.00	
91	benzene 66.7% di-*tert*-butyl peroxide	X-C_6H_4OH	$Me_3CO^\bullet$	−0.82	hydrogen abstraction 22 °C $\log k = -0.82(\pm 0.08)\sigma^+ + 8.54(\pm 0.03)$ $n = 12$, $s = 0.048$, $r^2 = 0.982$ (0.824), (0.867), $F_{1,10} = 537^§$ omit: 4-OH (0.208)	128
					4-I, 0.11; 4-Et, −0.06; 4-Me, −0.05; 4-C_6H_5, 0.04; 4-Br, −0.04; 4-OEt, 0.02; 4-OMe, 0.02; H, −0.02; 4-F, −0.02; 4-Cl, 0.01; 4-CN, −0.01; 4-CMe_3, −0.01	
92	reactants	X-C_6H_4OH	$Me_3CO^\bullet$	−0.82	hydrogen abstraction 25 °C $\log k_{rel} = -0.82(\pm 0.16)\sigma^+ + 8.57(\pm 0.07)$ $n = 5$, $s = 0.052$, $r^2 = 0.989$ (0.887), $F_{1,3} = 264^§$	129
					4-CF_3, 0.05; H, −0.05; 4-OMe, 0.05; 4-CMe_3, −0.03; 4-Cl, −0.01	
93	benzene	X-C_6H_4Me	$Me_3CO^\bullet$	−0.80	hydrogen abstraction 40 °C $\log k_{rel} = -0.80(\pm 0.15)\sigma^+ - 0.01(\pm 0.05)$ $n = 8$, $s = 0.051$, $r^2 = 0.982$ (0.967), (0.977), $F_{1,6} = 160^§$ omit: 4-OC_6H_5 (−0.23)	130
					4-C_6H_5, 0.08; 4-Cl, −0.07; 4-Me, −0.05; 3-Cl, 0.03; 3-Me, 0.02; 4-Br, −0.02; H, 0.01; 4-CN, 0.00	
94	CCl_4	X-$C_6H_4CH_2COC_6H_5$	$Br^\bullet$ (NBS)	−0.78	hydrogen abstraction 80 °C $\log k_{rel} = -0.78(\pm 0.16)\sigma^+ - 0.06(\pm 0.05)$ $n = 7$, $s = 0.050$, $r^2 = 0.968$ (0.844), $F_{1,5} = 149^§$	131
					4-Cl, −0.09; H, 0.06; 4-CMe_3, 0.03; 4-OC_6H_5, −0.02; 3-Br, 0.02; 4-Br, 0.01; 3-Cl, 0.00	
95	1,2-dichlorobenzene	diphenylamines	tetralin hydroperoxide radicals	−0.78	hydrogen abstraction 65 °C $\log k = -0.78(\pm 0.14)\sigma^+ + 4.50(\pm 0.14)$ $n = 7$, $s = 0.144$, $r^2 = 0.975$ (0.957), (0.928), $F_{1,5} = 197^§$	105
					4,4′-$(OMe)_2$, −0.02; 4-OMe, 0.19; H, 0.10; 4-NO_2, −0.10; 4,4′-$(NO_2)_2$, −0.06; 3-Cl, 0.05; 4,4′-Me_2, 0.02	
96	aqueous 50% acetic acid	X-C_6H_4SMe		−0.78	oxidation by peroxodiphosphate 35 °C $\log k_2 = -0.78(\pm 0.10)\sigma^+ - 2.18(\pm 0.04)$ $n = 13$, $s = 0.066$, $r^2 = 0.962$ (0.942), (0.921), $F_{1,11} = 274^§$	132
					3-OMe, 0.11; 4-COOH, −0.1-; 3-Cl, 0.10; 4-OMe, −0.08; 4-COMe, −0.05; 4-Cl, 0.05; 4-NO_2, −0.04; 4-$CHMe_2$, 0.04; 4-Br, −0.03; 4-Me, 0.02; 4-F, −0.02; H, 0.01; 3-Me, 0.00	
97	allylbenzene	X-$C_6H_4CH_2CH{=}CH_2$	$Br^\bullet$ (Br_2)	−0.75	hydrogen abstraction 69.5 °C $\log k_{rel} = -0.75(\pm 0.05)\sigma^+ - 0.02(\pm 0.03)$ $n = 12$, $s = 0.050$, $r^2 = 0.990$ (0.964), (0.960), $F_{1,10} = 964^§$	133
					4-OMe, −0.09; 4-C_6H_5, 0.08; 4-Cl, −0.05; 4-F, −0.04; 3-Me, 0.04; 4-CF_3, 0.04; 4-Me, 0.03; 4-NMe_2, 0.03; 3-CF_3, −0.03; 3-OMe, 0.02; H, −0.02; 3-Cl, −0.02	
98	C_6H_{12}	X-$C_6H_4C(Me){=}CH_2$	$ClC_6H_4S^\bullet$	−0.75	addition 23 °C $\log k = -0.75(\pm 0.14)\sigma^+ - 0.02(\pm 0.03)$ $n = 4$, $s = 0.016$, $r^2 = 0.996$ (0.958), (0.942), $F_{1,2} > 1000^§$	134
					4-Cl, −0.02; 3-Cl, 0.01; 4-Me, 0.01; H, 0.00	
99	benzene	X-$C_6H{=}CHC_6H_5$	$Me_3COO^\bullet$	−0.75	hydrogen abstraction 130 °C $\log k_{rel} = -0.75(\pm 0.15)\sigma^+ - 0.13(\pm 0.031)$ $n = 6$, $s = 0.027$, $r^2 = 0.980$ (0.954), (0.957), $F_{1,4} = 196,^§$ omit: 4-F (−0.239)	122
					H, 0.05; 4-Br, −0.02; 4-Me, −0.01; 4-Cl, −0.01; 3-Me, 0.00; 3-Cl, 0.00	
100	reactants	X-C_6H_4Me	$Cl^\bullet$	−0.73	photochlorination 70 °C $\log k_{rel} = -0.73(\pm 0.14)\sigma^+ - 0.02(\pm 0.05)$ $n = 8$, $s = 0.053$, $r^2 = 0.966$ (0.946), (0.963), $F_{1,6} = 168,^§$ omit: 3-C_6H_5 (0.116)	135
					4-Cl, −0.07; 3-Me, 0.05; 4-C_6H_5, 0.05; 4-CN, 0.05; 3-CN, −0.04; 4-Me, −0.03; H, −0.02; 3-Cl, 0.01	

Table 1 (Continued)

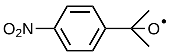
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
101	aqueous, 70% acetic acid	1-naphthyl methylsulfides		−0.73	oxidation by potassium peroxodisulfate 30 °C $\log k_2 = -0.73(\pm0.06)\sigma^+ - 2.36(\pm0.02)$ $n = 8$, $s = 0.025$, $r^2 = 0.993$ (0.892), (0.901), $F_{1,6} = 813^{\S}$	136
		4-COMe, −0.04; 4-Cl, 0.03; 4-Br, 0.03; 4-Et, −0.02; 4-F, 0.01; H, −0.01; 4-OMe, −0.01; 4-Me, 0.00				
102	CCl_4	X-$C_6H_4CH_2CMe_3$	$Br^{\bullet}$ (Br_2)	−0.72	abstraction of benzylic H 70 °C $\log k_{rel} = -0.72(\pm0.11)\sigma^+ - 0.06(\pm0.05)$ $n = 9$, $s = 0.062$, $r^2 = 0.973$ (0.894), (0.907), $F_{1,7} = 257^{\S}$	125
		3-Cl, −0.12; 4-Me, −0.06; H, 0.06; 4-CMe_3, 0.05; 3-CF_3, 0.03; 4-NO_2, 0.03; 4-Cl, 0.02; 3-Me, 0.01; 4-OMe, −0.01				
103	C_6H_5Cl	X-C_6H_4OH	$Me_3CO^{\bullet}$	−0.71	hydrogen abstraction 122 °C $\log k = -0.71(\pm0.10)\sigma^+ - 0.73(\pm0.05)$ $n = 7$, $s = 0.047$, $r^2 = 0.984$ (0.844), (0.902), $F_{1,5} = 316^{\S}$	116
		H, −0.09; 4-OMe, 0.04; 3-Cl, 0.04; 4-CN, 0.02; 4-Me, −0.01; 4-CMe_3, 0.01; 4-Cl, 0.00				
104	CCl_4	X-C_6H_4Me		−0.71	hydrogen abstraction 40 °C $\log k_{rel} = -0.71(\pm0.12)\sigma^+ - 0.02(\pm0.04)$ $n = 4$, $s = 0.019$, $r^2 = 0.997$ (0.957), (0.975), $F_{1,2} = 494^{\S}$	137
		4-Cl, 0.02; H, −0.02; 4-CN, 0.00; 4-Me, 0.00				
105	CCl_4	X-$C_6H_4CH_2CH{=}CH_2$	$Br^{\bullet}$ (NBS)	−0.70	hydrogen abstraction 80 °C $\log k = -0.70(\pm0.10)\sigma^+ - 0.02(\pm0.04)$ $n = 8$, $s = 0.041$, $r^2 = 0.980$ (0.783), (0.795), $F_{1,6} = 302^{\S}$	131
		4-Cl, −0.05; 3-Cl, 0.05; 4-OC_6H_5, 0.05; 4-Br, −0.03; 4-OMe, −0.03; 4-CMe_3, 0.02; H, −0.02; 4-Me, 0.02				
106	CCl_4	X-C_6H_4Et	$Br^{\bullet}$ (NBS)	−0.69	hydrogen abstraction 80 °C $\log k_{rel} = -0.69(\pm0.07)\sigma^+ - 0.01(\pm0.03)$ $n = 8$, $s = 0.033$, $r^2 = 0.989$ (0.944), (0.901), $F_{1,6} = 583^{\S}$	138
		4-OMe, −0.05; 4-Me, 0.04; 3-Cl, −0.03; 4-CMe_3, 0.03; 4-COOMe, −0.01; H, 0.01; 4-Br, 0.01; 4-Et, 0.00				
107	CCl_4	X-C_6H_4Me	$Me_3CO^{\bullet}$	−0.69	hydrogen abstraction 40 °C $\log k_{rel} = -0.69(\pm0.05)\sigma^+ - 0.02(\pm0.02)$ $n = 10$, $s = 0.032$, $r^2 = 0.993$ (0.914), (0.911), $F_{1,8} = 1218^{\S}$	137
		4-NO_2, −0.04; 3-Cl, 0.04; 4-Cl, 0.04; 3-NO_2, −0.03; 4-Me, −0.03; 4-CN, 0.03; H, 0.02; 4-OMe, −0.02; 3-Me, 0.00; 4-OC_6H_5, 0.00				
108	acetic acid	X-C_6H_4Me	$^{\bullet}CH_2COOH$	−0.68	hydrogen abstraction 130 °C $\log k_{rel} = -0.68(\pm0.0683)\sigma^+ + 0.03(\pm0.02)$ $n = 10$, $s = 0.026$, $r^2 = 0.987$ (0.822), (0.851), $F_{1,8} = 670^{\S}$	139
		4-C_6H_5 0.05; 4-F, −0.03; H, −0.03; 4-Me, −0.02; 3-OMe, 0.02; 4-Br, 0.01; 4-Cl, 0.01; 4-OMe, 0.00; 3-Me, 0.00; 3-Br, 0.00				
109	aqueous 70% acetic acid	1-naphthyl methyl sulfides		−0.65	oxidation by potassium peroxodiphosphate 30 °C $\log k_2 = -0.65(\pm0.04)\sigma^+ - 2.33(\pm0.01)$ $n = 8$, $s = 0.014$, $r^2 = 0.997$ (0.917), (0.901), $F_{1,6} = 2622^{\S}$	136
		H, 0.02; 4-F, 0.02; 4-Et, 0.02; 4-Br, −0.01; 4-Me, −0.01; 4-OMe, −0.01; 4-COMe, −0.01; 4-Cl, 0.00				
110	acetic anhydride	X-C_6H_4CHO	4-Cl-$C_6H_4COO^{\bullet}$	−0.65	oxidation at 30 °C $\log k_{rel} = -0.65(\pm0.18)\sigma^+ + 0.10(\pm0.08)$ $n = 6$, $s = 0.069$, $r^2 = 0.961$ (0.872), (0.876), $F_{1,4} = 98.7^{\S}$ omit 4-Cl (−0.30)	140
		H, −0.10; 3-Me, 0.06; 4-Me, 0.06; 4-OMe, −0.04; 4-C_3H_7, 0.02; 4-CN, 0.00				
111	reactants	X-$C_6H_4CH_2OCH_2C_6H_5$	$C_6H_5COO^{\bullet}$	−0.65	disproportion by peroxide to yield two aldehydes 80−90 °C $\log k_{rel} = -0.65(\pm0.19)\sigma^+ + 0.02(\pm0.08)$ $n = 5$, $s = 0.043$, $r^2 = 0.997$ (0.880), (0.889), $F_{1,3} = 1114^{\S}$	141
		3-Cl, 0.05; 4-Cl, −0.05; 4-CMe_3, −0.04; 4-OMe, 0.03; 4-C_6H_5, 0.01				
112	benzene	X-$C_6H_4C({=}CMe_2)C_6H_4$-X	$Br^{\bullet}$	−0.64	bromination 25 °C $\log k_{rel} = -0.64(\pm0.06)\sigma^+ + 2.09(\pm0.06)$ $n = 5$, $s = 0.043$, $r^2 = 0.997$ (0.880), (0.889), $F_{1,3} = 1114^{\S}$	142
		4-Br, −0.06; 4-CN, 0.03; H, 0.02; 4-OMe, 0.02; 4-CMe3, −0.01				

Table 1 (Continued)

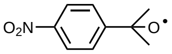
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
113^b	C_6H_5CN	X-C_6H_4Me	$Cl^\bullet$	−0.64	chlorination 80 °C $\log k_{rel} = -0.64(\pm 0.29)\sigma^+ - 0.07(\pm 0.14)$ $n = 6$, $s = 0.098$, $r^2 = 0.904$ (0.896), (0.981), $F_{1,4} = 38.0^\S$	143
		4-Cl, −0.15; 4-Me, 0.11; 4-CN, 0.04; 4-NO_2, 0.04; H, −0.02; 3-Cl, −0.02				
114	benzene	X-$C_6H_4C({=}C(Me)\text{-}Y)C_6H_4$-X	$Br^\bullet$ (NBS)	−0.63	bromination 80 °C $\log k_{rel} = -0.63(\pm 0.14)\sigma^{+},x + 1.72(\pm 0.09)$ $n = 7$, $s = 0.089$, $r^2 = 0.962$ (0.670), (0.757), $F_{1,5} = 128^\S$	142
		X = 4-CMe_3, Y = Me, −0.13; X = H, Y = C_6H_5, 0.13; X = 4-OMe, Y = Me, 0.05; X = Y = H, −0.05; X = H, Y = Me, −0.01; X = 4-Cl, Y = Me, 0.01; X = 4-Br, Y = Me, 0.00				
115	reactants	X-$C_6H_4CHMe_2$	$Cl_3C^\bullet$	−0.63	hydrogen abstraction 70 °C $\log k_{rel} = -0.63(\pm 0.07)\sigma^+ - 0.06(\pm 0.04)$ $n = 6$, $s = 0.035$, $r^2 = 0.993$ (0.975), (0.948), $F_{1,4} = 566$,§ omit: 4-Me(0.18)	144
		H, 0.06; 3-NO_2, −0.03; 4-OMe, −0.02; 4-Cl, −0.01; 4-NO_2, 0.01; 4-CN, 0.00				
116	C_6H_{12}	X-$C_6H_4CHMe_2$	$Br^\bullet$ [$HBr/O_2/(C_4H_9OOOC)_2$]	−0.62	hydrogen abstraction 50 °C $\log k_{rel} = -0.62(\pm 0.12)\sigma^+ - 0.04(\pm 0.06)$ $n = 11$, $s = 0.089$, $r^2 = 0.936$ (0.917), (0.896), $F_{1,9} = 132^\S$	145
		4-COMe, 0.17; 4-NO_2, −0.10; 4-F, −0.09; 4-CMe_3, 0.09; 4-CN, −0.08; 4-Me, 0.06; 4-SMe, −0.05; 4-COOMe, 0.03; 4-Br, 0.02; 4-Cl, 0.00				
117	CCl_4	X-$C_6H_4CH_2C_6H_5$	$Br^\bullet$ (NBS)	−0.62	hydrogen abstraction 80 °C $\log k = -0.62(\pm 0.11)\sigma^+ - 0.15(\pm 0.05)$ $n = 8$, $s = 0.051$, $r^2 = 0.968$ (0.887), (0.844), $F_{1,6} = 180^\S$	131
		H, 0.09; 4-OMe, −0.05; 4-Br, −0.05; 4-OC_6H_5, 0.03; 4-CMe_3, 0.03; 4-Cl, −0.02; 3-Br, −0.02; 3-Cl, 0.00				
118	unknown	X-C_6H_4Me	$Me_3CO^\bullet$	−0.62	hydrogen abstraction 40 °C $\log k = -0.62(\pm 0.13)\sigma^+ - 5.53(\pm 0.06)$ $n = 14$, $s = 0.105$, $r^2 = 0.894$ (0.877), (0.906), $F_{1,12} = 101^\S$	146
		4-C_6H_5, 0.19; 3-CN, 0.14; 4-NO_2, −0.14; 3-NO_2, −0.12; 4-OC_6H_5, −0.12; 3-Me, 0.08; 4-Br, −0.08; 3-Cl, 0.06; 4-OMe, −0.06; 4-CN, 0.06; 3,5-Me_2, −0.03; H, −0.02; 4-Cl, 0.02; 4-Me, 0.01				
119	reactants	X-$C_6H_4C(Me){=}CH_2$	$Cl_3C^\bullet$	−0.61	addition 105 °C $\log k_{rel} = -0.61(\pm 0.14)\sigma^+ + 0.69(\pm 0.06)$ $n = 4$, $s = 0.027$, $r^2 = 0.994$ (0.800), (0.821), $F_{1,2} = 480^\S$	147
		H, −0.03; 4-Me, 0.02; 4-Br, 0.01; 4-OMe, −0.01				
120	CCl_4	X-C_6H_4Me		−0.61	hydrogen abstraction 40 °C $\log k_{rel} = -0.61(\pm 0.13)\sigma^+ + 0.00(\pm 0.05)$ $n = 4$, $s = 0.021$, $r^2 = 0.995$ (0.962), (0.975), $F_{1,2} = 360^\S$	137
		4-Cl, 0.02; 4-Me, −0.01; 4-CN, −0.01; H, 0.00				
121	benzene	X-C_6H_4OH	$(C_6H_5)_2CO^\bullet$	−0.60	quenching of benzophenone triplets 22 °C $\log k = -0.60(\pm 0.12)\sigma^+ + 9.23(\pm 0.05)$ $n = 15$, $s = 0.092$, $r^2 = 0.894$ (0.814), (0.891), $F_{1,13} = 109$,§ omit: 4-NO_2 (0.70), 3-OMe (0.22), 3-OH (0.29)	148
		4-I, 0.15; 4-Cl, 0.13; 3-CN, −0.12; 3-F, −0.12; H, −0.12; 4-Br, 0.12; 4-Et, 0.05; 3-Br, 0.04; 4-OMe, −0.04; 4-F, −0.04; 4-OEt, −0.04; 4-CN, −0.02; 3-Me, 0.01; 4-CMe_3, −0.01; 4-Me, 0.00				
122	tetralin	X-$C_6H_4SSC_6H_4$-X	X-$C_6H_4S^\bullet$	−0.59	thermal decomposition 207 °C $\log k_1 = -0.59(\pm 0.91)\sigma^+ - 5.99(\pm 0.88)$ $n = 3$, $s = 0.084$, $r^2 = 0.984$ (0.854), (0.931), $F_{1,1} = 124$, omit: 4-Cl (0.47)	149
		4-Me, −0.07; H, 0.04; 4-OMe, 0.03				
123	$C_6H_{12}SH$	X-C_6H_4Et	$C_6H_{11}S^\bullet$	−0.58	hydrogen abstraction 80 °C $\log k_{rel} = -0.58(\pm 0.12)\sigma^+ + 0.03(\pm 0.05)$ $n = 7$, $s = 0.054$, $r^2 = 0.970$ (0.890), (0.891), $F_{1,5} = 154^\S$	150
		3-OMe, 0.08; 4-Br, −0.08; H, −0.03; 3-Me, 0.03; 4-Me, 0.00; 4-OMe, 0.00; 4-NO_2, 0.00				
124	C_6H_{12}	X-$C_6H_4CH{=}CH_2$	$ClC_6H_4S^\bullet$	−0.58	addition 23 °C $\log k = -0.58(\pm 0.15)\sigma^+ + 7.73(\pm 0.05)$ $n = 7$, $s = 0.055$, $r^2 = 0.949$ (0.885), (0.850), $F_{1,5} = 93.0^\S$	134
		3-Me, 0.09; 4-Cl, −0.08; H, −0.02; 4-Br, 0.02 3-Cl, 0.01; 4-Me, −0.01; 4-OMe, 0.01				

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
125	reactants	X-C_6H_4Me	$Me_3COO^\bullet$	−0.57	hydrogen abstraction 30 °C $\log k = -0.57(\pm0.11)\sigma^+ - 1.48(\pm0.05)$ $n = 13$, $s = 0.083$, $r^2 = 0.925$ (0.853), (0.911), $F_{1,11} = 135^{\S}$ omit: 4-COMe (−0.33) 4-COOMe, 0.16; 3-CN, −0.15; 4-NO_2, 0.09; 3-NO_2, −0.09; 4-Me, 0.06; 4-OMe, −0.04; 3-Cl, −0.04; 4-Cl, 0.03; H, −0.02; 4-OC_6H_5, 0.02; 3-OMe, −0.02; 3-Me, −0.01; 4-CN; 0.01	151
126	reactants	X-$C_6H_4CH{=}CHC_6H_4$-Y	$Cl_3C^\bullet$	−0.57	addition 105 °C $\log k_{rel} = -0.57(\pm0.25)\sigma^+ + 0.05(\pm0.10)$ $n = 5$, $s = 0.063$, $r^2 = 0.945$ (0.534), (0.751), $F_{1,3} = 51.3$,§ omit: X = 4-NO_2, Y = H (0.35) X = 4-Br, Y = 4-Br, 0.07; X = 3,5-Me_2, Y = H; −0.05; H, −0.05; X = 4-OMe, Y = H, 0.04; X = 4-Me, Y = H, 0.00	147
127	unknown	X-C_6H_4Me	$Me_3COO^\bullet$	−0.56	hydrogen abstraction 20 °C $\log k = -0.56(\pm0.11)\sigma^+ - 1.49(\pm0.06)$ $n = 12$, $s = 0.085$, $r^2 = 0.926$ (0.862), (0.922), $F_{1,10} = 125$,§ omit: H (0.26), 4-COMe (−0.33) 4-COOMe, 0.16; 3-CN, −0.15; 4-NO_2, 0.09; 3-NO_2, −0.09; 3-Cl, −0.04; 4-OMe, −0.03; 4-Cl, 0.03; 4-OC_6H_5, 0.03; 4-Me, −0.01; 3-OMe, −0.01; 3-Me, −0.01; 4-CN; 0.01	146
128	CCl_4	X-C_6H_4Et	$Cl_3C^\bullet$	−0.51	hydrogen abstraction 80 °C $\log k_{rel} = -0.51(\pm0.05)\sigma^+ + 0.01(\pm0.02)$ $n = 8$, $s = 0.021$, $r^2 = 0.992$ (0.868), (0.901), $F_{1,6} = 638^{\S}$ 4-Br, 0.033; 4-Et, −0.026; 4-Me, 0.019; 4-CMe_3, −0.016; H, −0.012; 4-OMe, 0.010; 4-COOMe, −0.005; 3-Cl, −0.002	152
129	reactants	X-$C_6H_4CH_2$CN	$Cl_3C^\bullet$	−0.51	hydrogen abstraction 70 °C $\log k_{rel} = -0.51(\pm0.04)\sigma^+ - 0.03(\pm0.02)$ $n = 8$, $s = 0.020$, $r^2 = 0.993$ (0.917), (0.898), $F_{1,6} = 966^{\S}$ H, 0.03; 3-CF_3, −0.03; 3-F, 0.01; 4-OMe, −0.01; 4-Me, 0.00; 4-Cl, 0.00; 4-CMe_3, 0.00; 3-Cl, 0.00	153
130	C_6H_{11}SH	X-$C_6H_4CHMe_2$	$C_6H_{11}S^\bullet$	−0.50	hydrogen abstraction 80 °C $\log k_{rel} = -0.50(\pm0.20)\sigma^+ + 0.49(\pm0.12)$ $n = 4$, $s = 0.054$, $r^2 = 0.983$ (0.961), (0.920), $F_{1,2} = 109^{\S}$ 4-Me, 0.06; 4-OMe, −0.04; 4-NO_2, −0.02; H, 0.01	154
131	benzene	X-$C_6H_4CH{=}CH_2$	$CH_3C_6H_4SO_2^\bullet$	−0.49	photochemical addition 43 °C $\log k_{rel} = -0.49(\pm0.11)\sigma^+ + 0.04(\pm0.04)$ $n = 5$, $s = 0.024$, $r^2 = 0.986$ (0.927), (0.977), $F_{1,3} = 180^{\S}$ H, −0.04; 4-Cl, 0.02; 4-Me, 0.01; 3-NO_2, 0.00; 4-Br, 0.00	155
132	benzene	X-$C_6H_4CH{=}CH_2$	$Cl_3C^\bullet$	−0.49	addition 80 °C $\log k_{rel} = -0.49(\pm0.13)\sigma^+ + 0.05(\pm0.04)$ $n = 8$, $s = 0.044$, $r^2 = 0.937$ (0.856), (0.970), $F_{1,6} = 86.0^{\S}$ omit: 4-CN (0.33), 4-NO_2 (0.28) 3-Me, −0.05; 3-CF_3, −0.05; H, −0.05; 4-Me, 0.04; 3-OMe, 0.03; 4-Cl, 0.03; 3-NO_2, 0.02; 3-Cl, 0.02	156
133	methyl methacrylate	methyl methacrylate	X-$C_6H_4S^\bullet$	−0.46	chain transfer in the polymerization of methyl methacrylate 45 °C $\log k = 0.46(\pm0.17)\sigma^+ + 0.69(\pm0.05)$ $n = 7$, $s = 0.049$, $r^2 = 0.899$ (0.808), (0.961), $F_{1,5} = 44.2$,§ omit: 3-COMe (0.10), 4-Br (0.12) 3-Br, 0.06; 3-Me, −0.05; 4-COMe, −0.05; 4-Me, 0.03; H, −0.023; 4-Cl, 0.02; 3-Cl, 0.02	157
134	CCl_4	X-$C_6H_4CH{=}CH_2$	$C_6H_5Se^\bullet$	−0.44	addition 23 °C $\log k = 0.44(\pm0.11)\sigma^+ + 6.36(\pm0.04)$ $n = 6$, $s = 0.035$, $r^2 = 0.970$ (0.896), (0.877), $F_{1,4} = 130^{\S}$ 4-Cl, −0.05; 3-Cl, 0.04; 4-Me, 0.02; 4-Br, −0.01; 3-Me, 0.01; 4-OMe, 0.00	158
135	CCl_4	X-$C_6H_4CH_2$OMe	$Br^\bullet$ (NBS)	−0.43	hydrogen abstraction 77 °C $\log k_{rel} = -0.43(\pm0.11)\sigma^+ + 0.13(\pm0.06)$ $n = 10$, $s = 0.066$, $r^2 = 0.910$ (0.779), (0.939), $F_{1,8} = 80.5$,§ omit: 4-Cl (−0.14), 3-CN (−0.19), 3-OMe (0.17) H, −0.13; 4-NO_2, 0.06; 4-OMe, 0.06; 4-Br, −0.02; 4-COOMe, 0.08; 4-CN, −0.04; 3-NO_2, −0.02; 3-Cl, 0.02; 3-Br, −0.01; 3-COOMe, 0.00	159

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
136	benzene	X-C_6H_4Me	$Me_3CO^\bullet$	−0.43	hydrogen abstraction 130 °C $\log k_{rel} = -0.43(\pm0.07)\sigma^+ - 0.74(\pm0.02)$ $n = 7$, $s = 0.025$, $r^2 = 0.980$ (0.886), (0.894), $F_{1,5} = 255^\S$	122
					4-Cl, 0.03; 3-Cl, −0.03; H, 0.03; 4-Me, −0.01; 4-F, −0.01; 4-OMe, 0.00; 4-Br, 0.00	
137	benzene	X-C_6H_5	$^\bullet CN$	−0.42	substitution $\log k = -0.42(\pm0.09)\sigma^+ + 0.05(\pm0.03)$ $n = 17$, $s = 0.058$, $r^2 = 0.865$ (0.665), (0.895), $F_{1,15} = 96.3$,§ omit: 4-F (−0.14)	160
					3-OMe, −0.10; 4-COOMe, 0.09; 4-Cl, 0.09; 3-CMe_3, −0.08; 4-OMe, 0.07; 3-$CHMe_2$, −0.06; 3-F, −0.05; 4-Br, 0.04; 3-Br, −0.04; 3-Cl, 0.02; 3-COOMe, 0.02; 4-Me, 0.02; 3-Et, −0.01; 4-$CHMe_2$, −0.01; 4-CMe_3, 0.01; 4-Et, 0.01; 3-Me, 0.00	
138	CH_3CN	X-C_6H_4Me	$Me_3CO^\bullet$	−0.41	hydrogen abstraction 45 °C $\log k_{rel} = -0.41(\pm0.04)\sigma^+ - 0.28(\pm0.01)$ $n = 7$, $s = 0.014$, $r^2 = 0.993$ (0.765), (0.811), $F_{1,5} = 695^\S$	161
					4-Me, −0.02; 4-OC_6H_5, 0.02; 4-Cl, −0.01; 3-CN, 0.01; 3-Cl, 0.00; 3-Me, 0.00; H, 0.00	
139	reactant	X-$C_6H_4CH{=}CHC_6H_5$	$^\bullet SCH_2COOH$	−0.40	addition 105 °C $\log k_{rel} = -0.40(\pm0.18)\sigma^+ - 0.00(\pm0.07)$ $n = 5$, $s = 0.041$, $r^2 = 0.944$ (0.889), (0.760), $F_{1,3} = 50.4$,§ omit: 3,4-$(OMe)_2$ (0.45)	147
					3,5-Me_2, 0.06; 4-Br, −0.04; 4-OMe, −0.01; 4-Me, −0.01; H, 0.00	
140	aqueous	X-$C_6H_4CH_2COOH$	$SO_4^{\bullet-}$	−0.40	decarboxylation 74.3 °C $\log k_{rel} = -0.40(\pm0.06)\sigma^+ + 0.04(\pm0.03)$ $n = 9$, $s = 0.033$, $r^2 = 0.973$ (0.870), (0.921), $F_{1,7} = 247^\S$	162
					4-OMe, 0.05; H, −0.04; 4-Cl, −0.04; 3-F, 0.04; 3-Br, 0.03; 4-OEt, −0.02; 4-Me, 0.00; 3-Cl, 0.00; 4-Br, 0.00	
141	C_6H_{12}	X-$C_6H_4C{\equiv}CH$	Y-$C_6H_4S^\bullet$	−0.40	addition 23 °C $\log k = 1.52(\pm0.09)\sigma^+ \text{ Y} - 0.40(\pm0.06)\sigma^+ \text{ X} + 6.273(\pm0.03)$ $n = 30$, $s = 0.079$, $r^2 = 0.980$ (0.960), (0.957), $F_{1,28} = 149^\S$ (σ^+, Y), $F_{1,27} = 184$§ (σ^+, X)	163
					X = 3-NO_2, Y = 4-OMe, 0.19; X = 4-OMe, Y = 4-Br, 0.19; X = 4-Cl, Y = H, −0.15; X = 4-Me, Y = 4-Br, 0.11; X = Y = 4-Cl, −0.09; X = H, Y = 4-Br, 0.08; X = Y = 4-OMe, −0.08, X = H, Y = 4-Me, −0.07; X = Y = H, −0.07; X = 4-OMe, Y = 4-Me, −0.06; X = 4-OMe, Y = 4-Cl, 0.06; X = 4-Cl, Y = 4-Me, −0.06; X = 4-Me, Y = H, −0.05; X = Y = 4-Me, −0.05; X = 4-Me, Y = 4-CMe_3, −0.05; X = H, Y = 4-CMe_3, −0.05; X = 4-OMe, Y = H, −0.04; X = 3-NO_2, Y = 4-Br, 0.04; X = 4-Me, Y = 4-OMe, −0.04; X = 4-Cl, Y = 4-OMe, 0.03; X = H, Y = 4-OMe, 0.03; X = H, Y = 4-Cl, −0.03; X = 3-NO_2, Y = 4-Me, 0.02; X = 4-Cl, Y = 4-CMe_3, −0.02; X = 4-Me, Y = 4-Cl, 0.02; X = 4-OMe, Y = 4-CMe_3, 0.02; X = 3-NO_2, Y = 4-Cl, −0.01; X = 4-Cl, Y = 4-Br, −0.01; X = 3-NO_2, Y = H, 0.01; X = 3-NO_2, Y = 4-CMe_3, −0.01	
142	benzene 17% *o*-dichlorobenzene	X-$C_6H_4C(Me){=}CH_2$	$C_6H_5S^\bullet$	−0.40	photoinduced addition 70 °C $\log k_{rel} = -0.40(\pm0.09)\sigma^+ - 0.00(\pm0.03)$ $n = 8$, $s = 0.039$, $r^2 = 0.949$ (0.915), (0.881), $F_{1,6} = 111$,§ omit; 4-NO_2 (0.315)	164
					3-CF_3, −0.07; 4-OMe, −0.04; 4-Cl, 0.04; 3-Me, 0.03; 3-OMe, 0.02; 4-Me, 0.01; H, 0.00; 3-Cl, 0.00	
143	reactants	X-$C_6H_4CHMe_2$	X-$C_6H_4COO^\bullet$	−0.40	hydrogen abstraction 90 °C $\log k_{rel} = -0.40(\pm0.09)\sigma^+ - 0.02(\pm0.04)$ $n = 8$, $s = 0.041$, $r^2 = 0.955$ (0.940), (0.989), $F_{1,6} = 129^\S$	165
					4-NO_2, 0.06; 4-$CHMe_2$, 0.05; 4-COOMe, −0.04; 4-Me, −0.03; 4-Br, −0.03; 4-CN, −0.02; H, 0.02; 4-CMe_3, −0.01	
144	CCl_4	X-$C_6H_4CH(OMe)_2$	$Br^\bullet$ (NBS)	−0.38	hydrogen abstraction 90 °C $\log k_{rel} = -0.38(\pm0.04)\sigma^+ - 0.02(\pm0.02)$ $n = 7$, $s = 0.018$, $r^2 = 0.992$ (0.936), (0.897), $F_{1,5} = 493^\S$	166
					4-OMe, −0.02; 4-Me, 0.02; 4-Cl, −0.02; H, 0.02; 4-CMe_3, 0.01; 3-NO_2, −0.01; 3-Cl, 0.00	
145	reactants	X-C_6H_5	$^3H^\bullet$	−0.37	addition 40 °C $\log F_o = -0.37(\pm0.14)\sigma^+ + 0.12(\pm0.09)$ $n = 7$, $s = 0.094$, $r^2 = 0.905$ (0.860), (0.963), $F_{1,5} = 48.2$,§ omit: COMe (0.34), NO_2 (0.31)	167
					H, −0.12; COOMe, 0.11; OH, −0.08; NH_2, 0.07; Me, 0.07; Br, −0.04; CN, −0.01	
146	CCl_4	X-$C_6H_4CH_2OMe$	$Br^\bullet$ (NBS)	−0.35	hydrogen abstraction 80 °C $\log k_{rel} = -0.35(\pm0.05)\sigma^+ - 0.00(\pm0.02)$ $n = 6$, $s = 0.016$, $r^2 = 0.990$ (0.886), (0.852), $F_{1,4} = 396^\S$	166
					4-CMe_3, −0.03; 4-Cl, 0.01; 4-OMe, 0.01; H, 0.00; 4-Me, 0.00; 3-Cl, 0.00	

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
147	reactants	X-$C_6H_4C(Me)=CH_2$	$^{\bullet}SCH_2COOMe$	−0.36	addition 105 °C $\log k_{rel} = -0.36(\pm 0.10)\sigma^+ + 0.85(\pm 0.05)$ $n = 4$, $s = 0.019$, $r^2 = 0.991$ (0.849), (0.821), $F_{1,2} = 164^{\S}$	147
		4-Me, 0.02; 4-OMe, −0.01; H, −0.01; 4-Br, −0.01				
148	CCl_4	X-$C_6H_4CH_2OMe$	$Cl_3C^{\bullet}$	−0.36	hydrogen abstraction 80 °C $\log k_{rel} = -0.36(\pm 0.05)\sigma^+ - 0.00(\pm 0.02)$ $n = 6$, $s = 0.015$, $r^2 = 0.992$ (0.793), (0.852), $F_{1,4} = 416^{\S}$	166
		4-CMe_3, −0.02; 4-OMe, 0.02; 3-Cl, 0.01; 4-Me, −0.01; 4-Cl, 0.00; H, 0.00				
149	CCl_2FCClF_2	X-C_6H_4Me	$Me_3CO^{\bullet}$	−0.35	hydrogen abstraction 45 °C $\log k_{rel} = -0.35(\pm 0.05)\sigma^+ + 0.34(\pm 0.02)$ $n = 8$, $s = 0.022$, $r^2 = 0.980$ (0.894), (0.866), $F_{1,6} = 286^{\S}$	161
		4-Cl, 0.04; 4-OC_6H_5, −0.03; 4-CN, −0.02; 3-Cl, 0.02; 4-Me, 0.01; 3-CN, −0.01; 3-Me, 0.00; H, 0.00				
150	C_6H_5Cl	X-C_6H_4Me	$Me_3CO^{\bullet}$	−0.34	hydrogen abstraction 45 °C $\log k_{rel} = -0.34(\pm 0.23)\sigma^+ + 0.80(\pm 0.09)$ $n = 4$, $s = 0.038$, $r^2 = 0.956$ (0.923), (0.986), $F_{1,2} = 42.7^{\S\S}$ omit: 3-Me (−0.06)	168
		3-Cl, −0.04; 4-CN, 0.03; 4-Me, 0.01; H, 0.00				
151	benzene	X-C_6H_4CHO	$Me_3COO^{\bullet}$	−0.34	hydrogen abstraction 130 °C $\log k_{rel} = -0.34(\pm 0.04)\sigma^+ + 1.12(\pm 0.01)$ $n = 9$, $s = 0.012$, $r^2 = 0.987$ (0.945), (0.963), $F_{1,7} = 497^{\S}$	169
		3-CN, 0.02; 4-Me, 0.02; 3-Me, −0.01; 4-Cl, −0.01; 3-CF_3, −0.01; 3-F, 0.01; 3-Cl, −0.01; H, 0.00; 4-Br, 0.00				
152	C_6H_5Cl	X-C_6H_4Me	$C_4H_9O^{\bullet}$	−0.33	hydrogen abstraction 40 °C $\log k_{rel} = -0.33(\pm 0.18)\sigma^+ + 0.96(\pm 0.09)$ $n = 5$, $s = 0.065$, $r^2 = 0.915$ (0.905), (0.921), $F_{1,3} = 31.6^{\S\S}$	168
		3-Cl, −0.07; 4-Me, 0.07; 4-OMe, −0.04; 4-CN, 0.03; H, 0.02				
153	benzene	X-$C_6H_4CH=CH_2$	$Me_3CO^{\bullet}$	−0.33	addition 60 °C $\log k_{rel} = -0.33(\pm 0.05)\sigma^+ + 0.03(\pm 0.02)$ $n = 12$, $s = 0.028$, $r^2 = 0.959$ (0.839), (0.911), $F_{1,10} = 229,^{\S}$ omit: 4-NO_2 (0.18)	170
		4-Cl, 0.06; 4-F, −0.04; 4-C_6H_5, 0.03; H, −0.03; 3-OMe, 0.02; 3-Cl, −0.01; 3-Me, −0.01; 4-Me, −0.01; 3-F, −0.01; 4-OMe, 0.01; 3-NO_2, 0.00; 4-COOMe, 0.00				
154	C_6H_5Cl	X-C_6H_4Me	$Me_3CO^{\bullet}$	−0.32	hydrogen abstraction 45 °C $\log k = -0.32(\pm 0.06)\sigma^+ + 0.11(\pm 0.02)$ $n = 8$, $s = 0.025$, $r^2 = 0.97$ (0.858), (0.866), $F_{1,6} = 186^{\S}$	161
		4-Me, 0.03; 4-Cl, −0.03; 3-Cl, −0.03; 4-CN, 0.02; 3-CN, 0.02; H, 0.01; 3-Me, −0.01; 4-OC_6H_5, −0.01				
155	C_6H_{12}	X-$C_6H_4CH=CH_2$	$C_6H_5S^{\bullet}$	−0.31	addition 23 °C $\log k = -0.31(\pm 0.09)\sigma^+ + 7.46(\pm 0.03)$ $n = 7$, $s = 0.033$, $r^2 = 0.937$ (0.671), (0.850), $F_{1,5} = 82.0^{\S}$	134
		4-Br, 0.05; H, −0.03; 4-Me, −0.03; 4-OMe, 0.03; 3-Me, −0.02; 3-Cl, 0.02; 4-Cl, −0.01				
156	benzene	X-$C_6H_4CH=CH_2$	$Me_3COO^{\bullet}$	−0.31	addition 20 °C $\log k_{rel} = -0.31(\pm 0.23)\sigma^+ + 0.04(\pm 0.09)$ $n = 5$, $s = 0.063$, $r^2 = 0.862$ (0.829), (0.887), $F_{1,3} = 18.3^{\S}$	121
		4-Me, 0.08; 4-Cl, −0.05; H, −0.04; 3-Cl, 0.03; 4-OMe, −0.02				
157	benzene	Y-$C_6H_4C(Me)=CH_2$	X-$C_6H_4S^{\bullet}$	−0.31	addition 70 °C $\log k_{rel} = -0.31(\pm 0.05)\sigma^+$, X $- 0.01(\pm 0.02)$ $n = 20$, $s = 0.045$, $r^2 = 0.917$ (0.813), (0.899), $F_{1,18} = 198,^{\S}$ omit: X = 4-OMe, Y = H, (−0.13); X = 4-Me, Y = 4-Cl (−0.08); X = 4-Cl, Y = 4-OMe (0.17); X = 4-Cl, Y = 4-Me(0.17); X = 3-CF_3, Y = 4-OMe(0.22); X = 3-CF_3, Y = 4-Me (0.19)	171
		X = Y = 3-CF_3, −0.10; X = 4-Cl, Y = 3-CF_3, −0.08; X = 4-NO_2, Y = H, 0.07; X = 3-CF_3, Y = 4-Cl, 0.05; X = 4-OMe, Y = 4-Me, 0.05; X = 4-OMe, Y = 4-OMe, −0.04; X = 4-Me, Y = 3-CF_3, 0.04; X = 4-OMe, Y = 3-CF_3, 0.04; X = 4-Me, Y = H, −0.04; X = 4-Cl, Y = H, 0.04; X = 4-Me, Y = 4-Me, −0.03; X = Y = 4-Cl, −0.02; X = 4-NO_2, Y = 4-Cl, −0.02; X = 4-OMe, Y = 4-Cl, −0.01; X = 4-Me, Y = 4-OMe, 0.01; X = H, Y = 4-OMe, 0.01; X = H, Y = 4-Me, 0.01; X = Y = H, 0.01; X = H, Y = 4-Cl, 0.01; X = H, Y = 3-CF_3, 0.01				

Table 1 (Continued)

