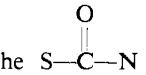
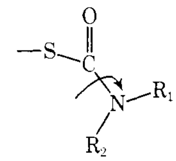
Proton Magnetic Resonance Spectroscopy of Thiocarbamate Herbicides

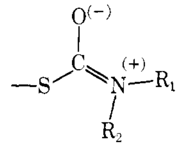
F. H. A. Rummens* and F. J. A. Louman

The 60 MHz proton nmr spectra of eight commercial thiocarbamate herbicides have been measured and analyzed. Measurements at variable temperature show that the rate of rotation around the C—N bond is strongly temperature dependent and differently so for each compound. The coalescence temperature t_c (*i.e.*, the transition point between free and frozen-out rotation on the nmr time scale) is a characteristic number for each compound that is directly related to the polarity of the  $S—\overset{O}{\overset{\|}{C}}—N$ moiety. Certain more indirect relations between t_c and other physical, chemical, and biological properties of thiocarbamates are also discussed.

Thiocarbamates contain an amide-type grouping of which the C—N bond has a certain degree of double bond character. The following two resonance structures can be drawn:



I



II

Structure I is characterized by low polarity and essentially free rotation around the C—N bond, while II is highly polar with a rigid planar structure. The real structure is of course a hybrid between I and II, with a sizable energy barrier to the rotation. This barrier (roughly 15 kcal per mole) can be crossed but k, the rotation rate, will be temperature dependent. It also happens that k is of the same order of magnitude as the inverse of the nmr relaxation times (*i.e.*, the time needed for a proton to go from one energy state to another).

Suppose now that R_1 and R_2 are two identical alkyl groups, say $R_1 = R_2 = CH_3$. At a sufficiently low temperature, k will be much smaller than τ^{-1} (τ being the relaxation time of the methyl protons). Then one of the methyl groups is long enough at the R_2 position (structure II) to undergo several nuclear spin transitions while being there, and it has ample opportunity to "see" its chemical environment (*cis* to an S-R group and *trans* to $C\text{-}O^{(-)}$). Similarly, and at the same time, the other methyl group spends a sufficiently long time at the R_1 (II) position to "see" its environment. Since the two methyl groups have a different chemical (and therefore magnetic) environment, they will exhibit two different chemical shifts (two peaks). At a sufficiently high temperature, however, k will be significantly larger than τ^{-1}, *i.e.*, the methyl groups switch positions several times during each spin transition. As a result, each methyl group "sees" the same averaged environment and consequently the nmr spectrum will show the two methyl groups with the same (average) chemical shift (one peak).

Furthermore, there is also the intermediate temperature range where $k \approx \tau^{-1}$ and where the two lines broaden then coalesce to one broad peak, which then sharpens up at higher temperatures. The transition point at the coalescence temperature t_c is sharply defined and can be measured readily.

While the above is well known and described more extensively in standard nmr literature (Jackman and Sternhell, 1969) an interesting further corrolary can be made. Within the nmr time scale the molecule has structure II at temperatures below t_c and structure I at temperatures above t_c. Or, to put it in other terms, a high t_c means that the molecule has more polar character (at any specified temperature) than a molecule of lower t_c. Since polarity is, at least potentially, related to such properties as solubility, adsorptivity (on soil), and chemical or microbial degradation, establishment of a relative order of coalescence temperatures could be useful to predict certain trends in these properties.

EXPERIMENTAL

All spectra were taken from 10% (v/v) solutions in $CDCl_3$ to which 1% of tetramethyl silane (TMS) was added as a reference. A Varian A-60A spectrometer equipped with a variable temperature probe was used. The probe temperatures were calibrated according to the method of Van Geet (1968). Temperature accuracy is believed to be within ±1° C, which could lead to a systematic error of up to 1° C in our t_c scale. Graphical methods with a readability of ±0.2° C were employed for the determination of t_c. The maximum random error in t_c for a single measurement is thought to be ±1° C. Repeated measurements gave average deviations ±0.6° C or less for each t_c. For this reason, t_c values were rounded off to the nearest whole degree (except for vernolate). Spectra were analyzed by standard (first order) methods, employing integrated intensities, spin-spin splitting, and chemical shift effects. The chemical shifts quoted in Table I are those from the high-temperature (free rotation) spectra (60° C for molinate, 37° C for all other compounds).