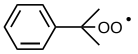
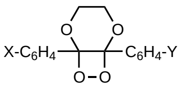
<table>
<tr><th>set</th><th>solvent</th><th>compound</th><th>radical</th><th>ρ^+</th><th>reaction, correlation</th><th>ref</th></tr>
<tr><td>**158**</td><td>benzene</td><td>X-C_6H_4SH</td><td>$Me_3CO^\bullet$</td><td>−0.29</td><td>hydrogen abstraction 130 °C
$\log k_{rel} = -0.29(\pm0.12)\sigma^+ + 0.01(\pm0.04)$
$n = 6$, $s = 0.035$, $r^2 = 0.915$ (0.721), (0.856), $F_{1,4} = 41.6^§$</td><td>51</td></tr>
<tr><td colspan="7">4-Cl, 0.06; 4-F, −0.04; 4-Br, −0.02; 4-OMe, 0.01; H, −0.01; 4-Me, 0.00</td></tr>
<tr><td>**159**</td><td>styrene</td><td>(X-$C_6H_4COO)_2$ and $C_6H_5CH{=}CH_2$</td><td>X-$C_6H_4COO^\bullet$</td><td>−0.29</td><td>initiation of polymerization 60 °C
$\log k = -0.29(\pm0.05)\sigma^+ - 5.17(\pm0.04)$
$n = 20$, $s = 0.079$, $r^2 = 0.887$ (0.808), (0.890), $F_{1,18} = 141^§$ omit: 3-NO_2 (−0.58), 4-NO_2 (−1.35)</td><td>172</td></tr>
<tr><td colspan="7">3-OMe, 0.15; 4-F, −0.15; 4-Me, 0.12; 4-CMe_3, 0.12; 4-CN, 0.12; 3-Me, −0.09; 4-$CH{=}CH_2$, −0.06; 3-F, −0.06; 3-I, −0.06; 4-$CHMe_2$, 0.04; 4-Cl, −0.03; 3-Cl, −0.03; H, 0.02; 4-I, −0.02; 4-Br, −0.02; 4-OMe, −0.01; 4-OEt, −0.01; 3-Br, −0.01; 4-Et, 0.00; 4-C_6H_5, 0.00</td></tr>
<tr><td>**160**</td><td>CCl_4</td><td>X-C_6H_4SH</td><td>$Me_3CO^\bullet$</td><td>−0.29</td><td>hydrogen abstraction 130 °C
$\log k_{rel} = -0.29(\pm0.07)\sigma^+ + 0.02(\pm0.03)$
$n = 6$, $s = 0.021$, $r^2 = 0.967$ (0.791), (0.856), $F_{1,4} = 102^§$</td><td>51</td></tr>
<tr><td colspan="7">4-F, 0.03; H, −0.02; 4-Br, −0.02; 4-Cl, 0.01; 4-OMe, 0.00; 4-Me, 0.00</td></tr>
<tr><td>**161**</td><td>C_6H_{12}</td><td>X-$C_6H_4C(Me){=}CH_2$</td><td>$C_6H_4S^\bullet$</td><td>−0.29</td><td>addition 23 °C
$\log k = -0.29(\pm0.03)\sigma^+ + 7.85(\pm0.01)$
$n = 4$, $s = 0.004$, $r^2 = 0.999$ (0.958), (0.942), $F_{1,2} > 1000^§$</td><td>134</td></tr>
<tr><td colspan="7">H, 0.00; 4-Cl, 0.00; 4-Me, 0.00; 3-Cl, 0.00</td></tr>
<tr><td>**162**</td><td>C_6H_5Cl</td><td>X-$C_6H_4CHMe_2$</td><td></td><td>−0.28</td><td>hydrogen abstraction 30 °C
$\log k = -0.28(\pm0.05)\sigma^+ - 0.73(\pm0.03)$
$n = 10$, $s = 0.033$, $r^2 = 0.955$ (0.873), (0.943), $F_{1,8} = 165,^§$ omit: 3-Br(−0.08)</td><td>173</td></tr>
<tr><td colspan="7">4-Cl, −0.07; 4-$CHMe_2$, 0.03; 4-OMe, 0.03; 4-NO_2, 0.03; 4-CN, 0.03; 4-COOMe, −0.02; 4-Me, −0.02; H, −0.02; 3-OMe, 0.02; 3-NO_2, 0.00</td></tr>
<tr><td>**163**</td><td>acetic acid</td><td>X-C_6H_4SH</td><td>$Me_3CO^\bullet$</td><td>−0.28</td><td>hydrogen abstraction 130 °C
$\log k_{rel} = -0.28(\pm0.05)\sigma^+ + 1.04(\pm0.02)$
$n = 5$, $s = 0.010$, $r^2 = 0.992$ (0.785), (0.856), $F_{1,3} > 1000^§$</td><td>51</td></tr>
<tr><td colspan="7">4-Me, −0.01; 4-F, 0.01; 4-OMe, 0.00; H, 0.00; 4-Cl, 0.00</td></tr>
<tr><td>**164**</td><td>aqueous</td><td>X-C_6H_4COO-</td><td>$HO^\bullet$</td><td>−0.27</td><td>addition 25 °C
$\log k = -0.27(\pm0.04)\sigma^+ - 8.70(\pm0.02)$
$n = 9$, $s = 0.028$, $r^2 = 0.978$ (0.962), (0.955), $F_{1,7} = 335,^§$ omit: H (0.10)</td><td>174</td></tr>
<tr><td colspan="7">4-Me, 0.04; 4-OMe, −0.03; 4-OH, −0.03; 4-NH_2, 0.03; 4-COO^-, −0.02; 4-Cl, 0.02; 4-NO_2, −0.01; 4-Br, 0.01; 4-F, 0.00</td></tr>
<tr><td>**165**</td><td>dioxane</td><td>X-$C_6H_4COOOCOC_6H_4$-X′</td><td></td><td>−0.26</td><td>free-radical formation 80 °C
$\log k_{rel} = -0.26(\pm0.04)\sigma^+ + 0.01(\pm0.03)$
$n = 14$, $s = 0.054$, $r^2 = 0.937$ (0.829), (0.904), $F_{1,12} = 180,^§$ omit: 3,3′-$(OMe)_2$(0.15)</td><td>175</td></tr>
<tr><td colspan="7">3,3′-Br_2, 0.12; 4-OMe, 3-Br, −0.08; 3-OMe, 0.06; 3-CN, −0.05; 4-OMe, 0.05; 4,4′-Br_2, −0.05; 4,4′-$(OMe)_2$, 0.04; 4,.4′-CN_2, −0.04; 3,3′-Me_2, −0.03; 4,4′-$(CMe_3)_2$, 0.02; 4,4′-Cl_2, −0.02; H, −0.01; 3,3′-Cl_2, −0.01; 4,4′-Me_2, 0.00</td></tr>
<tr><td>**166**</td><td>*o*-xylene</td><td> </td><td></td><td>−0.26</td><td>photochemical decomposition to X-$C_6H_4C({=}O)O$-$CH_2CH_2OC({=}O)(C_6H_4$-Y 25 °C
$\log k_{rel} = -0.26(\pm0.06)\sigma^+ + 0.14(\pm0.06)$
$n = 13$, $s = 0.084$, $r^2 = 0.893$ (0.779), (0.877), $F_{1,11} = 90.8,^§$ omit: X = Y = NMe_2 (1.57); X = Y = 4-Me (−0.22)</td><td>176</td></tr>
<tr><td colspan="7">X = Y = 4-$OCHMe_2$, 0.16; X = Y = H, −0.14; X = Y = 3-CF_3, 0.09; X = Y = 4-OH, −0.07; X = Y = 3-OMe, 0.07; X = Y = 4-OC_6H_5, 0.07; X = Y = 4-NHCOMe, −0.05; X = 4-OH, Y = H, −0.05; X = 4-OMe, Y = H, −0.03; X = Y = 3-Cl, −0.02; X = Y = 4-Cl, −0.02; X = Y = 4-C_6H_5, −0.01; X = Y = 4-OMe, 0.01</td></tr>
<tr><td>**167**</td><td>benzene</td><td>X-$C_6H_4CH{=}CH_2$</td><td>$C_6H_5COO^\bullet$</td><td>−0.23</td><td>bond cleavage to benzaldehyde
$\log k_{rel} = -0.23(\pm0.12)\sigma^+ - 0.01(\pm0.051)$
$n = 4$, $s = 0.023$, $r^2 = 0.973$ (0.932), (0.913), $F_{1,2} = 80.0,^{§§}$ omit: 4-Me (−0.10)</td><td>121</td></tr>
<tr><td colspan="7">4-Cl, −0.03; H, 0.01; 3-Cl, 0.01; 4-OMe, 0.00</td></tr>
<tr><td>**168**</td><td>aqueous</td><td>X-C_6H_5</td><td>$HO^\bullet$</td><td>−0.21</td><td>addition 25 °C
$\log k = -0.21(\pm0.06)\sigma^+ - 8.58(\pm0.05)$
$n = 12$, $s = 0.067$, $r^2 = 0.877$ (0.835), (0.955), $F_{1,10} = 70.7,^§$ omit: CH_2COO^- (−0.11), COMe (0.14)</td><td>174</td></tr>
<tr><td colspan="7">OH, 0.10; SO_3^-, −0.10; SO_2NH_2, −0.08; $CONH_2$, 0.07; NHCOMe, −0.06; CN, 0.051; NO_2, 0.05; NMe_2, −0.04; NH_2, 0.04; COO^-, −0.02; OMe, −0.02; OCOMe, 0.02</td></tr>
</table>

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
169	reactants	X-$C_6H_4CH{=}CH_2$		−0.20	polymerization with methyl methacrylate catalyzed by benzoyl peroxide 60 °C $\log k_{rel} = -0.20(\pm0.07)\sigma^+ - 0.06(\pm0.034)$ $n = 9$, $s = 0.047$, $r^2 = 0.870$ (0.785), (0.963), $F_{1,7} = 45.9$,§ omit: 3-Me (−0.14), 4-CN (0.39)	176a
					4-Me, −0.07; 4-I, 0.07; H, −0.065; 4-Br, 0.03; 4-NMe$_2$, 0.02; 4-OMe, 0.01; 3-Cl, 0.01; 4-Cl, 0.00; 3-Br, 0.00	
170	CCl_4	X-$C_6H_4CH(OMe)_2$	$Cl_3C^\bullet$	−0.18	hydrogen abstraction 80 °C $\log k_{rel} = -0.18(\pm0.02)\sigma^+ - 0.01(\pm0.01)$ $n = 7$, $s = 0.008$, $r^2 = 0.990$ (0.899), (0.857), $F_{1,5} > 1000$§	152
					4-CMe3, 0.01; 3-Cl, −0.01; 4-OMe, −0.01; H, 0.01; 4-Br, 0.01; 4-Me, 0.00; 4-Cl, 0.00	
171	benzene	X-C_6H_4-$CH{=}N(O)CMe_3$	Y-$C_6H_4^\bullet$	−0.18	addition (spin-trapping) unknown temperature $\log k_{rel} = -0.33(\pm0.05)\sigma$,X $- 0.18(\pm0.12)\sigma^+$, Y $- 0.02(0.02)$ $n = 48$, $s = 0.048$, $r^2 = 0.822$ (0.797), (0.895), $F_{1,46} = 167.5$§ (σ,X), $F_{1,45} = 93$§ (σ^+,Y), omit: X = 4-OMe, Y = 4-Me (−0.37); X = Y = 4-Me (−0.19); X = 4-Me, Y = H (−0.18); X = 3-Me, Y = 4-Me (−0.19); X = 4-Cl, Y = 4-Me (0.12); X = 3-Cl, Y = 4-Me (0.17); X = 3-NO$_2$, Y = 4-Me (0.32); X = 3-NO$_2$, Y = 2-F (0.15); X = 4-NO$_2$, Y = 4-Me (0.37); X = 4-NO$_2$, Y = H (0.13); X = 4-NO$_2$, Y = 4-Cl (0.12); X = 4-NO$_2$, Y = 2-F (0.18)	177
					X = 3-Me, Y = 4-Br, 0.10; X = 3-Cl, Y = 2-F, 0.10; X = 4-F, Y = H, −0.10; X = 3-NO$_2$, Y = 4-Cl, −0.10; X = 4-OMe, Y = H, −0.09; X = 3-Me, Y = H, −0.08; X = 3-OMe, Y = H, −0.07; X = 4-NO$_2$, Y = 4-F, 0.07; X = 4-F, Y = 4-Me, 0.06; X = 3-OMe, Y = 4-F, −0.06; X = 4-Me, Y = 4-Cl, 0.06; X = 3-NO$_2$, Y = 4-F, 0.05; X = Y = 4-F, −0.05; X = 3-NO$_2$, Y = H, 0.05; X = 4-OMe, Y = 2-F, 0.05; X = 3-Me, Y = 4-Cl, 0.05; X = 4-NO$_2$, Y = 4-Br, −0.04; X = H, Y = 4-Br, 0.04; X = 4-F, Y = 4-Cl, −0.04; X = H, Y = 4-Me, −0.04; X = H, Y = 4-Cl, 0.04; X = 3-Cl, Y = H, −0.04; X = 4-Cl, Y = 4-F, −0.03; X = 3-Me, Y = 2-F, −0.03; X = 4-Cl, Y = H, −0.03; X = 3-NO$_2$, Y = 4-Br, −0.03; X = 4-Cl, Y = 2-F, 0.03; X = 4-Me, Y = 2-F, 0.03; X = 4-Me, Y = 4-F, 0.03; X = 3-OMe, Y = 4-Br, 0.03; X = 3-Cl, Y = 4-F, 0.02; X = 4-Me, Y = 4-Br, 0.02; X = Y = 3-Cl, 0.02; X = H, Y = H, 0.02; X = 4-Cl, Y = 4-Br, −0.01; X = 4-OMe, Y = 4-Br, 0.01; X = 3-Cl, Y = 4-Br, 0.01; X = 4-OMe, Y = 4-Cl, −0.01; X = 4-F, Y = 2-F, −0.01; X = 3-Me, Y = 4-F, 0.01; X = 3-OMe, Y = 4-Cl, −0.01; X = 3-OMe, Y = 4-Me, −0.01; X = 4-OMe, Y = 4-F, −0.01; X = Y = 4-Cl, −0.00; X = H, Y = 2-F, 0.00	
172	0.1 mol % benzoyl peroxide	X-$C_6H_4CH{=}CH_2$		0.17	copolymerization with methyl methacrylate catalyzed by benzoyl peroxide 60 °C $\log k = -0.17(\pm0.06)\sigma^+ + 0.06(\pm0.04)$ $n = 9$, $s = 0.046$, $r^2 = 0.880$ (0.784), (0.969), $F_{1,7} = 53.5$,§ omit: 3-Me (−0.13), 4-CN (0.37)	7
					4-I, 0.07; H, −0.06; 4-Me, −0.06; 4-OMe, 0.04; 4-Br, 0.03; 3-Br, −0.02; 3-Cl, −0.01; 4-Cl, 0.01; 4-NMe$_2$, 0.00	
173	benzene	X-$C_6H_4C({=}CH_2)$-C_6H_4-Y	$C_2H_5O^\bullet$	−0.16	addition unknown temperature $\log k_{rel} = -0.16(\pm0.06)\sigma^+ + 0.22(\pm0.09)$ $n = 9$, $s = 0.113$, $r^2 = 0.843$ (0.769), (0.986), $F_{1,7} = 37.5$,§ omit: X = Y = H (−0.21); X = H, Y = 4-OMe (−0.22)	178
					X = H, Y = 4-CN, −0.17; X = Y = 4-OMe, −0.13; X = 4-NO$_2$, Y = 4-NMe$_2$, 0.13; X = 4-CN, Y = 4-OMe, 0.10; X = Y = 4-Br, −0.09; X = Y = 4-NO$_2$, 0.08; X = Y = 4-CN, 0.04; X = Y = NMe$_2$, 0.04; X = H, Y = 4-NO$_2$, 0.02	
174	benzene	X-C_6H_5	4-Me$C_6H_4^\bullet$	−0.11	free-radical arylation 20 °C $\log k_{rel} = -0.11(\pm0.06)\sigma^+ + 0.08(\pm0.03)$ $n = 6$, $s = 0.024$, $r^2 = 0.885$ (0.728), (0.935), $F_{1,4} = 36.0$,§ omit: 4-NO$_2$ (0.96), 3-Me (−0.08)	179
					3-OMe, −0.03; 3-NO$_2$, 0.03; 4-OMe, 0.01; 3-Cl, −0.01; 4-Me, 0.01; 4-Cl, −0.01	
174a	benzene	X-$C_6H_4CH_2NC$	$C_6H_5^\bullet$	0.21	NC abstraction 100 °C $\log k_{rel} = -0.21(\pm0.04)\sigma^+ + 0.68(\pm0.03)$ $n = 6$, $s = 0.012$, $r^2 = 0.981$ (0.964), (0.975), $F_{1,4} = 116$§	179a
					4-Cl, 0.02; 3-CN, −0.01; 4-Me, −0.01; 3-OMe, 0.01; H, 0.00; 4-CN, 0.00	
175	thiophene, 50% benzene	thiophene	X-$C_6H_4^\bullet$	0.23	phenylation at 2-position $\log k = -0.23(\pm0.04)\sigma^+ + 0.86(\pm0.02)$ $n = 8$, $s = 0.024$, $r^2 = 0.965$ (0.875), (0.923), $F_{1,6} = 192$§	180
					4-Me, 0.03; 4-Cl, 0.03; 4-NO$_2$, −0.02; 3-Me, −0.02; 4-OMe, −0.02; 3-NO$_2$, 0.01; H, 0.00; 3-Cl, 0.00	

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
176	aqueous	$X\text{-}C_6H_4NH_2^{\bullet +}$		0.34	one-electron reduction $E^\circ = 0.34(\pm0.05)\sigma^+ + 1.03(\pm0.03)$ $n = 11$, $s = 0.043$, $r^2 = 0.959$ (0.938), (0.950), $F_{1,9} = 231^\S$ (E°: one-electron reduction potential)	181
					4-CN, 0.07; 4-I, −0.06; 4-Cl, −0.06; 4-CF$_3$, 0.04; 4-Br, −0.04; 4-OH, 0.04; 4-OMe, 0.02; H, −0.01; 4-Me, −0.01; 4-CMe$_3$, 0.00; 4-NH$_2$, 0.00	
177	CCl_4	$X\text{-}C_6H_4I$	$C_6H_5^\bullet$	0.36	iodine abstraction 60 °C $\log k_{rel} = -0.36(\pm0.05)\sigma^+ + 1.30(\pm0.03)$ $n = 17$, $s = 0.051$, $r^2 = 0.938$ (0.921), (0.946), $F_{1,15} = 224^\S$ omit: 4-NO$_2$ (−0.23), 4-COOMe (−0.20), 4-COMe (−0.23)	182
					4-C$_6$H$_5$, −0.10; 4-NH$_2$, 0.09; 3-CN, 0.07; 3-NO$_2$, 0.07; 3-Br, 0.07; 4-Me, −0.06; 3-COOMe, −0.03; 4-Br, −0.03; 4-CHO, −0.02; 4-CN, −0.02; 4-OMe, −0.02; 3-OMe, −0.02; 3-Me, 0.01; 3-COMe, −0.01; 3-CHO, 0.01; 3-CF$_3$, −0.01; 3-NH$_2$, 0.01	
178	2,3-dimethylbutane	$X\text{-}C_6H_4CHO$	$EtC(=O)^\bullet + (C_4H_9)_3SnH$	0.46	react with propionyl radical 25 °C $\log k_{rel} = -0.46(\pm0.09)\sigma^+ + 0.02(\pm0.033)$ $n = 5$, $s = 0.023$, $r^2 = 0.990$ (0.900), (0.844), $F_{1,3} = 233,^\S$ omit: 4-Me (0.22)	182
					4-Cl, 0.03; H, −0.02; 3-Me, −0.02; 4-OMe, 0.01; 3-Cl, 0.00	
179	C_6H_{12}	$CH_2{=}CHCN$	$X\text{-}C_6H_4S^\bullet$	0.49	addition with flash photolysis 23 °C $\log k_1 = -0.49(\pm0.21)\sigma^+ + 5.67(\pm0.11)$ $n = 5$, $s = 0.076$, $r^2 = 0.947$ (0.800), (0.922), $F_{1,3} = 55.6^\S$	184
					4-Me, 0.11; 4-OMe, −0.06; 4-Cl, −0.03; 4-NO$_2$, −0.01; H, −0.01	
180	reactants	$X\text{-}C_6H_5$	$C_6H_5^\bullet$	0.59	substitution 65 °C $\log k_{rel} = -0.59(\pm0.14)\sigma^+ + 0.00(\pm0.07)$ $n = 7$, $s = 0.048$, $r^2 = 0.961$ (0.940), (0.985), $F_{1,5} = 126,^\S$ omit: Me (0.38)	185
					Cl, −0.07; Br, 0.05; COMe, 0.05; COOMe, −0.04; CMe$_3$, 0.01; CN, −0.01; NO$_2$, 0.00	
181	aqueous, 33.3%, dioxane	$X\text{-}C_6H_4N_2^{+}\cdot BF_4^-$	$C_6H_5^\bullet$	0.62	Sandmeyer react (chlorodediazoniation) with SnCl$_2$ 20 °C $\log k_{rel} = 0.62(\pm0.15)\sigma^+ + 0.08(\pm0.08)$ $n = 6$, $s = 0.066$, $r^2 = 0.972$ (0.907), (0.934), $F_{1,4} = 141^\S$	186
					4-Me, 0.08; H, −0.07; 4-COMe, 0.06; 4-Cl, −0.03; 4-NO$_2$, −0.02; 4-OMe, −0.02	
182	aqueous 33.3% dioxane	$X\text{-}C_6H_4N_2^{+}\cdot BF_4^-$	$C_6H_5^\bullet$	0.67	Sandmeyer react (chlorodediazoniation) with CuCl 20 °C $\log k_{rel} = 0.67(\pm0.12)\sigma^+ + 0.07(\pm0.06)$ $n = 6$, $s = 0.054$, $r^2 = 0.984$ (0.921), (0.934), $F_{1,4} = 235^\S$	186
					H, −0.07; 4-Cl, 0.06; 3-Me, 0.04; 4-NO$_2$, −0.03; 4-OMe, −0.03; 4-COMe, 0.01	
183	benzene	pentamethylnitrosobenzene	$X\text{-}C_6H_4S^\bullet$	0.70	spin-trapping 23 °C $\log k = 0.70(\pm0.11)\sigma^+ + 8.55(\pm0.04)$ $n = 6$, $s = 0.030$, $r^2 = 0.988$ (0.786), (0.795), $F_{1,4} = 296^\S$	187
					H, −0.05; CMe$_3$, 0.03; Br, 0.03; OMe, −0.01; Me, 0.01; Cl, −0.01	
184	1,2-dichlorobenzene	diphenylamines	tetralin hydroperoxide radicals	0.72	inhibition of oxidation of styrene 65 °C $\log k = 0.72(\pm0.18)\sigma^+ - 5.70(\pm0.15)$ $n = 5$, $s = 0.101$, $r^2 = 0.983$ (0.955), (0.903), $F_{1,3} = 176,^\S$ (k: the inhibited rate constant for styrenes)	105
					3-Cl, −0.12; 4-NO$_2$, 0.11; 4,4′-Me$_2$, 0.05; H, −0.04; 4,4′-(OMe)$_2$, 0.01	
185	C_6H_{12}		$X\text{-}C_6H_4S^\bullet$ and $(Me_3C)_2NO^\bullet$	0.77	recombination 23 °C $\log k = 0.77(\pm0.02)\sigma^+ + 9.12(\pm0.01)$ $n = 4$, $s = 0.004$, $r^2 = 1.000$ (0.829), (0.821), $F_{1,2} > 1000^\S$	188
					4-Cl, 0.00; 4-Me, 0.00; H, 0.00; 4-OMe, 0.00	
186	1,2-dichlorobenzene	diphenylamines	polystyryl peroxide radicals	0.78	inhibition of autooxidation of styrene 65 °C $\log k = 0.78(\pm0.14)\sigma^+ + 7.99(\pm0.13)$ $n = 7$, $s = 0.136$, $r^2 = 0.978$ (0.957), (0.928), $F_{1,5} = 218^\S$	105
					4,4′-(OMe)$_2$, 0.19; 4-OMe, −0.19; H, −0.09; 4,4′-(NO$_2$)$_2$, 0.07; 4-NO$_2$, 0.06; 3-Cl, −0.04; 4,4′-Me$_2$, 0.00	

Table 1 (Continued)

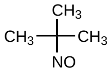
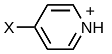
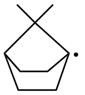
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
187	benzene	 $CH_3\overset{CH_3}{\underset{NO}{-}}CH_3$	4-X-$C_6H_4S^\bullet$	0.81	spin-trapping res 23 °C $\log k = 0.81(\pm 0.17)\sigma^+ + 8.24(\pm 0.06)$ $n = 6, s = 0.048, r^2 = 0.978$ (0.862), (0.795), $F_{1,4} = 177^{\S}$	187
		Cl, 0.07; CMe_3, −0.06; Br, −0.02; OMe, 0.02; H, −0.01; Me, 0.01				
188	benzene	C_6H_5NO	X-$C_6H_4S^\bullet$	0.84	spin-trapping res 23 °C $\log k = 0.84(\pm 0.14)\sigma^+ + 8.42(\pm 0.09)$ $n = 6, s = 0.061, r^2 = 0.986$ (0.971), (0.934), $F_{1,4} = 275,^{\S}$ omit: 4-OMe (0.18)	187
		H, −0.08; 4-Br, 0.07; 4-CMe_3, −0.06; 4-Cl, 0.04; 4-Me, 0.02; 4-NH_2, 0.02				
189	reactants	X-C_6H_4Me	$Me_3C^\bullet$	0.92	hydrogen abstraction 30 °C $\log k_{rel} = 0.92(\pm 0.39)\sigma^+ + 0.10(\pm 0.10)$ $n = 4, s = 0.044, r^2 = 0.981$ (0.929), (0.982), $F_{1,2} = 102^{\S}$	52
		3-Cl, 0.04; 4-Cl, −0.03; 4-Br, −0.03; 4-Me, 0.02				
190	C_6H_{12}	$CH_3OOCC(Me){=}CH_2$	X-$C_6H_4S^\bullet$	0.98	addition with flash photolysis 23 °C $\log k_1 = 0.98(\pm 0.39)\sigma^+ + 6.55(\pm 0.20)$ $n = 5, s = 0.143, r^2 = 0.954$ (0.817), (0.922), $F_{1,3} = 61.3^{\S}$	189
		4-Me, 0.18; 4-OMe, −0.13; 4-Cl, 0.07; 4-NO_2, −0.07; H, −0.05				
191	aqueous 33.3% dioxane	$FeCl_2$	X-$C_6H_4^\bullet$	1.00	Sandmeyer reaction (chlorodediazoniation) with $FeCl_2$ 20 °C $\log k_{rel} = 1.00(\pm 0.28)\sigma^+ - 0.01(\pm 0.15)$ $n = 6, s = 0.128, r^2 = 0.960$ (0.834), (0.934), $F_{1,4} = 94.6^{\S}$	186
		4-NO_2, −0.14; 4-OMe, −0.13; 4-Cl, 0.13; 4-Me, 0.09; 4-COMe, 0.04; H, 0.01				
192	reactants	X-C_6H_4CHO	$(n\text{-}C_4H_9)_3Sn^\bullet$	1.11	addition 110 °C $\log k_{rel} = 1.11(\pm 0.39)\sigma^+ + 0.02(\pm 0.14)$ $n = 7, s = 0.135, r^2 = 0.915$ (0.846), (0.840), $F_{1,5} = 53.7^{\S}$	190
		3-OMe, −0.24; 4-Cl, 0.13; 3-F, 0.09; 4-Me, 0.09; 3-Me, −0.04; H, −0.03; 4-OMe, −0.01				
193	benzene	$CH_2{=}CHCOOMe$	X-$C_6H_4S^\bullet$	1.22	addition 23 °C via flash photolysis $\log k_1 = 1.22(\pm 0.28)\sigma^+ + 5.48(\pm 0.10)$ $n = 6, s = 0.080, r^2 = 0.973$ (0.763), (0.795), $F_{1,4} = 145^{\S}$	191
		4-Me, 0.10; 4-Cl, 0.08; 4-Br, −0.07; H, −0.05; 4-OMe, −0.04; 4-CMe_3, −0.02				
194	benzene	$CH{\equiv}CCOOMe$	X-$C_6H_4S^\bullet$	1.27	addition via flash photolysis 23 °C $\log k_1 = 1.27(\pm 0.24)\sigma^+ + 3.97(\pm 0.09)$ $n = 6, s = 0.068, r^2 = 0.982$ (0.892), (0.795), $F_{1,4} = 217^{\S}$	191
		4-CMe_3, −0.06; 4-Cl, 0.07; 4-OMe, 0.06; H, −0.05; 4-Me, −0.05; 4-Br, 0.04				
195	reactants			1.35	substitution 90 °C $\log k_{rel} = 1.35(\pm 0.30)\sigma^+ - 0.00(\pm 0.15)$ $n = 6, s = 0.129, r^2 = 0.974$ (0.955), (0.928), $F_{1,4} = 151^{\S}$	192
		4-Me, −0.17; 4-CN, 0.12; 4-COMe, −0.11; 4-OMe, 0.10; 4-Cl, 0.06; H, 0.00				
196	C_6H_{12}	$C_6H_5CH{=}CH_2$	X-$C_6H_4S^\bullet$	1.36	addition via flash photolysis 23 °C $\log k_1 = 1.36(\pm 0.44)\sigma^+ + 7.51(\pm 0.23)$ $n = 5, s = 0.158, r^2 = 0.970$ (0.911), (0.922), $F_{1,3} = 96.7^{\S}$	189
		H, −0.21; 4-Me, 0.17; 4-Cl, 0.05; 4-OMe, −0.04; 4-NO_2, 0.02				
197	1,2-dichlorobenzene	X-C_6H_4NHMe	polystyryl peroxide radicals	1.38	inhibition of autoxidation of styrene 65 °C $\log k = 1.38(\pm 0.33)\sigma^+ - 5.14(\pm 0.10)$ $n = 4, s = 0.044, r^2 = 0.994$ (0.946), (0.974), $F_{1,2} = 320^{\S}$ (k: inhibited rate constant for styrenes)	105
		3-Me, 0.05; 4-Me, −0.03; 4-COOMe, −0.02; H, 0.00				
198	C_6H_{12}	$Me_2CHCH_2OCH{=}CH_2$	X-$C_6H_4S^\bullet$	1.40	addition 23 °C via flash photolysis $\log k_1 = 1.40(\pm 0.40)\sigma^+ + 5.23(\pm 0.21)$ $n = 5, s = 0.145, r^2 = 0.976$ (0.943), (0.922), $F_{1,3} = 124^{\S}$	184
		H, −0.15; 4-Cl, −0.13; 4-NO_2, 0.12; 4-Me, 0.09; 4-OMe, 0.07				

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
198a	34% acetic acid and 14% sulfuric acid	2-X-quinolines	$CH_3CO^\bullet$	1.42	acetylation with $CH_3CO^\bullet$ radicals generated from acetaldehyde unknown temperature $\log k_{rel} = 1.42(\pm 0.19)\sigma^+ + 0.46(\pm 0.09)$ $n = 6$, $s = 0.079$, $r^2 = 0.991$ (0.942), (0.926), $F_{1,4} = 445^§$	192a
					2-Cl, 0.12; 2-COOEt, −0.07; H, −0.07; 2-CN, 0.03; 2-Me, −0.02; 2-OMe, 0.01	
199	C_6H_{12}	$CH_3COOCH{=}CH_2$	$X\text{-}C_6H_4S^\bullet$	1.49	addition via flash photolysis 23 °C $\log k_1 = 1.49(\pm 0.45)\sigma^+ + 0.48(\pm 0.23)$ $n = 5$, $s = 0.164$, $r^2 = 0.974$ (0.950), (0.922), $F_{1,3} = 36.7^§$	184
					4-H, −0.25; 4-Me, 0.10; 4-NO_2, 0.08; 4-OMe, 0.05 4-Cl, 0.02	
200	aqueous	X-pyridium salts	$C_4H_9^\bullet$	1.56	alkylation 90 °C $\log k_{rel} = 1.56(\pm 0.45)\sigma^+ + 0.09(\pm 0.24)$ $n = 5$, $s = 0.168$, $r^2 = 0.975$ (0.967), (0.928), $F_{1,3} = 119^§$	193
					4-CN, 0.19; 4-OMe, 0.12; 4-COMe, −0.12; 4-Me, −0.10; H, −0.09	
200a	34% acetic acid and 14% sulfuric acid	2-X-quinolines	$C_6H_5CO^\bullet$	1.66	benzoylation unknown temperature $\log k_{rel} = 1.66(\pm 0.17)\sigma^+ + 0.55(\pm 0.08)$ $n = 6$, $s = 0.072$, $r^2 = 0.995$ (0.957), (0.926), $F_{1,4} = 725^§$	192a
					H, −0.11; 2-OMe, 0.06; 2-Me, −0.04; 2-COOEt, 0.03; 2-CN, 0.03; 2-Cl, 0.03	
201	benzene	$CH_2{=}CH\text{-}Y$	$X\text{-}C_6H_4S^\bullet$	1.69	addition 23 °C via flash photolysis $\log k_1 = 1.69(\pm 0.52)\sigma^{+},X - 8.92(\pm 1.40)\sigma I,Y + 2.22(\pm 0.72)B1,Y + 5.59(\pm 1.14)$ $n = 33$, $s = 0.477$, $r^2 = 0.884$ (0.697), (0.800), $F_{1,31} = 36.8^§$ (σI, Y), $F_{1,30} = 19.6^§$ (σ^+, X), $F_{1,29} = 39.5^§$ (B1,Y), (B1,*y*: sterimol parameter, B1, for Y) omit: X = 4-Cl, Y = OEt (−1.236); X = 4-CMe_3, Y = OEt (−1.274); X = 4-Me, Y = OEt (−1.291)	194
					X = H, Y = OEt, −1.21; X = 4-OMe, Y = OEt, −1.12; X = 4-Br, Y = OEt, −1.09; X = 4-OMe, Y = SOC_6H_5, 0.64; X = H, Y = $SO_2C_6H_5$, −0.54; X = 4-Cl, Y = SO_2Et, −0.52; X = 4-Br, Y = SEt, 0.51; X = 4-Cl, Y = SEt, 0.47; X = 4-Br, Y = SO_2Et, −0.43; X = 4-Cl, Y = SC_6H_5, 0.39; X = 4-Br, Y = SC_6H_5, 0.38; X = 4-Me, Y = OC_6H_5, 0.34; X = H, Y = SEt, 0.28; X = 4-Me, Y = SOC_6H_5, 0.27; X = 4-OMe, Y = SO_2Et, 0.27; X = 4-CMe_3, Y = OC_6H_5, 0.23; X = 4-Br, Y = SOC_6H_5, 0.22; X = 4-Cl, Y = SCO_6H_5, 0.22; X = 4-OMe, Y = SEt, −0.22; X = 4-Cl, Y = OC_6H_5, 0.21; X = 4-CMe_3, Y = SCO_6H_5, 0.19; X = 4-CMe_3, Y = SC_6H_5, 0.18; X = 4-Me, Y = SEt, 0.17; X = 4-Me, Y = SC_6H_5, 0.15; X = 4-CMe_3, Y = SO_2Et, −0.13; X = 4-Br, Y = OC_6H_5, 0.12; X = 4-OMe, Y = OC_6H_5, −0.09; X = H, Y = SC_6H_5, 0.08; X = 4-CMe_3, Y = SEt, 0.06; X = 4-OMe, Y = SC_6H_5, 0.05; X = 4-Me, Y = SO_2Et, −0.05; X = H, Y = OC_6H_5, −0.02; X = H, Y = SOC_6H_5, −0.01	
202	C_6H_{12}	$C_6H_5C(Me){=}CH_2$	$4\text{-}X\text{-}C_6H_4S^\bullet$	1.72	addition 23 °C via flash photolysis $\log k_1 = 1.72(\pm 0.24)\sigma^+ + 7.84(\pm 0.15)$ $n = 11$, $s = 0.339$, $r^2 = 0.881$ (0.864), (0.920), $F_{1,9} = 66.9,^§$ omit: 4-COMe (−1.52), 4-CN (−0.74)	195
					4-Cl, −0.59; 4-OMe, 0.41; 3-CN, 0.39; 3,4-Me_2, −0.38; 3-CF_3, 0.28; 4-CF_3, −0.22; H, 0.17; 4-Me, −0.15; 4-CMe_3, 0.15; 3-Me, −0.10; 3-Cl, 0.04	
203	CH_3CN	$X\text{-}C_6H_4\text{-}C({=}O)Me$		1.99	photoreduction by *p*-xylene at ambient temperature $\log k_r = 1.99(\pm 0.55)\sigma^+ + 5.67(\pm 0.23)$ $n = 11$, $s = 0.339$, $r^2 = 0.881$ (0.864)), (0.920), $F_{1,9} = 66.9,^§$ omit: 4-COMe (−1.52), 4-CN (−0.74)	196
					4-Cl, −0.59; 4-OMe, 0.41; 3-CN, 0.39; 3,4-Me_2, −0.38; 3-CF_3, 0.28; 4-CF_3, −0.22; H, 0.17; 4-Me, −0.15; 4-CMe_3, 0.15; 3-Me, −0.10; 3-Cl, 0.04	
204	benzene	$C_6H_5C(Me){=}CH_2$	$4\text{-}X\text{-}C_6H_4S^\bullet$	2.00	addition via flash photolysis 23 °C $\log k_1 = 2.00(\pm 0.62)\sigma^+ + 7.87(\pm 0.48)$ $n = 4$, $s = 0.151$, $r^2 = 0.990$ (0.974), (0.954), $F_{1,2} = 197^§$	195
					4-OMe, 0.18; 4-NH_2, −0.09; 4-Me, −0.07; 4-Cl, −0.01	
204a	34% acetic acid and 14% sulfuric acid	4-X-quinolines (protonated)	$CH_3CO^\bullet$	2.09	acetylation unknown temperature $\log k_{rel} = 2.09(\pm 0.47)\sigma^+ + 0.36(\pm 0.23)$ $n = 6$, $s = 0.201$, $r^2 = 0.974$ (0.847), (0.926), $F_{1,4} = 149^§$	192a
					4-OMe, −0.22; 4-Me, 0.29; 4-COOEt, −0.14; 4-Cl, 0.08; 4-CN, −0.04; H, 0.03	
205	*o*-dichlorobenzene	$C_6H_5C(Me){=}CH_2$	$4\text{-}X\text{-}C_6H_4S^\bullet$	2.10	addition via flash photolysis 23 °C $\log k_1 = 2.10(\pm 0.72)\sigma^+ + 7.88(\pm 0.56)$ $n = 4$, $s = 0.177$, $r^2 = 0.987$ (0.970), (0.954), $F_{1,2} = 197^§$	195
					4-OMe, 0.21; 4-NH_2, −0.12; 4-Me, −0.06; 4-Cl, −0.04	

Table 1 (Continued)

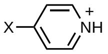
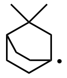
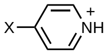
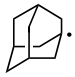
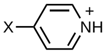
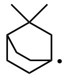
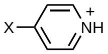
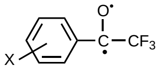
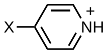
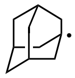
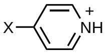
set	solvent	compound	radical	ρ^+	reaction, correlation	ref
206	reactants			2.63	substitution at ortho position 90 °C $\log k_{rel} = 2.63(\pm0.62)\sigma^+ + 0.06(\pm0.30)$ $n = 6$, $s = 0.262$, $r^2 = 0.972$ (0.917), (0.928), $F_{1,4} = 140$§ 4-Cl, 0.44; 4-Me, −0.020; 4-CN, −0.19; H, −0.06; 4-COMe, 0.02; 4-OMe, −0.01	192
207	reactants			2.64	substitution 90 °C $\log k_{rel} = 2.64(\pm0.22)\sigma^+ - 0.02(\pm0.09)$ $n = 4$, $s = 0.027$, $r^2 = 0.999$ (0.961), (0.966), $F_{1,2} = 2053$,§ omit: 4-Me (−0.84) 4-COMe, −0.03; 4-CN, 0.02; H, 0.02; 4-Cl, −0.01	192
208	reactants			2.70	substitution 90 °C $\log k_{rel} = 2.70(\pm0.81)\sigma^+ - 0.42(\pm0.39)$ $n = 6$, $s = 0.344$, $r^2 = 0.956$ (0.843), (0.928), $F_{1,4} = 85.5$§ H, 0.42; 4-Cl, 0.35; 4-CN, −0.27; 4-Me, −0.27; 4-OMe, −0.14; 4-COMe, −0.09	192
209	aqueous		$^{\bullet}CH(Me)C_2H_5$	2.83	alkylation 90 °C $\log k_{rel} = 2.83(\pm0.67)\sigma^+ + 0.34(\pm0.35)$ $n = 5$, $s = 0.249$, $r^2 = 0.984$ (0.971), (0.928), $F_{1,3} = 179$§ H, −0.34; 4-CN, 0.20; 4-OMe, 0.17; 4-Me, −0.02; 4-COMe, −0.01	193
210	CH_3CN	X-C_6H_4Me		2.96	hydrogen abstraction at ambient temperature $\log k = 2.96(\pm0.89)\sigma^+ + 6.91(\pm0.37)$ $n = 11$, $s = 0.473$, $r^2 = 0.897$ (0.820), (0.912), $F_{1,9} = 61.05$,§ omit: 3-Me (−0.87) 3-CF_3, 0.71; 4-Cl, −0.62; 4-F, 0.52; 3,4-Me_2, −0.43; 4-OMe, 0.29; 3-Cl, −0.34; 4-Me, −0.12; 4-CF_3, −0.08; H, 0.06	196
211	reactants			3.58	substitution at ortho position 90 °C $\log k_{rel} = 3.58(\pm0.52)\sigma^+ + 0.07(\pm0.23)$ $n = 4$, $s = 0.094$, $r^2 = 0.998$ (0.991), (0.988), $F_{1,2} = 858$,§ omit: 4-Cl (0.47) 4-COMe, 0.09; H, −0.08; 4-CN, −0.05; 4-Me, 0.04	192
212	aqueous		$Me_3C^{\bullet}$	3.78	alkylation 90 °C $\log k_{rel} = 3.78(\pm0.78)\sigma^+ + 0.45(\pm0.38)$ $n = 6$, $s = 0.332$, $r^2 = 0.978$ (0.972), (0.928), $F_{1,4} = 180.6$§ H, −0.45; 4-CN, 0.33; 4-OMe, 0.23; 4-COMe, −0.18; 4-Cl, 0.18; 4-Me, −0.10	193
213	CCl_4	X-C_6H_4-CH=N(O)CMe_3	Y-$C_6H_4^{\bullet}$		addition (spin-trapping) unknown temperature $\log k_{rel} = -0.27(\pm0.03)\sigma$,X − 0.10(±0.06)s+,Y + 0.15(±0.09)(σ^+,Y)^2 − 0.01(0.01) $n = 90$, $s = 0.044$, $r^2 = 0.815$ (0.068), (0.969), $F_{1,88} = 326$,§ (σ,X), $F_{1,87} = 1.39$§ (σ^+,Y), $F_{1,86} = 11.4$§ ((σ^+,Y)^2), omit: X = 4-OMe, Y = 4-Me (−0.36); X = 4-OMe, Y = 3-Me (−0.24); X = 4-OMe, Y = H (−0.21); X = Y = 4-Me (−0.22); X = Y = 4-F (−0.09); X = 3-Me, Y = 4-Me (−0.18); X = 4-Cl, Y = 4-Me (0.13); X = 4-Cl, Y = 2-Me (0.11); X = 3-Cl, Y = 4-Me (0.15); X = 3-Cl, Y = 3-Me (0.16); X = 3-Cl, Y = 2-Me (0.12); X = 3-NO_2, Y = 4-Me (0.35); X = 3-NO_2, Y = 3-Me (0.31); X = 3-NO_2, Y = 2-Me (0.28); X = 4-NO_2, Y = 4-Me (0.39); X = 4-NO_2, Y = 3-Me (0.27); X = 4-NO_2, Y = 2-Me (0.33) X = 4-Me, Y = 2-F, −0.17; X = Y = 4-NO_2, −0.10; X = 3-Cl, Y = 4-Br, −0.09; X = 4-NO_2, Y = 2-F, 0.09; X = 3-NO_2, Y = 2-F, 0.08; X = 3-Me, Y = 4-Br, 0.08; X = 4-NO_2, Y = 3-F, 0.08; X = 4-Cl, Y = 4-Br, −0.08; X = 4-Cl, Y = 3-Me, 0.08; X = 4-F, Y = 4-Cl, −0.08; X = 4-Me, Y = H, −0.08; X = 4-Me, Y = 4-F, 0.08; X = 4-OMe, Y = 4-NO_2, 0.07; X = 4-Me, Y = 3-Me, −0.07; X = 4-Me, Y = 3-F, 0.07; X = 4-NO_2, Y = 4-Br, −0.07; X = 4-NO_2, Y = 4-F, 0.06; X = 4-Cl, Y = 4-F, −0.06; X = 3-OMe, Y = 4-Me, 0.06; X = 4-Me, Y = 4-Cl, 0.06; X = Y = 3-Cl, 0.06; X = 3-NO_2, Y = 4-Br, −0.05; X = 4-OMe, Y = 4-Cl, −0.05; X = 3-Me, Y = 2-F, −0.05; X = 4-F, Y = 2-Me, 0.05; X = 3-NO_2, Y = 4-F, 0.04; X = 3-OMe, Y = 3-Cl, 0.04; X = 4-NO_2, Y = 3-Cl, 0.04; X = Y = 4-Cl, −0.04; X = H, Y = 2-Me, −0.04; X = H, Y = 4-Me, −0.04; X = 3-Cl, Y = 4-Cl, −0.04; X = 3-OMe, Y = 3-Me, 0.04; X = 3-OMe, Y = H, −0.04; X = 3-NO_2, Y = H, −0.04; X = 3-NO_2, Y = 4-Cl, 0.04; X = 4-OMe, Y = 4-Br, −0.03; X = 4-Cl, Y = 2-F, −0.03; X = 3-OMe, Y = 4-Br, −0.03; X = 3-OMe, Y = 4-F, −0.03; X = 4-OMe, Y = 2-F, 0.03; X = 3-Cl, Y = 3-F, −0.03; X = 3-Cl, Y = 4-NO_2, −0.03; X 3-Me, Y = H, −0.03; X = 4-Me, Y = 3-Cl, 0.03; X = 4-Me, Y = 2-Me, −0.03; X = 4-OMe, Y = 3-F, 0.03; X = 4-Me, Y = 4-Br, 0.03; X = 4-F, Y = H, −0.03; X = 3-OMe, Y = 2-Me, 0.03; X = 3-Me, Y = 4-F, 0.03; X = H, Y = 3-F, 0.02; X = H, Y = 3-Cl, 0.02; X = 4-F, Y = 3-F, 0.02; X = 4-NO_2, Y = H, 0.02; X = 3-NO_2, Y = 3-Cl, −0.02; X = 3-Cl, Y = 2-F, −0.02; X = 4-F, Y = 4-Me, 0.02; X = 4-F, Y = 3-Me, 0.02; X = 3-NO_2, Y = 3-F, −0.02; X = H, Y = 4-Br, 0.02; X = 4-Cl, Y = H, −0.02; X = 3-Cl, Y = H, −0.02; X = 3-Me, Y = 3-F, 0.02; X = 3-Me, Y = 3-Cl, 0.02; X = H, Y = 4-Cl, 0.02; X = 4-F, Y = 4-Br, −0.02; X = 4-F, Y = 2-F, −0.01; X = 3-OMe, Y = 2-F, −0.01; X = 4-F, Y = NO_2, −0.01; X = 4-Cl, Y = 3-F, −0.01; X = 3-Me, Y = 4-Cl, 0.01; X = 3-OMe, Y = 3-F, −0.01; X = 4-Cl, Y = 4-NO_2, −0.01; X = 4-Me, Y = 4-NO_2, 0.01; X = H, Y = 4-NO_2, −0.01; X = Y = H, 0.01; X = Y = 3-Me, 0.00; X = 3-OMe, Y = 4-Cl, 0.00; X = 3-Cl, Y = 4-F, 0.00; X = H, Y = 4-F, 0.00; X = 4-F, Y = 3-Cl, 0.00; X = 3-NO_2, Y = 4-NO_2, 0.00 X = H, Y = 2-F, 0.00 X = H, Y = 3-Me, 0.00 X = 4-OMe, Y = 4-F, 0.00 X = 3-Me, Y = 4-NO_2, 0.00 X = 3-OMe, Y = 4-NO_2, 0.00 X = 4-NO_2, Y = 4-Cl, 0.00 X 4-Cl, Y = 3-Cl, 0.00	177