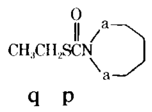
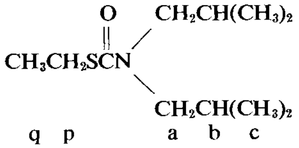
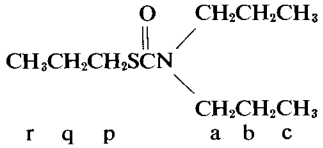
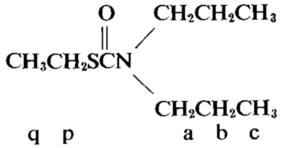
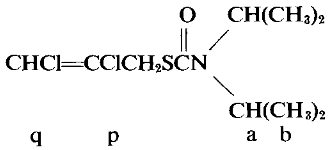
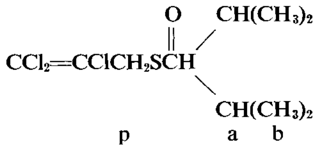
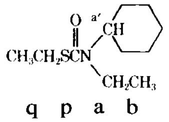
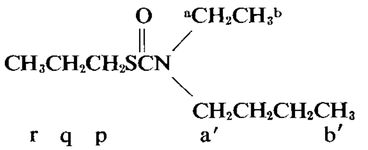
RESULTS AND DISCUSSION

All chemical shift and t_c data are tabulated in Table I, together with some other data taken from a recent compilation (Fang, 1969). (This compilation contains an apparent error; the solubility of diallate is 14 ppm, not 40 ppm.) Listing of compounds in Table I is in order of decreasing coalescence temperature. All chemical shifts were found within their empirical expectation ranges (Jackman and Sternhell, 1969). For some protons the signals were too complex (due to strong spin-spin coupling) to allow for a meaningful first order estimate of their chemical shift. Data for such protons have therefore been omitted from Table I. Diallate consisted of *cis*- and *trans*-isomers in an approximate 5:6 ratio. (Nmr provides an excellent means for the accurate determination of this *cis*/*trans* concentration ratio. The

---

Chemistry Department, University of Saskatchewan Regina Campus, Regina (Saskatchewan), Canada.
* To whom correspondence should be addressed.

Table I. Nmr Data and Other Properties of Thiocarbamate Herbicides

Name	Structure	Chemical Shift (ppm) a	b	c	p	q	r	t_c °C	Boiling point °C	Solubility in H_2O ppm	Acute oral LD_{50} mg/kg (rats)
S-Ethyl hexahydro-1*H*-azepine 1-carbothioate (R-4572, molinate, ordram)		3.50			2.84	1.28		+35	137	912	720
S-Ethyl diisobutyl-thiocarbamate (R-1910, Sutan)		3.20	2.05	0.91	2.90	1.27		+7	138 (21 mm)	45 (22° C)	3998
S-*n*-Propyl *N*,*N*-di-*n*-propyl-thiocarbamate (vernolate, Vernam)		3.30	1.63	0.90	2.89	1.6	0.99	+5.5	140 (20 mm)	107 (21° C)	1780
S-Ethyl *N*,*N*-di-*n*-propyl-thiocarbamate (EPTC, Eptam)		3.26	1.60	0.90	2.88	1.27		+5	127 (20 mm)	375 (20° C)	1630
S-2,3-Dichloroallyl *N*,*N*-diisopropylthiocarbamate (diallate)		3.84	1.31		3.88 4.07	6.53 6.25		+5	150 (9 mm)	14	395
S-Trichloroallyl *N*,*N*-diisopropyl thiocarbamate (triallate)		3.80	1.32		4.11			+5		4	1570
S-Ethyl *N*-ethyl-*N*-cyclo-hexylthiocarbamate (R-2063, Ro-Neet)		3.33 3.90 (a′)	1.18		2.90	1.28		+1	146 (10 mm)	85 (22° C)	3190
S-*n*-Propyl *N*-ethyl-*N*-*n*-butylthiocarbamate (PEBC, pebulate, Tillam)		3.40 3.33 (a′)	1.17 0.95 (b′)		2.88	1.6	0.98	−1	142 (20 mm)	92 (21° C)	1102