Table 1 (Continued)

set	solvent	compound	radical	ρ^+	reaction, correlation	ref
214	reactants	X-$C_6H_4CH{=}CH_2$			polymerization with maleic anhydride catalyzed by benzoyl peroxide 60 °C $\log k = -0.68(\pm 0.20)\sigma^+ + 1.28(\pm 0.37)\ (\sigma^+)^2 - 0.06(0.10)$ $n = 8$, $s = 0.087$, $r^2 = 0.976\ (0.790), (0.923)$, $F_{1,6} = 9.46^{\S\S}\ (\sigma^+)$, $F_{1,5} = 77.4^{\S}\ ((\sigma^+)^2$	197
		4-F, −0.12; 3-Br, 0.11; 4-CN, −0.07; H, 0.06; 4-Me, −0.03; 4-OMe, 0.02; 4-Cl, 0.02; 4-Br, 0.00				
215	acetophenone	$(X\text{-}C_6H_4COO)_2$	X-$C_6H_4COO^\bullet$		free-radical formation 80 °C $\log k = -0.42(\pm 0.13)\sigma^+ + 0.45(\pm 0.25)(\sigma^+)^2 - 4.39(\pm 0.09)$ $n = 9$, $s = 0.074$, $r^2 = 0.921(0.844), (0.933)$, $F_{1,7} = 4.76^{\S\S}\ (\sigma^+)$, $F_{1,6} = 19.6^{\S}\ ((\sigma^+)^2$, omit: 3-OMe (0.25)	198
		4-CN, −0.14; 4-NO_2, 0.08; 3-Cl, −0.05; 3-NO_2, 0.04; H, 0.03; 3-Me, 0.03; 4-Cl, 0.01; 4-OMe, −0.01; 4-Me, −0.01				

a. Hydrogen Abstraction from Unhindered Phenols Correlated by σ^+

set	solvents	reagent	ρ^+	T, °C
18	carbon tetrachloride	$Me_3CO^\bullet$	−1.81(±0.77)	130
27	styrene	styryl peroxy radical	−1.60(±0.08)	65
34	benzene	$Me_3CO^\bullet$	−1.46(±0.37)	130
63	styrene	styryl peroxide	−1.23(±0.10)	65
72	carbon tetrachloride	$Me_3CO^\bullet$	−1.13(±0.18)	120
81	acetonitrile	$Me_3CO^\bullet$	−1.02(±0.16)	130
91	benzene	$Me_3CO^\bullet$	−0.82(±0.08)	22
92	reactants	$Me_3CO^\bullet$	−0.82(±0.16)	25
103	chlorobenzene	$Me_3CO^\bullet$	−0.71(±0.10)	122
121	benzene	$(C_6H_5)_2CO^\bullet$	−0.60(±0.120)	22

b. Hydrogen Abstraction from Unhindered Toluenes Corrleated by σ^+

set	solvents	reagent	ρ^+	T, °C
11	benzene	$Br^\bullet$ (bromoarylalkoxyiodinane)	−2.53(±1.70)	50
14	dichloromethane	oxometalloporphyrin (Cl)(TPP)Cr=O	−2.08(±1.30)	27
21	dichloromethane	oxometalloporphyrin (Cl)(TPP)Fe=O	−1.71(±0.06)	27
22	CCl_3F	Br_2/ethylene oxide	−1.69(±0.72)	23
24	CCl_3F	$Br^\bullet$ (Br_2)	−1.66(±0.48)	23
28	benzene	$Br^\bullet$ (*N*-bromotetramethylsuccinimide)	−1.58(±0.35)	19
29	CCl_3F/CCl_2FCClF_2	$Br^\bullet$ (NBS)	−1.56(±0.26)	23
30	CCl_3F	$Br^\bullet$ (NBS/Br_2)	−1.53(±0.22)	23
33	benzene	$Br^\bullet$ (bromoarylalkoxyiodinane)	−1.50(±0.04)	50
35	CCl_4	$Br^\bullet$ (NBS)	−1.46(±0.17)	80
36	benzene	$Cl^\bullet$ (chloroarylalkoxyiodinane)	−1.45(±0.09)	50
37	toluene	$Cl_3C^\bullet$	−1.45(±0.11)	50
38	γ-picoline	$Me_3COO^\bullet$	−1.44(±0.62)	110
38a	CH_2Cl_2	$Br^\bullet$ (NBS)	−1.43(±0.15)	80
39	CCl_4	$Br^\bullet$ (NBS)	−1.43(±0.14)	80
39a	benzene	$Br^\bullet$ (NBS)	−1.43(±0.02)	80
40	benzene	$Br^\bullet$ (NBS)	−1.43(±0.13)	80
41	benzene	$Br^\bullet$ (NBS)	−1.42(±0.16)	80
42	benzene	$Br^\bullet$ (*N*-bromotetrafluorosuccinimide)	−1.42(±0.17)	80
45	CCl_4	$Br^\bullet$ (1-bromo-5-isobutyl-5-methylhydantoin)	−1.39(±0.43)	80
46	CCl_2FCClF_2	$Br^\bullet$ (NBS/Br_2)	−1.38(±0.25)	23
47	benzene	$Br^\bullet$ (Br_2)	−1.37(±0.61)	19
48	dichloromethane	oxometalloporphyrin (Cl)(TPP)Mn=O	−1.37(±0.11)	27
49	benzene	$Cl^\bullet$ (chloroarylakoxyiodinane)	−1.35(±0.03)	50
50	benzene	$Br^\bullet$ (Br_2)	−1.35(±0.14)	80
51	benzene	$Br^\bullet$ (Br_2)	−1.34(±0.15)	80
53	benzene	$Br^\bullet$ (NBS)	−1.34(±0.15)	80
54	benzene	$Br^\bullet$ (NBS)	−1.33(±0.17)	80
55	CCl_4	$Br^\bullet$ (NBS)	−1.32(±0.21)	80
58	CCl_4	$Br^\bullet$ (1-Br-3,5,5-trimethylhydantoin)	−1.31(±0.24)	80
60a	CCl_4	$Br^\bullet$ (NBS)	−1.28(±0.15)	80
61	reactants	$Br^\bullet$ ($BrCCl_3$)	−1.24(±0.10)	50
62	CCl_4	$Br^\bullet$ (3-Br-1,5,5-trimethylhydantoin)	−1.23(±0.24)	80
64	CCl_2FCCl_2F and CCl_2FCClF_2	$Br^\bullet$ (NBS/Br_2)	−1.20(±0.21)	23
65	CCl_2FCCl_2F	$Br^\bullet$ (NBS/Br_2)	−1.20(±0.19)	23
66	CCl_4	$Br^\bullet$ (NBS)	−1.19(±0.21)	10
67	dichloromethane	$Br^\bullet$ (NBS)	−1.19(±0.21)	10
69	CCl_2FCCl_2F	$Br^\bullet$ (Br_2)	−1.17(±0.49)	23
70	benzene	benzophenone triplet	−1.17(±0.24)	22
74	CCl_4	$Br^\bullet$ (MeCONHBr)	−1.11(±0.41)	80
78	benzene	$Br^\bullet$ (Br_2)	−1.06(±0.15)	80
93	benzene	$Me_3CO^\bullet$	−0.80(±0.15)	40
100	reactants	$Cl^\bullet$	−0.73(±0.14)	70
104	CCl_4	4-nitrocumyloxyl radical	−0.71(±0.12)	40

Table 1 (Continued)

b. Hydrogen Abstraction from Unhindered Toluenes Corrleated by σ^+

set	solvents	reagent	ρ^+	T, °C
107	CCl_4	$Me_3CO^\bullet$	$-0.69(\pm0.05)$	40
108	acetic acid	$HOOCCH_2^\bullet$	$-0.68(\pm0.06)$	130
113	C_6H_5CN	$Cl^\bullet$	$-0.64(\pm0.29)$	80
118	unknown	$Me_3CO^\bullet$	$-0.62(\pm0.13)$	40
120	CCl_4	4-nitrocumuloxyl radical	$-0.61(\pm0.13)$	40
125	reactants	$Me_3COO^\bullet$	$-0.57(\pm0.11)$	30
127	unknown	$Me_3COO^\bullet$	$-0.56(\pm0.1)$	20
136	benzene	$Me_3CO^\bullet$	$-0.43(\pm0.07)$	130
138	acetonitrile	$Me_3CO^\bullet$	$-0.41(\pm0.04)$	43
149	CCl_2FCClF_2	$Me_3CO^\bullet$	$-0.35(\pm0.05)$	45
150	chlorobenzene	$Me_3CO^\bullet$	$-0.34(\pm0.22)$	40
152	chlorobenzene	$C_4H_9O^\bullet$	$-0.33(\pm0.18)$	40
154	chlorobenzene	$Me_3CO^\bullet$	$-0.32(\pm0.05)$	60

c. Addition of Radicals to Unsaturated Systems Correlated by σ^+

set	solvent	substrate	radical	ρ^+	T, °C
77	methanol	$X\text{-}C_6H_4CH{=}CH_2$	$(^-OO)_2CH^\bullet$	$-1.06(\pm0.15)$	20
80	methanol	$X\text{-}C_6H_4CH{=}CH_2$	$(^-OO)_2CH^\bullet$	$-1.05(\pm0.27)$	20
98	cyclohexane	$X\text{-}C_6H_4C(Me){=}CH_2$	$ClC_6H_4S^\bullet$	$-0.75(\pm0.14)$	23
119	reactants	$X\text{-}C_6H_4C(Me){=}CH_2$	$Cl_3C^\bullet$	$-0.61(\pm0.14)$	105
124	cyclohexane	$X\text{-}C_6H_4CH{=}CH_2$	$ClC_6H_4S^\bullet$	$-0.58(\pm0.15)$	23
127	reactants	$X\text{-}C_6H_4CH{=}CHC_6H_4\text{-}Y$	$Cl_3C^\bullet$	$-0.57(\pm0.25)$	105
131	benzene	$X\text{-}C_6H_4CH{=}CH_2$	$MeC_6H_4SO_2^\bullet$	$-0.49(\pm0.11)$	43
132	benzene	$X\text{-}C_6H_4CH{=}CH_2$	$Cl_3C^\bullet$	$-0.49(\pm0.13)$	80
134	carbon tetrachloride	$X\text{-}C_6H_4CH{=}CH_2$	$C_6H_5Se^\bullet$	$-0.44(\pm0.11)$	23
139	reactants	$X\text{-}C_6H_4CH{=}CHC_6H_5$	$HOOCCH_2S^\bullet$	$-0.40(\pm0.18)$	105
141	cyclohexane	$X\text{-}C_6H_4C{\equiv}CH$	$Y\text{-}C_6H4S^\bullet$	$-0.40(\pm0.09)$	23
142	benzene	$X\text{-}C_6H_4C(Me){=}CH_2$	$C_6H_5S^\bullet$	$-0.40(\pm0.09)$	70
147	reactants	$X\text{-}C_6H_4C(Me){=}CH_2$	$MeOOCH_2S^\bullet$	$-0.36(\pm0.10)$	105
153	benzene	$X\text{-}C_6H_4CH{=}CH_2$	$Me_3CO^\bullet$	$-0.33(\pm0.05)$	60
155	cyclohexane	$X\text{-}C_6H_4CH{=}CH_2$	$C_6H_5S^\bullet$	$-0.31(\pm0.09)$	23
156	benzene	$X\text{-}C_6H_4CH{=}CH_2$	$Me_3COO^\bullet$	$-0.31(\pm0.22)$	20
157	benzene	$Y\text{-}C_6H_4C(Me){=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-0.31(\pm0.05)$	70
161	cyclohexane	$X\text{-}C_6H_4C(Me){=}CH_2$	$C_6H_5S^\bullet$	$-0.29(\pm0.03)$	23
173	benzene	$X\text{-}C_6H_4C({=}CH_2)C_6H_4\text{-}Y$	$C_2H_5O^\bullet$	$-0.16(\pm0.06)$	23
179	cyclohexane	$NCCH{=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-0.49(\pm0.21)$	23
190	cyclohexane	$MeOOCC(Me){=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-0.98(\pm0.39)$	23
193	benzene	$CH_2{=}CHCOOMe$	$X\text{-}C_6H_4S^\bullet$	$-1.22(\pm0.28)$	23
194	benzene	$CH{\equiv}CCOOMe$	$X\text{-}C_6H_4S^\bullet$	$-1.27(\pm0.24)$	23
196	cyclohexane	$C_6H_5CH{=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-1.36(\pm0.44)$	23
198	cyclohexane	$Me_2CHCH_2OCH{=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-1.40(\pm0.40)$	23
199	cyclohexane	$MeCOOCH{=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-1.49(\pm0.45)$	23
201	bezene	$Y\text{-}CH{=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-1.69(\pm0.52)$	23
202	cyclohexane	$C_6H_5C(Me){=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-1.72(\pm0.24)$	23
204	benzene	$C_6H_5C(Me){=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-2.00(\pm0.62)$	23
205	dichlorobenzene	$C_6H_5C(Me){=}CH_2$	$X\text{-}C_6H_4S^\bullet$	$-2.10(\pm0.73)$	23

[a] Key: *, value in parentheses is the correlation coefficient with σ; **, correlation between σ and σ^+; [b]in these halogenation reactions, we think hydrogen abstraction is the rate-limiting step; [&], substituents and their residuals; [‡], residuals of outliers; [§], significant at 0.99 F test; [§§], significant at 0.95 F test.

reactions there are two major points to consider: the bond dissociation energy in the substrate, which is effected by the substituents, and the electronegative character of the radical. The examples for alkyl radicals do not contain electronegative atoms. It was suggested that these examples follow eq 2, with the radicals donating electrons in the transition state. In an earlier study, Pryor et al.[53] used methyl radicals to study a set of toluenes and reported a ρ of -0.14. Repeating this correlation we found very wide confidence limits on ρ^+ ($\rho^+ = -0.17 \pm 0.68$), but by dropping two data points we find a very high correlation with ρ of -0.86 (set **20**, Table 2). The substituted methyl groups behave differently from the methyl radical. The methyl radical appears to more closely follow mechanism 1.

The one example of halogen abstraction in Table 1 (set **177**) has a positive ρ.

One generalization from Table 1 that is of value is that the more reactive the radical, the smaller the absolute value of ρ^+. Leffler[54] has considered selectivity and reactivity from the point of view of bromination (via $^\bullet$H abstraction) of substituted toluenes as shown in the following table:

Selectivity and Reactivity in Bromination of the α-Position

substrate	reactivity per H	ρ^+
$X\text{-}PhCH_3$	1	-1.38
$X\text{-}PhCH_2Ph$	18	-0.62
$X\text{-}PhCH_2COPh$	22	-0.72
$X\text{-}PhCH_2CH_3$	24	-0.86
$X\text{-}PhCH_2CH{=}CH_2$	25	-0.68
$X\text{-}PhCH(CH_3)_2$	54	-0.29
$X\text{-}PhCH(OCH_3)_2$	53	-0.38
$X\text{-}PhCH_2OCH_3$	54	-0.35
$X\text{-}PhCH_2OCH_2Ph$	79	-0.12
$(X\text{-}Ph)_2CHOCH_3$	99	0

The data are from different laboratories, and there

Table 2

Radical Reactions Correlated by σ^a

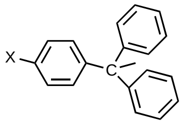
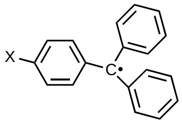
set	solvent	compound	radical	ρ	action, correlation	ref
1	acetonitrile	$X\text{-}C_6H_5$	$O_2NC_6H_4COO^\bullet$	−3.05	substitution 60 °C $\log k = -3.05(\pm 0.89)\sigma + 0.31(\pm 0.22)$ $n = 5$, $s = 0.151$, $r^2 = 0.976$ (0.943),* (0.874),** $F_{1,3} = 121^§$	96a
		$^\&$3-Me, −0.16; 4-Cl, 0.16; 4-OMe, 0.11; 3-Cl, −0.07; 4-Me, −0.04				
1a	reactants	$X\text{-}C_6H_5$	$MeCOCH_2^\bullet$	−2.69	acetonylation reflux temperature with acetone + Mn(III) cat. $\log f = -2.69(\pm 0.45)\sigma + 0.23(\pm 0.10)$ $n = 7$, $s = 0.104$, $r^2 = 0.979$ (0.860), (0.894), $F_{1,5} = 238^§$ (f: partial rate constant for meta and para position), omit: 4-Cl ($0.56^‡$)	199
		4-F, −0.18; 3-Me, 0.09; 3-OMe, 0.07; 3-Cl, 0.06; D-F, −0.04; 4-Me, −0.03; 4-OMe, 0.03				
2	air	$X\text{-}C_6H_5$	$HO^\bullet$	−2.44	reaction with $HO^\bullet$ 25 °C $\log k = -2.44(\pm 0.40)\sigma - 11.5(\pm 0.15)$ $n = 11$, $s = 0.049$, $r^2 = 0.954$ (0.760), (0.810), $F_{1,9} = 186,^§$ omit: 1,2,4-Me_3 (0.30); CHO (1.61)	77a
		Me, −0.15; 1-OH,3-Me, −0.08; 1,4-Me_2, 0.07; 1,2-Me_2, 0.06; 1-OH,4-Me, 0.04; 1,3-Me2, 0.04; 1,2,3-Me_3, −0.03; OH, 0.02; 1,3,5-Me_3, 0.01; OMe, 0.01; 1-OH,2-Me, 0.00				
2a	tetrahydrofuran			−2.20	single-electron transfer room temperature $\log k = -2.20(\pm 0.46)\sigma + 0.02(\pm 0.16)$ $n = 17$, $s = 0.279$, $r^2 = 0.875$ (0.809), (0.963), $F_{1,15} = 105^§$	200
		X = 4-Br, Y = H, −0.45; X = 4-$COOC_6H_5$, Y = H, −0.42; X = 4-$CONH_2$, Y = H, 0.39; X = 4-COOMe, Y = H, 0.37; X = 4-$COOC_6H_5$, Y = Me, −0.35; X = 4-Cl, Y = H, −0.32; X = 4-Me, Y = H, 0.30; X = 4-$CONH_2$, Y = Me, 0.28; X = 4-$CON(C_6H_5)_2$, Y = H, 0.25; X = 4-$CON(C_6H_5)_2$, Y = Me, 0.15; X = 4-OMe, Y = Me, −0.12; X = 4-OMe, Y = H, −0.06; X = 4-NH_2, Y = H, 0.04; X = 4-$CONMe_2$, Y = Me, −0.04; X = H, Y = Me, −0.02; X = Y = H, −0.02; X = 4-$CONMe_2$, Y = H, 0.02				
3	ethanol	α-tocopherol analogs	$C_6H_5O^\bullet$	−2.01	hydrogen abstraction $\log k = -2.01(\pm 0.49)\sigma + 0.30(\pm 0.24)B1{,}3 + 2.38(\pm 0.32)$ $n = 10$, $s = 0.080$, $r^2 = 0.935$ (0.782), (0.953), $F_{1,8} = 116^§$ (σ), $F_{1,7} = 7.65^{§§}$ ($B1{,}3$)	201
		5,7-$(CHMe)_2$, 0.16; H, −0.07; 5,7-Me_2, −0.07; 5-Me,7-CMe_3, −0.06; 5,7,8-Me_3, −0.05; 7-CMe_3, 0.04; 5,8-Me_2, 0.03; 8-Me, 0.02; 5,7-Et_2, −0.01; 7,8-Me_2, 0.00				
4	benzene	$X\text{-}C_6H_5$	pentafluorophenyl radical	−1.81	pentafluorophenylation 353 K $\log f = -1.81(\pm 0.36)\sigma - 0.88(\pm 0.42)F{,}2 + 0.48(\pm 0.41)B1{,}2 - 0.30(\pm 0.47)$ $n = 14$, $s = 0.116$, $r^2 = 0.949$ (0.910), (0.780), $F_{1,12} = 62.7^§$ (σ), $F_{1,11} = 9.60^{§§}$ ($F{,}2$), $F_{1,10} = 6.89^{§§}$ ($B1{,}2$)	202
		2-OMe,5-F, 0.26; 3-OMe, −0.17; 4-Me, 0.11; 2-OMe, −0.09; 2-F,5-Me, −0.09; 4-F, 0.04; 2-Me, −0.06; 4-OMe, 0.03; 2-F,5-OMe, −0.03; 3-F, −0.02; 2-Me,5-F, 0.02; 3-Me, −0.01; 2-F, 0.00; 2,5-F_2, 0.00				
5	benzene	$X\text{-}C_6H_4Me$	$Br^\bullet$	−1.61	hydrogen abstraction 60 °C $\log k = -1.61(\pm 0.26)\sigma - 0.47(\pm 0.12)$ $n = 6$, $s = 0.077$, $r^2 = 0.987$ (0.968), (0.981), $F_{1,4} = 295^§$	143
		4-CN, −0.10; 4-Cl, 0.08; 4-Me, −0.06; 3-Cl, 0.04; 4-NO_2, 0.03; H, 0.01				
6^b	C_6H_5Cl	$X\text{-}C_6H_4Me$	$Br^\bullet$	−1.61	bromination 80 °C $\log k = -1.61(\pm 0.19)\sigma + 0.05(\pm 0.08)$ $n = 7$, $s = 0.065$, $r^2 = 0.990$ (0.978), (0.978), $F_{1,5} = 494^§$	143
		4-CN, −0.08; 3-Cl, 0.07; 4-Me, 0.06; H, −0.05; 3-Me, −0.05; 4-NO_2, 0.04; 4-Cl, 0.01				
7	bromobenzene	$X\text{-}C_6H_4Me$	$Br^\bullet$	−1.59	bromination 80 °C $\log k = -1.59(\pm 0.27)\sigma - 0.01(\pm 0.12)$ $n = 6$, $s = 0.080$, $r^2 = 0.985$ (0.955), (0.984), $F_{1,4} = 263^§$	143
		4-Cl, −0.13; 4-Me, 0.05; 3-Cl, 0.05; 4-NO_2, 0.05; 4-CN, −0.02; H, 0.01				
8^b	benzene	$X\text{-}C_6H_4Me$	$Br^\bullet$	−1.59	bromination by 80 °C $\log k_{rel} = -1.59(\pm 0.48)\sigma + 0.21(\pm 0.18)$ $n = 4$, $s = 0.079$, $r^2 = 0.990$ (0.900), (0.881), $F_{1,2} = 205^§$	103
		4-Cl, 0.08; 4-CMe_3, −0.06; 4-CN, −0.04; 4-Me, 0.03				
9^b	benzene	5-X-3-CN-toluene	$Br^\bullet$	−1.58	bromination 80 °C $\log k_{rel} = -1.58(\pm 0.15)\sigma + 0.01(\pm 0.07)$ $n = 5$, $s = 0.033$, $r^2 = 0.997$ (0.926), (0.909), $F_{1,3} = 1173^§$	203
		CN, −0.05; NO_2, 0.02; Br, 0.02; H, −0.01; Me, 0.01				

Table 2 (Continued)

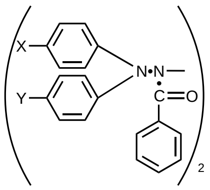
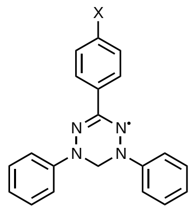
set	solvent	compound	radical	ρ	action, correlation	ref
10	acetone			−1.53	dissociation 30 °C $\log k = -1.53(\pm 0.29)\sigma - 3.42(\pm 0.16)$ $n = 5$, $s = 0.114$, $r^2 = 0.990$ (0.944), (0.932), $F_{1,3} = 294^{\S}$	204
		X = Me, Y = H, −0.13; X = Y = Me, 0.10; X = Br, Y = H, −0.08; X = Y = Br, 0.07; X = Y = H, 0.04				
11	acetic acid	$X\text{-}C_6H_4SCH_2CH_2COOH$	$O_2^{\bullet -}$	−1.45	oxidation 20 °C $\log k = -1.45(\pm 0.19)\sigma + 2.74(\pm 0.07)$ $n = 5$, $s = 0.050$, $r^2 = 0.995$ (0.930), (0.922), $F_{1,3} = 629^{\S}$	205
		4-Cl, 0.07; 4-Me, −0.04; 4-NO_2, −0.03; H, −0.02; 4-OMe, 0.01				
12	acetone	$X\text{-}C_6H_4S(CH_2)_3Me$	singlet oxygen	−1.42	photooxidation 25 °C $\log k = -1.42(\pm 0.14)\sigma + 6.22(\pm 0.03)$ $n = 6$, $s = 0.026$, $r^2 = 0.995$ (0.909), (0.888), $F_{1,4} = 765^{\S}$	206
		4-F, −0.03; 4-OMe, 0.03; 3-Cl, 0.03; H, −0.01 4-Me, −0.01; 4-Cl, 0.00				
13	benzene	$X\text{-}C_6H_4Me$	$Cl^{\bullet}$	−1.31	hydrogen abstraction 80 °C $\log k = -1.31(\pm 0.31)\sigma - 0.06(\pm 0.15)$ $n = 7$, $s = 0.108$, $r^2 = 0.960$ (0.935), (0.989), $F_{1,5} = 121^{\S}$	207
		4-NO_2, −0.14; 4-COOH, 0.13; 4-Cl, −0.10; 4-SO_2Me, 0.09; H, 0.06; 4-CMe_3, −0.04; 3-CN, 0.00				
14	CCl_4	$X\text{-}C_6H_4CHO$	$Cl_3C^{\bullet}$	−1.13	hydrogen abstraction 40 °C $\log k_{\mathrm{rel}} = -1.13(\pm 0.05)\sigma - 0.01(\pm 0.01)$ $n = 8$, $s = 0.011$, $r^2 = 0.998$ (0.761), (0.766), $F_{1,6} = 2952,^{\S}$ omit: 4-OMe (−0.31)	208
		3-Me, 0.02; 4-Cl, −0.02; 4-CMe_3, −0.01; H, 0.01; 3-Br, 0.01; 4-Me, −0.01; 3-Cl, 0.00; 4-OC_6H_5, 0.00				
15[b]	benzotrifluoride	$X\text{-}C_6H_4Me$	$Br^{\bullet}$	−0.99	bromination initiated by azobisisobutyronitrile 60 °C $\log k = -0.99(\pm 0.14)\sigma - 0.92(\pm 0.06)$ $n = 6$, $s = 0.041$, $r^2 = 0.990$ (0.962), (0.981), $F_{1,4} = 382^{\S}$	143
		H, 0.05; 4-NO_2, 0.04; 3-Cl, −0.03; 4-CN, −0.03; 4-Cl, −0.02; 4-Me, −0.01				
16	tetrahydrofuran	$X\text{-}C_6H_4C(Me){=}CH_2$	$Me_2N^{\bullet}$	−0.98	addition 85 °C $\log k_{\mathrm{rel}} = -0.98(\pm 0.16)\sigma + 0.06(\pm 0.05)$ $n = 7$, $s = 0.048$, $r^2 = 0.980$ (0.945), (0.913), $F_{1,5} = 250^{\S}$	209 209
		H, −0.06; 4-Cl, −0.05; 4-OMe, 0.05; 4-CN, 0.05; 4-Me, 0.03; 4-Br, −0.01; 4-F, 0.01				
17[b]	benzene	$X\text{-}C_6H_4Me$	$Cl^{\bullet}$	−0.95	chlorination initiated by azobis(isobutyronitrile) 60 °C $\log k = -0.95(\pm 0.12)\sigma - 0.05(\pm 0.06)$ $n = 6$, $s = 0.035$, $r^2 = 0.992$ (0.985), (0.981), $F_{1,4} = 489^{\S}$	143
		4-Cl, 0.06; 3-Cl, −0.03; 4-Me, −0.02; 4-CN, −0.02; H, 0.01; 4-NO_2, 0.01				
18	CCl_4	$C_6H_5CH_2C_6H_4\text{-}X$	$Br^{\bullet}$	−0.92	hydrogen abstraction 77 °C $\log k_{\mathrm{rel}} = -0.92(\pm 0.13)\sigma + 1.30(\pm 0.06)$ $n = 10$, $s = 0.046$, $r^2 = 0.973$ (0.959), (0.980), $F_{1,8} = 284^{\S}$	210
		3-NO_2, −0.08; 3-OMe, 0.06; H, −0.05; 4-F, −0.04; 4-Cl, 0.04; 4-NO_2, 0.03; 4-COOMe, 0.03; 4-CN, 0.01; 4-Br, 0.01; 4-$COOC_6H_5$, 0.00				
19	CH_3CN	C_6H_5SH		−0.90	hydrogen abstraction 30 °C $\log k_2 = -0.90(\pm 0.03)\sigma + 0.26(\pm 0.01)$ $n = 5$, $s = 0.008$, $r^2 = 1.000$ (0.923), (0.922), $F_{1,3} > 1000^{\S}$	211
		4-Me, 0.01; 4-Cl, −0.01; H, −0.01; 4-NO_2, 0.00; 4-OMe, 0.00				
20	CCl_4	$X\text{-}C_6H_4Me$	$^{\bullet}Me$	−0.86	hydrogen abstraction 100 °C $\log k_{\mathrm{rel}} = -0.86(\pm 0.19)\sigma - 0.33(\pm 0.04)$ $n = 5$, $s = 0.027$, $r^2 = 0.986$ (0.866), (0.932), $F_{1,3} = 230,^{\S}$ omit = H (−0.20) and 4-OC_6H_5 (−0.36)	53
		3-Me, 0.03; 4-Br, −0.02; 3-Cl, 0.02; 4-Me, −0.02; 4-Cl, −0.01				

Table 2 (Continued)

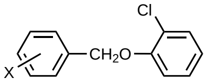
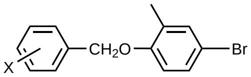
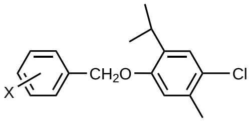
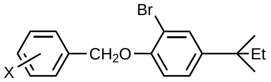
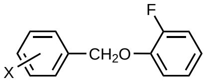
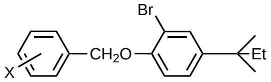
set	solvent	compound	radical	ρ	action, correlation	ref
21	99% CH_3COOH		$Cl^\bullet$	−0.86	chlorination 20 °C $\log k = -0.86(\pm 0.05)\sigma - 1.31(\pm 0.02)$ $n = 5$, $s = 0.011$, $r^2 = 0.999$ (0.995), (0.998), $F_{1,3} > 1000^{\S}$	212
		4-Me, 0.01; 4-F, −0.01; 4-NO_2 0.01; 4-Cl, 0.00; 4-Br, 0.00				
22	99% CH_3COOH		$Cl^\bullet$	−0.86	chlorination 20 °C $\log k_{\mathrm{rel}} = -0.86(\pm 0.06)\sigma + 1.71(\pm 0.02)$ $n = 9$, $s = 0.022$, $r^2 = 0.994$ (0.980), (0.978), $F_{1,7} = 1421^{\S}$	213
		4-CMe_3, −0.03; 4-Br, −0.02; 4-Et, 0.02; H, 0.02; 3-F, −0.02; 4-NO_2, 0.02; 4-Me, 0.02; 3-Cl, −0.01; 4-Cl, 0.01				
23	99% CH_3COOH		$Cl^\bullet$	−0.85	chlorination 16 °C $\log k = -0.85(\pm 0.03)\sigma + 0.25(\pm 0.01)$ $n = 4$, $s = 0.003$, $r^2 = 1.000$ (0.905), (0.912), $F_{1,2} > 1000^{\S}$	214
		H, 0.00; 4-Me, 0.00; 4-Br, 0.00; 4-Cl, 0.00				
24	99% CH_3COOH		$Cl^\bullet$	−0.85	chlorination 20 °C $\log k = -0.85(\pm 0.08)\sigma - 1.59(\pm 0.04)$ $n = 5$, $s = 0.021$, $r^2 = 0.997$ (0.975), (0.985), $F_{1,3} = 1548^{\S}$	214
		4-Cl, −0.03; H, 0.01; 4-Me, 0.01; 3-NO_2, 0.01; 4-NO_2, 0.01				
25	99% CH_3COOH		$Cl^\bullet$	−0.85	chlorination 20 °C $\log k = -0.85(\pm 0.14)\sigma - 1.24(\pm 0.06)$ $n = 4$, $s = 0.024$, $r^2 = 0.997$ (0.975), (0.987), $F_{1,2} = 740^{\S}$	215
		4-Br, −0.03; H, 0.02; 4-NO_2, 0.01; 4-Me, 0.00				
26	99% CH_3COOH		$Cl^\bullet$	−0.85	chlorination 20 °C $\log k = -0.85(\pm 0.10)\sigma - 1.13(\pm 0.05)$ $n = 4$, $s = 0.017$, $r^2 = 0.999$ (0.994), (0.998), $F_{1,2} = 846^{\S}$	214
		4-Cl, −0.02; 4-Me, 0.01; 3-NO_2, 0.01; 4-NO_2, 0.00				
27	CH_3CN	X-C_6H_4Me	$Me_3CO^\bullet$	−0.83	hydrogen abstraction 0 °C $\log k_{\mathrm{rel}} = -0.83(\pm 0.12)\sigma + 0.01(\pm 0.02)$ $n = 6$, $s = 0.019$, $r^2 = 0.990$ (0.948), (0.905), $F_{1,4} = 544^{\S}$	115
		4-Cl, 0.03; 3-Cl, −0.02; H, −0.01; 3-Me, −0.01; 4-F, 0.01; 4-Me, 0.01				
28	benzene	X-C_6H_5	$O_2NC_6H_4^\bullet$	−0.82	arylation 20 °C $\log k_{\mathrm{rel}} = -0.82(\pm 0.17)\sigma + 0.12(\pm 0.06)$ $n = 7$, $s = 0.055$, $r^2 = 0.968$ (0.922), (0.906), $F_{1,5} = 156,^{\S}$ omit: 4-NO_2 (0.70)	179
		3-OMe, −0.10; 4-Cl, 0.07; 4-OMe, 0.02; 3-NO_2, 0.01; 3-Me, 0.01; 3-Cl, 0.00; 4-Me, 0.00				
29	reactants	X-C_6H_4Me	$Me_3CO^\bullet$	−0.81	hydrogen abstraction 40 °C $\log k_{\mathrm{rel}} = -0.81(\pm 0.14)\sigma + 0.02(\pm 0.03)$ $n = 5$, $s = 0.020$, $r^2 = 0.991$ (0.958), (0.921), $F_{1,3} = 393^{\S}$	216
		H, −0.02; 4-Me, 0.02; 4-Cl, 0.01; 3-Me, −0.01; 3-Cl, 0.00				
30	benzene	X-C_6H_4Me	$Cl^\bullet$	−0.81	hydrogen abstraction 40 °C $\log k_{\mathrm{rel}} = -0.81(\pm 0.10)\sigma - 0.01(\pm 0.02)$ $n = 10$, $s = 0.026$, $r^2 = 0.977$ (0.907), (0.919), $F_{1,8} = 366^{\S}$	124
		4-CH_2Cl, −0.05; 4-Me, 0.04; 4-CMe_3, −0.03; 4-Cl, 0.02; 3-CH_2Cl, 0.01; 4-F, 0.01; 3-F, −0.01; 3-Cl, 0.01; H, −0.01; 3-Me, 0.00				
31	benzene	X-$C_6H_4CH_2CH_2Cl$	$Cl^\bullet$	−0.80	hydrogen abstraction 40 °C $\log k = -0.80(\pm 0.08)\sigma + 0.02(\pm 0.02)$ $n = 7$, $s = 0.019$, $r^2 = 0.992$ (0.967), (0.953), $F_{1,5} = 518^{\S}$	117
		H, −0.02; 4-Me, 0.02; 4-Cl, 0.02; 4-F, −0.02; 3-Cl, −0.01; 3-F, 0.01; 4-CMe_3, 0.00				
32	CCl_4	X-C_6H_4CHO	$Cl_3C^\bullet$	−0.77	hydrogen abstraction 80 °C $\log k_{\mathrm{rel}} = -0.77(\pm 0.05)\sigma + 0.01(\pm 0.01)$ $n = 9$, $s = 0.014$, $r^2 = 0.994$ (0.796), (0.763), $F_{1,7} = 1596,^{\S}$ omit: 4-OMe (−0.12)	217
		4-OC_6H_5, 0.02; 4-Cl, −0.02; 3-OMe, −0.02; 3-Cl, 0.01; 3-Br, 0.01; H, −0.01; 3-Me, 0.00; 4-CMe_3, 0.00; 4-Me, 0.00				
33	chlorobenzene	X-C_6H_4Me	$Cl^\bullet$	−0.75	hydrogen abstraction 80 °C $\log k = -0.75(\pm 0.09)\sigma - 1.45(\pm 0.04)$ $n = 7$, $s = 0.031$, $r^2 = 0.989$ (0.966), (0.978), $F_{1,5} = 452^{\S}$	143
		3-Cl, −0.05; 4-Me, −0.03; H, 0.03; 4-CN, 0.02; 4-Cl, 0.02; 3-Me, 0.02; 4-NO_2, −0.01				

Table 2 (Continued)

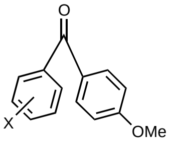
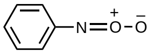
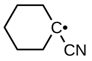
set	solvent	compound	radical	ρ	action, correlation	ref
34	reactant	X-C_6H_4Me	X-$C_6H_4COO^\bullet$	−0.74	hydrogen abstraction 90 °C $\log k_{rel} = -0.74(\pm0.13)\sigma - 1.05(\pm0.05)$ $n = 9$, $s = 0.056$, $r^2 = 0.966$ (0.949), (0.979), $F_{1,7} = 27.9^§$	165
					3,5-Me_2, 0.09; H, −0.08; 3-Me, −0.07; 4-CMe_3, 0.05; 4-NO_2, 0.03; 4-$CHMe_2$, −0.02; 4-Cl, 0.02; 4-CN, −0.02; 4-Me, 0.00	
35	benzene	X-C_6H_4Et	$Cl^\bullet$	−0.70	hydrogen abstraction 40 °C $\log k_{rel} = -0.70(\pm0.13)\sigma + 0.01(\pm0.03)$ $n = 8$, $s = 0.028$, $r^2 = 0.965$ (0.933), (0.915), $F_{1,6} = 149^§$	124
					4-Cl, 0.04; 4-Et, 0.03; 4-F, −0.03; 4-CH_2Cl, −0.02; 3-Et, −0.02; 4-CMe_3, 0.01; H, −0.01; 3-Cl, 0.00	
36	benzene	X-C_6H_4Et	$Cl^\bullet$	−0.69	hydrogen abstraction 40 °C $\log k_{rel} = -0.69(\pm0.15)\sigma + 0.01(\pm0.03)$ $n = 7$, $s = 0.029$, $r^2 = 0.966$ (0.873), (0.899), $F_{1,5} = 146,^§$ omit: 4-CH_2Cl (−0.04)	124
					4-Cl, 0.03; 4-F, −0.03; 3-Et, −0.03; 4-Et, 0.02; 4-CMe_3, 0.02; H, −0.01; 3-Cl, 0.00	
37	benzene	X-$C_6H_4CH_2Cl$	$Cl^\bullet$	−0.66	hydrogen abstraction 40 °C $\log k = -0.66(\pm0.11)\sigma + 0.00(\pm0.02)$ $n = 8$, $s = 0.024$, $r^2 = 0.971$ (0.879), (0.911), $F_{1,6} = 226^§$	107
					3-F, 0.03; 4-CH_2Cl, −0.03; 3-Cl, −0.03; 4-Cl, 0.02; 4-CMe_3, 0.01; 4-C_6H_5, 0.00; 4-F, 0.00; H, 0.00	
38	99% CH_3COOH		$Cl^\bullet$	−0.66	chlorination 20 °C $\log k = -0.66(\pm0.06)\sigma - 1.67(\pm0.02)$ $n = 10$, $s = 0.025$, $r^2 = 0.987$ (0.938), (0.973), $F_{1,8} = 619^§$	218
					3-Br, 0.04; 3-Me, 0.04; 4-F, −0.03; 4-Br, −0.03; 4-Cl, −0.02; 4-Me, 0.01; H, −0.01; 3-NO_2, 0.01; 4-NO_2, −0.01; 3-F, 0.01	
39	benzene	X-$C_6H_4CH_2C_6H_5$	$Cl^\bullet$	−0.65	hydrogen abstraction 40 °C $\log k_{rel} = -0.65(\pm0.05)\sigma + 0.00(\pm0.01)$ $n = 7$, $s = 0.009$, $r^2 = 0.996$ (0.942), (0.921), $F_{1,5} > 1000^§$	124
					4-Cl, 0.01; 4-C_6H_5, 0.01; 4-F, −0.01; 3-Cl, −0.01; 3-F, −0.01; H, 0.00; 4-CMe_3, 0.00	
40	benzene	X-$C_6H_4CH_2C_6H_5$	$Cl^\bullet$	−0.65	hydrogen abstraction 40 °C $\log k_{rel} = -0.65(\pm0.04)\sigma + 0.01(\pm0.01)$ $n = 7$, $s = 0.008$, $r^2 = 0.997$ (0.943), (0.921), $F_{1,5} > 1000^§$	124
					4-F, 0.01; 3-Cl, −0.01; H, −0.01; 4-C_6H_5, 0.01; 4-CMe_3, −0.01; 3-F, 0.00; 4-Cl, 0.00	
41	CH_3CN	(X-$C_6H_4)_2SO$		−0.64	relative reactivity with nitroso oxides, oxygen transfer $\log k = -0.635(\pm0.353)\sigma - 0.074(\pm0.139)$ $n = 4$, $s = 0.062$, $r^2 = 0.968$ (0.728), (0.821), $F_{1,2} = 57.75^{§§}$	219
					H,H, 0.07; 4,4′-Cl_2, −0.03; 4,4′-Me_2, −0.03; 4,4′-$(OMe)_2$, −0.01	
42	reactant	X-$C_6H_4CH_2CH{=}CH_2$	$Cl_3C^\bullet$	−0.63	hydrogen abstraction 69.5 °C $\log k_{rel} = -0.63(\pm0.05)\sigma + 0.01(\pm0.01)$ $n = 11$, $s = 0.019$, $r^2 = 0.988$ (0.893), (0.919), $F_{1,9} = 774^§$	220
					4-Me, 0.04; 4-Cl, 0.03; 3-OMe, −0.02; 4-OMe, −0.02; 4-C_6H_5, −0.02; H, −0.01; 3-CF_3, −0.01; 3-Me, 0.01; 3-Cl, 0.00; 4-CF_3, 0.00; 4-F, 0.00	
43	CCl_4	X-C_6H_4CHO	$Cl^\bullet$	−0.54	hydrogen abstraction 80 °C $\log k_{rel} = -0.54(\pm0.02)\sigma - 0.00(\pm0.01)$ $n = 7$, $s = 0.005$, $r^2 = 0.999$ (0.958), (0.953), $F_{1,5} > 1000^§$	221
					3-Cl, −0.01; 4-Cl, 0.01; 3-F, 0.01; 3-Me, 0.00; H, 0.00; 4-CMe_3, 0.00; 4-Me, 0.00	
44	reactants	X-$C_6H_4CH{=}CH_2$	n-$C_8F_{17}^\bullet$	−0.54	addition $\log k_{rel} = -0.54(\pm0.07)\sigma + 0.01(\pm0.02)$ $n = 5$, $s = 0.015$, $r^2 = 0.995$ (0.900), (0.916), $F_{1,3} = 369^§$	222
					4-Me, 0.02; H, −0.01; 4-OMe, −0.01; 4-CF_3, 0.00; 4-Cl, 0.00	
45	toluene	X-C_6H_4SH		−0.52	hydrogen abstraction 110 °C $\log k_{rel} = -0.52(\pm0.09)\sigma + 0.08(\pm0.03)$ $n = 7$, $s = 0.030$, $r^2 = 0.980$ (0.928), (0.855), $F_{1,5} = 265^§$	223
					4-Cl, 0.04; 4-CMe_3, −0.03; 4-Et, −0.03; 4-OMe, 0.02; 4-NO_2, −0.02; 3,4-$(CH)_4$, 0.01; H, 0.00	

Table 2 (Continued)

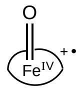
set	solvent	compound	radical	ρ	action, correlation	ref
46[b]	$C_6H_5NO_2$	X-C_6H_4Me	$Cl^{\bullet}$	−0.47	benzylic chlorination 80 °C $\log k = -0.47(\pm 0.08)\sigma - 0.60(\pm 0.04)$ $n = 6$, $s = 0.023$, $r^2 = 0.986$ (0.946), (0.981), $F_{1,4} = 300^{\S}$	143
					4-Me, −0.03; H, 0.03; 3-Cl, 0.01; 4-CN, −0.01; 4-Cl, 0.01; 4-NO_2, −0.01	
47[b]	CCl_4	X-C_6H_4Me	$Cl^{\bullet}$	−0.46	benzylic chlorination 60 °C $\log k = -0.46(\pm 0.05)\sigma - 0.31(\pm 0.02)$ $n = 6$, $s = 0.015$, $r^2 = 0.994$ (0.959), (0.981), $F_{1,4} = 572^{\S}$	143
					H, 0.03; 4-Me, −0.01; 4-Cl, −0.01; 3-Cl, −0.01; 4-NO_2, 0.00; 4-CN, 0.00	
48	CCl_2FCClF_2	X-C_6H_4OMe	$Me_3CO^{\bullet}$	−0.46	hydrogen abstraction 45 °C $\log k = -0.46(\pm 0.16)\sigma + 0.34(\pm 0.05)$ $n = 8$, $s = 0.048$, $r^2 = 0.893$ (0.844), (0.896), $F_{1,6} = 49.7^{\S}$	224
					4-OC_6H_5, 0.07; 4-OMe, −0.06; 4-Cl, 0.05; H, −0.04; 4-CN, −0.04; 3-OMe, 0.01; 3-OC_6H_5; 0.01; 3-Cl, −0.01	
49	C_6H_5Cl	X-$C_6H_4CHMe_2$	$Cl^{\bullet}$	−0.43	chlorination initiated by azobis(isobutyronitrile) 60 °C $\log k_{\mathrm{rel}} = -0.43(\pm 0.11)\sigma + 0.02(\pm 0.04)$ $n = 7$, $s = 0.044$, $r^2 = 0.952$ (0.936), (0.936), $F_{1,5} = 104^{\S}$	225
					4-OC_6H_5, −0.07; 4-$CHMe_2$, 0.06; 4-OMe, 0.04; H, −0.02; 4-COOMe, −0.02; 4-NO_2, 0.01; 4-Br, 0.00	
50	reactants	4-X-C_6H_5	$^3H^{\bullet}$	−0.41	addition 40 °C $\log f_{\mathrm{p}} = -0.41(\pm 0.19)\sigma - 0.01(\pm 0.08)$ $n = 7$, $s = 0.083$, $r^2 = 0.865$ (0.823), (0.962), $F_{1,5} = 31.7,^{\S}$ omit: COOMe (0.29), NO_2 (0.50)	167
					COMe, 0.15; Br, −0.07; CN, −0.07; OH, −0.04; NH_2, 0.04; H, 0.01; Me, −0.01	
51	benzene	X-$C_6H_4CH_2NH_2$	 (generated from Fe^{III}TPPCl-PHIO)	−0.40	oxidation room temperature $\log k_{\mathrm{rel}} = -0.40(\pm 0.06)\sigma + 0.02(\pm 0.02)$ $n = 6$, $s = 0.017$, $r^2 = 0.990$ (0.962), (0.960), $F_{1,4} = 448^{\S}$	226
					3-CN, 0.02; 4-Br, −0.02; 4-CN, −0.01; 4-OMe, 0.01; 4-Cl, 0.01; 4-Me, 0.00	
52	C_6H_5Cl	X-$C_6H_4CHMe_2$	$Br^{\bullet}$ (NBS)	−0.39	hydrogen abstraction 70 °C $\log k_{\mathrm{rel}} = -0.390(\pm 0.074)\sigma + 0.035(\pm 0.033)$ $n = 10$, $s = 0.036$, $r^2 = 0.948$ (0.907), (0.938), $F_{1,8} = 154^{\S}$	144
					4-CN, 0.07; 4-NO_2, −0.05; H, −0.04; 4-COOEt, 0.03; 4-Cl, −0.03; 4-OMe, 0.02; 3-OMe, 0.01; 4-F, −0.01; 3-NO_2, −0.01; 4-Me, 0.00	
53	$C_2F_3Cl_3$	X-C_6H_4Me	$Me_3CO^{\bullet}$	−0.38	hydrogen abstraction 50 °C $\log k_{\mathrm{rel}} = -0.38(\pm 0.10)\sigma - 0.01(\pm 0.02)$ $n = 5$, $s = 0.014$, $r^2 = 0.980$ (0.950), (0.922), $F_{1,3} = 87.0^{\S}$	42
					3-Me, −0.02; 4-Me, 0.01; H, 0.01; 4-Cl, 0.01; 3-Cl, 0.00	
54	fluorochloroform	X-C_6H_4Me	$Br^{\bullet}$	−0.37	hydrogen abstraction −50 °C $\log k_{\mathrm{rel}} = -0.37(\pm 0.08)\sigma - 0.00(\pm 0.03)$ $n = 6$, $s = 0.020$, $r^2 = 0.978$ (0.941), (0.978), $F_{1,4} = 148^{\S}$	55
					4-Cl, −0.03; 4-Me, 0.02; 4-NO_2, 0.01; 3-Cl, 0.01; 4-Br, 0.00; H, 0.00	
55[b]	$C_6H_5NO_2$	X-C_6H_4Me	$Br^{\bullet}$	−0.32	benzylic bromination 80 °C azobis(isobutyronitrile) initiated $\log k = -0.32(\pm 0.05)\sigma - 1.38(\pm 0.03)$ $n = 6$, $s = 0.016$, $r^2 = 0.985$ (0.970), (0.981), $F_{1,4} = 276^{\S}$	143
					4-Cl, 0.02; 4-Me, −0.02; 4-NO_2, −0.01; 4-CN, 0.01; H, 0.01; 3-Cl, −0.01	
56	reactant	X-$C_6H_4CH_2CH{=}CH_2$	$Cl_3C^{\bullet}$	−0.28	addition 69.5 °C $\log k_{\mathrm{rel}} = -0.28(\pm 0.04)\sigma + 0.02(\pm 0.01)$ $n = 11$, $s = 0.016$, $r^2 = 0.957$ (0.836), (0.919), $F_{1,9} = 230^{\S}$	220
					4-Me, 0.03; 3-Cl, 0.02; 4-C_6H_5, −0.02; 3-Me, 0.02; H, −0.02; 3-OMe, −0.01; 4-Cl, −0.01; 4-OMe, −0.01; 3-CF_3, 0.01; 4-CF_3, 0.00; 4-F, 0.00	
57	aqueous	X-C_6H_5	$HO^{\bullet}$	−0.24	substitution 22 °C $\log k_{\mathrm{rel}} = -0.24(\pm 0.07)\sigma - 0.40(\pm 0.03)$ $n = 9$, $s = 0.039$, $r^2 = 0.896$ (0.882), (0.907), $F_{1,7} = 59.2,^{\S}$ omit: NHC_6H_5 (0.32)	227
					H, −0.06; I, 0.05; CHO, 0.04; O^-, 0.03; COO^-, 0.03; CH_2OH, −0.03; Cl, 0.02; OMe, −0.02; NO_2, −0.01	