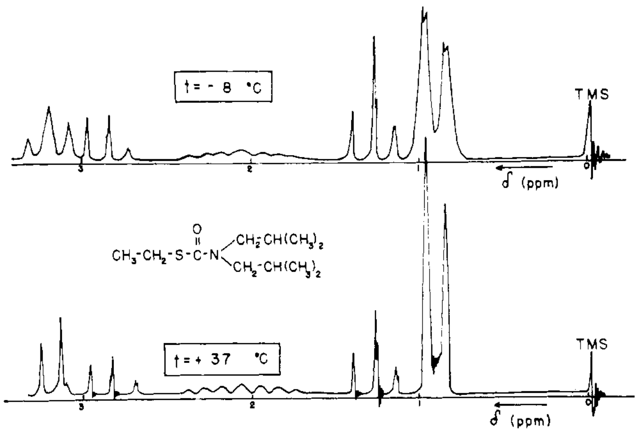


Figure 1. The 60 MHz proton nmr spectrum of R-1910 (Sutan) at two temperatures

olefinic proton signals are single lines, only slightly split by long-range coupling to the CH_2-S group and are well separated in chemical shift, thus allowing for accurate signal integration.)

Figure 1 shows both the high-temperature and the low-temperature spectra of R-1910 (Sutan).

In Figure 2 the nmr spectrum near $\delta = 3$ ppm of R-1910 (Sutan) is given for a number of temperatures, showing the coalescing process of the CH_2—N protons. The coalescence temperature can be directly determined by inspection of a series of spectra, taken at temperatures close to t_c, but it can also be found by measuring relative peak heights of coalescing and noncoalescing signals. In Figure 2 this is shown for the S-CH_2 and N-CH_2 signals. In the case of R-1910, t_c could also be found from the relative peak height of the isopropyl CH_3-protons (see Figure 1). Our variable temperature measurements also served as an invaluable tool for the assignment of the nmr signals to the proper protons in the molecule. Particularly when the S-R and N-R alkyl groups are equal (such as in vernolate for instance), the chemical shift differences will be so small as to disallow assignment along empirical lines. Such signals can be easily sorted out, however, by observing which signals stay sharp (S-R group) and which signals broaden or split (N-R groups) at lower temperatures.

The data of Table I lead to the following observations.

Molinate combines an exceptionally high coalescence temperature with the highest water-solubility and with a very high boiling point, in line with expectation, if one equates coalescence temperature to polarity. For the other compounds, the correlation of t_c with boiling point and solubility is crude at best; other effects like length of alkyl chain or incorporation of a chloroallylic group do influence the latter considerably, while being of little importance for the coalescence temperature.

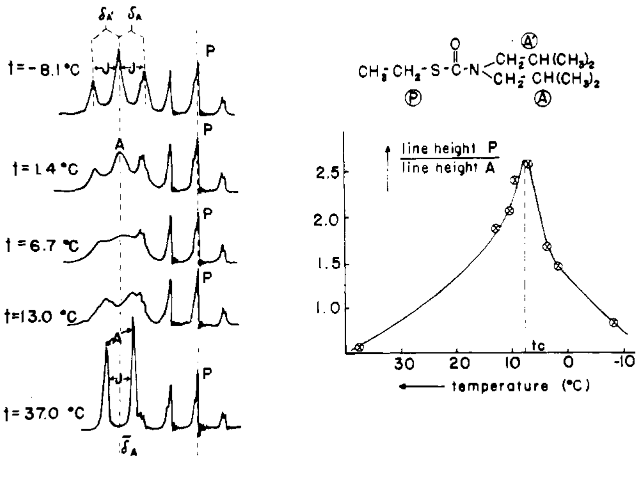


Figure 2. Determination of the coalescence temperature of R-1910 (Sutan) by two different methods

Coalescence temperatures of the aliphatic-substituted compounds R-1910, vernolate, EPTC, and pebulate seem to correlate well with toxicity.

The general herbicidal activity of the compounds studied is as follows (Gray, 1969): EPTC > vernolate > R-2063 > pebulate > R-1910 > molinate > diallate > triallate. A comparison of t_c with general herbicidal activity shows the absence of any correlation.