Table 2 (Continued)

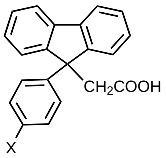
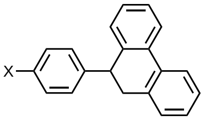
set	solvent	compound	radical	ρ	action, correlation	ref
58	CCl_4	$X\text{-}C_6H_4CH_2OCH_2C_6H_5$	$Br^\bullet$ (NBS)	−0.21	conversion to $X\text{-}C_6H_4CHO$ and C_6H_5CHO 80 °C $\log k = -0.21(0.06)\sigma + 0.02(0.03)$ $n = 6$, $s = 0.020$, $r^2 = 0.953$ (0.913), (0.908), $F_{1,4} = 66.0$§	228
		3-Cl, 0.03; H, −0.02; 4-OMe, 0.02; 4-Cl, −0.01; 4-CMe_3, −0.01; 4-NO_2, −0.01				
59	reactant	$X\text{-}C_6H_4CH_2CH_2CH{=}CH_2$	$Cl_3C^\bullet$	−0.19	addition 69.5 °C $\log k_{\mathrm{rel} = -0.19(0.05)\sigma - 0.00(0.01)}$ $n = 9$, $s = 0.015$, $r_2 = 0.890$ (0.638), (0.877), $F_{1,7} = 45.5$§	220
		3-Me, 0.02; 4-OMe, −0.02; 3-F, 0.02; 4-Cl, −0.01; 4-Me, 0.01; 3-Cl, −0.01; 3-OMe, 0.01; H, 0.00				
60	benzene	$X\text{-}C({=}CH_2)C_6H_4\text{-}Y$	$NCMe_2C^\bullet$	0.07	addition unknown temperature $\log k_{\mathrm{rel}} = -0.09(0.01)\sigma^{\prime},X + 0.073(0.01)\sigma,Y + 0.09(0.02)$ $n = 5$, $s = 0.002$, $r^2 = 1.000$ (0.994), (0.989), $F_{1,3} > 1000$,§ omit: X = SC_6H_5, Y = H (0.10); X = COOMe, Y = 4-OMe (0.59)	178
		X = OMe, Y = 4-COOMe, 0.00; X = OMe, Y = 4-NO_2, 0.00; X = OCOMe, Y = 4-OMe, 0.00; X = Y = 4-OMe, 0.00; X = NC_4H_8O, Y = 4-NO_2, 0.00				
61	benzene	$X\text{-}C_6H_4CH_2Cl$	$Et_3Ge^\bullet$	0.31	chlorine abstraction 80 °C $\log k_{\mathrm{rel}} = 0.31(0.07)\sigma + 0.04(0.03)$ $n = 8$, $s = 0.024$, $r^2 + 0.949$ (0.902), (0.975), $F_{1,6} = 128$§	229
		H, −0.04; 4-CN, 0.02; 3-CN, −0.02; 3-Me, 0.02; 4-Me, 0.02; 3-CF_3, −0.01; 3-Cl, 0.01; 4-Cl,0.00				
62	90% acetone	methyl acrylate	$X\text{-}C_6H_4^\bullet$	0.34	addition 25 to 30 °C $\log k_{\mathrm{rel}} = 0.34(\pm 0.10)\sigma - 0.12(\pm 0.04)$ $n = 8$, $s = 0.030$, $r^2 = 0.924$ (0.771), (0.912), $F_{1,6} = 76.8$,§ omit: 4-Me (0.09)	230
		3-OMe, −0.04; 4-Cl, 0.03; 3-Cl, 0.03; 4-F, 0.02; H, −0.02; 3,5-Cl_2, −0.01; 3-NO_2, −0.01; 2,4-Cl_2, 0.01				
63	1,2-dichloro-benzene			0.39	rearrangement to 9,10-dihydro-9-(4-X-C_6H_4)phenanthrenes $\log k_{\mathrm{rel}} = 0.39(\pm 0.07)\sigma + 0.02(\pm 0.03)$ $n = 7$, $s = 0.024$, $r^2 = 0.976$ (0.790), (0.830), $F_{1,5} = 190$,§ omit: 4-SMe (0.24)	31
		4-F, 0.03; H, −0.02; 4-OMe, −0.02; 4-SOMe, −0.02; 4-Me, 0.02; 4-Cl, 0.01; 4-SO_2Me, 0.00				
64	90% acetone	$CH_2{=}C(Me)COOMe$	$XC_6H_4^\bullet$	0.46	addition 25 to 30 °C $\log k_{\mathrm{rel}} = 0.46(\pm 0.09)\sigma + 0.03(\pm 0.03)$ $n = 14$, $s = 0.044$, $r^2 = 0.915$ (0.759), (0.897), $F_{1,12} = 126$,§ omit: 4-NO_2 (−0.14)	230
		4-Br, 0.07; 2,4-Cl_2, 0.06; 4-Me, −0.06; 3-NO_2, −0.06; 3-OMe, −0.04; 4-F, 0.04; 3-Cl, 0.03; H, −0.03; 3-F, −0.03; 3,5-Cl_2, −0.03; 4-Cl, 0.02; 4-OMe, 0.01; 3-Br, 0.00; 3-Me, 0.00				
65	CH_3CN	$X\text{-}C_6H_4CH_2I$	$(n\text{-}C_4H_9)_3Sn^\bullet$	0.49	iodine abstraction 90 °C $\log k_{\mathrm{rel}} = 0.49(\pm 0.27)\sigma + 0.00(\pm 0.11)$ $n = 5$, $s = 0.041$, $r^2 = 0.915$ (0.798), (0.958), $F_{1,3} = 32.4$,§§ omit: 4-Me (0.19)	232
		3-F, −0.05; 4-Cl, 0.05; 4-CN, 0.01; 3-Cl, 0.00; H, 0.00				
66	toluene	$X\text{-}C_6H_4CH_2Br$	$Re(CO)_4P(OCHMe_2)_3^\bullet$	0.52	bromine abstraction 22 °C $\log k = 0.52(0.18)\sigma + 8.06(0.07)$ $n = 7$, $s = 0.050$, $r^2 = 0.920$ (0.879), (0.979), $F_{1,5} = 55.8$,§ omit: 4-NO_2 (0.39)	233
		4-Br, 0.08; 4-Me, −0.05; 4-CF_3, −0.04; 3-Br, −0.03; H,0.02; 4-F, 0.02; 4-CN, 0.01				
67	CH_3CN	CuCl	$X\text{-}C_6H_4SO_2^\bullet$	0.53	oxidation 110 °C $\log k = 0.53(\pm 0.06)\sigma - 1.08(\pm 0.03)$ $n = 8$, $s = 0.025$, $r^2 = 0.988$ (0.952), (0.939), $F_{1,6} = 477$§	234
		4-NO_2, −0.36; H, 0.032; 3-NO_2, 0.022; 4-Me, −0.021; 4-OMe, −0.018; 4-Br, 0.015; 4-Cl, 0.008; 3,4-Cl_2, −0.002				
68	tetrahydro-furan	$X\text{-}C_6H_4C(Me){=}CH_2$	$Me_2N^\bullet$	0.69	addition 25 °C $\log k_{\mathrm{rel}} = 0.69(\pm 0.12)\sigma - 0.03(\pm 0.04)$ $n = 6$, $s = 0.031$, $r^2 = 0.985$ (0.903), (0.910), $F_{1,4} = 264$§	209
		4-Me, −0.05; H, 0.03; 4-F, 0.02; 4-CN, −0.02; 4-Cl, 0.01; 4-OMe, 0.00				
69	benzene	$X\text{-}C_6H_5$	$MeOC_6H_4^\bullet$	0.77	arylation 20 °C $\log k_{\mathrm{rel}} = 0.77(\pm 0.52)\sigma + 0.12(\pm 0.19)$ $n = 7$, $s = 0.178$, $r^2 = 0.742$ (0.527), (0.918), $F_{1,5} = 14.4$,§§ omit: 3-NO_2 (−0.59)	179
		3-OMe, −0.21; 4-OMe, 0.20; 4-NO_2, 0.20; 3-Cl, −0.15; 4-Me, 0.08; 3-Me, −0.07; 4-Cl, −0.06				

Table 2 (Continued)

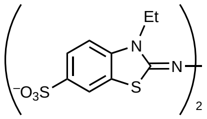
set	solvent	compound	radical	ρ	action, correlation	ref
69a	benzene	X-$C_6H_4CH_2NC$	$(C_4H_9)_3Sn^{\bullet}$	0.77	NC abstraction 80 °C log $k_{rel} = 0.77(\pm0.29)\sigma + 0.03(\pm0.10)$ $n = 5$, $s = 0.068$, $r^2 = 0.959$ (0.876), (0.911), $F_{1,3} = 69.4^{\S}$	179a
		4-Cl, 0.10; 4-CN, −0.05; H, −0.03; 4-OMe, −0.03; 4-Me, 0.00				
70	1,2-dimethoxyethane	X-$C_6H_4CH_2Cl$	$(C_4H_9)_3Sn^{\bullet}$	0.81	chlorine abstraction 25 °C log $k_{rel} = 0.81(\pm0.19)\sigma - 0.02(\pm0.06)$ $n = 7$, $s = 0.051$, $r^2 = 0.961$ (0.901), (0.961), $F_{1,5} = 125.4^{\S}$	235
		4-Cl, 0.09; 3-Cl, −0.06; 4-F, −0.03; H, 0.02; 4-Me, −0.01; 3-Me, −0.01; 4-CN, 0.00				
71	benzene	X-$C_6H_4CHMe_2$	polystyryl radical	0.81	chain-transfer constants in styrene 60 °C log $c = 0.81(\pm0.18)\sigma - 3.33(\pm0.06)$ $n = 8$, $s = 0.059$, $r^2 = 0.953$ (0.781), (0.898), $F_{1,6} = 121$,§ omit: 4-$CHMe_2$ (0.27)	236
		H, −0.08; 4-CN, 0.07; 4-OMe, 0.06; 3-Br, −0.05; 3-OMe, −0.05; 4-CMe_3, 0.03; 4-Br, 0.03; 4-Cl, −0.02				
72	reactants	X-C_6H_4Me	$Me_2CH^{\bullet}$	0.81	hydrogen abstraction 30 °C log $k_{rel} = 0.81(\pm0.16)\sigma + 0.01(\pm0.05)$ $n = 9$, $s = 0.052$, $r^2 = 0.954$ (0.869), (0.960), $F_{1,7} = 145^{\S}$	52
		4-Br, 0.10; 3-Cl, −0.07; 4-Cl, 0.04; 3,5-Me_2, −0.03; 4-CN, −0.03; 3-Me, −0.03; 3-F, 0.01; 4-Me, −0.01; 4-F, 0.01				
73	aqueous		X-$C_6H_4OO^{\bullet}$	0.84	one electron oxidation with 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonate ion) 20 °C log $k = 0.84(\pm0.07)\sigma + 8.83(\pm0.03)$ $n = 5$, $s = 0.018$, $r^2 = 0.998$ (0.911), (0.925), $F_{1,3} = 1335^{\S}$	237
		4-Cl, −0.02; 4-CN, 0.02; 4-OH, 0.01; H, −0.01; 4-Me, 0.00				
74	benzene	X-$C_6H_4CHMe_2$	polystyryl radical	0.85	chain-transfer constants in styrene 60 °C log $c = 0.85(\pm0.18)\sigma - 3.33(\pm0.06)$ $n = 7$, $s = 0.056$, $r^2 = 0.967$ (0.795), (0.891), $F_{1,5} = 143^{\S}$	238
		H, −0.09; 4-OMe, 0.06; 4-CN, 0.04; 4-CMe_3, 0.03; 4-Cl, −0.03; 4-$CHMe_2$, −0.03; 4-Br, 0.01				
75	C_6H_{12}	X-C_6H_4C(×d4=O)-OOC(=O)$CHMe_2$		0.90	decomposition (radical formation) 60 oC log $k = 0.90(\pm0.05)\sigma - 1.74(\pm0.02)$ $n = 8$, $s = 0.019$, $r^2 = 0.997$ (0.910), (0.913), $F_{1,6} = 2109^{\S}$	239
		4-Cl, 0.04; 4-NO_2, −0.02; 4-CMe_3, −0.01; 4-OMe, −0.01; 4-F, −0.01; 4-Me, 0.01; 3-Cl, 0.00; H, 0.00				
76	reactants	X-C_6H_4Me	$Me_3C^{\bullet}$	0.91	hydrogen abstraction 30 °C log $k_{rel} = 0.91(\pm0.14)\sigma - 0.01(\pm0.04)$ $n = 9$, $s = 0.048$, $r^2 = 0.971$ (0.942), (0.959), $F_{1,7} = 235^{\S}$ (k_{rel}: relative to the abstraction of D from t-BuSD)	52
		H, 0.09; 3,5-Me_2, −0.06; 3-Br, 0.05; 4-Br, −0.03; 3-NO_2, −0.02; 4-Cl, −0.02; 3-Me, −0.01; 4-Me, 0.01; 4-F, 0.00				
77	benzene	X-$C_6H_4CHMe_2$	polystyryl radical	0.98	chain-transfer constants in 4-methylstyrene 60 °C log $c = 0.98(\pm0.22)\sigma - 3.28(\pm0.07)$ $n = 7$, $s = 0.068$, $r^2 = 0.964$ (0.804), (0.891), $F_{1,5} = 134^{\S}$	
		H, −0.11; 4-Cl, −0.06; 4-OMe, 0.06; 4-CN, 0.05; 4-CMe_3, 0.04; 4-Br, 0.03; 4-$CHMe_2$, −0.01				
78	reactants	X-C_6H_4Me	$Me_3C^{\bullet}$	1.02	hydrogen abstraction 30 °C log $k_{rel} = 1.02(\pm0.33)\sigma + 0.00(\pm0.13)$ $n = 7$, $s = 0.104$, $r^2 = 0.927$ (0.868), (0.983), $F_{1,5} = 63.2^{\S}$ (k_{rel}: relative to the abstraction of D from PhSD)	52
		4-Br, 0.14; H, −0.13; 3-NO_2, −0.10; 4-Cl, 0.07; 4-CN, 0.03; 4-F, −0.02; 4-Me, 0.00				
79	reactants	X-C_6H_5	$C_6H_{11}^{\bullet}$	1.102	cyclohexylation by cyclohexyl radicals 90 °C log $f_m = 1.102(\pm0.509)\sigma - 0.010(\pm0.182)$ $n = 6$, $s = 0.112$, $r^2 = 0.900$, $F_{1,4} = 35.69^{\S}$ (f_m: partial rate constant for meta position), omit: OMe (0.157)	240
		Cl, 0.147; CMe_3, −0.102; CN, −0.088; Me, 0.078; F, −0.063; CF_3, 0.028				
80	reactants	X-C_6H_5	$MeCOOC_2H_4^{\bullet}$	1.16	homolytic substitution 160 °C log $k_{rel} = 1.16(\pm0.34)\sigma - 0.02(\pm0.13)$ $n = 7$, $s = 0.098$, $r^2 = 0.938$ (0.938), (0.975), $F_{1,5} = 75.31$,§ omit: OMe (0.59)	241
		COMe, 0.16; Br, −0.12; CN, −0.09; H, 0.02; COOMe, 0.01; Cl, 0.01; CMe_3, 0.00				

Table 2 (Continued)

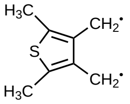
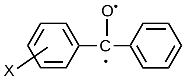
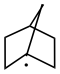
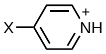
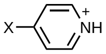
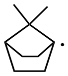
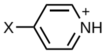
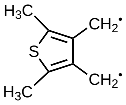
set	solvent	compound	radical	ρ	action, correlation	ref
81	benzene	X-$C_6H_4CHMe_2$	polystyryl radical	1.18	chain-transfer constants in 4-methoxystyrene 60 °C $\log c = 1.18(\pm 0.38)\sigma - 3.24(\pm 0.12)$ $n = 6$, $s = 0.104$, $r^2 = 0.950$ (0.776), (0.890), $F_{1,4} = 75.8$§	238
					H, −0.13; 4-Cl, −0.10; 4-OMe, 0.09; 4-CN, 0.07; 4-Br, 0.04; 4-CMe_3, 0.04	
82	CH_2Cl_2	X-$C_6H_4C{=}CH_2$		1.25	cycloaddition 24 °C $\log k_{rel} = 1.25(\pm 0.32)\sigma + 0.05(\pm 0.12)$ $n = 7$, $s = 0.108$, $r^2 = 0.953$ (0.828), (0.930), $F_{1,5} = 99.9$,§ omit: 4-NH_2 (0.55)	242
					4-F, −0.14; 4-OMe, 0.13; 4-COMe, 0.13; 4-Cl, −0.06; H, −0.05; 3-NO_2, −0.01; 4-Me, −0.01	
83	CH_3CN	4-MeC_6H_4Me		1.36	hydrogen abstraction at ambient temperature $\log k_{rel} = 1.36(\pm 0.32)\sigma + 6.73(\pm 0.14)$ $n = 10$, $s = 0.170$, $r^2 = 0.934$ (0.867), (0.893), $F_{1,8} = 99.3$,§ omit: 4,4′-Cl_2 (−0.44)	196
					H, −0.24; 3-Cl, 0.22; 4,4′-CMe_3, 0.19; 3-CF_3, 0.17; 4-CN, −0.15; 4,4′-$(OMe)_2$, −0.08; 4-CF_3, −0.06; 4,4′-Me, −0.04; 4,4′-F_2, −0.01	
84	reactants	4-X-C_6H_5		1.49	homolytic substitution 80 °C $\log k_{rel} = 1.49(\pm 0.77)\sigma - 0.09(\pm 0.20)$ $n = 4$, $s = 0.092$, $r^2 = 0.972$ (0.927), (0.975), $F_{1,2} = 68.1$,§§ omit: OMe (0.44)	243
					F, 0.11; Et, −0.07; COOMe, −0.04; CMe_3, 0.00	
85	benzene	X-C_6H_4COO- $OOCC_6H_4$-X	$(C_6H_5)_3C^{\bullet}$	1.50	substitution 15 °C $\log k = 1.50(\pm 0.26)\sigma - 0.18(\pm 0.11)$ $n = 8$, $s = 0.119$, $r^2 = 0.970$ (0.811), (0.844), $F_{1,6} = 191$§	244
					3-Me, 0.15; 3-OMe, −0.15; 4-F, 0.14; H, −0.13; 3-Cl, 0.07; 4-Cl, −0.05; 4-Me, −0.02; 4-OMe, −0.01	
86	polystyrene	X-C_6H_4CHO	polymethyl methacrylate radical	1.50	chain-transfer constant 60 °C $\log c = 1.50(\pm 0.59)\sigma - 3.27(\pm 0.21)$ $n = 6$, $s = 0.151$, $r^2 = 0.925$ (0.764), (0.925), $F_{1,4} = 49.9$§	245
					4-CN, 0.17; 4-OMe, 0.14; 3-Cl, −0.14; 4-Cl, −0.13; H, −0.07; 4-Br, 0.02	
87	aqueous		$CH_3^{\bullet}$	1.60	alkylation 90 °C $\log k_{rel} = 1.60(\pm 0.41)\sigma - 0.06(\pm 0.15)$ $n = 6$, $s = 0.123$, $r^2 = 0.967$ (0.930), (0.923), $F_{1,4} = 115$§	193
					4-COMe, −0.19; 4-CN, 0.10; 4-OMe, −0.08; 4-Cl, 0.07; H, 0.06; 4-Me, 0.05	
88	methanol	X-C_6H_4I	$CH_2O^{\bullet -}$	1.69	iodine abstraction 70.2 °C $\log k_{rel} = 1.69(\pm 0.21)\sigma + 0.63(\pm 0.30)B1{,}2 + 0.56(\pm 0.55)F{,}2 - 1.27(\pm 0.35)$ $n = 51$, $s = 0.280$, $r^2 = 0.925$ (0.861), (0.903), $F_{1,49} = 155$§(σ), $F_{1,48} = 93.3$§($B1,2$), $F_{1,47} = 4.2$§($F,2$) ($B1,2$: sterimol parameter for ortho positions; $F,2$: field effect for ortho position; less substituted ortho position was defined as 6 position)	246
					3,5-I_2, 0.68; 3-NH_2, −0.57; 4-COC_6H_5, 0.50; 3-I, 0.48; 2-Me, −0.50; 3,5-Cl_2, 0.39; 4-NMe_2, 0.39; 4-CF_3, −0.37; 2-CF_3, −0.35; 3-Me, −0.35; 2-Br,4-Me, 0.35; H, −0.32; 4-Me, −0.30; 4-NHC_6H_5, 0.30; 3-OMe, −0.29; 2-Cl,5-CF_3, −0.29; 4-O^-, 0.27; 3-Cl,4-Me, 0.27; 4-Br, −0.26; 2-F, 0.26; 2,5-I_2, 0.25; 2-I, 0.23; 2,6-Me_2, −0.22; 2,6-Cl_2, 0.21; 2-Br,4,6-Cl_2, −0.21; 2,4-I_2, 0.19; 2-I,5-Me, 0.19; 4-NH_2, 0.17; 4-CN, −0.16; 2,4,6-Br_3, −0.16; 2,4,6-Me_3, −0.14; 2-OMe, −0.14; 2-Cl, −0.14; 4-OMe, −0.13; 3-F, −0.13; 2,4-Br_2, 0.13; 2-I,4-Me, 0.12; 2-Br, −0.12; 2,4,6-Cl_3, −0.12; 3-CF_3, −0.09; 4-F, −0.08; 4-I, 0.06; 3-Br,4-Cl, 0.04; 2-NH_2, 0.04; 2,4-Cl_2, 0.04; 2-I,5-Br, −0.03; 3-Br, 0.02; 2-I,4-Br, −0.01; 3-Cl, 0.01; 4-Cl, 0.01; 2-Br,4-Cl, 0.00	
89	reactants			1.93	substitution at ortho position 90 °C $\log k_{rel} = 1.93(\pm 0.29)\sigma + 0.01(\pm 0.11)$ $n = 6$, $s = 0.086$, $r^2 = 0.989$ (0.943), (0.928), $F_{1,4} = 343$§	192
					4-Cl, 0.10; 4-OMe, −0.09; 4-Me, 0.08; 4-COMe, −0.07; H, −0.01; 4-CN, 0.00	
90	aqueous		$C_3H_7^{\bullet}$	2.13	alkylation 90 °C $\log k_{rel} = 2.13(\pm 0.67)\sigma - 0.17(\pm 0.27)$ $n = 5$, $s = 0.174$, $r^2 = 0.972$ (0.971), (0.9238), $F_{1,3} = 189$§	193
					H, 0.17; 4-OMe, −0.17; 4-COMe, −0.15; 4-Me, 0.08; 4-CN, 0.06	
91	reactants	X-C_6H_4CHO	$(n\text{-}C_4H_9)_3Sn^{\bullet}$	2.14	addition initiated by azobisisobutyronitrile 65 °C $\log k_{rel} = 2.14(\pm 0.70)\sigma - 0.13(\pm 0.15)$ $n = 7$, $s = 0.151$, $r^2 = 0.925$ (0.893), (0.845), $F_{1,5} = 61.4$§	190
					3-OMe, −0.19; 4-OMe, −0.18; H, 0.13; 4-Me, 0.12; 3-Me, 0.10; 4-Cl, 0.06; 3-Cl, −0.03	

Table 2 (Continued)

set	solvent	compound	radical	ρ	action, correlation	ref
92	dichloromethane	X-C_6H_4CHO		2.86	cycloaddition 24 °C $\log k_{rel} = 2.86(\pm0.33)\sigma - 0.14(\pm0.12)$ $n = 7$, $s = 0.108$, $r^2 = 0.990$ (0.961), (0.932), $F_{1,5} = 504^{\S}$	242
		4-OMe, −0.14; H, 0.14; 4-CF_3, −0.09; 4-Me, 0.08; 4-Cl, −0.06; 4-CN, 0.06; 4-F, 0.01				
93	dichloromethane	X-C(=CH_2)COO-Y	$C_6H_{11}^{\bullet}$	3.24	addition 25 °C $\log k_{rel} = 3.24(\pm0.80)\sigma,X + 0.36(\pm0.24)$ $n = 8$, $s = 0.280$, $r^2 = 0.928$ (0.710), (0.813), $F_{1,6} = 90.8^{\S}$	247
		X = C_6H_5, Y = Et, 0.48; X = H, Y = Me, −0.36; X = OMe, Y = Me, −0.28; X = COOEt, Y = Et, −0.21; X = CH_2Cl, Y = Me, 0.14; X = Y = Me, 0.06; X = Cl, Y = Me, −0.03; X = CN, Y = Et, −0.01				
94	dichloromethane	X-C(=CH_2)CN	$C_6H_{11}^{\bullet}$	3.87	addition 25 °C $\log k_{rel} = 3.87(\pm0.81)\sigma + 0.75(\pm0.19)$ $n = 7$, $s = 0.198$, $r^2 = 0.968$ (0.554), (0.639), $F_{1,5} = 150,^{\S}$ omit: NC_4H_8O (1.58), C_6H_5 (1.11)	247
		SeC_6H_5, 0.28; Me, 0.21; H, −0.19; Cl, −0.15; OEt, −0.12; CMe_3, −0.02; COOEt, 0.00				
95	THF	X-$C_6H_4CH{=}CH_2$	polystyryl radical	5.20	addition to living polystyrene 25 °C $\log k = 5.20(\pm0.75)\sigma + 3.10(\pm0.13)$ $n = 7$, $s = 0.124$, $r^2 = 0.984$ (0.715), (0.754), $F_{1,5} = 315,^{\S}$ omit: 2,3-$(CH)_4$ (0.80)	248
		4-C_6H_5, 0.18; 4-F, −0.15; H, −0.12; 4-Cl, 0.07; 4-Me, 0.04; 4-CMe_3, −0.02; 4-OMe, 0.00				

a. Hydrogen Abstraction from Toluenes Correlated by σ

set	solvent	reagent	ρ	T, °C
5	benzene	$Br^{\bullet}$	−1.61(±0.26)	60
6	chlorobenzene	$Br^{\bullet}$	−1.61(±0.19)	80
7	bromobenzene	$Br^{\bullet}$	−1.59(±0.48)	80
8	benzene	$Br^{\bullet}$	−1.58(±0.15)	80
13	benzene	$Cl^{\bullet}$	−1.31(±0.31)	80
15	benzotrifluoride	$Br^{\bullet}$	−0.99(±0.14)	60
17	benzene	$Cl^{\bullet}$	−0.95(±0.12)	60
20	carbon tetrachloride	$Me^{\bullet}$	−0.86(±0.19)	100
27	acetonitrile	$Me_3CO^{\bullet}$	−0.83(±0.12)	0
29	reactants	$Me_3CO^{\bullet}$	−0.81(±0.14)	40
30	benzene	$Cl^{\bullet}$	−0.81(±0.10)	40
33	chlorobenzene	$Cl^{\bullet}$	−0.75(±0.09)	80
34	reactants	$C_6H_5COO^{\bullet}$	−0.74(±0.13)	90
46	nitrobenzene	$Cl^{\bullet}$	−0.47(±0.08)	80
47	carbon tetrachloride	$Cl^{\bullet}$	−0.46(±0.05)	60
53	CF_3CCl_3	$Me_3CO^{\bullet}$	−0.38(±0.10)	50
54	$CFCl_3$	$Br^{\bullet}$	−0.37(±0.08)	−50
55	nitrobenzene	$Br^{\bullet}$	−0.32(±0.05)	80
72	reactants	$Me_2CH^{\bullet}$	0.81(±0.16)	30
76	reactants	$Me_3C^{\bullet}$	0.91(±0.14)	30
78	reactants	$Me_3C^{\bullet}$	1.02(±0.33)	30

[a] Key: *, correlation with σ^+; **, correlation between σ and σ^+; [b], in these halogenation reactions, we think hydrogen abstraction is the rate-limiting step; [&], substituents and their residuals; [‡], residuals of outliers; [§], significant at 0.99 F test; [§§], significant at 0.95 F test.

is wide structural variation. Still, there is a clear trend between relative reactivity and the absolute value of ρ^+. This is illustrated by eq 4.

$$\rho^+ = 0.66 \pm(0.15) \log(\text{reactivity of H}) - 1.47 \pm(0.23) \qquad (4)$$

$$n = 9, \quad r^2 = 0.940, \quad s = 0.108, \quad \text{omitted: X-PhCH}_2\text{CH}_3$$

The authors of set **86** (Table 1) found an absence of a temperature effect which they point out may signify violation of the reactivity−selectivity principle.

2. Addition of Radicals to Unsaturated Systems

Examples from Table 1 of the addition of radicals to olefinic bonds are collected in Table 1c. The two most negative ρ^+ values are for the addition of malonyl radicals to styrenes. In these instances the lone electron is strongly delocalized by the two adjacent anions so that the role of the substituents (in bond breaking) becomes more important. Omitting these, we find that the next 17 examples in Table 1c have negative ρ^+ in the range −0.75 (set **98**) to −0.16(set **173**). The mean value for these examples is −0.42. A wide variety of radicals adding to styrenes or phenylacetylene have values of ρ^+ near to −0.40. These radicals are behaving as electrophiles whose reactivity is enabled by electron-releasing substituents. The relative electronegativity of the radical seems to be of little importance in setting the magnitude of ρ^+.

Starting with set **179** the values of ρ become positive. In all of these examples the radicals have been generated by flash photolysis of the disulfide.

Table 3

Radical Reactions Correlated by σ^{-} [a]

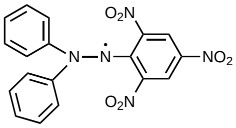
set	solvent	compound	radical	ρ^-	reaction, correlation	ref
1	aqueous	$X\text{-}C_6H_4OH$	$X\text{-}C_6H_4O^{\bullet}$	−3.66	oxidation by ClO_2 unknown temperature $\log k = -3.66(\pm 0.45)\sigma^- + 0.80(\pm 0.64)B1{,}2 + 7.13(\pm 0.81)$ $n = 15$, $s = 0.347$, $r^2 = 0.966$ (0.843)*, (0.837),** $F_{1,13} = 220.8^{\S}$ (σ^-), $F_{1,12} = 7.40^{\S\S}$ ($B1{,}2$) ($B1{,}2$: sterimol parameter, $B1$, for ortho position), omit: 4-COMe (1.04‡)	249
					$^{\&}$4-CN, −0.67; 2-COOH, 0.51; 4-OMe, 0.35; 2-Cl, −0.33; 4-NO_2, 0.32; 4-Cl, 0.31; 2,4-Me_2, −0.27; H, −0.24; 4-CMe_3, −0.22; 3-OMe, 0.20; 3-Me, −0.18; 4-Me, 0.17; 2,4-Cl_2, 0.16; 2-OMe, −0.08; 4-COOH, −0.02	
1a	acetic acid	$X\text{-}C_6H_5$	$NO_2CH_2^{\bullet}$	−3.43	nitromethylation catalyzed by $Mn(OAc)_3$ unknown temperature $\log f = -3.43(\pm 0.80)\sigma^- + 0.33(\pm 0.18)$ $n = 6$, $s = 0.153$, $r^2 = 0.973$ (0.920), (0.869), $F_{1,4} = 142^{\S}$ (F: partial rate constant for meta and para positions)	93
					4-Cl, 0.22; 3-Me, −0.14; 4-OMe, 0.11; 3-OMe, −0.08; 3-Cl, −0.06; 4-Me, −0.05	
2	CCl_4	$X\text{-}C_6H_4NH_2$		−3.26	hydrogen abstraction 16.1 °C $\log k_3 = -3.26(\pm 0.55)\sigma^- + 4.84(\pm 0.14)$ $n = 6$, $s = 0.104$, $r^2 = 0.985$ (0.974), (0.963), $F_{1,4} = 272^{\S}$	78
					3-Cl, 0.12; 3-Br, −0.12; 4-Me, 0.07; 3-Me, −0.06; H, −0.06; 4-Cl, 0.05	
3	benzene	$X\text{-}C_6H_4Me$	$Me_3CO^{\bullet}$	−2.15	hydrogen abstraction 40 °C $\log k_{rel} = -2.15(\pm 0.82)\sigma^- - 0.04(\pm 0.12)$ $n = 4$, $s = 0.039$, $r^2 = 0.984$ (0.883), (0.921), $F_{1,2} = 125^{\S}$	250
					H, 0.04; 4-F, −0.03; 4-OC_6H_5, −0.02; 4-OMe, 0.01	
4	aqueous	$X\text{-}C_6H_5$	$SO_4^{\bullet -}$	−1.41	electron-transfer unknown temperature $\log k = -1.41(\pm 0.47)\sigma^- + 9.40(\pm 0.29)$ $n = 7$, $s = 0.221$, $r^2 = 0.921$ (0.844), (0.887), $F_{1,5} = 58.4$,§ omit: COOH (0.76)	251
					COMe, 0.27; $CONH_2$, −0.27; NMe_3^+, −0.24; NHCOMe, 0.15; CN, 0.08; OMe, −0.08; H, 0.08	
5	aqueous	$X\text{-}C_6H_4OH$	singlet oxygen	−1.25	oxidation 27.1 °C $\log k = -1.25(\pm 0.20)\sigma^- + 7.05(\pm 0.13)$ $n = 15$, $s = 0.201$, $r^2 = 0.935$ (0.735), (0.854), $F_{1,13} = 186$,§ omit: H (−0.63); 2,4,6-Cl_3 (0.90); 2-OMe (−0.59); 2-NO_2 (0.65)	252
					4-CN, −0.42; 4-Me, −0.28; 3-NO_2, 0.27; 3-OMe, 0.22; 4-COMe, 0.18; 2-Cl, 0.16; 2,6-$(OMe)_2$, −0.14; 3-Cl, 0.15; 2,4-Cl_2, 0.14; 4-CMe_3, −0.13; 2,3,4,5,6-Cl_5, −0.11; 4-OH, 0.07; 4-NO_2, −0.05; 4-Cl, −0.03; 4-OMe, −0.03	
6	aqueous phosphate buffer	$X\text{-}C_6H_4OH$	singlet oxygen	−1.23	oxidation 27 °C $\log k = -1.23(\pm 0.18)\sigma^- - 0.29(\pm 0.12)E_s\text{-}2{,}6 + 8.35(\pm 0.14)$ $n = 19$, $s = 0.227$, $r^2 = 0.937$ (0.729), (0.823), $F_{1,17} = 81.3^{\S}$ (σ^-), $F_{1,16} = 28.1^{\S}$ (E_s-2,6), omit: 4,6-$(NO_2)_2$-2-Me (−1.42); penta-Cl (0.68)	252
					2,6-$(OMe)_2$, −0.37; 2,4-$(NO_2)_2$, −0.34; 4-CN, −0.33; 3-Cl, 0.30; 3-NO_2, 0.30; 2,6-$(NO_2)_2$-4-Me, 0.27; 3-OMe, 0.25; 2-OMe, −0.19; 4-Cl, 0.17; H, −0.16; 4-OMe, 0.15; 2-Cl, −0.12; 4-NO_2, −0.08; 2,4-Cl_2, 0.07; 4-COMe, 0.05; 4-CMe_3, 0.04; 2-NO_2, 0.02; 4-Me, −0.02; 2,4,6-Cl_3, 0.00	
7	aqueous	$X\text{-}C_6H_4COOH$	$SO_4^{\bullet -}$	−1.01	electron-transfer unknown temperature $\log k = -1.01(\pm 0.21)\sigma^- + 9.13(\pm 0.09)$ $n = 10$, $s = 0.116$, $r^2 = 0.938$ (0.679), (0.783), $F_{1,8} = 120$,§ omit: 4-Cl (−0.38) and 4-CN (−0.60)	251
					4-OMe, 0.15; 2-Me, −0.15; 4-Br, 0.13; 4-COOH, −0.12; 4-OH, −0.10; 3-Me, 0.10; 2-Br, 0.07; H, −0.05; 4-Me, −0.04; 4-COMe, 0.02	
8	CCl_4	$X\text{-}C_6H_4CHO$	$Cl^{\bullet}$	−0.63	chlorination by sulfuryl chloride (SO_2Cl_2) 40 °C $\log k_{rel} = -0.63(\pm 0.13)\sigma^- + 0.02(\pm 0.03)$ $n = 8$, $s = 0.032$, $r^2 = 0.960$ (0.874), (0.897), $F_{1,6} = 146^{\S}$	208
					4-OC_6H_5, 0.05; 4-OMe, −0.04; 4-Cl, 0.03; H, −0.02; 3-Cl, −0.02; 4-CMe_3, 0.01; 3-F, −0.01; 3-OMe, 0.00	
9	aqueous	X-pyridines	$HO^{\bullet}$	−0.63	substitution $\log k_{rel} = -0.63(\pm 0.15)\sigma^- - 0.77(\pm 0.06)$ $n = 16$, $s = 0.112$, $r^2 = 0.854$ (0.674), (0.857), $F_{1,14} = 82.3$,§ omit: 4-$CONH_2$ (0.24), 4-COO^- (0.29), 4-O^- (0.39), 4-Cl (0.29)	
					2-Br, 0.21; 2-NH_2, 0.20; 2-O^-, −0.17; 3-$CONH_2$, −0.15; 3-O^-, 0.11; 3-CN, −0.09; 2-COO^-, 0.08; 2,6-Cl_2, −0.06; 2-Cl, 0.04; 2,4-Me, −0.04; 2-Me, −0.03; 3-COO^-, −0.03; 3-Br, −0.03; H, −0.03; 4-NH_2, −0.03; 3-Me, 0.01	

Table 3 (Continued)

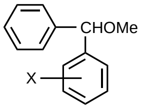
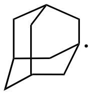
set	solvent	compound	radical	ρ^-	reaction, correlation	ref
10	CCl_4		$Cl_3C^\bullet$	−0.27	hydrogen abstraction 80 °C $\log k_{rel} = -0.27(\pm 0.09)\sigma^- + 0.01(\pm 0.02)$ $n = 5$, $s = 0.010$, $r^2 = 0.970$ (0.846), (0.820), $F_{1,3} > 1000$,§ omit: 3-Cl (0.04)	152
					4-CMe_3, −0.01; 4-Me, 0.01; H, −0.01; 4-Cl, 0.01; 4-OMe, 0.00	
11	reactants	X-C_6H_5	$^3H^\bullet$	−0.13	addition 40 °C $\log f_m = -0.13(\pm 0.07)\sigma^- + 0.04(\pm 0.06)$ $n = 6$, $s = 0.040$, $r^2 = 0.870$ (0.851), (0.897), $F_{1,4} = 28.7$,§ omit: OH (−0.20), Me (0.19), COOMe (−0.18)	167
					COMe, 0.06; H, −0.04; NO_2, −0.03; NH_2, 0.01; CN, −0.01; Br, −0.01	
12	benzene	X-$C_6H_4CH_2Br$	$(n\text{-}C_4H_9)_3Sn^\bullet$	0.16	bromine abstraction 90 °C $\log k_{rel} = 0.16(\pm 0.04)\sigma^- + 0.00(\pm 0.02)$ $n = 8$, $s = 0.015$, $r^2 = 0.956$ (0.860), (0.917), $F_{1,6} = 186$§	232
					4-Br, 0.0; 4-COOEt, −0.01; 3-Br, −0.01; 3-F, −0.01; 3-Me, −0.01; H, 0.00; 4-Me, 0.00; 4-CN, 0.00	
13	benzene	X-$C_6H_4CH_2Cl$	$(n\text{-}C_4H_9)_3Sn^\bullet$	0.33	chlorine abstraction 90 °C $\log k_{rel} = 0.33(\pm 0.07)\sigma^- + 0.06(\pm 0.03)$ $n = 13$, $s = 0.039$, $r^2 = 0.915$ (0.792), (0.899), $F_{1,11} = 121$§	232
					3-F, −0.06; H, −0.06; 4-C_6H_5, 0.06; 4-COOEt, −0.04; 4-Cl, 0.04; 4-CMe_3, −0.03; 3-CN, 0.03; 4-F, 0.02; 4-CN, 0.02; 3-Cl, 0.01; 4-Me, 0.01; 3-CF_3, 0.01; 3-Me, 0.00	
14	toluene	X-C_6H_4Me	$Me_3C^\bullet$	0.42	hydrogen abstraction 80 °C $\log k_{rel} = 0.42(\pm 0.06)\sigma^- - 0.06(\pm 0.02)$ $n = 8$, $s = 0.025$, $r^2 = 0.984$ (0.953), (0.938), $F_{1,6} = 332$§	253
					3-Cl, 0.04; 3-Me, −0.03; 3,5-Me_2, 0.02; 4-CN, −0.02; 4-Cl, −0.01; 3,4-Cl_2, 0.01; 4-Me, −0.01; 4-CMe_3, 0.00	
15	reactants	4-X-C_6H_5	$^\bullet CO_2Me$	0.56	homolytic substitution 65 °C $\log k_{rel} = 0.56(\pm 0.12)\sigma^- - 0.13(\pm 0.09)$ $n = 7$, $s = 0.056$, $r^2 = 0.968$ (0.914), (0.979), $F_{1,5} = 149$,§ omit: Me (0.39)	185
					Br, −0.08; CMe_3, 0.07; COOMe, 0.05; Cl, −0.05; COMe, 0.02; CN, −0.02; NO_2, 0.00	
16	reactants	X-C_6H_4Me	$Me_2CH^\bullet$	0.71	hydrogen abstraction 30 °C $\log k_{rel} = 0.71(\pm 0.26)\sigma^- - 0.00(\pm 0.07)$ $n = 6$, $s = 0.049$, $r^2 = 0.934$ (0.843), (0.960), $F_{1,4} = 54.4$§	52
					4-Br, 0.06; 3-Cl, −0.06; 4-Cl, 0.04; 4-Me, −0.02; 3-Me, −0.01; 3-Br, −0.01	
17	reactants	4-X-C_6H_5	$C_6H_5^\bullet$	0.74	phenylation 90 °C $\log f_p = 0.74(\pm 0.32)\sigma^- + 0.04(\pm 0.15)$ $n = 5$, $s = 0.098$, $r^2 = 0.946$ (0.852), (0.974), $F_{1,3} = 52.3$,§ omit: OMe (0.27), CF_3 (−0.26)	240
					Cl, −0.10; Me, 0.09; F, −0.08; CMe_3, 0.06; CN, 0.04	
18	benzene	X-$C_6H_4CH_2I$	$(n\text{-}C_4H_9)_3Sn^\bullet$	0.77	iodine abstraction 90 °C $\log k_{rel} = 0.77(\pm 0.12)\sigma^- + 0.07(\pm 0.06)$ $n = 8$, $s = 0.053$, $r^2 = 0.974$ (0.806), (0.856), $F_{1,6} = 229$§	232
					3-F, −0.07; H, −0.07; 4-C_6H_5, 0.06; 4-Cl, 0.05; 4-CN, 0.03; 4-Me, 0.03; 3-Cl, −0.02; 4-COOEt, 0.00	
19	CCl_4	X-C_6H_4I	$C_6H_5^\bullet$	0.83	iodine abstraction 60 °C $\log k_{rel} = 0.83(\pm 0.15)\sigma^- + 0.54(\pm 0.18)B1{,}2 - 0.53(\pm 0.33)F{,}2 + 0.63(\pm 0.28)$ $n = 14$, $s = 0.076$, $r^2 = 0.976$ (0.900), (0.856), $F_{1,12} = 74.0$§ (σ^-), $F_{1,11} = 16.9$§ ($B1{,}2$), $F_{1,10} = 12.6$§ ($F{,}2$)	254
					2-Cl, −0.13; 2-I, 0.09; 2-NH_2, 0.08; 2-Me, −0.08; 2-OMe, −0.07; 2-OEt, −0.06; 2-F, 0.06; H, 0.06; 2-Br, 0.05; 2-CF_3, −0.03; 2-C_6H_5, 0.02; 2-NO_2, 0.01; 2,6-Me_2, 0.00; 2-Et, 0.00	
19a	reactants	X-$C_6H_4CH{=}CH_2$	poly-*p*-methoxystyryl radical	0.86	addition 30 °C $\log k = 0.86(\pm 0.21)\sigma^- + 2.01(\pm 0.10)$ $n = 5$, $s = 0.063$, $r^2 = 0.982$ (0.727), (0.827), $F_{1,3} = 163$§	254a
					H, −0.08; 4-OMe, 0.07; 4-CN, 0.02; 4-Br, 0.00; 4-Cl, 0.00	
20	reactants	X-C_6H_5		1.29	homolytic substitution 80 °C $\log k_{rel} = 1.29(\pm 0.20)\sigma^- + 0.03(\pm 0.10)$ $n = 8$, $s = 0.101$, $r^2 = 0.975$ (0.806), (0.899), $F_{1,6} = 246$,§ omit: CMe_3 (−0.37)	243
					F, 0.14; OMe, 0.12; Et, −0.10; Cl, −0.08; Me, −0.07; Br, −0.05; COOMe, 0.04; CN, 0.00	

Table 3 (Continued)

set	solvent	compound	radical	ρ^-	reaction, correlation	ref
21	reactants	$X\text{-}C_6H_4COSSO\text{-}CC_6H_4\text{-}X$	$X\text{-}C_6H_4COS^\bullet$	1.33	chain-transfer constant in the polymerization of styrene 60 °C $\log c = 1.33(\pm 0.50)\sigma^- - 1.82(\pm 0.35)$ $n = 6, s = 0.253, r^2 = 0.931$ (0.817), (0.901), $F_{1,4} = 53.6$,[§] omit: H (−0.63) 4-Br, 0.36; 4-Me, −0.29; 4-Cl, −0.15; 4-OMe, 0.14; 4-NO_2, −0.05; 4-CN, −0.01	255
22	reactants	$X\text{-}C_6H_4COSSO\text{-}CC_6H_4\text{-}X$	$X\text{-}C_6H_4COS^\bullet$	1.41	chain-transfer constant in the polymerization of methyl metharylate 60 °C $\log c = 1.41(\pm 0.45)\sigma^- - 3.00(\pm 0.30)$ $n = 6, s = 0.208, r^2 = 0.950$ (0.865), (0.971), $F_{1,4} = 76.0$,[§] omit: 4-OMe (0.53) 4-Me, 0.28; 4-Cl, −0.27; 4-Br, −0.13; 4-CN, 0.06; 4-NO_2, 0.06; H, 0.00	255
22a	34% acetic acid and 14% sulfuric acid	4-X-quinolines (protonated)	$CH_3CO^\bullet$	1.46	acetylation 40 °C $\log k_{rel} = 1.46(\pm 0.42)\sigma^- + 0.34(\pm 0.22)$ $n = 4, s = 0.088, r^2 = 0.991$ (0.989), (0.961), $F_{1,2} = 214$[§] 4-Me, −0.09; H, 0.06; 4-Cl, 0.06; 4-CN, −0.03	192a
23	reactants	$X\text{-}C_6H_5$	$C_6H_{11}^\bullet$	1.72	partial rate constant cyclohexylation 90 °C $\log F_p = 1.72(\pm 0.69)\sigma^- + 0.08(\pm 0.30)$ $n = 6, s = 0.260, r^2 = 0.922$ (0.677), (0.855), $F_{1,4} = 47.5$[§] (f_p: partial rate constant for para position), omit: CF_3 (−0.49) F, −0.35; Me, 0.26; OMe, 0.21; CMe_3, −0.18; CN, 0.07; Cl, 0.00	240
23a	34% acetic acid and 14% sulfuric acid	4-X-quinolines (protonated)	$C_6H_5CO^\bullet$	1.73	acetylation 90 °C $\log k_{rel} = 1.73(\pm 0.54)\sigma^- + 0.30(\pm 0.34)$ $n = 4, s = 0.115, r^2 = 0.990$ (0.978), (0.983), $F_{1,2} = 194$[§] 4-COOEt, −0.13; 4-CN, 0.08; 4-Cl, 0.05; 4-Me, −0.01	192a
24	MeOH	$X\text{-}C_6H_4CHO$	$(n\text{-}C_4H_9)_3Sn^\bullet$	2.06	addition 65 °C $\log k_{rel} = 2.06(\pm 0.33)\sigma^- + 0.04(\pm 0.07)$ $n = 7, s = 0.068, r^2 = 0.981$ (0.761), (0.849), $F_{1,5} = 263$[§] 4-OMe, 0.09; 3-Cl, 0.09; 4-Cl, −0.06; 3-Me, −0.04; H, −0.04; 3-OMe, −0.03; 4-Me, −0.02	190
25	*m*-xylene	$X\text{-}C_6H_4COCl$	$(n\text{-}C_4H_9)_3Sn^\bullet$	2.12	chlorine abstraction 25 °C $\log k_{rel} = 2.12(\pm 0.44)\sigma^- - 0.09(\pm 0.20)$ $n = 10, s = 0.226, r^2 = 0.938$ (0.881), (0.840), $F_{1,8} = 122$[§] 4-CF_3, 0.29; 3-F, −0.26; 4-CN, −0.24; 3-Cl, 0.22; 4-Cl, −0.21; 3-Me, 0.21; 3-CF_3, 0.15; 4-OMe, −0.14; 4-Me, −0.09; H, 0.09	256
26	*o*-dichlorobenzene	$X\text{-}C_6H_4COCl$	$(n\text{-}C_4H_9)_3Sn^\bullet$	3.23	chlorine abstraction 25 °C $\log k_{rel} = 3.23(\pm 1.19)\sigma^- - 0.15(\pm 0.29)$ $n = 4, s = 0.129, r^2 = 0.986$ (0.970), (0.916), $F_{1,2} = 138$[§] H, 0.15; 4-OMe, −0.09; 3-Cl, −0.06; 4-Cl, 0.00	256
27	benzene	$X\text{-}C_6H_4CH_2C_6H_4\text{-}Y$	$O_2^{\bullet -}$	3.59	oxidation $\log k_{rel} = 3.59(\pm 0.23)\sigma^- + 0.17(\pm 0.14)$ $n = 9, s = 0.150, r^2 = 0.995$ (0.943), (0.927), $F_{1,7} = 1347$,[§] omit: X = Y = 4-Cl (0.66) X = 4-NO_2, Y = H, −0.19; X = Y = H, −0.17; X = 4-Cl, Y = H, 0.17; X = 4-OMe, Y = H, −0.13; X = 4-Br, Y = H, 0.12; X = 3-NO_2, Y = H, 0.12; X = 4-Me, Y = H, 0.09; X = Y = 4-F, −0.09; X = 4 -CN, Y = H, 0.06	257
28	benzene	$X\text{-}C_6H_4CH_2C_6H_5$	$O_2^{\bullet -}$	3.60	oxidation $\log k_{rel} = 3.60(\pm 0.25)\sigma^- + 0.15(\pm 0.15)$ $n = 9, s = 0.163, r^2 = 0.994$ (0.873), (0.858), $F_{1,7} = 1149$[§] 4-NO_2, −0.19; 4-Cl, 0.18; 4-F, −0.18; H, −0.15; 4-Br, 0.14; 3-NO_2, 0.13; 4-Me, 0.11; 4-OMe, −0.11; 4-CN, 0.06	257
29	methyl acetate	$X\text{-}C_6H_4COCl$	$(n\text{-}C_4H_9)_3Sn^\bullet$	4.03	chlorine abstraction 25 °C $\log k_{rel} = 4.03(\pm 0.88)\sigma^- + 0.06(\pm 0.22)$ $n = 4, s = 0.096, r^2 = 0.995$ (0.885), (0.916), $F_{1,2} = 393$[§] 3-Cl, 0.08; 4-Cl, −0.08; H, −0.06; 4-OMe, 0.06	256
30	*p*-cymene	$X\text{-}C_6H_4C(Me)N{=}N\text{-}C(Me)C_6H_4\text{-}X$	$X\text{-}C_6H_4C^\bullet H(Me)$		thermal decomposition 105 °C $\log k_{rel} = -0.16(\pm 0.12)\sigma^- + 1.77(\pm 0.47)(\sigma^-)^2 - 0.03(\pm 0.03)$ $n = 10, s = 0.026, r^2 = 0.939$ (0.829), (0.881), $F_{1,8} = 2.75$ (σ^-), $F_{1,7} = 74.2$[§] ($(\sigma^-)^2$), $F_{2,7} = 102$,[§] omit: 4-Cl (0.30), 2-OMe (0.25) 3-OMe, −0.05; H, 0.03; 4-Et, −0.02; 3-F, 0.02; 4-Me, 0.01; 3-Me, 0.01; 3-Cl, 0.01; 3-CF_3, −0.01; 4-F, 0.01; 4-OMe, −0.01	258

[a] Key: *, correlation with σ^+; **, correlation between σ^- and σ^+; [&], substituents and their residuals; [‡], residuals of outliers; [§], significant at 0.99 *F* test; and [§§], significant at 0.95 *F* test.

In these studies Ito and Matsuda suggest that the polar effect reflected in the correlation by σ^+ is in part due to the polar effect on the stability of the radical and in part to the polar character of the transition state. The largest negative ρ^+ is associated with the solvent methanol; however, this is more likely related to the stability of the radical.

Set **122** is clearly an unacceptable correlation. It has been included simply to call attention to an unusual reaction in the hope it will stimulate others to do further studies.

3. Reactions Correlated by σ (Table 2)

In Table 2 the same kind of reactions occur that are found in Table 1, and again we find that r^2 values are often very close for correlation with σ or σ^+. There is an urgent need to repeat some of the radical studies with larger, better-selected sets of substituents. Still, what tips the balance between correlation by σ^+ and correlation with σ is not a simple matter to decide.

Examples where halogens are abstracted from substituted benzyl moieties by relatively weak radicals (sets **61**, **65**, **66**, and **70**) have positive ρ values like those in Table 1, and again, we find very high collinearity between σ and σ^+.

In Table 2a are listed examples from Table 2 where abstraction of $^\bullet$H from toluene is correlated with σ. The pattern is similar to that in Table 1b. Of special interest is set **54** which has one of the smallest negative ρ's. This study was made at −50 °C. The authors[55] compare this result with data for 4-chlorotoluene at −18.5 and −32 °C, and they also compare their results with those of Kim et al.[56] and conclude that the isokinetic relationship does not appear to hold. In Table 2, where the reaction is halogen abstraction and the attacking radical is on metal atoms Ge or Sn (sets **61**, **65**, and **70**), ρ is positive and ranges from 0.31 to 0.81. In set **91** where addition is involved ρ is much larger (2.1).

4. Reactions Correlated by $\sigma-$ (Table 3)

Set **2** is similar to set **1a** in Table 1 in that sterically hindered radicals are involved. We have simply placed sets in this table on the basis that σ^- gives a better correlation than σ or σ^+. To be sure that this is meaningful, a set needs to have substituents with large σ^- values such as 4-NO_2, 4-CN, 4-COMe, and 4-SO_2Me. A number of sets do not meet this standard, but have been placed here for the sake of consistency (sets **1a**, **2**, **3**, **8**, **9**, **10**, **16**, **24**, **26**, **29**, and **30**). Both sets have large $-\rho$ values, but in one instance phenols are being oxidized and in the other, anilines. The reaction with the anilines is more complex being best considered as third order.

Set **3** is based on only four data points and the confidence limits on ρ^- are large; hence, little weight can be placed on the value of ρ^-.

Set **6** is of particular interest in that it contains phenols many of which are ortho substituted. The parameter E_s-2,6 is the sum of steric constants for substituents. Its negative coefficient indicates that larger substituents appear to be more easily oxidized (E_s values are negative). It is not clear how large substituents might assist $^\bullet$H abstraction, but what is interesting is that they do not hinder the reaction. Singlet oxygen is a small entity and one might expect little steric hindrance. This is in line with the results found in set **35** (Table 4) for ortho substituted anilines where we suspect that lack of a steric effect implies reaction with a small radical ($^\bullet$OH).

Set **8** can be compared with sets **13**, **31**, and **42** in Table 2. The latter three sets have ρ's of −1.13, −0.77, and −0.54. The larger absolute ρ is associated with the $Cl_3C^\bullet$ at 40 °C. The lowest absolute ρ is associated with the more active $^\bullet$Cl which is comparable in magnitude to ρ^- of −0.63 where $^\bullet$Cl is also involved.

The $^\bullet$OH substitution of pyridines of set **9** can be compared with sets **164** ($\rho^+ = -0.27$) and **168** ($\rho^+ = -0.21$) of Table 1. The benzenes with the less tightly held electrons have the smaller ρ's although this is in part due to different scale of σ^+ and σ^-.

The very activated benzylic H of set **10** has a small ρ compared to $^\bullet$H abstraction from toluene or diphenylmethane (set **117**, Table 1) reacting with the more active $^\bullet$Br. The substituent effects for sets **10** and **11** are quite small. Starting with set **12**, ρ^- values become positive so that for benzylic hydrogen abstraction the reaction may follow the mechanism of eq 2.

Hydrogen abstraction from toluene by $Me_3C^\bullet$ at 80 °C (set **14**) has a smaller ρ than comparable reactions done at 30 °C (sets **75** and **77**, Table 2). Even employing σ in place of σ^- for set **14** increases ρ only to 0.49 (with $r^2 = 0.936$).

We have nothing with which to compare the unusual radical of set **15**. This set does not have a good selection of substituents with negative σ^+ substituents.

The abstraction of $^\bullet$I by phenyl radicals of set **19** is noteworthy in that all of the substituents are in the ortho position and Bl for ortho substituents is necessary for a good correlation. As with set **26** we find a positive steric effect even though a larger radical (phenyl) is involved. Set **88** in Table 2 has a positive Bl-2 (0.51) and a negative Bl−6 (−0.34). In this example Bl−6 applies when a second ortho substituent is present. This example involves identical substituents in ortho positions except for one (2-Br, 4,6-Cl_2) out of $n = 51$. Thus when only one ortho substituent is present we find it hard to explain the positive steric effect.

Sets **1a** and **9** in Table 1 do not follow this pattern, but instead show negative steric effects. This is not surprising since huge radicals are involved. Set **63** in Table 1 is interesting in that when a single ortho substituent is present a steric parameter does not improve the correlation. However, when substituents are present in both ortho positions a steric parameter (B1−6) brings out a negative steric effect. It should be noted that this set contains a large number of bulky ortho substituents. There are two examples (sets **9** and **21**) in the biological examples of Table 4 where negative steric effects are seen for ortho substituents. These cannot be considered at the present since it is not clear whether the steric effect is intermolecular or intramolecular.

The evidence in hand is intriguing. Ortho substituents do seem to show an unusual positive steric effect in some instances; however, a more systematic study of this problem needs to be done before we can begin to understand what lies behind this phenomenon.

The addition of phenyl radicals to substituted benzenes is similar to that of set **180** in Table 1. Again we wonder if a better selection of substituents would have placed set **17** in Table 1.

The abstraction of benzylic iodine in set **18** has a positive ρ^- that compares with the positive ρs for benzylic halogen abstraction in sets **65**, **66**, and **70** in Table 2. Sets **12**, **13**, and **18** were the first reported instances where σ^- was the parameter of choice. The authors found the benzylic F was not abstracted by the alkyl−Sn radicals.

Set **20** has a positive ρ^- similar to set **17**, but much larger. Why the substituent effect is so much larger with the adamantyl radical is not clear.

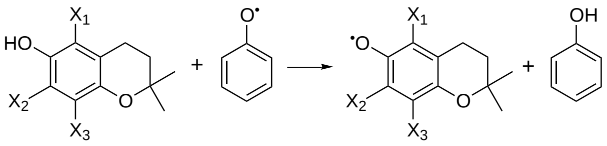
Set **23** is of interest in that ρ^- is positive. This is reminiscent of the example of cyclohexylation of substituted benzenes by cyclohexyl radical (set **79**) in Table 2.

The examples of sets **21** and **22** might be expected to fall in Table 7 since most radical polymerizations do. However, a much better correlation is found with σ^-. The reaction of the large $(C_4H_9)_3Sn^\bullet$ radical (sets **24**−**26** and **29**) with benzaldehydes or benzoyl chlorides all have large ρ^-s as one would expect when the radical is spread over such a large area of the Sn atom.

In set **27** the superoxide radical anion probably removes an H^+, leaving a negative charge to be delocalized by the substituents. Of course one would expect σ^- to be the parameter of choice for such a process.

The concluding remarks about Tables 1−3 must note that much of the potential insight that might be gained by σ^+ is compromised by the collinearity problem. In Table 1 only 10 examples (sets **1**, **1a**, **2**, **3**, **70**, **87**, **94**, **114**, **126**, and **139**) have r^2 less than 0.795 for correlation between σ^+ and σ. In Table 2 there are only five examples (**4**, **14**, **32**, **94**, **and 95**), and in Table 3 there are no examples. In a recent evaluation of radical parameters Héberger[146] concludes that there is no single suitable parameter. However, in doing so no discussion is given about the importance of proper substituent selection. The situation has not changed much since Dust and Arnold[40] pointed out that "relative rates of many free radical reactions correlate reasonably well with the substituent parameters (σ, σ^+, σ^-)".

Finally we need to reiterate the importance of having the best possible spread in parameter values. This is most important in biological work where the noise in the data is normally much greater and with a narrow spread it is easier to obtain a misleading slope. One has more leeway working with the simple Hammett equation. An interesting example is eq 3 in Table 2: Correlating the abstraction of •H from vitamin E analogs:



This QSAR was placed in Table 2 on the basis of its r^2 values, using σ^+ in eq 4a yields almost as good a correlation.

$$\log k = -1.08(\pm 0.32)\sigma^+ + 0.37(\pm 0.28)B1,3 + 2.35(\pm 0.39) \quad (4a)$$

$$n = 10, \quad r^2 = 0.908, \quad s = 0.095, \quad F_{1,8} = 28.9\ (\sigma^+),^\S \quad F_{1,7} = 9.52\ (B1,3)^\S$$

Since only alkyl groups were used as substituents,[201] the correlation between σ^+ and σ is very high (0.952). Nevertheless the poor selection of substituents does not preclude a meaningful result. The value of ρ^+ in eq 4a is what one would expect from Table 1a. Lateral support from other QSAR helps us place this set in proper context.

We believe that the $B1,3$ term may arise from the shielding of the adjacent oxygen from hydrogen bonding with the aqueous solvent thus making the lone pair electrons more available for stabilization of the radical.

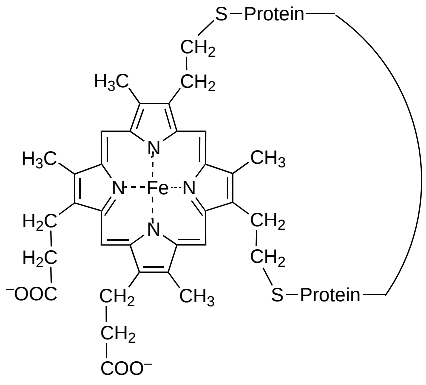
III. Discussion of Biological QSAR (Tables 4–6)

1. Correlation with σ^+ (Table 4)

Of course the formulation of QSAR for biological processes is much more difficult than for those for physical organic chemistry. Steric factors are more difficult to isolate and in addition the hydrophobic properties of the ligands must also be considered. Another problem that has been uncovered is that in a number of instances of enzymic reactions we have found the overall process based on k_{cat}/K_m may not show an electronic term in the QSAR while both the k_{cat} and K_m steps do depend on such effects. We have found the electronic term in k_{cat} can be canceled by an electronic term of opposite sign in $1/K_m$.[60] The same kind of cancellation can obscure hydrophobic effects.[60] Hence for the biological QSAR one cannot expect the same quality of statistics found for work from physical organic chemistry.

The range in ρ^+ in Table 4 (−3.2 to +1.7) is narrower than in Table 1, especially for positive ρ^+. For one example (**43**), a significantly better correlation is obtained using an equation with parabolic electronic terms.

The examples of the peroxidases with large negative ρ^+ are the first to enter Table 4. These are for enzymes containing a metalloporphyrin moiety as illustrated by cytochrome C:



cytochrome C

Horseradish peroxidase (HRP) has been the subject of many investigations. It is a hemoprotein similar to cytochrome C. For SAR studies it is activated with hydrogen peroxide as follows:

$$\mathrm{HRP} + \mathrm{H_2O_2} \rightarrow \mathrm{HRP\text{-}I} + \mathrm{H_2O}$$

$$\mathrm{HRP\text{-}I} + \mathrm{AH_2} \rightarrow \mathrm{HRP\text{-}II} + {}^{\bullet}\mathrm{AH}$$

$$\mathrm{HRP\text{-}II} + \mathrm{AH_2} \rightarrow \mathrm{HRP} + {}^{\bullet}\mathrm{AH} + \mathrm{H_2O}$$

The overall reaction is

$$\mathrm{H_2O_2} + 2\mathrm{AH_2} \rightarrow 2\mathrm{H_2O} + 2{}^{\bullet}\mathrm{AH}$$

In these equations AH_2 represents an aniline, but phenols (AH) are also oxidized by the oxidized forms of HRP. Rather large values of ρ^+ are obtained for oxidation of phenols or anilines with both HRP-I and HRP-II. These values are similar to those in Table 1, where radicals formed from various metalloporphyrins have been studied in $^{\bullet}$H abstraction reactions. It has been shown via ESR studies that in HRP oxidation of phenols the phenoxy radical is formed.[57] It has been proposed in the case of set **2** that it is the neutral form of the amine that reacts with the acidic form of the enzyme. An electron is then abstracted from the nitrogen atom followed by loss of a hydrogen. Of course this is difficult to distinguish from direct $^{\bullet}$H abstraction, even using isotope studies.

The large negative ρ^+ for HRP reactions is similar to ρ^+ for examples in Table 1 where “hindered” radicals are abstracting $^{\bullet}$H from phenols, or example **2** in Table 3 where a hindered radical abstracts $^{\bullet}$H from a set of anilines. In the examples of the metalloporphyrin the authors point out that the activity of metalloporphyrins in hydrogen abstraction might be expected to increase in the order Mn=O > Fe=O > Cr=O. As expected we find the absolute values of ρ to decrease in the opposite order: Cr=O > Fe=O > Mn=O. That is, the greater the activity of the radical the smaller the value of ρ. Thus the metalloporphyrins, HRP, and cytochrome C are not highly active in radical oxidation and benefit by substituent assistance. They behave much like the hindered phenol radicals.

The simple metallic ions such as Ce^{2+}, Co^{3+}, and Mn^{3+} all have large negative ρ^+ values, similar to the metalloporphyrins and the metalloporphyrin enzymes.

Sets **1** and **2** for the oxidation of anilines by HRP-I and HRP-II have very similar QSAR, and each contain small hydrophobic terms. Set **4** for phenol oxidation has a considerably larger hydrophobic term for 4-substituents; 3-substituents do not show a hydrophobic interaction. Set **6** has a hydrophobic term of marginal importance, and set **9** has a strong hydrophobic term. Although the results are not consistent, hydrophobicity of the phenols and anilines can be important. The most extensive study (set **9**) contains a strong log *P* term of the type seen where complete desolvation of the ligand occurs (i.e., slope near 1).[58] This is similar to what has been observed for ligands binding to cytochrome P450.[59]

In addition to hydrophobic effects, set **9** clearly shows that steric effects of ortho substituents are deleterious.

The peculiar behavior of HRP-II can be seen from another point of view. For example, set **25**, where log V_{max}/K_m for the oxidation of phenols yields a relatively low value of ρ^+ and a negative term in log *P*. A troublesome point about this set is that in contrast to many other sets correlated by σ^+ the 4-OR and 4-Cl substituents are outliers. The number of data points/variable is also too low. It is not clear how helpful this study will be to those hoping to extend the action of this enzymes on phenols. In set **11**, where the reaction is run in 40% methanol, we see a normal ρ^+. Set **8** has a high ρ^+. Ryu and Dordick[61] have studied the effect of various solvents on HRP-II oxidation of phenols from which we have derived the following QSAR:

95% dioxane

$$\log V_{max}/K_m = -0.50(\pm 0.19)\log P + 1.29(\pm 0.49) \tag{5}$$

$$n = 7, \quad r^2 = 0.898, \quad s = 0.135, \quad F_{1,5} = 43.7^{\S}$$

80% dioxane

$$\log V_{max}/K_m = -0.62(\pm 0.39)\log P + 2.17(\pm 1.0) \tag{6}$$

$$n = 5, \quad r^2 = 0.893, \quad s = 0.221, \quad F_{1,3} = 25.2^{\S\S}$$

70% dioxane

$$\log V_{max}/K_m = -0.54(\pm 0.19)\log P + 2.03(\pm 0.50) \tag{7}$$

$$n = 5, \quad r^2 = 0.964, \quad s = 0.108, \quad F_{1,3} = 79.9^{\S}$$

99% butyl acetate

$$\log V_{max}/K_m = -1.03(\pm 0.49)\log P + 2.49(\pm 1.3) \tag{8}$$

$$n = 5, \quad r^2 = 0.937, \quad s = 0.276, \quad F_{1,3} = 44.5^{\S}$$

Even though the substituent selection was not very good (collinearity between σ^+ and log *P*, $r^2 = 0.5$) it is clear that hydrophobicity is by far the most important parameter in eqs 5−8. Because of the small number of data points a term in σ^+ cannot be completely ruled out.

Why the sets based on reaction with aqueous methanol clearly have a strong ρ^+ and those based on dioxane and butyl acetate do not is intriguing. The

OH group of methanol and water would seem to determine the shape of the active site.

Hosoya et al.[62] investigated the binding of a set of phenols and anilines to HRP and lactoperoxidase. We have obtained a good QSAR for the dissociation constants of the 1:1 complex with lactoperoxidase:

$$\log 1/K_D = -0.73(\pm 0.30) \log P + 1.74(\pm 0.32) \tag{9}$$

$$n = 5, \quad r^2 = 0.952, \quad s = 0.069, \quad F_{1,3} = 61.9,^{\S} \quad \text{omitted: } p\text{-cresol}$$

Strangely this is opposite to what one would expect from the QSAR of set **19**. However a satisfactory QSAR could not be found for their HRP data.

While in normal aqueous solution HRP-I and -II show a strong correlation with σ^+ for the oxidation of anilines and phenols; the dependence of these reactions on the hydrophobic properties of substrates is not clear. It would seem that the enzymes are quite sensitive to reaction conditions. Small changes in these conditions could yield results producing the somewhat different QSAR.

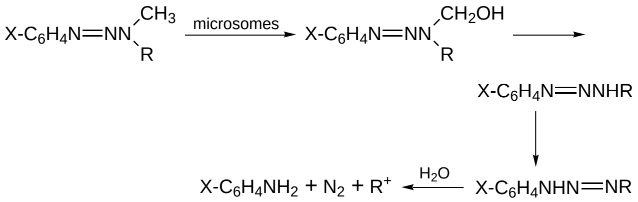
There are three QSARs for the oxidation of anilines by various cytochrome C peroxidases (sets **3**, **10**, and **17**). All of these show strong dependence on σ^+, similar to HRP and the porphyrins of Table 1, but with no evidence for hydrophobic or steric interactions of the substituents. Of course the study of a large set of substituents might uncover such possibilities. Studies of small sets of compounds in biological systems cannot be taken very seriously. They only indicate the possibility for serious work.

This dependence on σ^+ is in contrast to set **2** in Table 3. This set, however, is based on a third-order mechanism. There is a paucity of data on the radical reactions of aniline from simple physical organic systems. Presumably this is due to the complexity of the mechanism and the variety of products that may occur. The biochemical reactions, on the other hand, seem to be relatively straightforward.

Horseradish peroxidase has been used to explore the oxidative deacylation of aromatic tertiary amines (sets **5** and **16**). The confidence limits on ρ^+ are wide, but ρ^+ appears to be about -2. In addition to the electronic effect of the substituents there is in each case a negative steric effect of para substituents brought out by the sterimol parameter $B1$. It is of interest that this steric interaction is not seen in the QSAR for the oxidation of phenols (sets **4**, **6**, and **8**), anilines, or sulfides (set **18**). The orientation of the dimethylamino compounds for demethylation appears to be different from the anilines (set **13**) and phenols undergoing oxidation.

There has been considerable discussion as to whether or not the first step in N-demethylation is removal of a single electron from the nitrogen atom or abstraction of $^{\bullet}$H. Recent evidence inclines one to believe that $^{\bullet}$H abstraction may be the most likely path.[58a−c]

Set **14** provides an intriguing example in comparative QSAR for the anticancer triazenes. The evidence suggests that triazenes undergo dealkylation to yield carbocations and that these alkylate DNA to either restrict fast-growing cancer cells or cause cancer themselves according to the following mechanism:[58d,58e]



The large absolute value of ρ^+ makes the normal dealkylation by P450 seem unlikely since these reactions show little or no electronic effect.[59,60] The ρ^+ of -1.63 is more like that seen for a peroxidase such as in sets **3**, **10**, and **17**. Of course it would be expected that ρ^+ would be somewhat lower for dealkylation of $-$NMeR separated from an aromatic ring by $-$N=N$-$ than when the dialkylamino group is directly attached, as in set **5**.[1]

A much smaller absolute ρ^+ is observed in the QSAR of set **38** for the LD_{50} of triazenes for mice with sarcoma 180. This low value of ρ^+ might be expected if a much more active radical such as $^{\bullet}$OH initiated the dealkylation process. Set **8** in Table 5 for the curative action of triazenes is a bit better correlated by σ, but also has a low ρ.

Lactoperoxidase (set **19**) oxidation of phenols has a somewhat smaller ρ^+ than that found for horseradish and cytochrome peroxidase. Also, the QSAR of set **19** contains a positive hydrophobic term; in contrast to what might be expected from eq 9. The binding correlated by eq 9 may be at a different site from the oxidation reaction.

The QSAR for a large set of phenols inhibiting prostaglandin cyclooxygenase (set **12**) contains a strong σ^+ term similar to that found for the peroxidases. The hydrophobic terms describe a bilinear relationship which initially increases activity with slope of 1.01 and then begins to level off ($1.01 - 1.34 = -0.33$). The optimum $\log P$ is 2.5 ± 1.7. That is, phenols having $\log P$ of 2.5 or less show a linear relationship with slope of 1. Again, this reminds us in terms of the slope of the binding of ligands to P450.[59] But the high negative ρ^+ shows an otherwise different mechanism that resembles the porphyrins of Table 1.

The large absolute values of ρ^+ seen for the metalloporphyrin enzymes in Table 4 stands in sharp contrast to what we have found for cytochrome P450 (also a metalloporphyrin) where the QSAR for the overall reaction (k_{cat}/K_m) often shows little or no electronic effect by substituents and even for the kcat equation ρ^+ has a small value.[59,60]

The chloroperoxidase of set **13** was isolated from soil fungus. Its natural role is that of a halogenating enzyme. However, with H_2O_2 it oxidizes arylamines to nitroso compounds. All but one of the substituents are in the para position so that the negative MR term reflects a steric effect of the substituents in that position. This steric effect is somewhat like that found for other peroxidases (sets **5**, **16**, and **24**).

The electronic term in the QSAR of set **15** for phenylalanines inhibiting phenylalanine hydroxylase is very similar to that of phenols inhibiting prostaglandin cyclooxygenase (set **12**). In set **15** r^2 is low

Table 4. Biological QSARs Correlated by σ^+ [a]

set	action, correlation	substrate	ref
1	horseradish peroxidase I reduction of compound I, oxidation of anilines $\log k = -3.16(\pm 0.33)\sigma^+ + 0.39(\pm 0.07)\pi\text{-sum} + +5.52(\pm 0.18)$ $n = 9$, $s = 0.162$, $r^2 = 0.995$ (0.926), (0.872), $F_{1,7} = 31.8$ (σ^+),[§] $F_{1,6} = 207$ (π-sum)[§] [&]4-COO$^-$, −0.22; 4-OH, 0.18; 3-COO$^-$, 0.14; 4-OEt, −0.14; 3-COMe, 0.13; H, −0.13; 4-SO$_3^-$, 0.02; 3-OEt, 4-Me, 0.00	X-C$_6$H$_4$NH$_2$	259
2	horseradish peroxidase II oxidation at pH 7.6 $\log k = -2.99(\pm 0.51)\sigma^+ + 0.29(\pm 0.12)\pi\text{-sum} + 4.79(\pm 0.28)$ $n = 8$, $s = 0.237$, $r^2 = 0.988$ (0.928), (0.902), $F_{1,6} = 48.2$ (σ^+),[§] $F_{1,5} = 41.0$ (π-sum)[§] H, −0.34; 4-OEt, −0.24; 4-OH, 0.19; 4-Me, 0.16; 3-OEt, 0.15; 3-COMe, 0.11; 4-SO$_3^-$, −0.07; 4-COO$^-$, 0.05	X-C$_6$H$_5$NH$_2$	260
3	cytochrome *c* peroxidase from *E. coli* oxidation by enzyme at pH 6.0 $\log k_2 = -2.86(\pm 0.43)\sigma^+ + 1.09(\pm 0.21)$ $n = 7$, $s = 0.193$, $r^2 = 0.983$ (0.887), (0.884), $F_{1,5} = 292$,[§] omit: 3-OMe (0.83[‡]) (k_2: second-order rate constant) 3-Cl, −0.29; 4-Cl, 0.29; 4-Me, 0.11; 4-OMe, −0.10; 4-OH, −0.04; 3-Me, 0.02; H, 0.01	X-C$_6$H$_4$NH$_2$	261
4	horseradish peroxidase I reduction of compound, oxidation of phenols $\log k_2 = 1.31(\pm 0.71)\pi,_4 - 2.68(\pm 0.78)\sigma^+ + 6.36(\pm 0.30)$ $n = 12$, $s = 0.397$, $r^2 = 0.872$ (0.773), (0.913), $F_{1,10} = 16.8$ (σ^+),[§] $F_{1,9} = 17.3$ (π-sum),[§] omit: 3,4-Me$_2$ (−1.27); 3-OH (0.87) 3-CHO, −0.80; 4-Cl,3-Me, 0.37; 3-Me, 0.36; 3-OMe, 0.36; 3-OH,5-Me, 0.33; 4-OMe, −0.31; 4-Me, −0.30; 3.5-Me$_2$, −0.27; 4-NH$_2$, 0.12; H, 0.08; 4-Cl, 0.06; 3-OEt, 0.01	X-C$_6$H$_4$OH	259
5	horseradish peroxidase oxidative dealkylation $\log k = -2.58(\pm 0.69)\sigma^+ - 2.85(\pm 0.79)B1{,}4 + 0.25(\pm 1.0)$ $n = 12$, $s = 0.317$, $r^2 = 0.907$ (0.555), (0.710), $F_{1,10} = 2.85$ (σ^+), $F_{1,9} = 66.6$ ($B1{,}4$),[§] $F_{2,9} = 88.1$[§] ($B1{,}4$; sterimol parameter for para position), omit: X = 4-Cl, Y = Me (1.73); X = 4-Cl, Y = Et (2.19); X = 4-CN, Y = Me (1.31) X = 4-F, Y = Et, 0.53; X = 3-Me, Y = Me, −0.47; X = 3-Cl, Y = Et, 0.39; X = 3-NO$_2$, Y = Me, −0.27; X = 4-CHMe$_2$, Y = Et, −0.26; X = 3-OMe, Y = Et, 0.18; X = 4-NHCOMe, Y = Et, 0.17; X = 4-NHCOMe, Y = Me, −0.15; X = 3-Me, Y = Et, −0.12; X = 3-F, Y = Me, −0.07; X = 4-CHMe$_2$, Y = Me, 0.04; X = 4-F, Y = Me, 0.02	X-C$_6$H$_4$N(-Y)$_2$	262
6	horseradish peroxidase compound II oxidation $\log k = -2.48(\pm 0.53)\ \sigma^+ + 4.68(\pm 0.34)$ $n = 9$, $s = 0.352$, $r^2 = 0.945$ (0.902), (0.939), $F_{1,7} = 120$,[§] omit: H (0.80) 4-Me, 0.55; 4-COO$^-$, −0.45; 4-NH$_2$, −0.39; 3-CHO, −0.30; 3-OEt, 0.27; 4-OH, 0.14; 4-OMe, 0.14; 3,4-Me$_2$, −0.07; 4-Cl, −0.03	X-C$_6$H$_4$OH	263
7	fungal Laccases oxidation 20 °C $\log k_{\text{cat}}/K_{\text{m}} = -2.39(\pm 0.49)\sigma^+ + 0.84(\pm 0.66)M_{\text{r}},2 - 1.01(\pm 0.58)I + 4.49(\pm 0.48)$ $n = 18$, $s = 0.328$, $r^2 = 0.922$ (0.825), (0.654), $F_{1,16} = 57.5$ (σ^+),[§] $F_{1,15} = 8.70$ (I),[§] $F_{1,14} = 7.14$ (M_{r},2),[§§] omit: 2-OMe,4-CH$_2$COO$^-$ (−1.08) (I = 1.0 for 2,6-disubstituted compounds) 2-OMe,4-NO$_2$, −0.61; 2,6-(OMe)$_2$,4-CHO, 0.57; 2,6-(OMe)$_2$, −0.28; 2-OH, 0.32; 2,6-(OMe)$_2$,4-COO$^-$, −0.32; 2-OMe, 0.26; 2-OH,4-COO$^-$, −0.25; 2,6-(OMe)$_2$,4-COMe, 0.23; 2-OMe,4-COOMe, 0.20; 2-OMe,4-CH$_2$OH, 0.20; 2-OMe,4-Me, −0.19; 2-Et, 0.14; 2-OMe,4-COMe, −0.14; 2-Me, 0.14; 2-OMe,4-CHO, −0.13; 2-OMe,4-COO$^-$, 0.11; 4-COO$^-$, −0.03; H, −0.01	X-C$_6$H$_4$OH	264
8	horseradish peroxidase II oxidation by enzyme in 80% methanol $\log V_{\max}/K_{\text{m}} = -2.35(\pm 1.19)\sigma^+ - 0.36(\pm 0.51)$ $n = 5$, $s = 0.335$, $r^2 = 0.930$ (0.796), (0.896), $F_{1,3} = 39.8$,[§] omit: 4-OC$_3$H$_7$ (−1.26) 4-Cl, 0.47; 3-Cl, −0.30; 3-Me, −0.14; 4-OC$_4$H$_9$, −0.07; 4-Me, 0.04	X-C$_6$H$_4$OH	265
9	horseradish peroxidase compound II oxidation (hydrogen abstraction) by horseradish peroxidase compound II $\log k = -2.24(\pm 0.44)\sigma^+ - 0.69(\pm 0.35)B5{,}2 + 0.94(\pm 0.54)C\log P + 4.27(\pm 1.15)$ $n = 15$, $s = 0.357$, $r^2 = 0.920$ (0.856), (0.927), $F_{1,13} = 20.5$ (σ^+),[§] $F_{1,12} = 13.3$ ($B5$,2),[§] $F_{1,11} = 14.3$ ($C\log P$)[§] ($B5$,2: sterimol parameter, B5, for ortho position), omit: 3-CN(−1.66), 3-OH(1.48), 2-Cl(0.84) H, 0.54; 2-Me, −0.50; 3-CHO, −0.49; 4-Cl, 0.38; 4-CN, 0.36; 2-OMe, 0.31; 3-Cl, −0.25; 2-CN, −0.25; 3-OMe, 0.22; 2-OH, −0.18; 4-CHO, −0.16; 2-CHO, 0.15; 4-Me, −0.10; 4-OMe, −0.03; 3-Me, 0.01	X-C$_6$H$_4$OH	266
10	cytochrome *c* peroxidase W51A oxidation by enzyme $\log k = -2.10(\pm 0.58)\sigma^+ + 3.07\ (0.29)$ $n = 7$, $s = 0.263$, $r^2 = 0.945$ (0.901), (0.897), $F_{1,5} = 85.7$,[§] omit: 4-Cl (0.72) (k$_2$: second-order rate constant) 4-OMe, −0.39; 4-Me, 0.29; 4-OH, 0.21; 3-OMe, 0.18; H, −0.14; 3-Cl, −0.13; 3-Me, −0.03	X-C$_6$H$_4$NH$_2$	261

Table 4 (Continued)

set	action, correlation	substrate	ref
11	horseradish peroxidase II oxidation by enzyme in 40% methanol $\log V_{\max}/K_{\mathrm{m}} = -2.00(\pm0.24)\sigma^{+} + 1.35(\pm0.12)$ $n = 4$, $s = 0.51$, $r^2 = 0.998$ (0.958), (0.952), $F_{1,2} = 1273$,§ omit: 4-OC_3H_7(−0.96) 4-Cl, −0.06; 3-Cl, 0.03; 4-Me, 0.03; 4-OC_4H_9, 0.00	X-C_6H_4OH	265
12	prostoglandin cyclooxygenase from sheep vesicle I50 $\log 1/C = 1.01(\pm0.19)\log P - 1.34(\pm0.52)\log(\beta\, 10^{\log P} + 1) - 1.84(\pm0.22)\sigma^{+} + 1.35(\pm0.36)$ $n = 25$, $s = 0.145$, $r^2 = 0.961$ (0.855), (0.749), $F_{1,23} = 22.5$ (σ^{+}),§ $F_{1,22} = 95.1$ (log P),§ $F_{2,20} = 30.5(\beta/10^{\log P})$§ omit: 3,5-$Me_2$ (−0.32), 2-OMe,4-$CH_2CH = CH_2$ (−0.44) 2,4,6-Me_3, −0.26; 2,3,5,6-Me_4, −0.24; 2-OEt, −0.22; 2,5-Me_2, 0.17; 2,4-Me_2, 0.17; 2,6-Me_2, 0.16; 3-Me, −0.15; 2-$OCH_2C_6H_5$, 0.14; 2,3,6-Me_3, 0.14; 2-$CHMe_2$k, −0.13; 2-$CHMe_2$, 5-Me, 0.13; 2-Et, −0.13; 4-Me, 0.10; 2-Br, −0.10; 2-CH(Me)Et, 0.08; 2-C_3H_7, −0.08; 2-CMe_3, 0.07; 3,4-Me_2, 0.07; 2-Cl, −0.05; 2,3,5-Me_3, 0.05; 2-OMe, 0.05; 2,3-Me_2, −0.04; 2-Me, 0.03; 2-OMe,4-CH_2OH, 0.02; H, 0.01	X-C_6H_4OH	267
13	chloroperoxidase oxidation to nitroso compound $\log V_{\max}/K_{\mathrm{m}} = -1.02(\pm0.32)\mathrm{MR} - 1.67(\pm0.64)\sigma^{+}$ $3.46(\pm0.31)$ $n = 9$, $s = 0.192$, $r^2 = 0.950$ (0.942), (0.964), $F_{1,7} = 28.1$ (σ^{+}),§ $F_{1,6} = 8.43$ (Mr)§§ 4-Br, 0.34; 3,4-Cl_2, −0.18; 4-Me, −0.18; 4-F, 0.14; H, −0.09; 4-$CHMe_2$, 0.08; 4-Et, −0.06; 4-Cl, −0.03; 4-I, −0.02	X-$C_6H_4NH_2$	268
14	*S. typhimurium* (*Salmonella*) Ames test, 30 mutations per 100 million bacteria mutagenesis $\log 1/C = -1.63(\pm0.35)\sigma^{+} + 1.04(\pm0.17)\log P + 3.06(\pm0.43)$ $n = 17$, $s = 0.315$, $r^2 = 0.949$ (0.894), (0.878), $F_{1,15} = 20.3$ (log P),§ $F_{1,14} = 102$ (σ^{+}),§ omit: X = 4-$CONH_2$, R = CMe_3 (−2.43) 4-$CONH_2$, R = $CHCH{=}CH_2$, −0.49; H, R = Me, −0.43; 4-Me, R = Me, 0.39; 4-$CONH_2$, R = C_4H_9, 0.38; 3-$CONH_2$, R = Me, −0.35; 4-SO_2NH_2, R = Me, 0.34; 4-$CONH_2$, R = Me, 0.32; 3-Me, R = Me, 0.30; 3-$NHCONH_2$, R = Me, −0.26; 4-C_6H_5, R = Me, −0.26; 4-NHCOMe, R = Me, 0.19; 4-Cl, R = Me, 0.14; 4-COMe, R = Me, −0.14; 4-$NHCONH_2$, R = Me, −0.14; 4-CF_3, R = Me, 0.08; 3,5-CN, R = Me, −0.04; 4-CN, R = Me, −0.04	X-$C_6H_4N{=}NN(Me)$-R	269
15	phenylalanine hydroxylase of rat liver oxidation inhibition $\log \mathrm{RBR} = 0.56(\pm0.33)\pi{,}3 - 1.621(\pm0.98)\sigma^{+} + 1.61(\pm0.18)$ $n = 8$, $s = 0.108$, $r^2 = 0.808$ (0.725), (0.969), $F_{1,6} = 0.8$ (π,3), $F_{1,5} = 17.9$ (σ^{+}),§ $F_{2,5} = 20.93$§ 3-F, 0.14; 3-Cl, −0.14; 4-Br, −0.08; 4-I, −0.08; 4-Cl, 0.06; 4-F, 0.04; 3-Br, 0.04; 3-I, 0.0	halophenylalanines	270
16	peroxidase horseradish oxidative dealkylation $\log k = -0.81(\pm0.79)B1{,}4 - 1.60(\pm0.68)\sigma^{+} + 0.67(\pm0.52)\ C\log P + 0.62(\pm1.16)$ $n = 14$, $s = 0.413$, $r^2 = 0.828$ (0.651), (0.766), $F_{1,12} = 13.2$ (σ^{+}),§ $F_{1,11} = 8.95$(C log P),§§ $F_{1,10} = 5.21$(B1,4),§§ omit: X = 4-$CHMe_2$, R = C_2H_5 (−1.89) X = 4-$CHMe_2$, R = Me, −0.92; X = 4-Cl, R = Me, 0.59; X = 4-Cl, R = Et, 0.38; X = 3-NO_2, R = Me, −0.37; X = 4-NHCOMe, R = Me, 0.33; X = 3-Me, R = Me, 0.19; X = 4-F, R = Et, −0.19; X = 3-Cl, R = Me, 0.17; X = 3-Me, R = Et, −0.12; X = 3-Cl, R = Et, −0.05; X = 4-CN, R = Me, 0.04; X = 4-NHCOMe, R = Et, −0.02; X = 4-F, R = Me, −0.02; X = 3-OMe, R = Et, −0.01	X-$C_6H_4NR_2$	271
17	cytochrome c peroxidase W51F oxidation by enzyme $\log k_2 = -1.57(\pm0.41)\sigma^{+} + 3.08(\pm0.21)$ $n = 6$, $s = 0.263$, $r^2 = 0.966$ (0.932), (0.910), $F_{1,4} = 113$,§ omit: 4-Cl (0.65), 4-Me (0.52) (k_2: second-order rate constant) 4-OMe, −0.22; 3-OMe, 0.15; 4-OH, 0.15; 3-Cl, −0.13; 3-Me, 0.07; H, −0.02	X-$C_6H_4NH_2$	261
18	horseradish peroxidase oxidation (S-oxygenation) $\log V_{\max} = -1.48(\pm0.13)\sigma^{+} + 0.13(\pm0.08)$ $n = 4$, $s = 0.021$, $r^2 = 0.999$ (0.887), (0.888), $F_{1,2} = 2140$§ 4-Me, 0.02; H, −0.02; 4-$OCHMe_2$, −0.01; 4-OMe, 0.00	X-$C_6H_4SCH_3$	272
19	lactoperoxidase-II oxidation $\log k = 0.41(\pm0.16)\pi{,}4 - 1.34(\pm0.55)\sigma^{+} + 5.74(\pm0.24)$ $n = 11$, $s = 0.326$, $r^2 = 0.893$ (0.867), (0.895), $F_{1,9} = 7.81$ (π,4),§§ $F_{1,8} = 32.1$ (σ^{+}),§ omit: 3-OEt (1.00), 4-OEt (−0.70) H, 0.41; 4-OMe, −0.40; 4-OH, 0.36; 4-Me, −0.34; 4-CHO, −0.33; 4-I, 0.21; 3-Me, 0.21; 3,4-Me_2, −0.20; 4-Cl, 0.17; 3-CHO, −0.11; 4-COO^-, 0.01	X-C_6H_4OH	273
20	prostaglandin H synthase inhibition of cyclooxygenase activity I50 $\log 1/C = 0.91(\pm0.46)\pi{,}4 - 1.23(\pm0.52)^{+} + 2.29(\pm0.33)$ $n = 6$, $s = 0.130$, $r^2 = 0.954$ (0.695), (0.870), $F_{1,4} = 2.16$ (σ^{+}), $F_{1,3} = 39.7$ (π,4),§ $F_{2,3} = 62.7$,§ omit: 3-OEt (0.64) 4-OMe, 0.16; 4-Cl, 0.09; 4-Me, −0.09; 4-OEt, −0.08; H, −0.06; 4-OH, −0.03	X-C_6H_4OH	64

Table 4 (Continued)