Little is known about the mechanism of the microbial degradation of the thiocarbamates, but it has been suggested (Fang, 1969) that the process starts with an attack on the C-N bond in which case t_c data might be expected to be of some relevance. Preliminary data (Smith, 1969) show that for EPTC, vernolate, diallate, and triallate (which all have a coalescence temperature of about 5° C) the rate of microbial degradation in moist soils is about the same for EPTC, vernolate, and diallate, while somewhat higher for triallate, indicating a partial correlation.

The rate of chemical degradation of diallate, triallate, EPTC, vernolate, and pebulate in $10N$ sulfuric acid, where indeed a C-N bond cleavage is observed, shows no correlation (Smith, 1969) with the coalescence temperatures. This, however, is not surprising, since at $10N\ H_2SO_4$ thiocarbamates are protonated (Rummens, 1969) so that the C—N bond has no partial double bond character anymore.

Koren *et al.* (1969) reported that the adsorptivity on soil is in the order pebulate > R-2063 > EPTC (independent of the adsorbent). This order is opposed to that of the coalescence temperatures. Since adsorptivity studies deal with a two-phase system of water and solid adsorbent, this is not entirely unexpected. An increase in polarity (higher t_c) results in a higher affinity for both phases, and it is difficult to decide beforehand which effect will predominate. Interesting in this respect is the finding (Freed *et al.*, 1967) that thiocarbamates have a negative heat of solution in water. The increasing solubility with decreasing temperature can be readily understood from the model we have given, which states that at lower temperature these molecules acquire a higher polarity (more contribution of the resonance form II). Apparently in water this counteracting effect is rather strong, strong enough in fact to reverse the normal solubility behavior. It is then quite conceivable that an increased affinity for water (either by lowering the temperature of one particular thiocarbamate or by choosing molecules with a higher t_c) is more important than the increased affinity for an adsorbent. The above reasoning might be taken as a tentative explanation of the inverse correlation between adsorptivity and coalescence temperature noted above.

Leaching of thiocarbamates in soil has also been reported (Gray and Weierich, 1968). These data on leaching depth correlate better with solubility than with our t_c data. For a transport property of poorly soluble material this is reasonable, but it does not preclude a possibly different behavior under equilibrium conditions.

CONCLUSION

In this paper we have pointed to the fact that the structure (and all other properties) of the thiocarbamates is inherently dependent upon temperature. This may have wide-ranging consequences. Field studies on herbicidal activity, degradation, leaching, evaporation, etc., will have to take the field temperature into account. Optimum timing of field application as well as the recommended rate may well depend on the prevailing temperatures. In the more theoretical area, a possible explanation has been given as to why thiocarbamate properties such as solubility, heat of solution, adsorptivity, and rate of leaching are sometimes puzzling, anomalous, and often lacking in intercorrelation. To sort out quantitatively the various effects discussed will require extensive further work, particularly in the area of thermodynamic properties.

ACKNOWLEDGMENT

We are indebted to the staff of the Research Station, Canada Department of Agriculture (Regina), in particular A. E. Smith, for many useful discussions. We thank the Stauffer Chemical Co. for samples of several thiocarbamates.

LITERATURE CITED

Fang, S. C., in "Degradation of Herbicides," Chap. 5, Thiolcarbamates, D. D. Kaufman, Ed., Marcel Dekker, New York (1969).
Freed, V. H., Hague, H., Vernetti, J., J. AGR. FOOD CHEM. **15**, 1121 (1967).
Gray, R. A., Stauffer Chemical Co., private communication (1969).
Gray, R. A., Weierich, A. J., *Weed Sci.* **16**, 77 (1968).
Jackman, L. M., Sternhell, S., "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," 2nd ed., Pergamon, London, New York (1969).
Koren, E., Foy, C. L., Ashton, F. M., *Weed Sci.* **17**, 148 (1969).
Rummens, F. H. A., unpublished nmr study (1969).
Smith, A. E., Canada Dept. of Agriculture, Regina (Sask.), private communication (1969).
Van Geet, A. L., *Anal. Chem.* **40**, 2227 (1968).

Received for review February 3, 1970. Accepted August 18, 1970. This study was funded from an NRC operating research grant.