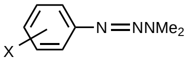
set	action, correlation	substrate	ref
21	peroxidase from *Geotruchum candidum* biotransformation (oxidation) $\log A = -1.21(\pm0.17)\sigma^+ - 1.32(\pm0.58)B1,6 + 0.53(\pm0.15)\ C\log P - 0.83(\pm0.31)F,o + 3.03(\pm0.56)$ $n = 32$, $s = 0.170$, $r^2 = 0.904$ (0.745), (0.871), $F_{1,30} = 52.1$ (σ^+),§ $F_{1,29} = 7.45$ ($C\log P$),§ $F_{1,28} = 18.9$ (F,o),§ $F_{1,27} = 21.9$ ($B1,6$)§ ($B1,6$: sterimol parameter, $B1$, for more electron donating ortho substituents; F,o: sum of the field effects of ortho postions), omit: H (0.78) and 3-OMe (0.47) 4-Me, 0.35; 2,4,6-Me_3, 0.31; 2,3,4-Cl_3, 0.28; 4-F, −0.26; 2-Cl,6-Me, −0.22; 2-Me,3-Cl, −0.22; 2-Me,5-Cl, −0.20; 3-I, −0.18; 2,5-Cl_2, −0.18; 3,4-Cl_2, 0.17; 2,4-Cl_2, 0.15; 4-Br, 0.15; 2-Me,4-Cl, −0.14; 3,4,5-$(OMe)_3$, −0.13; 4-OMe, 0.12; 2,3-Cl_2, −0.12; 2-Me, −0.11; 4-Cl, 0.11; 2-Cl, 0.09; 2,4,5-Me_3, −0.09; 3,5-Cl_2, −0.09; 4-I, 0.08; 2-F, 0.08; 2-Br, 0.08; 2-OMe, 0.05; 3-Me, −0.04; 3-F, −0.02; 3-Br, −0.02; 3-Cl,4-Me, 0.02; 2-I, −0.02; 3-Cl, 0.01; 2-Cl,4-Me, 0.00	X-$C_6H_4NH_2$	274
22	hypothalamus rat brain *in vitro* I50 inhibition of norepinephrine uptake $\log 1/C = 0.67(\pm0.28)\ C\log P - 0.45(\pm0.17)B5,4 - 1.05(\pm0.45)\sigma^+,X + 3.57(\pm1.13)$ $n = 20$, $s = 0.278$, $r^2 = 0.697$ (0.608), (0.891), $F_{1,18} = 1.36$ ($B5,4$), $F_{1,17} = 3.63$($C\log P$),§§ $F_{1,16} = 24.5$(σ^+),§ $F_{3,16} = 36.9$§ ($B5,4$: sterimol parameter, $B5$, for para position), omit: R = NHMe, X = 3-CF_3-4-Cl (−0.49); R = NHMe, X = 2-OMe (−0.93); R = NH_2, X = 3,4-Cl_2 (1.07) R = NMe_2, X = 4-CF_3, −0.52; R = NH_2, X = 4-CF_3, 0.38; R = NMe_2, X = H, 0.36; R = NHMe, X = 2,4-Cl_2, 0.35; R = NHMe, X = 3-CF_3, −0.35; R = NHMe, X = 3,4-Cl_2, 0.33; R = NMe_2, X = 3,4-Cl_2, 0.24; R = NMe_2, X = 3-CF_3, −0.24; R = NHMe, X = 3-OMe, 0.23; X = NMe_2, R = 4-Cl, −0.21; = NH_2, X = 3-CF_3, −0.20; R = NHMe, X = 4-F, −0.17; R = NHMe, X = 4-F, −0.11; R = NHMe, X = 4-OMe, −0.11; R = NHMe, X = 4-OC_4H_9, 0.10; R = NHMe, X = 4-OC_6H_5, −0.10 R = NHMe, X = H, −0.07; R = NHMe, X = 4-Br, 0.06; R = NHMe, X = 4-Cl, 0.05; R = NHMe, X = 4-CF_3, −0.01	 	275
23	methylamine dehydrogenase from *Paracoccus denitrificans* $\log K_s = -1.17(\pm0.49)\sigma^+ + 0.81(\pm0.28)$ $n = 4$, $s = 0.132$, $r^2 = 0.982$ (0.916), (0.954), $F_{1,2} = 98.6$,§ omit: H(−0.44) (K_s: dissociation constant of enzyme−substrate complex) 4-Me, −0.13; 4-Br, 0.13; 4-OMe, 0.04; 4-NO_2, −0.04	X-$C_6H_4CH_2NH_2$	276
24	p450 LM2 from rabbit liver hydroxylation $\log k_{cat} = -1.16(\pm0.34)\sigma^+ - 0.51(\pm0.31)B1,4 + 3.03(\pm0.43)$ $n = 11$, $s = 0.155$, $r^2 = 0.913$ (0.893), (0.975), $F_{1,9} = 27.7$ (σ^+),§ $F_{1,8} = 14.6$($B1,4$)§ ($B1,4$: sterimol parameter, B', for para position), omit: 3-CN (0.29), 3-NO_2 (0.40) 3-Me, −0.16; 3-F, 0.15; 3-Cl, 0.15; 4-F, −0.15; H, −0.14; 4-NO_2, −0.14; 3-Br, 0.13; 4-Br, 0.13; 4-CN, −0.11; 4-Me, 0.07; 4-Cl, 0.07	X-$C_6H_4CH_3$	277
25	horseradish peroxidase II oxidation by enzyme $\log V_{max}/K_m = -1.11(\pm0.42)\sigma^+ - 0.54(\pm0.25)\log P + 4.03(\pm0.66)$ $n = 7$, $s = 0.133$, $r^2 = 0.956$ (0.751), (0.802), $F_{1,5} = 645$ (σ^+), $F_{1,4} = 35.3$ ($\log P$),§ $F_{2,4} = 86.1$,§ omit: 4-OMe (−1.10), 4-OC_4H_9 (1.21), 4-Cl (0.79) 3-Me, −0.15; 4-Et, −0.14; 3-Cl, 0.12; 4-OC_3H_7, 0.09; 4-Me, 0.07; 4-C_4H_9, −0.04; 4-C_3H_7, 0.04	X-C_6H_4OH	265
26	bacteria, gram-negative oxidase positive metabolism via the catechols $\log k = 1.64(\pm0.69)\log P - 1.01(\pm0.53)\sigma^+ - 16.6(\pm1.03)$ $n = 6$, $s = 0.215$, $r^2 = 0.964$ (0.896), (0.786), $F_{1,4} = 4.34$ ($\log P$), $F_{1,3} = 37.1$ (σ^+),§ $F_{2,3} = 80.5$,§ omit: H (2.39) 3-NO_2, 0.22; 3-CN, −0.22; 3-Me, 0.16; 3-Br, −0.12; 3-OMe, −0.05; 3-Cl, 0.00	X-$C_6H_4NH_2$	278
27	cytochrome p450-terp oxidation $\log \% = -0.93(\pm0.23)\sigma^+ + 0.64(\pm0.11)$ $n = 5$, $s = 0.075$, $r^2 = 0.983$ (0.964), (0.911), $F_{1,3} = 1.71$,§ (%: percentage of R form of sulfoxide) Me, 0.08; H, 0.06; OMe, −0.06; Cl, −0.06; CN, −0.03	4-X-C_6H_4SMe	279
28	monoamine oxidase A from rat liver competitive inhibition $\log 1/K_i = 0.46(\pm0.21)\ C\log P + 0.88(\pm0.26)MR,3 - 0.87(\pm0.32)\sigma^+ + 3.70(\pm0.50)$ $n = 17$, $s = 0.232$, $r^2 = 0.889$ (0.887), (0.934), $F_{1,15} = 7.16$ (Mr,3),§§ $F_{1,14} = 16.9$ (σ^+),§ $F_{1,13} = 22.9$($C\log P$),§ omit: 4-COOEt (0.76), 3-$COOCH_2C_6H_5$ (−3.20) 3-NO_2, 0.34; 4-$COOCH_2C_6H_5$, −0.29; 4-CN, −0.29; 4-Cl, 0.27; 4-Br, 0.26; 3-Me, −0.23; 3-Cl, 0.20; 4-NO_2, −0.19; 3-COOMe, 0.18; H, 0.16;; 4-OMe, −0.15; 3-OMe, −0.13; 3-Br, −0.13; 3-COOEt, −0.11; 4-COOMe, 0.11; 4-Me, 0.09; 3-CN, −0.08	X-$C_6H_4CH_2N$-(Me)$CH_2C{\equiv}CH$	280
29	prostaglandin H synthase increase in O_2 consumption $\log 1/C = 0.32(\pm0.08)\pi,4 - 0.78(\pm0.29)\sigma^+ - 4.30(\pm0.16)$ $n = 8$, $s = 0.128$, $r^2 = 0.975$ (0.923), (0.886), $F_{1,6} = 15.7$ (π,4),§ $F_{1,5} = 49.6$ (σ^+) 4-OEt, 0.21; H, −0.11; 4-OH, −0.10; 3-OEt, 0.08; 4-Me, −0.08; 4-OMe, −0.05; 4-COO^-, 0.03; 4-Cl, 0.02	X-C_6H_4OH	64

Table 4 (Continued)

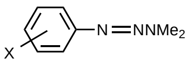
set	action, correlation	substrate	ref
30	*P. aeruginosa* (*Pseudomonas*) kill $\log 1/C = -0.73(\pm0.21)\sigma^+ - 0.42(\pm0.13)B1{,}3 + 0.86(\pm0.12)\ C\log P + 0.25(\pm0.26)$ $n = 20$, $s = 0.103$, $r^2 = 0.943$ (0.912), (0.890), $F_{1,18} = 32.4$($C \log P$),§ $F_{1,17} = 11.5$ (σ^+),§ $F_{1,16} = 43.9$ (B1,2),§ omit: 3-OMe (0.23) 4-Me, −0.17; 2,4-Br_2, −0.16; 4-Cl, −0.15; 3-I, 0.15; 2-Me, 0.15; 3-Br, 0.13; 2-F, −0.11; 4-I, 0.08; 2-OMe, 0.08; 2-I, 0.06; 4-Cl-3-Me, −0.04; H, −0.03; 4-OMe, 0.02; 4-Br, −0.02; 2,4-I_2, 0.02; 3-F, 0.02; 3-Cl, −0.01; 4-F, −0.01; 3-Me, 0.01; 2-Cl, 0.00	X-C_6H_4OH	281
31	sulfoxidase from soybean oxidation to X-C_6H_4SOMe $\log V_{\max} = -0.65(\pm0.29)\sigma^+ - 0.10(\pm0.23)$ $n = 5$, $s = 0.148$, $r^2 = 0.944$ (0.874), (0.972), $F_{1,3} = 50.7^{\S}$ 4-Me, −0.18; 4-OMe, 0.15; 4-Br, 0.10; 4-NH_2, −0.05; 4-NO_2, −0.03	X-C_6H_4SMe	282
32	rat embryo *in vitro* 10% somite number reduction teratogenicitty $\log 1/C = -0.65(\pm0.22)\sigma^+ + 3.74(\pm0.15)$ $n = 11$, $s = 0.188$, $r^2 = 0.828$ (0.744), (0.960), $F_{1,9} = 43.4$,§ omit: H (−0.81), 4-NO_2 (0.50) 4-OMe, −0.33; 4-F, −0.21; 4-OH, 0.20; 4-Me, −0.19; 4-OC_7H_{15}, 0.19; 4-OC_5H_{11}, 0.14; 4-Cl, 0.13; 4-I, 0.12; 4-NH_2, −0.06; 4-Br, 0.03; 4-CN, −0.01	4-X-C_6H_4OH	283
33	pregnant rat reduction of maternal weight, teratogenic effect $\log 1/C = 0.83(\pm0.48)\log P - 0.18(\pm0.14)(\log P)^2 - 0.63(\pm0.24)\sigma^+ + 1.13(\pm0.39)$ $n = 19$, $s = 0.237$, $r^2 = 0.748$ (0.734), (0.939), $F_{1,17} = 11.8$ (σ^+),§ $F_{1,16} = 10.2$ ($\log P$),§ $F_{1,15} = 7.16$ (bilin($\log P$)),§§ omit: 4-I (0.43), 4-NHCOMe (0.41), 4-COEt (−1.57), 4-F (0.39) 4-SH, 0.44; 4-OC_3H_7, −0.32; 4-Cl, −0.28; 4-COMe, 0.28; 4-COOH, −0.25; 4-$CONH_2$, −0.25; 3-OMe, 0.23; 4-CH_2CH_2OH, −0.23; 4-CHO, −0.20; 4-NH_2, 0.19; 3-OH, 0.16; H, 0.16; 4-OC_5H_{11}, 0.15; 4-Me, 0.15; 4-Br, −0.15; 4-NO_2, 0.08; 4-OMe, −0.08; 4-OEt, −0.07; 4-OH, −0.02	X-C_6H_4OH	284
33a	*R. oryzae* growth inhibition $\log 1/C = 1.22(\pm0.36)\log P - 0.59(\pm0.42)\ \sigma^+ - 0.10(\pm1.25)$ $n = 11$, $s = 0.208$, $r^2 = 0.882(\pm0.854)$, (0.914), $F_{1,9} = 24.2$ ($\log P$),§ $F_{1,8} = 10.4$ (σ^+),§§ omit: 3-Me (−0.61); 4-NO_2 (1.21); 4-CN (1.46) 2-Br, −0.40; 3-I, 0.32; 3-Br, −0.20; 4-Cl, 0.17; 3-Cl, 0.07; 4-Br, −0.07; 4-OMe, 0.07; 3-NO_2, 0.04; 4-Me, −0.03; 4-I, 0.02; H, 0.01	X-$C_6H_4CH_2NCS$	284a
34	horseradish peroxidase chloroperoxidase oxidation to sulfoxide $\log k_{\mathrm{cat}} = -0.57(\pm0.18)\sigma^+ + 0.18(\pm0.14)\pi + 0.77(\pm0.42)B1{,}4 + 4.83(\pm0.63)$ $n = 9$, $s = 0.091$, $r^2 = 0.961$ (0.863), (0.891), $F_{1,7} = 11.8(\sigma^+)$,§§ $F_{1,6} = 14.4(B1{,}4)$,§ $F_{1,5} = 10.8(\pi)^{\S\S}$ (B1,4: sterimol parameter, B1, for para position) Me, −0.13; OMe, 0.10; CN, 0.07; OCOMe, −0.06; $OCHMe_2$, 0.06; NHCOMe, −0.03; NO_2, 0.03; Cl, −0.02; H, −0.01	4-X-C_6H_4SMe	285
35	rat embryo *in vitro* 20% incidence of tail defects (teratogenicity) $\log 1/C = -0.56(\pm0.23)\sigma^+ + 3.66(\pm0.15)$ $n = 9$, $s = 0.169$, $r^2 = 0.833$ (0.800), (0.964), $F_{1,7} = 35.0$,§ omit: H (−0.80), 4-NO_2 (0.62) 4-Cl, 0.27; 4-CN, −0.21; 4-Br, 0.18; 4-OH, 0.14; 4-Me, −0.12; 4-F, −0.09; 4-OC_5H_{11}, −0.09; 4-NH_2, −0.08; 4-I, 0.00	4-X-C_6H_4OH	283
36	mouse embryo fibroblast cells, BALB/3T3 I50 $\log 1/C = -0.22(\pm0.15)\log P - 0.55(\pm0.19)\sigma^+ + 4.07(\pm0.22)$ $n = 20$, $s = 0.211$, $r^2 = 0.849$ (0.745), (0.940), $F_{1,18} = 57.6$ (σ^+),§ $F_{1,17} = 9.72$ ($\log P$),§ omit: H (−1.14) 2-OH, 0.38; 3-NH_2, −0.31; 4-Cl, 0.30; 3-OMe, −0.28; 4-OMe, 0.27; 4-C_3H_7, −0.23; 4-Me, −0.23; 4-NH_2, −0.17; 4-Et, −0.16; 4-OH, 0.13; 3-OH, 0.12; 2-Me, −0.11; 2-OMe, −0.10; 2-NH_2, 0.10; 2-Cl, 0.10; 3-Me, −0.07; 3-NO_2, 0.07; 2-NO_2, 0.06; 3-Cl, −0.04	X-$C_6H_4NH_2$	286
37	rat liver microsomes inhibition of lipid peroxidation $\log 1/C = -0.46(\pm0.09)\sigma^+ - 6.73(\pm0.09)$ $n = 11$, $s = 0.109$, $r^2 = 0.931$ (0.901), (0.964), $F_{1,9} = 121$,§ omit: 4-C_6H_5 (0.28), 4-Cl (0.24) 4-F, −0.16; 4-OH, 0.15; 4-Me, 0.13; 4-NHC_6H_5, −0.11; 4-OMe, 0.10; 4-NH_2, −0.10; 4-CF_3, −0.08; 4-NO_2, 0.05; 4-NMe_2, 0.02; 4-Br, −0.01; H, 0.00	$(X\text{-}C_6H_4)_2Te$	65
38	mouse sarcoma 180 ascites tumor LD50 $\log 1/C = -0.35(\pm0.17)\sigma^+ + 2.87(\pm0.07)$ $n = 11$, $s = 0.078$, $r^2 = 0.718$ (0.688), (0.977), $F_{1,9} = 23.2$,§ omit: 4-C_6H_5 (−0.22), 4-NO_2 (0.40), 3-COOH, (−0.21) 3-CF_3, 0.11; 4-COC_6H_5, 0.10; 3-NHCOMe, −0.10; 4-F, 0.09; 4-CN, −0.08; 3-SMe, −0.06; 3-Cl, −0.05; H, −0.03; 3-Me, 0.02; 4-CH=CHCOH, 0.01; 4-C_3H_7, −0.01		287

Table 4 (Continued)

set	action, correlation	substrate	ref
39	cytochrome P 450 from rabbit liver microsomes oxidation by P 450 $\log V_{max} = -0.20(\pm0.09)\sigma^+ + 0.36(\pm0.04)$ $n = 4$, $s = 0.014$, $r^2 = 0.980$ (0.914), (0.821), $F_{1,2} = 4000^{\S}$ 4-Me, 0.01; 4-Cl, −0.01; 4-OMe, −0.01; H, 0.01	X-$C_6H_4S(O)Me$	288
40	mitochondria from bovine liver oxidation benzylamines $\log k = 0.63(\pm0.11)Es\text{-}4 + 0.50(\pm0.21)\log P + 0.45(\pm0.19)\sigma^+ + 0.78(\pm0.34)$ $n = 12$, $s = 0.125$, $r^2 = 0.965$ (0.940), (0.897), $F_{1,10} = 15.4$ ($E\sigma^-4$),§ $F_{1,9} = 12.7$ ($\log P$),§ $F_{1,8} = 30.0$ (σ^+),§ omit: 3-OMe-4-OH(0.92) 3-Cl, −0.16; H, 0.16; 3-Me, 0.13; 4-Me, −0.12; 3-NO_2, −0.11; 4-I, 0.08; 4-Cl, −0.08; 4-OMe, −0.07; 3-I, 0.06; 4-NO_2, 0.06; 3-OMe, 0.04; 3,4-$(OMe)_2$, 0.01	X-$C_6H_4CH_2NH_2$	
41	oxidase monoamine of bovine kidney cortex oxidation $\log V_{max} = 0.47(\pm0.20)\sigma^+ + 0.34(\pm0.07)$ $n = 6$, $s = 0.062$, $r^2 = 0.917$ (0.837), (0.853), $F_{1,4} = 44.8$,§ omit: 4-Me (−0.47) 4-F, 0.10; H, −0.06; 3-Cl, −0.04; 4-Cl, 0.03; 4-OMe, −0.02; 3-Me, −0.01	X-$C_6H_4CH_2NH_2$	290
42	microsome of rabbit liver hydroxylation para pH 8 37 °C $\log RBR = 1.68(\pm0.90)\sigma^+ + 1.90(\pm0.30)$ $n = 7$, $s = 0.289$, $r^2 = 0.822$ (0.575), (0.869), $F_{1,5} = 23.1$,§ omit: 2-NO_2 (−1.64), (RBR: relative biological response) 2-Me, 0.49; 2-OMe, −0.25; 2-F, 0.22; H, −0.18; 2-Br, −0.16; 2-Cl, −0.09; 2-I, −0.03	2-X-$C_6H_4NH_2$	291
43	amino acid oxidase from pig kidney oxidation $\log V_{max} = 1.21(\pm0.59)\sigma^+ - 0.80(\pm0.47)(\sigma^+)^2 + 0.44(\pm0.25)$ $n = 15$, $s = 0.370$, $r^2 = 0.943$, $F_{1,13} = 94.7$ (σ^+),§ $F_{1,12} = 13.5$ ($(\sigma^+)^2$)§ 4-Me, −0.59; 4-F, 0.49; 4-OH, −0.47; H, 0.45; 4-NMe_2, 0.40; 3-NO_2, −0.39; 3-OMe, −0.29; 4-NH_2, −0.29; 3-NH_2, 0.28; 3-Me, 0.19; 3-OH, 0.13; 3-F, 0.10; 4-OMe, −0.05; 4-Cl, 0.05; 3-Cl, −0.01	X-$C_6H_4CH(NH_2)COOH$	292

[a] Key: *, value in parentheses is the correlation coefficient within σ; **, correlation between σ and σ^+; &, substituents and their residuals; ‡, residuals of outliers; §, significant at 0.99 F test; and §§, significant at 0.95 F test.

and this set does not contain a 4-OR substituent despite these two shortcomings the ρ^+ agrees well with set **12**, despite the fact that set **12** contains the complex hydrophobic effect based on the bilinear model. There is no reason to expect the hydrophobic effects to be similar for the two systems. This would imply radical scavenging by the benzylic hydrogen of the phenylalanines.

The peroxidase from soil fungus of set **21** oxidizes aromatic amines to azo analogues. In addition to the electron-releasing resonance effect of substituents, ortho substituents promote activity by a field/inductive effect. A single ortho substituent does not produce a steric effect, but two ortho substituents do. This is accounted for by $B1$ of the larger of the two ortho substituents. This study was undertaken because a variety of pesticides are converted to toxic anilines in the soil and a better understanding of the health hazard was desired.

Sets **22**−**24** *may* operate by the common mechanism of benzylic •H abstraction. The ρ^+ are within the range seen in Table 1b. This would seem to be most likely for set **24**; however, for this set ρ^+ for log $1/K_m$ is similar but of opposite sign, so that for the overall QSAR ($\log k_{cat}/K_m$) there is no electronic term.[60] Data set **22** has been included simply because it has the hallmarks of a benzylic •H abstraction; negative ρ^+ and a negative steric effect of para substituents. For set **22**, R represents three types of substituents: NH_2, $NHCH_3$, and $N(CH_3)_2$. No parameterization of these was possible as they seem to effect activity to a small degree. Although $-\rho^+$ for this set might be associated with a kind of charge interaction with an electron-rich benzene ring, we have found no such examples for comparison. Therefore •H abstraction seems the most likely explanation.

The bacterial oxidation of anilines (set **26**) to catechols is dependent on σ^+ of the substituents. In this case it seems likely that radical attack on the aromatic ring is the initial reaction. The authors show that simple phenols behave in a parallel way. Although the number of data points is too small, the set has been included for suggestive purposes.

There are three examples where oxidation of X-$C_6H_4SCH_3$ has been reported (sets **27**, **31**, and **34**). Example **27** is a special case where the end point is the percent of R isomer formed. Nevertheless, $\rho^+(-0.92)$ for this definition of activity is similar to the other examples (−0.65 and −0.57), where $\log V_{max}$ and $\log k_{cat}$ are the parameters of the QSAR. Three different oxidases are involved, yet the QSAR are much the same. The biological reactions have higher absolute ρ^+ than the straight chemical oxidations of Table 1. This implies weaker oxidizing potency of the enzymes. Set **39** for the oxidation of the sulfoxides has a lower ρ^+ (−0.20), suggesting easier oxidation.

One might expect $Te(X\text{-}C_6H_4)_2$ of set **37** to behave like the sulfides in the way they yield an electron, and indeed they do with ρ^+ of −0.45. In this instance the tellurides are behaving as scavengers to inhibit lipid oxidation, possibly by reacting with ROO• of the oxidized lipid. The oxidation of unsaturated lipids occurs by a radical chain reaction in which •H is abstracted from an allylic CH_2. The authors report[65] that the $N(CH_3)_2$ derivative is among the most potent antioxidants in the microsomal system ever reported. Surprisingly, in another of their studies[65a] with the analogous selenium compounds, no QSAR could be formulated from the data.

Monoamine oxidase catalyzes the oxidation of a variety of amine neurotransmitters, such as serotonin and dopamine, as well as other amines. It belongs to flavoenzymes and the evidence indicates radical mechanisms are involved.[63] The enzyme normally catalyzes the oxidation of an amine to an imine. In the QSAR of set **28** the significant ρ^+ term suggests that these inhibitors may be inhibiting the enzyme by the donation of a benzylic $^{\bullet}$H. If reaction were occurring at some other point in the side chain, the resonance parameter would be much less likely, but not out of the question.[1]

Hsuanyu and Dunford[64] have shown that phenols have two types of action on prostaglandin H synthase. At low concentrations phenols stimulate activity (set **29**), but at higher concentrations they inhibit it (set **20**). In each instance the activity is dependent on σ^+ of the substituents and the hydrophobicity of para substituents. The phenols inhibit by interfering with binding of arachidonic acid and by competing with arachidonic acid as reducing agents.[64] Phenols stimulate the cyclooxygenase activity being reducing agents for compound II and protect the enzyme by removing radicals of prostaglandin G_2.

Sets **32**, **33**, and **35** call attention to a toxicity of phenols which is rather unique in that hydrophobicity of the phenol appears to plays little or no role. Toxicity depends heavily on σ^+ of the substituent. This stands in marked contrast to many kinds of phenolic toxicity where hydrophobicity is of overriding importance.[66] Set **33** does contain hydrophobic terms, but σ^+ is the most important parameter. For none of these three QSARs is the correlation high; however, taken together they point to a special type of phenol toxicity that has been missed in the past because of the poor choice of substituents. As we have emphasized in the first part of this review, care must be taken in the selection of substituents to include those with wide variation in σ^+ or important features of the SAR will be overlooked. Set **30** for the toxic action of phenols on *P. aeruginosa* and set **33a** for the toxic action of benzylisothiocynate have ρ^+ values comparable to that for the action of phenols on rat embryos.

The QSAR of set **33** is of particular interest because it is on whole animals. Although the correlation is not as high as one would like, the fact that ρ^+ is so close to the values in sets **30**, **32**, and **35** supports its significance. The end point, the concentration of phenol required to decrease the maternal weight gain of pregnant rats by 10 g in 24 h, is not easy to quantify: Loss in weight could occur from the rat itself as well as from fetal weight loss.

All of the QSARs on the rat embryos and the pregnant rats are poor correlations which is not surprising given the difficult end points. The somite number is a measure of spinal deformation which is difficult to standardize as is the incidence of tail defects (set **35**). The weight loss of pregnant rats is also a fuzzy end point, despite these problems which no doubt contribute to the low correlations the agreement among the tests with respect to the electronic effect of the substituents is surprisingly good.

The radical toxicity of the phenols is characterized by the low absolute value of ρ^+. This is somewhat smaller than the smallest value in Table 1a. It would indicate that a very active radical is involved in the activation of the phenols. The most likely candidate is the $^{\bullet}$OH which is constantly being formed in aerobic organisms via oxygen metabolism. As mentioned in the introduction, Ames[25] has shown that the large amount of damage done to DNA in animals cells is due to $^{\bullet}$OH.

In this connection it is noteworthy that radicals have been shown to cause hemolysis of erythrocytes and that this action can be suppressed by ascorbic acid.[67b]

The unexpected phenol toxicity brought out by the correlation with σ^+ motivated us to make a more extensive study of this type of toxicity. If activation of phenol to radicals is the basis of this type of toxicity then the more rapidly growing cells system utilizing more oxygen should be best for study. We therefore selected L1210 leukemia cells. Equations 10 and 10a for the 50% inhibition of cell growth were developed.[72]

C is the molar concentration causing growth inhibition of L1210 leukemia cells by 3- and 4-substituted phenols. Distinctly different correlations are found for phenols that contain electron-releasing substituents ($-\sigma^+$) and electron-attracting substitents($+\sigma^+$).[72]

inhibition by phenols containing electron-releasing substituents

$$\log 1/C = -1.58(\pm 0.26)\sigma^+ + 0.21(\pm 0.06) \log P + 3.10(\pm 0.24) \tag{10}$$

$$n = 23, \quad r^2 = 0.898, \quad s = 0.191, \quad \text{omitted: 3-NH}_2\text{, 4-NHCOMe}$$

inhibition by phenols containing electron-attracting substituents

$$\log 1/C = 0.62(\pm 0.16) \log P + 2.35(\pm 0.31) \tag{10a}$$

$$n = 15, \quad r^2 = 0.845, \quad s = 0.232, \quad \text{omitted: 3-OH}$$

In eq 10 ρ^+ is significantly larger than for the rat studies. The hydrophobic term is small. Electron-attracting substituents appear to inhibit the reaction and no electron term is found for eq 10a.

If indeed the phenols are toxic by virtue of their conversion to radicals as the evidence suggests, then the phenoxyl radicals would react with some sensitive site in the cell. That is, the overall ρ^+ we find may be a composite of ρ^+ for radical formation and ρ^+ for the substituent effect on the reaction of the radical with the sensitive site within the cell.

A similar result has been found for the inhibition of the incorporation of [^{3}H]TdR into DNA by Chinese hamster cells:[72]

$$\log 1/C = -0.82(\pm 0.46)\sigma^+ + 3.22(\pm 0.22) \tag{11}$$

$$n = 9, \quad r^2 = 0.721, \quad s = 0.464, \quad F_{1,3} = 18.1^{\S}$$

Although eq 11 is not a sharp correlation the dependence on σ^+ agrees with the other examples.

One of the fascinating lessons which can be learned from studying the toxicity of phenols using Hammett constants and QSAR is that phenols behave in different ways depending on what substituents they carry and on the test system. The above examples show how σ^+ can be used to uncover one type of toxicity. Equation 12 for the uncoupling of oxidative phosphorylation in mitochondria[72a] illustrates a totally different type of toxicity.

$$\log 1/C = 2.18(\pm 0.22)\sigma^- + 1.01(\pm 0.24)\log P + 0.27(\pm 0.57) \tag{12}$$

$$n = 22, \quad r^2 = 0.966, \quad s = 0.445, \quad F_{1,20} = 94.4,^{\S}\ F_{1,19} = 78.5,^{\S}$$

$$\text{omitted: 2,6-di-I, 4-NO}_2\text{, 4-COMe}$$

ρ^- in eq 12 is very close to that found for the ionization of phenols in aqueous solution (eq 13)[72b]

$$\mathrm{p}K_a = -2.00(\pm 0.14)\sigma^- + 9.84(\pm 0.07) \tag{13}$$

$$n = 20, \quad r^2 = 0.982, \quad s = 0.114, \quad F_{1,18} = 955^{\S}$$

In eq 13 ρ^- is negative, for ionization it would be positive. Thus it appears that it is the ionized form of phenols that is effective in uncoupling oxidative phosphorylation. Recently Gange et al. took advantage of this idea to design novel insecticides.[73]

A third class of phenol toxicity yields QSAR having terms only in log *P*.[66]

The variety of possibilities for human contact with chemicals containing a phenolic group makes it important to have good understanding of their mechanisms for toxicity. Recently 4-methoxyphenol and 4-methylcatechol[67c] have been shown to be carcinogenic in rats, and butylated hydroxyanisole and sesamol are carcinogens for hamster forestomach epithelium. The catechol derivative dopamine has been shown to break DNA strands in human fibroblast cells.[68] Giri[69] has analyzed the evidence for the genetic toxicity of aspirin and acetaminophen. While neither appear to be mutagenic, there is evidence for their clastogenicity. Of course human exposure to phenolic compounds is common from various industrial products, drugs, and components of foods.

A class of phenols that shows ambivalent good and bad sides is that of the flavonoids. Many of them occur in foods and also show mutagenic activity.[74] While eq 10 brings out the toxic side of ordinary phenols, there is increasing evidence that polyphenols in the diet have beneficial properties in the prevention of heart disease[74a] and the prevention of cancer.[74b] Since there is little evidence for the toxicity of such compounds in normal individuals, one assumes that the various radical scavenging systems in the body provide protection. Nevertheless, those lacking a good diet containing antioxidants may be open to serious toxic effects.

A potentially serious toxic action of phenols may be that for smokers. Two of the major components in cigarette tar, hydroquinone and catechol, have led to the suggestion that radicals derived from these substances are important in promoting lung disease.[69a]

The phenoxyl radical has been shown to cause the oxidation of protein thiols with subsequent damage to DNA.[69b] *p*-Nonylphenol and bis-phenol A have been classified as estrogenic xenobiotics, but whether or not radical activity is involved is not known.[69c]

Of course it is possible that what seems to be the toxic action of a phenoxy radical attacking proteins or nucleic acid may be more complex. That is, while the rate-limiting step might be an initial hydrogen abstraction, further oxidation could produce quinones which have their own toxic effects. For example, acetaminophen is oxidized in biological systems to an iminoquinone which reacts with biologically important SH moieties and nucleic acids.[70]

The QSAR of set **36** of the toxicity of anilines to mouse fibroblast cells is also unusual because of its negative ρ^+, although such a term might not be unexpected from knowledge of the examples in Table 4 for enzymic processes. However, examples of aromatic amines with ρ^+ do not seem to have appeared in toxicology studies with the exception of set **36**. As in the case of the phenols, this is probably due to poor selection of substituents. There are many examples of the toxicity of aromatic amines which depend largely on hydrophobicity factors. An important aspect of set **36** is that a good selection of substituents in the ortho position was included in the study. It is of special interest that it was not possible to find a steric effect for these groups. This indicates that ortho substituents do not interfere with the toxic action of the NH_2 moiety. The small ρ^+ and the lack of a steric effect point to the involvement of a small highly active radical, possibly $^\bullet$OH. Because of its hydrophilicity, $^\bullet$OH is constrained in aqueous compartments, but the more stable and less hydrophilic phenol and aniline radicals would be freer to move about in cells to cause toxic reactions. The $^\bullet$OH is so reactive that it may abstract $^\bullet$H from almost any cellular component with which it comes into contact.[71] These radicals then in turn abstract $^\bullet$H from less active donors. This chain of reactions can ultimately be stopped by ascorbic acid which after the loss of the first $^\bullet$H then can lose a second by radical abstraction or disproportination to yield a stable species. Sharma and Buettner[71a] have shown by ESR studies how ascorbic acid serves to regenerate vitamin E by donating a $^\bullet$H after vitamin E has itself been converted to a radical in its scavenging process.

Another point of interest for set **36** is its small negative log *P* term. This would suggest activation in an aqueous compartment. In contrast, set **30** has a positive hydrophobic term. The study of better-designed sets would likely yield parabolic or bilinear equations defining optimum log *P* values.

Sets **40** and **41** show QSAR for the oxidation of benzylamines by two quite different types of enzymes. Since monoamine oxidase appears to follow a radical mechanism of action,[63] one would expect the QSAR of set **41** to be similar to that of set **28**. In fact, it is not. In set **28** ρ^+ is negative, and in set **41** it is positive. While the hydrophobic effects of sets **28** and **40** are similar, the steric effects of 4-substituents and the ρ^+'s are different. The active sites must be different. Since the ρ values for set **40** and **41** are small it may be that the electronic effect of substituents is actually operating on the NH_2 moiety. Another possible explanation is that sets **40** and **41** may be following the mechanism for eq 2.

The last set in Table 4 is parabolic in character, indicating a change in mechanism coupled to changing values of σ^+. In the case of set **43**, V_{max} increases until σ^+ reaches 0.76, when the rate starts to decline with increase in σ^+. With values of σ^+ less than 0.76, the mechanism seems to be similar to that in sets **40** and **41**. In set **40** the largest σ^+ is 0.78, in set **41** it is 0.40 and in set **43** it is 0.71. It would be interesting to repeat the studies of sets **40** and **41** with substituents having a wider range of σ^+ values.

A point of special interest for the sets in Table 4 is that often QSARs are obtained which contain only terms in σ^+. Enzymic QSAR which do not contain steric or hydrophobic terms imply that outside of the particular point of action on the substrate, the rest of the substrate molecule does not make significant contact with the enzyme (note sets **3**, **8**, **10**, **11**, **17**, **18**, **23**, **27**, **31**, **32**, **35**, **37**−**39**, **41**, **42**, and **43**). Of course this could be due to the limited variety of substituents and the sites of substitution, but this observation needs to be followed up with more extensive testing to broaden our understanding of the reaction mechanisms.

2. Correlation with σ (Table 5)

Turning now to Table 5, we consider examples of biological reactions that are likely to be radical in character correlated by σ. As in the other tables, in addition to the usual r^2 we have given r^2 for the alternative correlation with σ^+, and r^2 for the correlation between σ^+ and σ.

For the 11 examples in Table 5, the collinearity between σ and σ^+ is high. In only two of the examples is r^2 less than 0.9. A number of the sets (set **4**, **7**, **10**, and **11**) have too few data points to support a serious QSAR. Nevertheless, we have included them since they may provide hints to others considering working with these systems.

In accord with Table 4, the metalloporphyrins of sets **1**−**3** have large absolute ρ values. Examples **5** and **7** do not. In examples **9** and **11**, correlation is with k_{cat}. In the overall reaction (k_{cat}/K_m) the QSAR do not contain significant electronic terms.[60] The mechanism for set **9** has been discussed in section III.1.

In the example of set **1**, collinearity between σ and σ^+ is somewhat lower than usual. Still, in contrast to σ^+, σ gives a much better correlation. The values of ρ with the σ correlations are much higher due to the fact that para σ values are considerably smaller than σ^+.

For set **2** ρ is large and negative, similar to set **1**, but in both instances confidence limits on ρ are wide. The fact that the correlations are so high in terms of r^2 is the result of very wide range in activity.

In set **3** oxidation of S to S−O occurs and the value of ρ for substituents para to S is high. Hence it is surprising that σ gives a considerably better correlation than σ^+. The large ρ implies that this type of S is more difficult to oxidize by HRP than the sulfides of sets **27**, **31**, and **34** in Table 4. That is, substituent assistance is highly important. Note that set **34** contains only three data points/variable.

Set **4** does not contain enough data points for a two-variable equation. Still, the coefficients with σ and π are sensible, and for this reason it has been included. Also, it is the only QSAR we have on an oxidase from neutrophils.

The oxidation of acetylenes (set **5**) by P450 is of special importance since we have so often found that QSAR for P450 oxidations lack electronic terms. The negative ρ makes sense. Nevertheless, one must wonder what the QSAR for log V_{max}/K_m would show.[60]

Sets **6**, **7**, **10**, and **11** are correlations of P450 or microsomal oxidations in which k_{cat} or V_{max} are the dependent variables. For these reactions it was found that log $1/K_m$ is correlated with σ^+ with a positive sign for ρ, so that in the overall reaction (k_{cat}/K_m) no electronic term is seen. Hydrophobicity is the dominant term.[60]

3. Correlation with $\sigma-$ (Table 6)

Again as in Table 5, we find few examples of QSAR containing hydrophobic terms. About 50% of the examples in Table 6 contain such terms. Out of 900 QSARs for all types of enzymic reactions we find that 65% contain a hydrophobic term. In cell, organelle, and whole organism QSAR, 80−90% contain hydrophobic terms.

Table 3 contains rather few examples where we are sure radical reactions are occurring and are best correlated with by σ^-. We are more uncertain about the examples in Table 6.

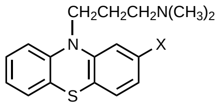
In the case of set **1** the enzyme was isolated from a soil fungus to study anilines which are sometimes hydrolysis products of herbicides. A wide variety of anilines yields a good QSAR despite the fact that a specific product was not used as an end point. A spectrophotometric analysis was made and a range of absorption regions were integrated. The hydrophobic and electronic terms are similar to those in set **1** and **2** of Table 4. In these two sets no ortho substituents were present; hence, they contain no steric parameter as seen with the soil enzyme. Because of the similarity to HRP of Table 4, we suspect that the aniline oxidase is a metalloporphyrin-based enzyme.

Set **2** also has a large $-\rho^-$, suggesting a metalloporphyrin enzyme.

The authors of set **3** correlated their data with σ^+; however, we find a better correlation with σ^- ($r^2 =$ 1.0 vs 0.972). The mechanism of this flavin-dependent monoxygenase is complex, and it may not involve a rate-limiting one-electron transfer. The magnitude of ρ is close to that of set **4**. This supports eq 3 which is based on only four data points.

The mechanism of oxidation of the thioanisoles of set **5** appears to be different from the examples of

Table 5. Biological QSARs Correlated by σ[a]

set	action, correlation	substrate	ref
1	horseradish peroxidase compound II oxidation $\log k = -5.91(\pm 1.26)\sigma + 0.66(\pm 0.60)E_s,2 + 5.03(\pm 0.32)$ $n = 10$, $s = 0.359$, $r^2 = 0.947$ (0.840),* (0.854),** $F_{1,8} = 69.0(\sigma)$,§ $F_{1,7} = 6.71$ (E_s,2),§§ omit: 2-SH (2.70‡) &4-Cl, −0.60; 3-OMe, 0.48; 3-Cl, 0.34; 4-Me, −0.25; 2-OMe, 0.20; 4-OMe, 0.20; 3-Me, −0.19; H, −0.09; 2-Me, −0.07; 2-Cl, −0.02	X-C_6H_4OH	266
2	cytochrome *c* from horse heart oxidation of catechols $\log k = -5.83(\pm 0.97)\sigma + 2.80(\pm 0.38)$ $n = 9$, $s = 0.479$, $r^2 = 0.966$ (0.930), (0.925), $F_{1,7} = 200$,§ omit: 4-CH = $CHCOO^-$ (2.05) and 4-COO^- (−1.56) 4-CHO, −0.72; H, 0.72; 3,5-$(CMe_3)_2$, −0.47; 4-Me, 0.41; 4-$CH_2CH_2COO^-$, 0.25; 4-NO_2, 0.23; 4-CH_2COO^-, −0.21; 4-CMe_3, −0.12; 4-NH_2, −0.10	catechols	293
3	oxidation oxidation $\log k = -2.78(\pm 0.48)\sigma + 5.47(\pm 0.20)$ $n = 10$, $s = 0.201$, $r^2 = 0.957$ (0.868), (0.946), $F_{1,8} = 179$§ 2-CN, −0.30; 2-CF_3, −0.29; 2-COEt, 0.23; 2-COOMe, 0.19; 2-OMe, −0.15; 2-CHO, 0.13; 2-COMe, 0.12; H, 0.05; 2-Me, 0.00; 2-Cl, 0.00		294
4	human neutrophill myeloperoxidase inhibition of loss of H_2O_2 25 °C $\log 1/C = -1.33(\pm 0.23)\sigma + 0.51(\pm 0.04)\pi + 1.22(\pm 0.11)$ $n = 4$, $s = 0.009$, $r^2 = 1.000$ (0.998), (0.986), $F_{1,2} = 11.9(\pi)$, $F_{1,1} > 1000(\sigma)$,§ $F_{2,1} > 1000$,§ omit: 4-SO_3^- (0.74) 4-COOEt, 0.01; 4-Br, −0.01; 4-NO_2, 0.00; 3-COO^-, 0.00	X-$C_6H_4NH_2$	295
5	cytochrome P450 from rat liver oxidation by enzyme to phenylacetic acids $\log V_{\max} = -1.12(\pm 0.56)\sigma + 0.77(\pm 0.21)$ $n = 5$, $s = 0.140$, $r^2 = 0.930$ (0.912), (0.984), $F_{1,3} = 40.2$§ 2-Me, 0.18; 4-Cl, −0.12; 4-Me, −0.09; 4-NO_2, 0.06; H, −0.03	X-$C_6H_4C{\equiv}CH$	296
6	microsomes from rabbit liver N-hydroxylation $\log V_{\max} = -0.88(\pm 0.22)\sigma - 0.21(\pm 0.07)$ $n = 6$, $s = 0.060$, $r^2 = 0.969$ (0.856), (0.914), $F_{1,4} = 126$§ Me, 0.07; H, −0.06; OMe, −0.05; Br, 0.04; Cl, 0.03; CN, −0.03	4-X-$C_6H_4C(=NH)NH_2$	297
7	cytochrome P450 2B4 hydroxylation $\log k_{\text{cat}} = -0.77(\pm 0.54)\sigma + 0.53(\pm 0.32)\ C\log P - 0.67(\pm 1.04)$ $n = 7$, $s = 0.134$, $r^2 = 0.930$ (0.886), 0.977), $F_{1,5} = 9.73(\sigma)$,§§ $F_{1,4} = 15.6(C\log P)$,§§ omit: 4-CN(0.39) H, 0.15; 4-F, −0.14; 4-Cl, −0.14; I, 0.08; 4-Br, 0.05; 4-NO_2, 0.02; 4-Me, −0.01	4-X-C_6H_4Me	298
8	mouse with sarcoma 180 increase in life span $T/C = 130$ $\log 1C = -0.68(\pm 0.19)\sigma + 3.41(\pm 0.08)$ $n = 13$, $s = 0.094$, $r^2 = 0.844$ (0.786), (0.960), $F_{1,11} = 59.3$q§ 3-NHCOMe, 0.19; 3-COOH, −0.15; 4-F, −0.13; 3-Me, −0.11; 3-CF_3, 0.07; 4-C_3H_7, 0.07; 4-CN, −0.05; 4-COC_6H_5, 0.05; 3-SMe, 0.03; 4-C_6H_5, 0.02; H, 0.01; 3-Cl, 0.01; 4-CH=CHCOOH, 0.00	X-$C_6H_4N{=}N{-}NMe_2$	287
9	P450 2B4 from rabbit liver oxidation $\log k_{\text{cat}} = -0.61(\pm 0.20)\sigma + 0.42(\pm 0.08)$ $n = 7$, $s = 0.073$, $r^2 = 0.929$ (0.854), (0.961), $F_{1,5} = 64.1$,§ omit: H (0.36), 4-COO^- (−0.93) 4-Me, 0.12; 4-Br, −0.08; 4-NO2, 0.06; 4-OMe, −0.05; 4-CN, −0.03; 4-F, −0.03; 4-Cl, 0.01	X-$C_6H_4CH(Me)OH$	299
10	D-amino acid oxidase from porcine kidney oxidation pH 8.5 38 deg in air $\log k = -0.46(\pm 0.24)\sigma + 0.30(\pm 0.14)\ C\log P + 1.70(\pm 0.27)$ $n = 7$, $s = 0.071$, $r^2 = 0.914$ (0.741), (0.821), $F_{1,5} = 2.39$, $F_{1,4} = 28.2$ (s),§ $F_{2,4} = 43.6$,§ omit: 4-NMe_2 (−1.05) 4-OH, −0.10; 3-NH_2, 0.07; 4-F, 0.05; 4-NO_2, −0.03; 3-F, −0.03; H, 0.02; 4-Cl, 0.01	phenylalanines	300
11	P450-2E1 of rabbit liver oxidation $\log k_{\text{cat}} = -0.35(\pm 0.09)\sigma - 0.13(\pm 0.06)\ C\log P + 0.67(\pm 0.08)$ $n = 7$, $s = 0.024$, $r^2 = 0.970$ (0.861), (0.913), $F_{1,5} = 10.3$ (σ),§§ $F_{1,4} = 46.0$ ($C\log P$),§ omit: 4-NO_2 (0.18) H, 0.03; 4-F, −0.03; 4-Cl, 0.02; 4-Br, −0.02; 4-OMe, −0.01; 4-Me, 0.01; 4-CN, 0.00	X-$C_6H_4CH_2OH$	299

[a] Key: *, value in parentheses is the correlation coefficient with σ^+; **, correlation between σ and σ^+; &, substituents and their residuals; ‡, residuals of outliers; §, significant at 0.99 *F* test; and §§, significant at 0.95 *F* test.

Table 6. Biological QSARs Correlated by σ^- [a]

set	action, correlation	substrate	ref
1	aniline oxidase from *Geotrichum candidum* biotransformation (oxidation) $\log A = -2.29(\pm0.39)\sigma - 1.16(\pm0.41)B1{,}2 + 0.31(\pm0.22)C\log P + 3.90(\pm0.44)$ $n = 19$, $s = 0.190$, $r^2 = 0.934$ (0.778), (0.866), $F_{1,17} = 71.8\ (\sigma^-)$,§ $F_{1,16} = 14.9\ (B1{,}2)$,§ $F_{1,15} = 7.75\ (C\log P)$,§§ omit: 3-Me (−0.81‡); 4-F (−1.28) &2-Me,4-Cl, 0.32; 4-OMe, 0.30; 4-Me, −0.25; 2-Cl,4-Me, −0.24; 3,4-Cl_2, −0.21; 4-Cl, −0.18; 4-I, 0.18; 2,4,5-Me_3, 0.17; 2-Me,3-Cl, −0.17; 2,4-Cl_2, 0.16; 3,4,5-$(OMe)_3$, −0.15; 2,4,6-Me_3, −0.08; 4-Br, 0.08; 3-Cl,4-Me, 0.06; 2-Me,5-Cl, −0.04; H, 0.03; 2-Me, 0.02; 2-OMe, −0.01; 3-OMe, 0.00	$X\text{-}C_6H_4NH_2$	274
2	tyrosinase from mushrooms oxidation $\log k_{cat}/K_m = -2.13(\pm1.36)\sigma^- + 1.96(\pm1.17)$ $n = 5$, $s = 0.414$, $r^2 = 0.893$ (0.825), (0.994), $F_{1,3} = 24.9$§§ 4-NO_2, −0.51; 4-CHO, 0.37; H, −0.23; 4-COMe, 0.20; 4-SCN, 0.17	catechols	301
3	phenol hydroxylase hydroxylation pH 7.6 $\log k = -0.82(\pm0.05)\sigma^- - 0.00(\pm0.02)$ $n = 4$, $s = 0.006$, $r^2 = 1.000$ (0.972), (0.968), $F_{1,2} > 1000$§ 3-Me, −0.01; 3-Cl, 0.00; 3-NH_2, 0.00; 3-OH, 0.00	$X\text{-}C_6H_4OH$	302
4	phenol hydroxylase form *Trichosporon cutaneum* hydroxylation with NADPH $\log k_{cat} = -0.73(\pm0.16)\sigma^- - 0.44(\pm0.14)I + 2.73(\pm0.13)$ $n = 20$, $s = 0.140$, $r^2 = 0.879$ (0.832), (0.927), $F_{1,18} = 130(\sigma^-)$,§ $F_{1,17} = 17.2\ (I)$§ ($I = 1$ for ortho substituents) F_5, −0.25; 2,6-F_2, 0.24; 3,5-F_2, 0.21; 3-Cl,4-F, −0.20; F_4, −0.14; 2-F, −0.13; 2,5-F_2, 0.12; 2,3-F_2, −0.11; 2,3,6-F_3, 0.10; 2,3,4-F_3, 0.10; 2-F,4-NO_2, 0.09; 3,4-F_2, 0.09; 4-Cl,3-F, 0.09; 3-F,4-NO_2, −0.08; 4-F, −0.08; 3,4,5-F_3, 0.07; H, −0.06; 2,4-F_2, −0.05; 3-F, −0.03; 2,3,5-F_3, 0.03	$X\text{-}C_6H_4OH$	303
5	microsomes from rabbit liver oxidation to $X\text{-}C_6H_4S(O)Me$ $\log V_{max} = -0.31(\pm0.08)\sigma^- + 0.09(\pm0.05)$ $n = 4$, $s = 0.024$, $r^2 = 0.992$ (0.808), (0.873), $F_{1,2} = 286$,§ omit: 4-Cl (0.22) H, 0.02; 4-OMe, −0.02; 4-NO_2, 0.00; 4-Me, 0.00	$X\text{-}C_6H_4SMe$	304
6	bovine liver mitochondrial monoamine oxidase B oxidation in air saturation condition 25 °C $\log k_{cat}/K_m = -0.32(\pm0.17)\sigma^- - 0.41(\pm0.22)M_r3{,}4 + 0.61(\pm0.16)$ $n = 9$, $s = 0.041$, $r^2 = 0.866$ (0.833), (0.913), $F_{1,7} = 4.87(\sigma^-)$, $F_{1,6} = 20.3(M_r3{,}4)$,§ $F_{2,6} = 38.6$,§ omit: H (−0.17), 3-Me (−0.28) 4-Br, 0.08; 3-Cl, −0.08; 4-Cl, 0.07; 3-OMe, −0.06; 4-OMe, −0.03; 4-Me, 0.02; 4-F, 0.01; 3-CF_3, −0.01; 4-CF_3, 0.00	$X\text{-}C_6H_4CH_2NH_2$	305
7	xanthine oxidase from bovine milk oxidation in dodecyltrimethylammonium bromide system $\log k_{cat}/K_m = 0.93(\pm0.67)\sigma^- - 0.33(\pm0.40)$ $n = 5$, $s = 0.264$, $r^2 = 0.869$ (0.819), (0.683), $F_{1,3} = 19.9$§ 4-OMe, 0.36; 4-NMe_2, −0.25; 4-Me, −0.13; 4-NO_2, 0.03; 4-Cl, −0.01	$X\text{-}C_6H_4CHO$	306
8	milk xanthine-xanthine oxidase reduction to $X\text{-}C_6H_4NHOH$ under anaerobic condition $\log k! = 0.99(\pm0.16)\sigma^- - 0.57(\pm0.40)B1{,}2 + 2.35(\pm0.44)$ $n = 26$, $s = 0.205$, $r^2 = 0.879$ (0.754), (0.861), $F_{1,24} = 120.9\ (\sigma^-)$,§ $F_{1,23} = 8.59\ (B1{,}2)$§ ($B1{,}2$: sterimol parameter, $B1$, for ortho position), omit: 4-SO_3^- (−0.77), 4-SO_2NH_2 (−0.46), 2-CHO (−0.53) 4-SH, −0.46; 4-$CONH_2$, 0.33; 3-Cl, −0.30; 4-COC_6H_5, 0.26; 4-Cl, 0.24; 4-NO_2, −0.23; 4-COMe, 0.21; 4-Br, 0.21; 4-COOMe, 0.21; 4-NH_2, 0.20; 3-NO_2, −0.18; 4-COO^-, −0.18; 3-NH_2, 0.18; 4-Me, −0.15; 2-Cl, 0.13; 2-NH_2, −0.11; 4-OMe, −0.11; 4-CH_2Cl, −0.10; H, −0.10; 2-NO_2, −0.10; 4-CN, −0.09; 4-OH, 0.05; 4-CHO, 0.04; 3-CHO, 0.03; 4-CH_2OH, 0.03; 4-C_6H_5, −0.02	$X\text{-}C_6H_4NO_2$	307
9	NAD(P)-linked methyl *p*-nitrobenzoate reductase from *E. coli* B/R reduction to $X\text{-}C_6H_4NHOH$ $\log k = 1.10(\pm0.26)\sigma^- + 1.50(\pm0.19)$ $n = 12$, $s = 0.214$, $r^2 = 0.901$ (0.846), (0.917), $F_{1,10} = 90.8$§ ($B5{,}4$: sterimol parameter, $B5$, for para position), omit: 4-OH(0.46) 4-COOMe, 0.42; 4-COO^-, −0.34; 4-CHO, −0.21; 4-COC_6H_5, 0.20; 4-NO_2, −0.16; 4-NH_2, 0.15; 4-COMe, 0.13; 4-OMe, −0.10; 4-Cl, −0.10; 4-SO_2NH_2, 0.02; 4-SO_3^-, −0.01; 4-Br, 0.01	$X\text{-}C_6H_4NO_2$	308
10	xanthine oxidase reduction to 2-NHOH-imidazoles $\log k = 0.15(\pm0.12)\log P + 1.87(\pm0.26)\sigma^- + 0.96(\pm0.14)$ $n = 13$, s = 0.165, r2 = 0.963 (0.916), (0.929), $F_{1,11} = 161(\sigma^-)$,§ $F_{1,10} = 7.47(C\log P)$,§§ omit: 1-CH_2COOMe(0.37) 1-$CH_2CH_2OC_6H_5$, 0.28; 1-$CH_2CH(OH)CH_2OCH(CH_2Cl)CH_2OCHMe_2$, −0.26; 1-Me,5-$CONH_2$, 0.21; 1-$CH_2CH(OH)CH_2NC_5H_{10}$, −0.20; 1-$CH_2CONHCH_2C_6H_5$, 0.16; 1-Me,5-CHO, −0.12; 1-CH_2CH_2OH, −0.07; 1-Me,5-COOMd, −0.05; 1-$CH_2CH(OH)CH_2OH$, 0.03; 1-Me, 5-CN, 0.02; 1-$CH_2CH_2CH_2OC_6H_5$, −0.02; 1-$CH_2CH(OH)CH_2NMe_2$, 0.02; 1-$CH_2CH(OH)CH_2OMe$, 0.00	X-2-NO_2-imidazoles	309

[a] Key: *, value in parentheses is the correlation coefficient with σ^+; **, correlation between σ and σ^+; &, substituents and their residuals; ‡, residuals of outliers; §, significant at 0.99 *F* test; and §§, significant at 0.95 *F* test.

Table 4 (set **18**, **27**, **31**, and **34**) in that ρ is less negative. Again we worry about the collinearity problem and the small number of data points.

Xanthine oxidase is a metalloflavoprotein which appears to cause damage in postischemic tissue by free-radical generation.[66a] Substrate oxidation occurs at the metal center which catalyzes oxidation in which the oxygen linked to the substrate is derived from water rather than molecular oxygen. The values of ρ are essentially identical for set **7** and **8**, although set **7** was studied in dodecyl trimethylammonium micelles. For these reductions, ρ is positive. The reductase of set **9** has a similar ρ and a marginal $B5$ for para substituents, indicating a very small positive steric effect.

Set **10** shows a very marginal hydrophobic effect.

IV. Reactions Correlated by $\sigma^\bullet$ or E_R (Table 7)

In Table 7 we have listed examples where the data are best correlated by either $\sigma^\bullet$ or E_R. We cannot really generalize well about these two special radical parameters since there is a limited number of substituents for which they have been determined (however see section V).

V. Reactions Best Correlated by Dual Parameter Equations (Table 8)

There have been a number of efforts over the years to formulate parameters to correlate radical reactions.[31,33,38,41,41a,41b] More recently the trend has been to combine a radical-based parameter ($\sigma^\bullet$) with a σ constant to achieve a better correlation of the data. Problems which have hampered these efforts are the lack of such parameters for a wide variety of substituents and data sets based on 10 or more data points. The lack of attention of those doing the experimental work to the collinearity problem has also made mechanistic conclusions difficult. In order to gain perspective we have compared three sets of $\sigma^\bullet$ parameters (Table 10) to see what improvement could be obtained using dual parameter equations (Table 9). In none of the equations correlated by σ *alone* (Table 2) did adding a $\sigma^\bullet$ significantly improve the correlation. In only two of the σ^- equations (Table 3) was the added $\sigma^\bullet$ term helpful. It would seem that when correlation is with σ alone resonance interaction between the substituent and the radical containing center is not particularly strong; hence, there is no role for $\sigma^\bullet$. Exactly why this occurs is not clear. There seems to be no pattern of circumstances such as reaction type, solvent, or reaction conditions which favor $\sigma^\bullet$. The sign of the $\sigma^\bullet$ term also seems to vary randomly and the confidence limits on $\rho^\bullet$ are often wide compared to the size of ρ. Nevertheless, out of 18 possible examples in Table 8, 13 yield significantly better, although often not important, improvements in correlation. The last two examples in Table 8 involve σ^-. As with σ^+ there is a significant, but small, improvement using the additional term.

For the equations in Table 8, we used Creary's $\sigma^\bullet$ values, since these are available for a large number of substituents.

In Table 9 we have compared $\sigma^\bullet$ from Arnold, Jiang, and Creary (see Table 10). In these examples set size was sometimes limited because of the lack $\sigma^\bullet$ for one or more substituents for one of the three types of substituent constants. It is hard to say from the results that any one of the three parameters is a great improvement over the others.

VI. Atmospheric Radical Reactions

For many industrial chemicals present in the troposphere important elimination pathways are reaction with HO[321] radicals during the day and NO_3[322] radicals at night. Hence there have been numerous studies of the reactions of organic compounds in the vapor phase with these substances. Recently Sabljic and Güsten have been formulating QSAR to rationalize the relative reactivity of miscellaneous organic compounds with these radicals.[323−325] They have found good correlations with vertical ionization energies (in electronvolts).[323] The following equation for the oxidation by NO_3 radical of miscellaneous compounds illustrates how reactivity can be correlated with vertical ionization energies.

$$\log k = 2.16(\pm 0.09)E_{i,v} - 7.02(\pm 0.87)$$

$$n = 62, \quad r = 0.948, \quad s = 0.468, \quad F_{1,60} = 537^{\S}$$

These results cannot easily be compared with our approach based on Hammett parameters. Therefore we have taken their data for benzene derivatives and correlated it with σ^+ and σ. Example **1** in Table 1 for the reaction with NO_3 radicals has the highest absolute ρ^+ and example **2** in Table 2 for reaction with HO radicals has the second highest ρ in the table. It is surprising that the absence of solvent has such a large influence on ρ. The NO_3 radicals clearly are much better correlated by σ^+ while the $HO^\bullet$ reactions are far better correlated by σ. The very large absolute values of ρ may be associated with the low dielectric constant of gaseous nitrogen (1.0006) and oxygen (1.0005) compared to solvents (liquid benzene = 2.27).

DeMore[326] has developed a useful method for calculating rate constant for the $^\bullet$OH abstraction of H from a number of halocarbons whose tropospheric lifetime is an important measure of their potential environmental impact.

VII. Conclusions

We hope that the QSARs contained in this review will provide leads for broadening our understanding of radical reactions in biological as well as chemical systems. The Hammett parameters can provide clues about reaction mechanisms if proper care is taken in selecting substituents for study. As we have pointed out, care must be taken to avoid the collinearity problem; but in addition to this, thought must be given to avoiding substituents which themselves readily react with radicals.

Table 7. Physical-Organic and Biological QSARs Correlated by E_R or $\sigma^\bullet$ [a]

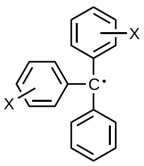
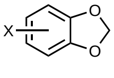
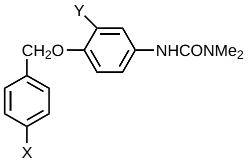
set	solvents	compounds	reaction, correlation	ref
			Physical-Organic QSARs	
1	unknown	X-$C_6H_4CHMe_2$	chain-transfer constant toward polymethyl methacrylate radicals 60 °C $\log c = 1.23(\pm 0.32)E_R - 3.60(\pm 0.04)$ $n = 6$, $s = 0.022$, $r^2 = 0.966$, $F_{1,4} = 106$,[§] omit: 4-$CHMe_2$ (0.32[‡]) [&]4-Cl, −0.04; 4-Br, 0.02; H, 0.01; 4-OMe, 0.00; 4-CN, 0.00; 4-CMe_3, 0.00	310
2	polymethyl methacrylate	X-C_6H_4CHO	chain-transfer constants 60 °C $\log c = 1.69(\pm 0.86)E_R - 4.11(\pm 0.11)$ $n = 6$, $s = 0.053$, $r^2 = 0.882$, $F_{1,4} = 31.3$[§] 4-Br, 0.07; 4-Cl, −0.05; 3-Cl, −0.05; H, 0.04; 4-OMe, −0.03; 4-CN, 0.01	245
3	methyl methacrylate	4-X-$C_6H_4SSC_6H_4$-X-4	chain-transfer constant 50 °C $\log k = 1.81(\pm 0.69)E_R - 2.52(\pm 0.14)$ $n = 5$, $s = 0.071$, $r^2 = 0.958$, $F_{1,3} = 69.4$,[§] omit: 4-Cl (0.20) H, 0.10; 4-Me, −0.05; 4-OMe, −0.04; 4-Br, −0.03; 4-NO_2, 0.02	311
4	benzene	X-C_6H_4COMe	chain-transfer constants in styrene initiated by azobis(isobutyronitrile) 60 °C $\log c = 2.07(\pm 0.68)E_R - 4.23(\pm 0.10)$ $n = 8$, $s = 0.064$, $r^2 = 0.901$, $F_{1,6} = 54.5$[§] 4-COMe, −0.11; 4-CN, 0.07; 4-OMe, 0.06; 4-Br, 0.05; 4-Cl, −0.03; 4-CMe_3, −0.02; 3-Cl, −0.02; H, −0.01	312
5	unknown	X-C_6H_5	radical methylation 110 °C by *tert*-butyl peracetate $\log k_{ref} = 2.10(\pm 0.65)E_R - 0.13(\pm 0.10)$ $n = 8$, $s = 0.090$, $r^2 = 0.913$, $F_{1,6} = 63.3$,[§] omit: 3-NO_2 (−0.62), 4-CN (0.60) 4-Cl, −0.14; H, 0.13; 3-Cl, −0.08; 4-NO_2, 0.05; 4-Br, −0.05; 3-Me, 0.04; 3-Br, 0.04; 4-Me, 0.01	313
6	methanol	4-X-$C_6H_4CH_2Br$	polarographic reduction $E_{1/2} = 2.11(\pm 0.76)E_R - 1.36(\pm 0.16)$ $n = 6$, $s = 0.9$, $r^2 = 0.937$, $F_{1,4} = 60.0$[§] 4-COOMe, −0.12; 4-NO_2, 0.10; 4-Me, 0.08; 4-OMe, −0.07; H, 0.03; 4-Br, −0.02	314
7	benzene	X-C_6H_5	free-radical arylation by $C_6H_5^\bullet$ 20 °C $\log k_{rel} = 2.37(\pm 0.59)E_R - 0.04(\pm 0.10)$ $n = 7$, $s = 0.080$, $r^2 = 0.955$, $F_{1,5} = 206$,[§] omit: 3-NO_2 (−0.73) 3-Cl, −0;15; 4-Me, 0.07; 3-OMe, 0.06; 4-NO_2, 0.03; 4-Cl, −0.03; 4-OMe, 0.01; 3-Me, 0.01	179
8	hexane	X-$C_6H_4CH_2^\bullet$	quenching by molecular oxygen at room temperature $\log k_{ox} = -1.64(\pm 0.36)\sigma^\bullet + 9.39(\pm 0.06)$ $n = 9$, $s = 0.068$, $r^2 = 0.943$, $F_{1,7} = 119$,[§] omit: 4-F (−0.34) ($\sigma^\bullet$ from authors; good correlation not found with $\sigma^\bullet$ from Creary or Jiang) 4-Me, 0.11; 4-OMe, −0.10; 4-CN, −0.07; 3-CN, −0.05; 4-Cl, 0.04; 4-C_6H_5, 0.04; H, 0.02; 4-NO_2, 0.01; 4-Br, 0.00	315
8a	benzene	X-$C_6H_4CHMe_2$	chain-transfer constant toward poly(methyl methacrylate) radical 60 °C $\log c = 0.65(\pm 0.25)\sigma^\bullet - 3.61(\pm 0.06)$ $n = 6$, $s = 0.027$, $r^2 = 0.958$, $F_{1,4} = 75.0$,[§] omit: 4-Br (0.09) ($\sigma^\bullet$ from Creary) 4-CMe_3, −0.04; 4-Cl, 0.02; H, 0.02; 4-CN, 0.01; 4-OMe, −0.01	315a
9	benzene		dimerization of form quinoid trityl dimers (equilibrium constant) 25 °C $\log k = 1.21(\pm 0.23)\sigma^\bullet - 3.24(\pm 0.15)$ $n = 17$, $s = 0.177$, $r^2 = 0.891$, $F_{1,15} = 122$,[§] omit: 4,4′-$(CMe_3)_2$ (0.65), 4,4′-$(CF_3)_2$ (0.62), ($\sigma^\bullet$ from Arnold) H, 4′-SMe, −0.30; H, H, −0.24; 4,4′-CN_2, 0.24; H, 4′-OMe, 0.20; H, 4′-CF_3, 0.20; 4,4′-$(C_6H_5)_2$, 0.19; H, 4′-OC_6H_5, −0.19; H, 4′-COMe, −0.19; 4′,4′-$(OMe)_2$, 0.16; 4,4′-$(COC_6H_5)_2$, −0.14; H, 4′-CN, 0.09; H, 4′-COC_6H_5, 0.08; H, 4′-NO_2, −0.07; H, 4′-C_6H_5, −0.07; H, 4-CMe_3, 0.04; 4,4′-$(OC_6H_5)_2$, 0.01; 4,4′-$(SMe)_2$, −0.01	316
			Biological QSARs	
1	fly		ID_{50} of carbaryl synergized by benzodioxoles $\log SR = 0.23(\pm 0.11)\ C\log P + 1.82(\pm 0.37)\sigma^\bullet + 0.78(\pm 0.14)\ E_s + 1.32(\pm 0.30)$ $n = 15$, $s = 0.115$, $r^2 = 0.937$, $F_{1,13} = 5.01$[§§] (E_s), $F_{1,12} = 32.6$[§] ($\sigma^\bullet$), $F_{1,11} = 23.3$[§] ($C\log P$), omit: 5,6,7-Br_3 (−1.56) (SR: synergistic ratio) ($\sigma^\bullet$ from ref. 318a) 5,6-Cl_2, 0.19; H, −0.18; 5-NO_2, 6-Cl, 0.17; 5,6,7-Cl_3, −0.14; 6-Br, 0.11; 5-Br,6-OMe, −0.08; 5-Cl,6-OMe, 0.06; 5-NO_2, 6-Br,−0.06; 6-OMe, 0.05; 6-NO_2, −0.04; 5,6-$(NO_2)_2$, −0.04; 6-Cl, −0.02; 6-Me, −0.02; 5-NO_2,6-OMe, −0.01; 5,6-Brr^2, 0.00	317

Table 7 (Continued)

set	solvents	compounds	reaction, correlation	ref
		Biological QSARs		
2	wild mustard		85% kill $\log 1/C = 0.52(\pm0.35)\ C\log P - 0.82(\text{I}0.39) \log(\beta\cdot10^{C\log P} + 1) - 5.14(\pm1.87)E_R - 0.07(\pm1.18)$ $n = 21$, $s = 0.359$, $r^2 = 0.859$, $F_{1,19} = 7.35^{§§}(E_R)$, $F_{1,18} = 22.6^{§}$ ($C\log P$), $F_{2,16} = 32.5^{§}$(bilin($C\log P$)	318
	$X = 4\text{-}C_8H_{17}$, Y = Cl, −0.55; X = 4-Me, Y = Cl, 0.48; $X = 4\text{-CMe}_3$, Y = Cl, −0.47; X = 4-Me, Y = H, 0.45; X = 4-SMe, Y = H, −0.41; X = 4-Cl, Y = Cl, 0.39; $X = C_{18}H_{37}$, Y = Cl, 0.36; X = 4-Cl, Y = H, 0.34; X = 4-Br, Y = H, −0.33; X = 4-OMe, Y = H, −0.31; $X = 4\text{-CMe}_3$, Y = H, 0.30; X = Y = H, −0.25; $X = 4\text{-}C_{10}H_{Y = Cl,}$ −0.25; X = 4-F, Y = Cl, −0.22; $X = 3\text{-CF}_3$, Y = H, 0.15; $X = 4\text{-NO}_2$, Y = H, 0.13; X = H, Y = Cl, 0.12; X = 4-Et, Y = Cl, −0.11; $X = 4\text{-}C_4H_9$, Y = Cl, 0.10; $X = 4\text{-SO}_2\text{Me}$, Y = H, 0.07; $X = 4\text{-CHMe}_2$, Y = Cl, 0.00			
3	fungus spp.: *Aspergillus*, Penicillium, Cladosporium, *Mucor*	$X\text{-}C_6H_4CH_2OH$	growth inhibition pH 6.5 25 °C $\log 1/C = 1.41(\pm0.85)E_R + 0.67(\pm0.08) \log P + 0.78(\pm0.21)$ $n = 18$, $s = 0.160$, $r^2 = 0.962$, $F_{1,16} = 104^{§}$ ($\log P$), $F_{1,17} = 32.5^{§}$ (E_R), omit: 2-NO_2 (0.55)	319
	$2,4\text{-Cl}_2$, 0.29; $2,4\text{-Me}_2$, −0.24; 4-I, 0.23; 4-NO_2, −0.21; 4-OH, 0.20; 4-Cl, −0.17; $3,4\text{-Cl}_2$, 0.15; $2,4,5\text{-Cl}_3$, −0.13; 4-Br, −0.11; 4-Me, −0.10; $4\text{-Cl},3,5\text{-Me}_2$, 0.06; 2-Br, −0.04; 3-OH, 0.04; $3,4,5\text{-Cl}_3$, 0.04; 4-CN, 0.03; $4\text{-I},3,5\text{-Me}_2$, −0.01; H, −0.01; 2-OH, −0.01			
4	*P. vulgaris (Proteus)* + E. coli *(Escherichia)* + *Pseudomonas*	$X\text{-}C_6H_4CH_2OH$	growth inhibition $\log 1/C = 2.49(\pm0.63)E_R + 0.66(\pm0.08)\ C\log P + 0.62(\pm0.20)$ $n = 16$, $s = 0.127$, $r^2 = 0.960$, $F_{1,14} = 40.0^{§}$ ($C\log P$), $F_{1,13} = 72.2^{§}$ (E_R)	319
	4-Cl, −0.31; 4-NO_2, −0.20; $3,4\text{-Cl}_2$, 0.18; 4-CN, 0.10; 2-Br, −0.07; $3,4,5\text{-Cl}_3$, 0.06; 3-OH, 0.06; 4-OH, 0.06; 4-Cl,3,5-Me, −0.06; $2,4\text{-Cl}_2$, 0.05; 4-COOH, 0.05; 4-Br, 0.05; 2-NO_2, 0.03; 4-Me, 0.03; H, −0.02; $2,4\text{-Me}_2$, 0.00			

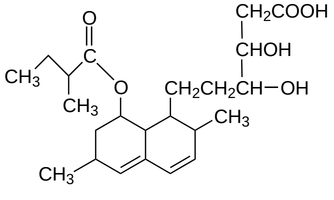
[a] Key: $^{\&}$, substituents and their residuals; ‡, residuals of outliers; §, significant at 0.99 *F* test; and §§, significant at 0.95 *F* test.

From Table 1 it is clear that aromatic amines, phenols, and thiophenols readily donate •H to radicals. Benzylic hydrogens are readily lost to produce radicals. We need better understanding of the implications of this for the design of drugs, for example. Antiinflammatory drugs, which often contain benzylic hydrogen, are not recommended for pregnant women because of the possibility of birth defects. Toluene has been shown to cause birth defects in pregnant women who have inhaled it for sport.[75] However, it is not the short-term toxic effects of these chemicals that are worrisome; rather, it is the chronic use with individuals lacking good protective radical-scavenging systems.

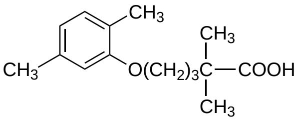
It is the very long-term contact with drugs and environmental chemicals that pose toxicological problems that will be extremely difficult to uncover. Recall that people often smoke, bathing their lungs 16 h/day, for 20−40 years before serious problems are detected. It was a long arduous battle before epidemiological studies could convince the majority that smoking was indeed bad. It is still not clear just which of the more than 5000 chemicals in cigarette smoke are the cause of the problems and why some people can smoke for 50 years without serious difficulties.

We believe that as QSAR continues to become more sophisticated and as we work the information into a science, such as organic chemistry, more and more difficulties will be avoided in drug design even before animal testing begins. The same will be true for the design of industrial chemicals.

Recently it was pointed out that a number of lipid lowering drugs now on the market cause cancer in mice.[76] The following examples are representative:



lovastatin



gemfibrozil

Lovastatin (and other statins) contains three allylic hydrogens. Radical stabilization by the double-bond system would favor •H abstraction at these points. Also the double-bond system is a likely point for epoxidation for the production of the epoxide function. Gemfibrozil contains two aromatic methyl groups, one of which is conjugated with the strongly activating alkoxy moiety. Ease of radical formation may be the cause of the carcinogenicity. What the long-term use (10−30 years) of these drugs will produce is yet to be learned. Unfortunately it will be extremely difficult to establish toxicities via epidemiology.

The connection between the toxicity of xenobiotics and their activation by the P450 enzyme has long been appreciated. One wonders from the QSAR for the other oxidases of Tables 4−7 if these enzymes play any role in activating otherwise innocuous xenobiotics.

Although the connections between the QSAR from physical organic chemistry and biological systems are not numerous, this is not unexpected since the two fields have tended to work in separate compartments. In fact, whether or not all of the biological reactions

Table 8. Radical Reactions Correlated by Dual Parameter Equations[a]

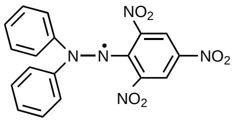
set	solvent	compound	radical	reaction, correlation
9[b]	benzene	X-C_6H_4OH		hydrogen abstraction 30 °C $\log k = -2.62(\pm 0.35)\sigma^{+} + 1.14(\pm 0.74)\sigma^{\bullet} - 1.31(\pm 0.30)B1{,}2 + 3.09(\pm 0.39)$ $n = 17$, $s = 0.255$, $r^2 = 0.956(\pm 0.918)$,* $F_{1,15} = 37.5$ (σ^{+}),§ $F_{1,14} = 48.9$ ($B1{,}2$)§, $F_{1,13} = 12.2$ ($\sigma^{\bullet}$),§ omit: 2,3,4,5,6-Cl_5 (2.53‡), 3-OMe (0.68)
&2-Cl, 0.44; H, −0.55; 4-OMe, 0.37; 2-Me, 0.21; 2,6-Me_2, −0.21; 3-NO_2, 0.20; 4-NO_2, −0.20; 4-C_6H_5, 0.20; 4-Me, 2,6-$(CMe_3)_2$, −0.18; 3-Me, −0.17; 4-Me, −0.15; 2-C_6H_5, 0.13; 2,6-$(CMe_3)_2$, −0.09; 4-F, 0.09; 4-CMe_3, −0.09; 3-Cl, −0.07; 4-Cl, −0.03				
42a[b]	air	X-C_6H_5	$HO^{\bullet}$	react with $HO^{\bullet}$ radicals 25 °C $\log k = -1.87(\pm 0.26)\sigma^{+} + 1.57(\pm 0.60)\sigma^{\bullet} - 12.0(\pm 0.16)$ $n = 13$, $s = 0.152$, $r^2 = 0.963$ (0.837), $F_{1,12} = 119$ (σ^{+}),§ $F_{1,11} = 59.7$ ($\sigma^{\bullet}$)§
F, −0.24; 1,2-Cl_2, 0.18; C_6H_5, −0.18; 1,4-Me_2, 0.16; H, 0.15; 1,2-Me_2, 0.15; Cl, −0.12; 1,3-Me_2, −0.08; Me, 0.08; 1,3-Cl_2, −0.07; CN, 0.07; NO_2, −0.06; Br, −0.04				
43a[b]	air	X-C_6H_5	$HO^{\bullet}$	react with $HO^{\bullet}$ radicals 300 K $\log k = -1.53(\pm 0.19)\sigma^{+} + 1.56(\pm 0.44)\sigma^{\bullet} - 12.2(\pm 0.14)$ $n = 20$, $s = 0.200$, $r^2 = 0.949$ (0.783), $F_{1,18} = 319$ (σ^{+}),§ $F_{1,17} = 23.8$ ($\sigma^{\bullet}$)§
Me, 0.39; F_6, −0.31; H, 0.31; 1,3-Me_2, 0.29; 1,4-Cl_2, −0.27; 1,2,3-Me_3, −0.27; 1,2-Cl_2, −0.17; 1,2,4-Me_3, −0.15; Br, 0.13; NO_2, −0.11; 1,2,4-Cl_3, −0.11; 1,2-Me_2, 0.08; CN, 0.06; Cl, 0.05; 1,3-Cl_2, 0.05; 1,4-Me_2, 0.04; OMe, −0.03; 1,3,5-Me_3, 0.02; C_6H_5, 0.02; F, 0.00				
88[b]	CCl_4	X-$C_6H_4CH_2CMe_3$	$Cl_3C^{\bullet}$	hydrogen abstraction 70 °C $\log k_{\mathrm{rel}} = -0.87(\pm 0.11)\sigma^{+} - 0.37(\pm 0.26)\sigma^{\bullet} - 0.03(\pm 0.06)$ $n = 9$, $s = 0.058$, $r^2 = 0.987$ (0.960), $F_{1,7} = 169$ (σ^{+}),§ $F_{1,6} = 12.0$ ($\sigma^{\bullet}$)§
4-CMe_3, −0.10; 4-Me, 0.089; H, 0.03; 3-CF_3, −0.03; 4-Cl, 0.02; 4-OMe, −0.01; 4-NO_2, 0.00; 3-Me, 0.00; 3-Cl, 0.00				
96[b]	aqueous 50% acetic acid	X-C_6H_4Me	$^{\bullet}CH_2COOH$	hydrogen abstraction 130 °C $\log k_{\mathrm{rel}} = -0.65(\pm 0.05)\sigma^{+} + 0.15(\pm 0.09)\sigma^{\bullet} - 0.02(\pm 0.02)$ $n = 9$, $s = 0.016$, $r^2 = 0.996$ (0.983), $F_{1,7} = 274$ (σ^{+}),§ $F_{1,6} = 9.00$ ($\sigma^{\bullet}$)§
3-OMe, 0.03; H, −0.02; 4-Cl, −0.01; 4-Me, −0.01; 3-Me, 0.01; 4-OMe, 0.01; 4-F, 0.00; 4-C_6H_5, 0.00; 4-Br, 0.00				
108[b]	acetic acid	X-C_6H_4Me	$^{\bullet}CH_2COOH$	hydrogen abstraction 130 °C $\log k_{\mathrm{rel}} = -0.65(0.05)\sigma^{+} + 0.15(0.09)\sigma^{\bullet} + 0.02(0.02)$ $n = 9$, $s = 0.016$, $r^2 = 0.996$ (0.983), $F_{1,7} = 274$ (σ^{+}),§ $F_{1,6} = 9.00$ ($\sigma^{\bullet}$)§§
3-OMe, 0.03; H, −0.02; 4-Cl, −0.01; 4-Me, −0.01;3-Me, 0.01; 4-Me, 0.01; 4-F, 0.00; 4-C_6H_5, 0.00; 4-Br, 0.00				
125[b]	reactants	X-C_6H_4Me	$Me_3COO^{\bullet}$	hydrogen abstraction 30 °C $\log k = -0.59(\pm 0.09)\sigma^{+} + 0.27(\pm 0.19)\sigma^{\bullet} - 1.52(\pm 0.05)$ $n = 12$, $s = 0.063$, $r^2 = 0.957$ (0.910), $F_{1,10} = 135$ (σ^{+}),§ $F_{1,9} = 120.0$ ($\sigma^{\bullet}$)§
4-COOMe, 0.11; 4-OMe, −0.08; 3-CN, −0.08; 4-CN, −0.07; 4-Me, 0.06; 4-Cl, 0.03; 3-OMe, 0.03; 3-NO_2, −0.02; 3-Me, 0.01; 3-Cl, 0.01; H, 0.01; 4-NO_2, −0.01				
127[b]	unknown	X-C_6H_4Me	$Me_3COO^{\bullet}$	hydrogen abstraction 2 °C $\log k = -0.57(\pm 0.10)\sigma^{+} + 0.27(\pm 0.20)\sigma^{\bullet} - 1.53(\pm 0.06)$ $n = 11$, $s = 0.063$, $r^2 = 0.960$ (0.911), $F_{1,9} = 125$ (σ^{+}),§ $F_{1,8} = 10.1$ ($\sigma^{\bullet}$),§ omit: H (0.30)
4-COOMe, 0.11; 3-CN, −0.08; 4-CN, −0.07; 4-OMe, −0.07; 4-Cl, 0.04; 3-OMe, 0.03; 3-Me, 0.02; 4-Me, 0.02; 3-Cl, 0.02; 3-NO_2, −0.02; 4-NO_2, −0.01				
137[b]	benzene	X-C_6H_5	$^{\bullet}CN$	substitution $\log k = -0.28(\pm 0.12)\sigma^{+} + 0.88(\pm 0.39)\sigma^{\bullet} - 0.01(\pm 0.03)$ $n = 10$, $s = 0.039$, $r^2 = 0.967$ (0.833), $F_{1,8} = 55.5$(σ^{+}),§ $F_{1,7} = 10.5$($\sigma^{\bullet}$),§§ omit: 4-COOMe (−0.30)
3-Cl, 0.05; 4-Br, −0.05; 3-OMe, −0.04; 3-Me, 0.03; 4-CMe_3, −0.02; 4-Cl, 0.02; 4-OMe, 0.02; 4-F, −0.01; 4-Me, 0.01; 3-F, −0.01				
141[b]	C_6H_{12}	X-$C_6H_4C{\equiv}CH$	Y-$C_6H_4S^{\bullet}$	addition 23 °C $\log k = 1.62(\pm 0.11)\sigma^{+}, \mathrm{Y} - 0.40(\pm 0.05)\sigma^{+}, \mathrm{X} + 0.72(\pm 0.51)\sigma^{\bullet}, \mathrm{Y} + 6.21(\pm 0.06)$ $n = 30$, $s = 0.070$, $r^2 = 0.985$ (0.980), $F_{1,28} = 150$ (σ^{+}, Y),§ $F_{1,27} = 184$ (σ^{+}, X),§ $F_{1,26} = 8.39$ ($\sigma^{\bullet}$, Y)§
X = 3, NO_2, Y = 4-OMe, 0.17; X = 4-OMe, Y = 4-Br, 0.15; X = Y = 4-Cl, −0.13; X = Y = 4-OMe, −0.10; X = 4-OMe, Y = 4-Me, 0.09; X = 4-Cl, Y = H, −0.08; X = 3-NO_2, Y = H, 0.08; X = 4-Me, Y = 4-Br, 0.07; X = 4-Me, Y = 4-OMe, −0.06; X = H, Y = 4-Cl, −0.06; X = 4-Cl, Y = 4-Br, −0.05; X = H, Y = 4-Me, −0.05; X = 3-NO_2, Y = 4-Me, 0.05; X = 4-Me, Y = 4-CMe_3, −0.05; X = H, Y = 4-CMe_3, −0.04; X = 3-NO_2, Y = 4-Cl, −0.04; X = H, Y = 4-Br, 0.04; X = 4-Cl, Y = 4-Me, −0.04; X = 4-OMe, Y = 4-Cl, 0.03; X = 4-OMe, Y = H, 0.03; X = Y = 4-Me, −0.03; X = 4-Cl, Y = 4-CMe_3, −0.02; X = 4-OMe, Y = 4-CMe_3, 0.02; X = 4-Me, Y = H, 0.01; X = 4-Me, Y = 4-Cl, −0.01; X = 4-Cl, Y = 4-Cl, Y = 4-OMe, 0.01; X = 3-NO_2, Y = 4-CMe_3, 0.01; X = 3-NO_2, Y = 4-Br, −0.00; X = H, Y = 4-OMe, 0.00; X = Y = H, 0.00				

Table 8 (Continued)

set	solvent	compound	radical	reaction, correlation
159[b]	styrene	$(X\text{-}C_6H_4COO)_2$ and $C_6H_5CH{=}CH_2$	$X\text{-}C_6H_4COO\bullet$.	initiation of polymerization 60 °C $\log k = -0.79(\pm 0.19)\sigma^+ - 0.61(\pm 0.50)\sigma^\bullet - -5.11(\pm 0.15)$ $n = 14$, $s = 0.202$, $r^2 = 0.886$ (0.810), $F_{1,12} = 83.7$ (σ^+),[§] $F_{1,11} = 12.2$ $(\sigma^\bullet)$,[§] omit: 4-OMe(−0.70); 4-CN(1.00) 4-F, −0.33; 4-NO_2, −0.29; 3-Cl, 0.28; 3-Me, −0.20; 4-$CH{=}CH_2$, 0.20; 3-F, 0.19; 4-Br, 0.15; 3-OMe, 0.13; 4-CMe_3, −0.12; 4-Cl, 0.09; 3-NO_2, −0.05; H, −0.04; 4-C_6H_5, 0.04; 4-Me, −0.03
177[b]	CCl_4	$X\text{-}C_6H_4I$	$C_6H_5^\bullet$	iodine abstraction 60 °C $\log k = 0.32(\pm 0.07)\sigma^+ - 0.38(\pm 0.14)\sigma^\bullet + 1.32(\pm 0.04)$ $n = 11$, $s = 0.044$, $r^2 = 0.957$ (0.738), $F_{1,9} = 25.5$ (σ^+),[§] $F_{1,8} = 41.6(\sigma^\bullet)$,[§] omit: 4-CN (0.17) 4-COOMe, −0.06; 4-C_6H_5, 0.05; 4-Me, −0.05; 3-NO_2, 0.04; 3-CN, 0.04; 3-OMe, −0.03; 3-CF_3, −0.03; 4-OMe, 0.02; 4-Br, 0.01; 4-NO_2, 0.01; 3-Me, 0.01
203[b]	CH_3CN	$X\text{-}C_6H_4C({=}O)Me$		photoreduction by *p*-xylene at ambient temperature $\log k = 2.00(\pm 0.42)\sigma^+$ - $1.94(\pm 1.04)\sigma^\bullet + 5.71(\pm 0.19)$ $n = 11$, $s = 0.221$, $r^2 = 0.947$ (0.824), $F_{1,9} = 42.2$ (σ^+),[§] $F_{1,8} = 18.4$ $(\sigma^\bullet)$,[§] omit: 4-OMe(0.84) 4-Cl, −0.40; 4-CMe_3, 0.36; 3,4-Me_2, −0.15; H, 0.13; 3-CN, 0.11; 4-CF_3, −0.11; 4-CN, 0.11; 3-CF_3, 0.10; 3-Me, −0.09; 3-Cl, −0.08; 4-Me, 0.02
5[c]	aqueous	$X\text{-}C_6H_4O^-$	singlet oxygen	oxidation 27.1 °C $\log k = -1.06(\pm 0.23)\sigma^- - 0.68(\pm 0.56)\sigma^\bullet + 0.58(\pm 0.40)B1{,}2 + 7.88(\pm 0.48)$ $n = 18$, $s = 0.231$, $r^2 = 0.963$ (0.946), $F_{1,16} = 296$ (σ^+),[§] $F_{1,15} = 4.60$ (B1,2),[§§] $F_{1,14} = 7.31$ $(\sigma^\bullet)$,[§§] omit: 2,3,4,5,6-Cl_5 (0.63), 2,6-$(NO_2)_2$-4-Me (1.65) 2-NO_2, 0.41; 2-Cl, −0.35; 2-Me-4,6-$(NO_2)_2$, −0.31; 4-CN, −0.30; H, −0.26; 4-OMe, 0.26; 2,4-$(NO_2)_2$, 0.21; 2,4,6-Cl_3, 0.16; 2-OMe, −0.12; 2,4-Cl_2, −0.12; 3-Cl, 0.12; 3-OMe, 0.12; 4-Cl, 0.12; 2,6-$(OMe)_2$, 0.06; 4-CMe_3, 0.05; 4-NO_2, −0.02; 4-Me, −0.01; 3-NO_2, 0.01
6[c]	aqueous	$X\text{-}C_6H_4OH$	singlet oxygen	oxidation 27.1 °C $\log k = -1.20(\pm 0.19)\sigma^- - 0.63(\pm 0.54)\sigma^\bullet + 7.14(\pm 0.15)$ $n = 13$, $s = 0.169$, $r^2 = 0.958$ (0.930), $F_{1,11} = 186$ (σ^+),[§] $F_{1,10} = 8.29$ $(\sigma^\bullet)$,[§§] omit: 2,4,6-Cl_3 (1.01), 2-NO_2 (0.87), H (−0.72), 2-OMe (−0.52) 4-Me, −0.29; 4-CN, −0.26; 2,4-Cl_2, 0.18; 4-NO_2, 0.17; 4-CMe_3, −0.13; 2-Cl, 0.13; 3-OMe, 0.11; 2,6-$(OMe)_2$, 0.10; 2,3,4,5,6-Cl_5, −0.08; 3-NO_2, 0.08; 4-Cl, −0.05; 4-OMe, 0.05; 3-Cl, 0.02

[a] Key: [b], set number from Table 1; [c], set number from Table 3; *, value in parentheses if the correlation coefficient without $\sigma^\bullet$; [&], substituents and their residuals; [‡], residuals of outliers; [§], significant at 0.99 *F* test; [§§], significant at 0.95 *F* test.

Table 9. Comparison of Dual Parameter Correlations Using Different $\sigma^\bullet$ Values[a]

		r^2			
			$\sigma^+ + \sigma^\bullet$		
set	*n*	σ^+	Arnold	Creary	Jiang
9[b]	15	0.676	0.798	0.838	0.852
42a[b]	10	0.829	0.922	0.918	0.876
43a[b]	17	0.781	0.954	0.945	0.945
57[b]	13	0.892	0.903	0.946	0.911
88[b]	8	0.969	0.970	0.975	0.977
96[b]	8	0.978	0.983	0.981	0.985
108[b]	9	0.983	0.994	0.995	0.995
125[b]	10	0.906	0.968	0.943	0.926
127[b]	10	0.829	0.861	0.841	0.829
137[b]	10	0.803	0.913	0.931	0.889
159[b]	11	0.823	0.875	0.861	0.885
177[b]	8	0.837	0.930	0.897	0.875
203[b]	12	0.838	0.942	0.912	0.882
5[c]	14	0.571	0.834	0.825	0.658
6[c*]	14	0.678	0.679	0.678	0.713

[a] Key: [b], set number from Table 1; [c], set number from Table 3; *, correlated with σ^- and $\sigma^- + \sigma^\bullet$.

we have classified as radical actually are remains to be seen.

Still, the generalizations that the lower the absolute value of ρ the more active the radical seems to apply to the biological systems. The oxidases with porphyrin active sites have large negative ρ's, as do those in simple chemical systems where porphyrins are involved. It remains to be shown that phenol and aniline toxicity based on small ρ^+ values are indeed based on radicals; the evidence is highly suggestive. We sorely need studies of well-designed sets of congeners to see how far the use of ρ^+ can be used for diagnostic purposes.

We believe that the time is ripe, and the need urgent, to push a large effort to organize the countless structure−activity studies that have been done in the past 60 years into a coherent group of generalizations.[1] The power of computers now makes this possible, and indeed, QSAR is not the only way. The EMIL project directed by Toshio Fujita[77] is leading the way toward a computerized approach to qualitative structure−activity relationships. They have shown interesting patterns among pharmaceutical and agricultural chemicals that might be considered as a kind of computer age bioisosterism.

This report, as well as others,[1,10,12] shows how inextricably physical organic chemistry has become entwined with biology. The trend started with Linus Pauling who in the late 1930s brought biologists into the chemistry department at CalTech much to the consternation of his colleagues. Toward the end of the 1950s David Bonner a self-styled bioorganic chemist at Yale, proclaimed that the time was coming when chemistry departments would be absorbed into biology departments. The latest wake-up call comes from Harvard University where the Chemistry De-

Table 10. $\sigma^\bullet$ Values

	Arnold's[40,41]		Jiang's[41b]		Creary's[41a]	
substituents	para	meta	para	meta	para	meta
NMe_2			1.000		0.900	
HgCl					0.170	
NO_2			0.360	0.000	0.570	−0.110
$P{=}O(OET)_2$					0.180	−0.110
$P(S)(OEt)_2$					0.290	
$SnMe_3$					0.130	
C_6H_5			0.470		0.460	
$CH{=}CH_2$					0.670	
c-C_3H_5			0.290		0.240	
$CONH_2$			0.380			
CH_2SiMe_3					0.270	
COOH			0.380			
Br			0.230	0.120	0.130	
$C(Me){=}CH_2$					0.530	
$-B(OCH_2)_2$					0.280	
F	−0.110	−0.090	−0.020	0.030	−0.080	−0.050
CF_3	−0.090	−0.170	−0.010	−0.070	0.080	−0.070
OCOMe	−0.050					
H	0.000	0.000	0.000	0.000	0.000	0.000
$OCOC_6H_5$	0.000					
SO_2Me	0.050		0.380		0.180	−0.070
CMe_3	0.080		0.260	0.110	0.130	
$CHMe_2$	0.090					
Cl	0.110	−0.070	0.220	−0.050	0.120	−0.040
C_2H_5	0.120		0.150			
SO_2OMe	0.130					
Me	0.150	0.020	0.150	0.000	0.110	0.030
$S{=}O(OMe)$	0.160					
$SiMe_3$	0.170		0.310		0 180	0.030
SOMe	0.180		0.500		0.180	0.010
$SO_2C_6H_5$	0.180					
OMe	0.180	−0.010	0.230	0.100	0.240	−0.020
OC_6H_5	0.180	−0.020				
$S{=}O(C_6H_5)$	0.260					
$SC{=}O(Me)$	0.290					
CN	0.400	−0.260	0.420	0.110	0.460	−0.120
COOMe	0.430	−0.140	0.330	0.100	0.350	
COC_6H_5	0.550					
SC_6H_5	0.580					
COMe	0.600		0.540			
SMe	0.630		0.620		0.430	−0.030

partment has recently been renamed Chemistry and Chemical Biology!

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IX. References

(1) Hansch, C; Hoekman, D.; Gao, H. *Chem. Rev.* **1996**, *96*, 1045.
(2) Afanas'ev, I. B. *Russ. Chem. Rev. (E.E.).* **1971**, *40*, 216.
(3) Afanas'ev, I. B. *Int. J. Chem. Kinet.* **1981**, *13*, 173. (a) Hansch, C.; Leo, A.; Hoekman, D. *Exploring QSAR. Hydrophobic, Electronic, and Steric constants*; American Chemical Society: Washington DC, 1995.
(4) Brønsted, J. N.; Pederson, K. *Z. Phys. Chem.* **1924**, *108*, 185.
(5) Hammett, L. P. *J. Am. Chem. Soc.* **1937**, *59*, 96. (a) Jaffé, H. H. *Chem. Rev.* **1953**, *53*, 191.
(6) Stock, L. M.; Brown, H. C. *Adv. Phys. Org. Chem.* **1963**, *1*, 35.
(7) Walling, C.;Briggs, E. R.;Wolfstirn, K. B.;Mayo, F. R. *J. Am. Chem. Soc.* **1948**, *70*, 1537.
(8) Overton, C. E. *Studies of Narcosis;* Lipnick, R. L., Ed.; Chapman and Hall: New York, 1991.
(9) Hansch, C.; Maloney, P. P.; Fujita, T.; Muir, R. M. *Nature* **1962**, *194*, 178.
(10) Hansch, C.; Leo, A. Exploring QSAR. *Fundamentals and Applications in Chemistry and Biology*; American Chemical Society; Washington DC, 1995.
(11) Hoekman, D.; Leo, A.; Li, P.; Zhang, L.; Hansch, C. In Proceeding of the Twenty-Seventh Annual International Conference on Systems Science. *Biotechnology Computing*; Hunter, L., Ed.; IEEE, Computer Society Press: Piscataway, NJ, 1994; Vol. V, p 193.
(12) Hansch, C. *Acc. Chem. Res.* **1993**, *26*, 147.
(13) Hansch, C.; Hoekman, D.; Leo, A.; Zhang, L.; Li, P. *Toxicol. Lett.* **1995**, *79*, 45.
(14) Hansch, C.; Telzer; B. R.; Zhang, L. *Crit. Rev. Toxicol.* **1995**, *25*, 67.
(15) Debnath, A. K.; Shusterman, A. J.; de Compadre, R. L. L.; Hansch, *C. Mutat. Res.* **1994**, *305*, 63. (a) Hansch, C. In *Computer Aided Molecular Design;* Reynolds, C. H., Holloway, M. K., Cox, A. K., Eds.; *ACS Symp. Ser.* 589, American Chemical Society: Washington, DC, 1995; p 281.
(16) Tarbell, D. S.; Tarbell, T. *The History of Organic Chemistry in he United States, 1875−1955*; Folio Publishers: Nashville, TN, 1986; p 42. (a) Acheson, R. M. *J. Chem. Educ.* **1996**, *73*, 320.
(17) Halliwell, B.; Gutteridge, J. M. C. *Free Radicals in Biology and Medicine,* 2nd ed.; Clarendon Press: Oxford, 1989.
(18) Roberfroid, M.; Calderon, P. B. *Free Radicals and Oxidation Phenomena in Biological Systems;* Dekker: New York, 1995. (a) *Free Radicals and Oxidative Stress*; Rice-Evans, Halliwell, B., Lunt, G. G., Eds.; Portland Press: Portland, OR, 1995.
(19) Stubbe, J. A. *Annu. Rev. Biochem.* **1989**, *58*, 257.
(20) Fridovich, I. *Annu. Rev. Biochem.* **1995**, *64*, 97.
(21) Grissom, C. B. *Chem. Rev.* **1995**, *95*, 3.
(22) Hansch, C.; Zhang, L. *SAR and QSAR, Environ. Res.* **1995**, *4*, 73.
(23) Reference 17, p 30.
(24) Cadenas, E. *Annu. Rev. Biochem.* **1989**, *58*, 79.
(25) Ames, B. N.; Shigenaga, M. K.; Hagen, T. M. *Proc. Natl. Acad. Sci. U.S.A.* **1993**, *90*, 7915.
(26) Shigenaga, M. K.; Hagen, T. M.; Ames, B. N. *Proc. Natl. Acad. Sci. U.S.A.* **1994**, *91*, 10771.
(27) Scott, G. *Chem. Br.* **1995**, *31*, 879.
(28) Cutler, R. G. *Ann. N.Y. Acad. Sci.* **1991**, 6211.
(29) Sohal, R. S.; Allen, R. G. *Adv. Free Radical Biol. Med.* **1986**, *2*, 117.
(30) Brown, H. C.; Okamoto, Y. *J. Am. Chem. Soc.* **1958**, *80*, 4979.
(31) Alfrey, T.; Price, C. C. *J. Polym. Sci.* **1947**, *2*, 101.
(32) Streitwieser, A.; Perrin, C. *J. Am. Chem. Soc.* **1964**, *86*, 4938.
(33) Yamamoto, Y.; Otsu, T. *Chem. Ind. (London).* **1967**, 787.
(34) Otsu, T.; Ito, T.; Fuji, Y.; Imoto, M. *Bull. Chem. Soc. Jpn.* **1968**, *41*, 204.
(35) Hansch, C.; Kerley, R. *Chem. Ind. (London).* **1969**, 294.
(36) Cammarata, A.; Yau, S. *J. Med. Chem.* **1970**, *13*, 93.
(37) Fischer, T. H.; Meierhoefer, A. W. *Tetrahedron.* **1975**, *31*, 2019.
(38) Fischer, T. H.; Meierhoefer, A. W. *J. Org. Chem.* **1978**, *43*, 224.
(39) Dinctürk, S.; Jackson, R. A. *J. Chem. Soc. Perkin Trans. 2* **1981**, 1127.
(40) Dust, J. M.; Arnold, D. R. *J. Am. Chem. Soc.* **1983**, *105*, 1221.
(41) Nicholas, A. M. de P.; Arnold, D. R. *Can. J. Chem.* **1984**, *62*, 1850. (a) Creary, X.; Mehrsheikh-Mohammadi, M. E.; McDonald, S. *J. Org. Chem.* **1987**, *52*, 3254. (b) Jiang, X.-K.; Ji, G. Z. *J. Org. Chem.* **1992**, *57*, 6051. (c) Tipker, J.; Verloop, A. In *The Chemistry of Excitation at Interfaces*; Thomas, J. K., Ed.; ACS Monograph 255; American Chemical Society: Washington, DC, 1984; p 279.
(42) Zavitsas, A. A.; Pinto, J. A. *J. Am. Chem. Soc.* **1972**, *94*, 7390.
(43) Russell, G. A. *J. Org Chem.* **1958**, *23*, 1407.
(44) Bordwell, F. G.; Zhang, X.-M.; Satish, A. V.; Cheng, J. P. *J. Am. Chem. Soc.* **1994**, *116*, 6605.
(45) Bordwell, F. G.; Harrelson, J. A.; Zhang, X. *J. Org. Chem.* **1991**, *56*, 4448.
(46) Bordwell, F. G.; Cheng, J.-P.; Ji, G.-Z.; Satish, A. V.; Zhang, X.-M. *J. Am. Chem. Soc.* **1991**, *113*, 9790.
(47) Bordwell, F. G.; Cheng, J. P.; Bausch, M. J. *J. Am. Chem. Soc.* **1988**, *110*, 2867. (a) Mulder, P.; Saastad, O. W.; Griller, D. *J. Am. Chem. Soc.* **1988**, *110*, 4090.(b) Wayner, D. D. M. *Acc. Chem. Res.* **1993**, *26*, 287. (c) Arnett, E. M.; Ludwig, R. T. *J. Am. Chem. Soc.* **1995**, *117*, 6627. (d) Livingston, D. *Data Analysis for Chemists*; Oxford University Press: Oxford, 1995. (e) Charton, M.; Clemonti, S.; Ehrenson, S.; Exner, O.; Shorter, J.; Wold, S. *Quant. Struct. Act. Relat.* **1985**, *4*, 29. (f) Fujita, T.; Nishioka, T. *Prog. Phys. Org. Chem.* **1976**, *12*, 49.
(48) Leffler, J. E. *An Introduction to Free Radicals*, Wiley-Interscience: New York, 1993.
(49) Reference 10, p 15. (a) Giese, B. *Angew. Chem.* **1976**, *15*, 688 E.E. (b) Tanner, D. D.; Meintzer, C. P.; Tasi, E. C.; Oumar-Mahamat, H. *J. Am. Chem. Soc.* **1990**, *112*, 7369.
(50) Russell, G. A. *J. Am. Chem. Soc.* **1958**, *80*, 4987.
(51) Kim, S. S.; Kim, Y. K.; Ryou, S. S.; Lee, C. S.; Yoo, K. H. *J. Org. Chem.* **1993**, *58*, 192.
(52) Davis, W. H.; Pryor, W. A. *J. Am. Chem. Soc.* **1977**, *99*, 6365.
(53) Pryor, W. A.; Tonellato, U.; Fuller, D. L.; Jumonville, S. *J. Org. Chem.* **1969**, *34*, 2018.
(54) Reference 48, Chapter 6.
(55) Wright, J. G.; Gilliom, R. D. *J. Am. Chem. Soc.* **1986**, *108*, 2340.
(56) Kim, S. S.; Choi, S. Y.; Kang, C. H. *J. Am. Chem. Soc.* **1985**, *107*, 4234.
(57) Shiga, T.; Imaizumi, K. *Arch. Biochem. Biophys.* **1975**, *167*, 469.
(58) Hansch, C.; Klein, T. *Acc. Chem. Res.* **1986**, *19*, 392 (a) Karki, S. B.; Dinnocenzo, J. P. *Xenobiotica* **1995**, *25*, 711. (b) Guengerich, F. P.; Okazaki, O.; Seto, Y.; MacDonald, T. L. *Xenobiotica*

1995, *25*, 689. (c) Reference 10, p 326. (d) Preussmann, R.; von Hodenberg, A.; Hengy, H. *Biochem. Pharmacol.* **1969**, *18*, 1. (e) Kleihues, P.; Kolar, G. F.; Margison, G. P. *Cancer Res.* **1976**, *36*, 2189.

(59) Hansch, C.; Zhang, L. *Drug Metab. Rev.* **1993**, *25*, 1.

(60) Gao, H.; Hansch, C. *Drug Metab. Rev.* **1996**, *28*, 513.

(61) Ryu, K.; Dordick, J. S. *Biotechnol. Tech.* **1992**, *6*, 277.

(62) Hosoya, T.; Sakurada, J.; Kurokawa, C.; Toyoda, R.; Nakamura, S. *Biochemistry* **1989**, *28*, 2639.

(63) Silverman, R. B. *Acc. Chem. Res.* **1995**, *28*, 335.

(64) Hsuanyu, Y.; Dunford, H. B. *J. Biol. Chem.* **1992**, *267*, 17649.

(65) Andersson, C.-M.; Brattsand, R.; Hallberg, A. *Free Radical Res.* **1994**, *20*, 401. (a) Andersson, C.-M.; Hallberg, A.; Linden, M.; Brattsand, R.; Moldeus, P.; Cotgreave, I. *Free Radical. Biol. Med.* **1994**, *16*, 17.

(66) Hansch, C.; Kim, D.; Leo, A. J.; Novellino, E.; Silipo, C.; Vittoria, A. *Critical Rev. Toxicol.* **1989**, *19*, 185. (a) Xia, Y.; Zweier, J. L. *J. Biol. Chem.* **1995**, *270*, 18797.

(67) Asakawa, E.; Hirose, M.; Hagiwara, A.; Takahashi, S.; Ito, N. *Int. J. Cancer* **1994**, *56*, 146. (b) Sato, Y.; Kamo, S.; Takahashi, T.; Suzuki, O. *Biochemistry* **1995**, *34*, 8940. (c) Selassie, C.; DeSoysa, T.; Hansch, C. Unpublished results.

(68) Moldéus, P.; Nordenskjöld, M.; Bolesfoldi, G.; Eiche, A.; Hagland, U.; Lambert, B. *Mutat. Res.* **1983**, *124*, 9.

(69) Giri, A. K. *Mutat. Res.* **1993**, *296*, 199. (a) Pyror, W. A.; Stone, K. *Ann. N.Y. Acad. Sci.* **1993**, *686*, 12. (b) Stoyanovsky, D. A.; Goldman, R.; Claycamp, H. G.; Kagan, V. E. *Arch. Biochem. Biophys.* **1995**, *317*, 315. (c) Soto, A. M.; Justicia, H.; Uray, J. W.; Sonnenschein, C. *Environ. Health Persp.* **1991**, *92*, 167.

(70) Corbett, M. D.; Corbett, B. R.; Hannothiaux, M.-H.; Quintana, S. J. *Toxicol. Appl. Pharmacol.* **1992**, *113*, 80.

(71) Reference 17, p 30. (a) Sharma, M. K.; Buettner, G. R. *Free Radicals Biol. Med.* **1993**, *14*, 649.

(72) Selassie, C. D.; De Soyza, T. V.; Gao, H.; Hansch, C. Submitted for publication. (a) Tollenaere, J. P.; Moereels, H. *Comp. Biochem. Parasites Proc. Int. Sym., 1971*; Van den Bossche, E., Ed.; Adademic Press: New York, 1972, p 469. (b) Referemce 10, p 30.

(73) Gange, D. M.; Donovan, S.; Lopata, R. J.; Henegar, K. In *Classical and Three-Dimensional QSAR in Agrochemistry;* Hansch, C., Fujita, T., Eds.; ACS Symp. Series 606; American Chemical Society: Washington, DC, 1995; pp 199−212.

(74) Das, A.; Wang, J. H.; Lien, E. J. *Prog. Drug. Res.* **1994**, *42*, 133. (a) Hertog, M. G. L.; Feskens, E. J. M.; Hollman, P. C. H.; Katan, M. B.; Kromhout, D. *Lancet* **1993**, *342*, 1007. (b) Verma, A. K.; Johnson, J. A.; Gould, M. N.; Tanner, M. A. *Cancer Res.* **1988**, *48*, 5754.

(75) Hersh, J. H.; Podruch, P. E.; Roger, S. G.; Weisskur, F. B. *J. Pediatr.* **1985**, *106*, 922.

(76) Newman, T. B.; Hulley, S. B. *J. Am. Med. Assoc.* **1996**, *275*, 55.

(77) Fujita, T.; et al. *Pharmacochem. Libr.* **1995**, *23*, 235. (a) Sabljic, A., Gusten, H. *Atmospheric. Environ.* **1990**, *24A*, 73.

(78) McGowan, J. C.; Powell, T.; Raw, R. *J. Chem. Soc.* **1959**, 3103. (a) Elovitz, M. S., Fish, W. *Environ. Sci. Technol.* **1994**, *28*, 2161. (b) Radhakrishnamurti, P. S.; Panda, R. K. *Indian J. Chem.* **1970**, *8*, 946.

(79) Mahoney, L. R.; Darooge, M. A. *J. Am. Chem. Soc.* **1975**, *97*, 4722.

(80) Darooge, M. A.; Mahoney, L. R. *J. Org. Chem.* **1967**, *32*, 1.

(81) Nishimura, N.; Okahashi, K.; Yukutomi, T.; Fujiwara, A.; Kubo, S. *Aust. J. Chem.* **1978**, *31*, 1201.

(82) Trahanovsky, W. S.; Cramer, J.; Brixius, D. W. *J. Am. Chem. Soc.* **1974**, *96*, 1077.

(83) Friedrich, S. S.; Friedrich, E. C.; Andrews, L. J.; Keefer, R. M. *J. Org. Chem.* **1969**, *34*, 900.

(84) Hogg, J. S.; Lohmann, D. H.; Russell, K. E. *Can. J. Chem.* **1961**, *39*, 1588. (a) Stone, A. T. *Environ. Sci. Technol.* **1987**, *21*, 979.

(85) Amey, R. L.; Martin, J. C. *J. Am. Chem. Soc.* **1979**, *101*, 3060.

(86) Morimoto, T.; Hirano, M.; Echigoya, K.; Sato, T. *J. Chem. Soc. Perkin Trans. 2* **1986**, 1205.

(87) Kovacic, P.; Reid, C. G.; Kurz, M. E. *J. Org. Chem.* **1969**, *34*, 3302.

(88) Khanna, R. K.; Pauling, T. M.; Vajpayee, D. *Tetrahedron Lett.* **1991**, *32*, 3759.

(89) Mahoney, L. R.; Darooge, M. A. *J. Am. Chem. Soc.* **1970**, *92*, 890.

(90) Name, P. M.; Trahanovsky, W. S. *J. Am. Chem. Soc.* **1971**, *93*, 4536.

(91) Applequist, D. E.; McKenzie, L. F. *J. Org. Chem.* **1976**, *41*, 2262.

(92) Schwartz, N.; Wilmarth, W. K. *J. Chem. Phys.* **1952**, *20*, 748.

(93) Kurz, M. E.; Ngoviwatchai, P. *J. Org. Chem.* **1981**, *46*, 4672.

(94) Thomas, M. J.; Foote, C. S., *Photochem. Photobiol.* **1978**, *27*, 683.

(95) Martelli, G.; Spagnolo, P.; Tiecco, M. *J. Chem. Soc. (B).* **1970**, 1413.

(96) Howard, J. A.; Ingold, K. U. *Can. J. Chem.* **1963**, *41*, 1744. (a) Kurz, M. E., Pellegrini, M. *J. Org. Chem.* **1970**, *35*, 990.

(97) Pearson, R. E.; Martin, J. C. *J. Am. Chem. Soc.* **1963**, *85*, 3142.

(98) Tanaseichuk, B. S.; Zhivechkova, L. A.; Ermishov, A. Yu. *Zh. Org. Khim.* **1972**, *8*, 768. (a) Behrman, E. J., *J. Am. Chem. Soc.* **1963**, *85*, 3478.

(99) Walling, C.; Rieger, A. L.; Tanner, D. D. *J. Am. Chem. Soc.* **1963**, *85*, 3129.

(100) Huyser, E. S. *J. Am. Chem. Soc.* **1960**, *82*, 394.

(101) Johnston, K. M.; Williams, G. H. *J. Chem. Soc.* **1960**, 1446.

(102) Fisher, T. H.; Meierhoefer, A. W. *J. Org. Chem.* **1978**, *43*, 220.

(103) Pearson, R. E.; Martin, J. C. *J. Am. Chem. Soc.* **1963**, *85*, 354. (a) Hodson, J. *Chemosphere* **1988**, *17*, 2339.

(104) Kooyman, E. C.; van Helden, R.; Bickel, A. F. *Proc. K. Ned. Akad. Wet. Ser. B: Palaentol., Geol., Phys., Chem.* **1953**, *56*, 75. (a) Gusten, H. Klasinc, L., Maric, D. *J. Atm. Chem.* **1984**, *2*, 83.

(105) Brownlie, I. T.; Ingold, K. U. *Can. J. Chem.* **1967**, *45*, 2419.

(106) Walling, C.; Rieger, A. L. *J. Am. Chem. Soc.* **1963**, *85*, 3134.

(107) Howard, J. A.; Ingold, K. U. *Can. J. Chem.* **1965**, *43*, 2724.

(108) Lee, K. H.; Teo, T. O. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1617.

(109) Netto-Ferreira, J. C.; Avellar, I. G. J.; Scaiano, J. C. *J. Org. Chem.* **1990**, *55*, 89.

(110) Olsen, F. P.; Sasaki, Y. *J. Am. Chem. Soc.* **1970**, *92*, 3810.

(111) Walling, C.; Clark, R. T., *J. Am. Chem. Soc.* **1974**, *96*, 4530.

(112) Tanner, D. D.; Arhart, R. J.; Blackburn, E. V.; Das, N. C.; Wada, N. *J. Am. Chem. Soc.* **1974**, *96*, 829.

(113) Howard, J. A.; Ingold, K. U. *Can. J. Chem.* **1963**, *41*, 2800.

(114) Kim, S. S.; Seo, J. S.; Yoon, M. H. *J. Org. Chem.* **1987**, *52*, 3691.

(115) Walling, C.; Gibian, M. J. *J. Am. Chem. Soc.* **1965**, *87*, 3361.

(116) Ingold, K. U. *Can. J. Chem.* **1963**, *41*, 2816.

(117) Lee, K. H. *J. Chem. Soc., Perkin Trans. 2* **1973**, 693.

(118) Janzen, E. G.; Hinton, R. D.; Kotake, Y. *Tetrahedron Lett.* **1992**, *33*, 1257.

(119) Howard, J. A.; Furimsky, E. *Can. J. Chem.* **1973**, *51*, 3738. (a) Krishnamurthi, T. K.; Venkatasubramanian, N. *Indian J. Chem.* **1978**, *16A*, 28.

(120) Baciocchi, E.; Giese, B.; Farshchi, H.; Ruzziconi, R. *J. Org. Chem.* **1990**, *55*, 5688.

(121) Sawaki, Y.; Ogata, Y. *J. Org. Chem.* **1984**, *49*, 3344.

(122) Kim, S. S.; Koo, H. M.; Choi, S. Y. *Tetrahedron Lett.* **1985**, *26*, 891. (a) Inoue, K.; Matsuura, T.; Saito, I. *Tetrahedron* **1985**, *41*, 2177.

(123) Kim, S. S.; Kim, C. J.; Toun, S. J.; Ra, H. S.; Lee, J. C. *Tetrahedron Lett.* **1991**, *32*, 4725.

(124) Lee, K. H.; Teo, T. O. *J. Chem. Soc., Perkin Trans. 2* **1973**, 689.

(125) Totherow, W. D.; Gleicher, G. J. *J. Am. Chem. Soc.* **1969**, *91*, 7150.

(126) Saito, I.; Matsuura, T.; Inoue, K. *J. Am. Chem. Soc.* **1983**, *105*, 3200.

(127) Chang, S.-C.; Gleicher, G. J. *J. Org. Chem.* **1975**, *40*, 3800.

(128) Das, P. K.; Encinas, M. V.; Steenken, S.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 4162.

(129) Mulder, P.; Saastad, O. W.; Griller, D. *J. Am. Chem. Soc.* **1988**, *110*, 4090.

(130) Gilliom, R. D.; Ward, B. F. *J. Am. Chem. Soc.* **1965**, *87*, 3944.

(131) Low, T. P.; Lee, K. H. *J. Chem. Soc. (B)* **1970**, 535.

(132) Srinivasan, C.; Kuthalingam, P.; Arumugam, N. *J. Chem. Soc., Perkin Trans. 2* **1980**, 170.

(133) Martin, M. M.; Gleicher, G. J. *J. Org. Chem.* **1963**, *28*, 3266.

(134) Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1982**, *104*, 1701.

(135) Walling, C.; Miller, B. *J. Am. Chem. Soc.* **1957**, *79*, 4181.

(136) Srinivasan, C.; Perumal, S.; Arumugam, N. *J. Chem. Soc., Perkin Trans. 2.* **1984**, 2065.

(137) Kennedy, B. R.; Ingold, K. U. *Can. J. Chem.* **1966**, *44*, 2381.

(138) Huang, R. L.; Lee, K. H. *J. Chem. Soc. (C)* **1966**, 935.

(139) Heiba, E. I.; Dessau, R. M.; Koehl, W. J. *J. Am. Chem. Soc.* **1969**, *91*, 138.

(140) Walling, C., Mcelhill, E. A. *J. Am. Chem. Soc.* **1951**, *73*, 2927.

(141) Huang, R. L.; Lee, H. H.; Ong, S. H. *J. Chem. Soc.* **1962**, 3336.

(142) Incremona, J. H.; Martin, J. C. *J. Am. Chem. Soc.* **1970**, *92*, 627.

(143) Hradil, J.; Chvalovsky, V. *Collect. Czech. Chem. Commun.* **1968**, *33*, 2029.

(144) Gleicher, G. J. *J. Org. Chem.* **1968**, *33*, 332.

(145) Jiang, X.-K.; Liu, W. W.-Z.; Wu, S.-H. *Tetrahedron* **1994**, *50*, 7503.

(146) Heberger, K. *J. Phys. Org. Chem.* **1994**, *7*, 244.

(147) Cadogan, J. I. G.; Sadler, I. H. *J. Chem. Soc. (B)* **1966**, 1191.

(148) Das, P. K.; Encinas, M. V.; Scaiano, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 4154.

(149) Miyashita, T.; Matsuda, M.; Iino, M. *Bull. Chem. Soc. Jpn.* **1975**, *48*, 3230.

(150) Pryor, W. A.; Gojon, G.; Church, D. F. *J. Org. Chem.* **1978**, *43*, 793.

(151) Howard, J. A.; Chenier, J. H. B. *J. Am. Chem. Soc.* **1973**, *95*, 3054.

(152) Chang, E. P.; Huang, R. L.; Lee, H. H. *J. Chem. Soc. (B)* **1969**, 878.

(153) Chess, E. K.; Schatz, B. S.; Gleicher, G. J. *J. Org. Chem.* **1977**, *42*, 752.

(154) Pryor, W. A.; Gojon, G.; Church, D. F. *J. Org. Chem.* **1978**, *43*, 793.

(155) da Silva-Correa, C. M., M.; Waters, W. A. *J. Chem. Soc. Perkin Trans. 2* **1972**, 1575.

(156) Sakurai, H.; Hayashi, S.-I.; Hosomi, A. *Bull. Chem. Soc. Jpn.* **1971**, *44*, 1945.

(157) Barton, S. C.; Bird, R. A.; Russell, K. E. *Can. J. Chem.* **1963**, *41*, 2737.
(158) Ito, O. *J. Am. Chem. Soc.* **1983**, *105*, 850.
(159) Lovins, R. E.; Anderson, L. J.; Keeper, R. M. *J. Org. Chem.* **1965**, *30*, 1577.
(160) Spagnolo, P.; Testaferri, L.; Tiecco, M. *J. Chem. Soc. (B)* **1971**, 2006.
(161) Sakurai, H.; Hosomi, A. *J. Am. Chem. Soc.* **1967**, *89*, 458.
(162) Tanner, D. D.; Osman, A. A. *J. Org. Chem.* **1987**, *52*, 4689.
(163) Ito, O.; Fleming, M. D. C. M. *J. Chem. Soc., Perkin Trans. 2* **1989**, 689.
(164) Church, D. F.; Gleicher, G. J. *J. Org. Chem.* **1975**, *40*, 536.
(165) Russell, G. A. *J. Am. Chem. Soc.* **1956**, *78*, 1047.
(166) Huang, R. L.; Lee, L. H. *J. Chem. Soc.* **1964**, 5963.
(167) Pryor, W. A.; Lin, T. H.; Stanley, J. P.; Henderson, R. W. *J. Am. Chem. Soc.* **1973**, *95*, 6993.
(168) Walling, C.; McGuinness, J. A. *J. Am. Chem. Soc.* **1969**, *91*, 2053.
(169) Kim, S. S.; Sohn, S. C. *Tetrahedron lett.* **1982**, *23*, 3703.
(170) Jones, M. J.; Moad, G.; Rizzardo, E.; Solomon, D. H. *J. Org. Chem.* **1989**, *54*, 1607.
(171) Geers, B. N.; Gleicher, G. J.; Church, D. F. *Tetrahedron.* **1980**, *36*, 997.
(172) Cooper, W. *J. Chem. Soc.* **1951**, 3106.
(173) Howard, J. A.; Ingold, K. U.; Symonds, M. *Can. J. Chem.* **1968**, *46*, 1017.
(174) Anbar, M.; Meyerstein, D.; Neta, P. *J. Phys. Chem.* **1966**, *70*, 2660.
(175) Swain, C. G.; Stockmayer, W. H.; Clarke, J. T. *J. Am. Chem. Soc.* **1950**, *72*, 5426.
(176) Schaap, A. P.; Gagnon, S. D.; Zaklika, K. A. *Tetrahedron Lett.* **1982**, *23*, 2943. (a) Walling, C.; Briggs, E. R.; Wolfstirn, K. B. *J. Am. Chem. Soc.* **1948**, *70*, 1543.
(177) Murofushi, K.; Abe, K.; Hirota, M. *J. Chem. Soc., Perkin Trans. 2* **1987**, 1829.
(178) LaHousse, F.; Merenyi, R.; Desmurs, J. R; Allaime, H.; Borghese, A; Viehe, H. G. *Tetrahedron Lett.* **1984**, *25*, 3823.
(179) Ito, R.; Migita, T.; Morikawa, N.; Shimamura, O. *Tetrahedron* **1965**, *21*, 955. (a) Kim, S. S.; Yang, K. W.; Lee, C. S. *J. Org. Chem.* **1996**, *61*, 4827.
(180) Camaggi, C. M.; Leardini, R.; Tiecco, M.; Tundo, A. *J. Chem. Soc. (B)* **1970**, 1683.
(181) Jonsson, M.; Lind, J.; Eriksen, T. E.; Merenyi, G. *J. Am. Chem. Soc.* **1994**, *116*, 1423.
(182) Tanner, D. D.; Reed, D. W.; Setiloane, B. P. *J. Am. Chem. Soc.* **1982**, *104*, 3917.
(183) Walsh, E. J.; Kuivila, H. G. *J. Am. Chem. Soc.* **1966**, *88*, 576.
(184) Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1981**, *103*, 5871.
(185) Fiorentino, M.; Testaferri, L.; Tiecco, M.; Troisi, L. *J. Org. Chem.* **1976**, *41*, 173.
(186) Galli, C. *J. Chem. Soc., Perkin Trans. 2* **1984**, 897.
(187) Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1983**, *105*, 1937.
(188) Nakamura, M.; Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1980**, *102*, 698.
(189) Ito, O.; Matsuda, M. *J. Am. Chem. Soc.* **1979**, *101*, 5732.
(190) Grady, G.; Saucier, J. R.; Foley, W. J., III; O'Hern, D. J.; Weidmann, W. J. *J. Organomet. Chem.* **1972**, *35*, 307.
(191) Ito, O.; Omori, R.; Matsuda, M. *J. Am. Chem. Soc.* **1982**, *104*, 3934.
(192) Fiorentino, M.; Testaferri, L.; Tiecco, M.; Troisi, L. *J. Chem. Soc., Perkin Trans 2* **1977**, 87. (a) Caronna, T.; Fronza, G.; Minisci, F.; Porta, D.; Gardini, G. P. *J. Chem. Soc., Perkin Trans. 2* **1972**, 1477.
(193) Minisci, F.; Mondelli, R.; Gardini, G. P.; Porta, O. *Tetrahedron* **1972**, *28*, 2403.
(194) Ito, O.; Furuya, S.; Matsuda, M. *J. Chem. Soc., Perkin Trans. 2* **1984**, 139.
(195) Ito, O.; Matsuda, M. *J. Org. Chem.* **1982**, *47*, 2261.
(196) Wagner, P. J.; Truman, R. J.; Puchalski, A. E.; Wake, R. *J. Am. Chem. Soc.* **1986**, *108*, 7727.
(197) Walling, C.; Seymour, D.; Wolfstirn, K. B. *J. Am. Chem. Soc.* **1948**, *70*, 1544.
(198) Blomquist, A. T.; Buselli, A. J. *J. Am. Chem. Soc.* **1951**, *73*, 3883.
(199) Kurz, M. E.; Baru, V.; Nguyen, P.-N. *J. Org.Chem.* **1984**, *49*, 1603.
(200) Ballester, M.; Pascual, I.; Torres, J. *J. Org. Chem.* **1990**, *55*, 3035.
(201) Mukai, K.; Yokoyama, S.; Fukuda, K.; Uemoto, Y. *Bull. Chem. Soc. Jpn.* **1987**, *60*, 2163
(202) Bolton, R.; Sandall, J. P. B.; Williams, G. H. *J. Chem. Res. (S)* **1977**, 24.
(203) Fischer, T. H.; Dershem, S. M.; Prewitt, M. L. *J. Org. Chem.* **1990**, *55*, 1040.
(204) Wilmarth, W. K.; Schwartz, N. *J. Am. Chem. Soc.* **1955**, *77*, 4543.
(205) Kresze, G.; Schramm, W.; Cleve, G. *Chem. Ber.* **1961**, *94*, 2060.
(206) Clennam, E. L.; Yang, K.; Chen, X. *J. Org. Chem.* **1991**, *56*, 5251.
(207) Van Helden, R.; Kooyman, E. C. *Recl. Trav. Chim. Pays-Bas.* **1954**, *73*, 269.
(208) Lee, K. H. *Tetrahedron* **1970**, *26*, 2041.
(209) Michejda, C. J.; Campbell, D. H. *J. Am. Chem. Soc.* **1979**, *101*, 7687.
(210) Friedrich, S. S.; Andrews, L. J.; Keefer, R. M. *J. Org. Chem.* **1970**, *35*, 944.
(211) Polumbric, O.; Zaika, E. *Organic Reactivity.* EE. **1977**, *14*, 388.
(212) Jones, B. *J. Chem. Soc.* **1935**, 1835.
(213) Jones, B. *J. Chem. Soc.* **1941**, 267.
(214) Jones, B. *J. Chem. Soc.* **1941**, 358.
(215) Jones, B. *J. Chem. Soc.* **1938**, 1414.
(216) Walling, C.; Jacknow, B. *J. Am. Chem. Soc.* **1960**, *82*, 6113.
(217) Lee, K. H. *Tetrahedron* **1968**, *24*, 4793.
(218) Jones, B. *J. Chem. Soc.* **1936**, 1854.
(219) Sawaki, Y.; Ishikawa, S. *J. Am. Chem. Soc.* **1987**, *109*, 584.
(220) Martin, M. M.; Gleicher, G. J. *J. Am. Chem. Soc.* **1964**, *86*, 233.
(221) Lee, K. H. *Tetrahedron* **1970**, *26*, 1503.
(222) Avila, D. V.; Ingold, K. U.; Lusztyk, J.; Dolbier, W. R.; Pan, H.-Q.; Muir, M. *J. Am. Chem. Soc.* **1994**, *116*, 99.
(223) Schaafsma, Y.; Bickel, A. F.; Kooyman, E. C. *Recl. Trav. Chim. Pays-Bas.* **1957**, *76*, 180.
(224) Sakurai, H.; Hosomi, A.; Kumada, M. *J. Org. Chem.* **1970**, *35*, 993.
(225) Russell, G. A.; Williamson, R. C., Jr. *J. Am. Chem. Soc.* **1964**, *86*, 2357.
(226) Smith, J. R. L.; Mortimer, D. N., *J. Chem. Soc., Perkin Trans. 2* **1986**, 1743.
(227) Shevchuk, L. G.; Zhikharev, V. S.; Vysotskaya, N. A. *Zh. Org. Khim.* **1969**, *5*, 1606.
(228) Huang, R. L.; Lee, H. H.; Malhotra, M. S. *J. Chem. Soc.* **1964**, 5947.
(229) Sakurai, H.; Mochida, K. *J. Organomet. Chem.* **1972**, *42*, 339.
(230) Dickerman, S. C.; Desouza, D. J.; Fryd, M.; Megna, I. S. *J. Org. Chem.* **1969**, *34*, 714.
(231) Goerner, R. N.; Cote, P. N.; Vittimberga, B. M. *J. Org. Chem.* **1977**, *42*, 19.
(232) Blackburn, E. V.; Tanner, D. D. *J. Am. Chem. Soc.* **1980**, *102*, 692.
(233) Lee, K.-W.; Brown, T. L. *J. Am. Chem. Soc.* **1987**, *109*, 3269.
(234) Orochov, A.; Asscher, M.; Vofsi, D. *J. Chem. Soc. (B).* **1969**, 255.
(235) Grady, G. L.; Danyliw, T. J.; Rabideux, P. *J. Organomet. Chem.* **1977**, *142*, 67.
(236) Yamamoto, T. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 642.
(237) Alfassi, Z. B.;Marguet, S.; Neta, P. *J. Phys. Chem.* **1994**, *98*, 8019.
(238) Yamamoto, T.; Otsu, T. *J. Polym. Sci. (A1).* **1969**, *7*, 1279.
(239) Lamb, R. C.; Sanderson, J. R. *J. Am. Chem. Soc.* **1969**, *91*, 5034.
(240) Shelton, R. J.; Uzelmeier, C. W. *J. Am. Chem. Soc.* **1966**, *88*, 5222.
(241) El Zein, M.; Gardrat, C.; Maillard, G. B. *Bull. Soc. Chim. Belg.* **1978**, *87*, 67.
(242) Haider, K. W.; Clites, J. A.; Berson, J. A. *Tetrahedron Lett.* **1991**, *32*, 5305.
(243) Testaferri, L.; Tiecco, M.; Spagnolo, P.; Zanirato, P.; Martelli, G. *J. Chem. Soc., Perkin Trans. 2* **1976**, 662.
(244) Suehiro, T.; Kanoya, A.; Hara, H.; Nakahama, T.; Omori, M.; Komori, T. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 668.
(245) Yamamoto, T.; Hasegawa, M.; Otsu, T. *Bull. Chem. Soc. Jpn.* **1969**, *42*, 1364.
(246) Tomaselli, G. A.; Cui, J. J.; Chen, Q. F.; Bunnett, J. F. *J. Chem. Soc., Perkin Trans. 2* **1992**, 9.
(247) Giese, B.; Meixner, J. *Chem. Ber.* **1981**, *114*, 2138.
(248) Shima, M.; Bhattacharyya, D. N.; Smid, J.; Szwarc, M. *J. Am. Chem. Soc.* **1963**, *85*, 1306.
(249) Tratnyek, P. G., Hoigne, J. *Water Res.* **1994**, *28*, 57.
(250) Gilliom, R. D.; Howles, J. R. *Can. J. Chem.* **1968**, *46*, 2752.
(251) Neta, P.; Madhavan, V.; Zemel, H.; Fessenden, R. W. *J. Am. Chem. Soc.* **1977**, *99*, 163.
(252) Tratnyek, P. G.; Hoigne, *J. Environ. Sci. Technol.* **1991**, *25*, 1596.
(253) Pryor, W. A.; Tang, F. Y.; Tang, R. H.; Church, D. F. *J. Am. Chem. Soc.* **1982**, *104*, 2885.
(254) Danen, W. C.; Saunders, D. G.; Rose, K. A. *J. Am. Chem. Soc.* **1973**, *95*, 1612. (a) Imoto, M.; Kinoshita, M.; Nishigaki, M. *Makromol. Chem.* **1966**, *94*, 238.
(255) Tsuda, K.; Otsu, T. *Bull. Chem. Soc. Jpn.* **1966**, *39*, 2206.
(256) Kuivila, H. G.; Walsh, E. J. *J. Am. Chem. Soc.* **1966**, *88*, 571.
(257) Frimer, A. A.; Farkash-Solomon, T.; Alhadeffe, G. *J. Org. Chem.* **1986**, *51*, 2093.
(258) Shelton, R. J.; Liang, C. K. *J. Org. Chem.* **1973**, *38*, 2301.
(259) Job, D.; Dunford, H. B. *Eur. J. Biochem.* **1976**, *66*, 607.
(260) Huang, J.; Dunford, H. B. *Can. J. Chem.* **1990**, *68*, 2159.
(261) Roe, J. A.; Goodin, D. B. *J. Biol. Chem.* **1993**, *268*, 20037.
(262) Galliani, G.; Rindone, B. *Bioorg. Chem.* **1981**, *10*, 283.
(263) Dunford, H. B.; Adeniran, A. J.; *Arch. Biochem. Biophys.* **1986**, *251*, 536.
(264) Xu, F. *Biochemistry* **1996**, *35*, 7608.
(265) Ryu, K.; Dordick, J. S. *Biochemistry* **1992**, *31*, 2588.
(266) Sakurada, J.; Sekiguchi, R.; Sato, K.; Hosoya, T. *Biochemistry* **1990**, *29*, 4093.
(267) Dewhirst, F. E. *Prostaglandins.* **1980**, *20*, 209.
(268) Corbett, M. D.; Baden, D. G.; Chipko, B. R. *Bioorg. Chem.* **1979**, *8*, 91.
(269) Venger, B. H.; Hansch, C.; Hatheway, G. J.; Amrein, Y. U. *J. Med. Chem.* **1979**, *22*, 473.

(270) Counsell, R. E.; Desai, P.; Smith, T. D.; Chan, P. S.; Weinhold, P. A.; Rethy, V. B.; Burke, D. *J. Med. Chem.* **1970**, *13*, 1040.
(271) Lucini, R.; Orlandi, M.; Rindone, B. *J. Mol. Catal.* **1993**, *85*, 97.
(272) Kobayashi, S.; Nakano, M.; Goto, T.; Kimura, T.; Schaap, P. A. *Biochem. Biophys. Res. Commu.* **1986**, *135*, 166.
(273) Zhang, H.; Dunford, H. B. *Can. J. Chem.* **1993**, *71*, 1990.
(274) Bordeleau, L. M.; Bartha, R. *Can. J. Microbiol.* **1972**, *18*, 1873.
(275) Singh, P.; Goyal, A. *Arzneim.-Forsch.* **1987**, *37*, 51.
(276) Davidson, V. L.; Jones, L. H.; Graichen, E. M. *Biochemistry* **1992**, *31*, 3385.
(277) Blake, R. C.; Coon, M. J. *J. Biol. Chem.* **1981**, *256*, 12127.
(278) Paris, D. F.; Wolfe, N. L. *Appl. Environ. Microbiol.* **1987**, *53*, 911.
(279) Fruetel, J. A.; Mackman, R. L.; Peterson, J. A.; Ortiz de Montallano, P. R. *J. Biol. Chem.* **1994**, *269*, 28815.
(280) Ali, A.; Robinson, J. B. *J. Pharm. Pharmacol.* **1991**, *43*, 750.
(281) Burton, D. E.; Clark, K.; Gray, G. W. *J. Chem. Soc.* **1964**, 1314.
(282) Blee, E.; Schuber, F. *Biochemistry* **1989**, *28*, 4962.
(283) Oglesby, L. A.; Eborn-McCoy, M. T.; Logsdon, T. R.; Copeland, F.; Beyer, P. E.; Kavlock, R. J. *Teratology* **1992**, *45*, 11.
(284) Kavlock, R. J. *Teratology* **1990**, *41*, 43. (a) Drobnica, L.; Zemanova, M.; Nemec, P.; Antos, K.; Kristian, P.; Stullerova, A.; Knoppova, V.; Nemec, P., Jr. *Appl. Microbiol.* **1967**, *15*, 701.
(285) Kobayashi, S.; Nakano, M.; Kimura, T.; Schaap, A. P. *Biochemistry* **1987**, *26*, 5019.
(286) Harada, A.; Hanazawa, M.; Saito, J.; Hashimoto, K. *Environ. Toxicol. Chem.* **1992**, *11*, 973.
(287) Dunn, W. J.; Greenberg, M. J.; Callejas, S. S. *J. Med. Chem.* **1976**, *19*, 1299.
(288) Watanabe, Y.; Iyanagi, T.; Oae, S. *Tetrahedron Lett.* **1982**, *23*, 533.
(289) Zeller, E. A. *Ann. N.Y. Acad. Sci.* **1963**, *107*, 811.
(290) Hellerman, L.; Erwin, V. G. *J. Biol. Chem.* **1968**, *243*, 5234.
(291) Ichikawa, Y.; Yamano, T.; Fujishima, H. *Biochim. Biophys. Acta* **1969**, *171*, 32.
(292) Hansch, C. and Kerley, R. *J. Med. Chem.* **1970**, *13*, 957.
(293) Saleem, M. M. M.; Wilson, M. T. *Biochem. J.* **1982**, *201*, 433.
(294) Kelder, P. P.; De Mol, N. J.; Fischer, M. J. E.; Janssen, L. H. M. *Biochim. Biophys. Acta* **1994**, *1205*, 230.
(295) Kettle, A. J., Winterbourn, C. C. *Biochem. Pharmacol.* **1991**, *41*, 1485.
(296) Komives, E. A.; Ortiz de Montellano, P. R. *J. Biol. Chem.* **1987**, *262*, 9793.
(297) Clement, B.; Zimmermann, M. *Biochem. Pharmacol.* **1988**, *37*, 4747.
(298) Lewis, D. F. V.; Ioannides, C.; Parke, D. V. *Biochem. Pharmacol.* **1995**, *50*, 619.
(299) Vaz, A. D. N.; Coon, M. J. *Biochem.* **1994**, *33*, 6442.
(300) Neims, A. H.; Deluca, D. C.; Hellerman, L. *Biochemistry* **1966**, *5*, 203.
(301) Duckworth, H. W.; Coleman, J. E. *J. Biol. Chem.* **1970**, *245*, 1613.
(302) Detmer, K.; Massey, V. *J. Biol. Chem.* **1985**, *260*, 5998.
(303) Peelen, S.; Rietjens, M. C. M.; Boersma, M. G.; Vervoort, J. *Eur. J. Biochem.* **1995**, *227*, 284.
(304) Watanabe, Y.; Oae, S.; Iyanagi, T. *Bull. Chem. Soc. Jpn.* **1982**, *55*, 188.
(305) Walker, M. C.; Ednondson, D, E. *Biochemistry* **1994**, *33*, 7088.
(306) Bommarius, A. S.; Hatton, A. T.; Wang, D. I. C. *J. Am. Chem. Soc.* **1995**, *117*, 4515.
(307) Tatsumi, K.; Kitamura, S.; Yoshimura, H.; Kawazoe, Y. *Chem. Pharm. Bull.* **1978**, *26*, 1713.
(308) Kitamura, S.; Narai, N.; Tatsumi, K. *J. Pharm. Dyn.* **1983**, *6*, 18.
(309) Clarke, E. D.; Goulding, K. H.; Wardman, P. *Biochem. Pharmacol.* **1982**, *31*, 3237.
(310) Yamamoto, T.; Otsu, T. *J. Polym. Sci. B* **1966**, *4*, 1039.
(311) Otsu, T.; Kinoshita, Y.; Imoto, M.; *Makromol. Chem.* **1964**, *73*, 225.
(312) Yamamoto, T.; Hasegawa, M.; Otsu, T. *Bull. Chem. Soc. Jpn.* **1968**, *41*, 2788.
(313) Pryor, W. A.; Davis, W. H., Jr.; Gleaton, J. H. *J. Org. Chem.* **1975**, *40*, 2099.
(314) Klopman, G. *Helv. Chim. Acta* **1961**, *44*, 1908.
(315) Tokumura, K.; Ozaki, T.; Nosaka, H.; Saigusa, Y.; Itoh, M. *J. Am. Chem. Soc.* **1991**, *113*, 4974. (a) Yamamoto, T.; Otsu, T. *J. Polym. Sci.* **1968**, *6*, 49.
(316) Neumann, W. P.; Penenory, A.; Stewen, U.; Lehnig, M. *J. Am. Chem. Soc.* **1989**, *111*, 5845.
(317) Hansch, C. *J. Med. Chem.* **1968**, *11*, 920. (a) Williams, G. H. *Homolytic Aromatic Substitution*; Pergamon: New York, NY, 1960.
(318) Cross, B.; Hoffman, P. P.; Santora, G. T.; Spatz, D. M.; Templeton, A. R. *J. Agric. Food. Chem.* **1983**, *31*, 260.
(319) Carter, D. V.; Charlton, P. T.; Fenton, A. H.; Housley, J. R.; Lessel, B. *J. Pharm. Pharmacol.* **1958**, *10*, 149.
(320) Creary, X.; Mehrsheikh-Mohammadi, M. E.; McDonald, S. *J. Org. Chem.* **1989**, *54*, 2904.
(321) Atkinson, R. *Chem. Rev.* **1986**, *86*, 69.
(322) Atkinson, R.; Aschmann, S. M.; Pitts, J. N., Jr. *J. Phys. Chem.* **1988**, *92*, 3454.
(323) Sabljic, A.; Güsten, H. *Atmos. Environ.* **1990**, *24A*, 73.
(324) Güsten, H.; Medven, Z.; Sekusak, S.; Sabljic, A. *SAR QSAR Environ. Res.* **1995**, *4*, 197.
(325) Medven, Z.; Güsten, H.; Sabljic, A. *J Chemom.* **1996**, *10*, 135.
(326) DeMore, W. B. *J. Phys. Chem.* **1996**, *100*, 5813.

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