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HYDROLYTIC BEHAVIOR OF SOME ALUMINUM ANTIPERSPIRANT MATERIALS IN ACID

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SUMMARY

The hydrolysis rates of a series of aluminum chlorohydrate materials in hydrochloric acid solutions were studied using a colorimetric procedure. In acidic solutions, these materials exist as polynuclear hydroxy complexes that hydrolyze to monomeric aluminum species at rates which are related to their aluminum to chlorine ratios (basicity) and the pH of the solution. In general, the slower the observed hydrolytic rate the greater was the atomic ratio of aluminum to chlorine. The fraction of polynuclear aluminum species in aqueous solutions of the compounds varied in accordance with their basicity, increasing as the basicity increases.

All the chlorohydrates exhibited similar X-ray diffraction patterns. They were typical of non-crystalline materials.

INTRODUCTION

In the mid-1940s aluminum chlorohydrate was introduced by the cosmetic industry as an antiperspirant. The chlorohydrate was much less acidic than the sulfate or chloride salts which were being used. Products formulated with this material were, therefore, less irritating to the skin and less destructive to fabrics.

The originator's compound is a basic aluminum chloride having an atomic ratio of two aluminums to one chlorine ($Al_2(OH)_5Cl$) (Govett and de Navarre, 1947). It is commonly referred to as 5/6 basic aluminum chlorohydrate which means that it is formed by the partial neutralization (5/6) of aluminum chloride ($AlCl_3$) to aluminum hydroxide ($Al(OH)_3$). Today, a number of basic aluminum chlorides with varying aluminum to chlorine ratios are used in commercial antiperspirant products. The most widely used are the 2/3, 3/4, and 5/6 basic materials. Despite their widespread use, little has been reported about their chemistry or the relationship between their chemical composition and antiperspirant effectiveness. It should be noted that the mechanism by which aluminum materials influence perspiration has not been established (Brun et al., 1967; Shelly and Hurley, 1975).

In aqueous solutions aluminum ions can exist as polynuclear hydroxy polymers (Smith, 1971; Brosset et al., 1954; Ruff and Tyree, 1958; Turner, 1968, 1969, 1975). The degree of polymerization appears to be sensitive to a number of variables, the most important of which is hydroxyl ion concentration. Both Smith (1971) and Turner (1968, 1969, 1975) found that when hydroxyl ion is added to aluminum chloride solutions three distinct forms of aluminum will be present simultaneously on the basis of reactivity. They postulated that one form is primarily composed of the soluble monomeric entities whose formulae are $Al(H_2O)_6^{3+}$, $Al(OH)(H_2O)_5^{2+}$, $Al(OH)_2(H_2O)_4^{+}$, and $Al(OH)_4^{-}$. The relative concentration of each of these species is dependent on the molar ratio of hydroxyl ion to aluminum in the solution. The second form is a range of polynuclear species having hydroxide to aluminum ratios greater than two. The third form consists of submicroscopic crystalline particles of $Al(OH)_3$ displaying the characteristics of a solid. The three forms of aluminum all reacted with the organic ligands used to produce colored complexes; however, their rates of reaction with the ligands were vastly different. These differences in rate served as the basis for the determination of the amount of the various forms of aluminum present in solutions which were aged under different experimental conditions.

Some progress has been made toward illuminating the relationship between the physico-chemical properties of the aluminum chlorohydrates and their antiperspirant effectiveness by Bretschneider et al. (1975). They indicated that the ability of these materials to reduce perspiration is related to their degree of dissociation together with the average charge on the complex. Aluminum complexes exhibiting both the highest molar conductance (an indicator of degree of dissociation) and the highest positive charge were found to be the most efficacious.

The aim of the present study was to characterize a number of aluminum chlorohydrates in terms of their hydrolytic behavior. Towards this end, acidic solutions of the various materials were examined by a colorimetric procedure which appears to be most sensitive to the non-polymeric species of aluminum as a function of time. As part of our effort to understand the differences between these materials, they were also analyzed by X-ray diffraction.

MATERIALS AND METHODS

Aluminum antiperspirant materials

Four aluminum-containing antiperspirant materials were studied. They were 2/3 basic aluminum chlorohydrate [a], 3/4 basic aluminum chlorohydrate [b], 5/6 basic aluminum chlorohydrate [c], and zirconium aluminum trichlorohydroxide [d]. Their aluminum to chlorine ratios, and the percent aluminum in each material are presented in Table 1. Aqueous solutions of these compounds are acidic as shown in Table 1.

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[a] Control no. R127-66, Reheis Chemical Company, Berkeley Heights, New Jersey.
[b] Control no. R127-77, Reheis Chemical Company, Berkeley Heights, New Jersey.
[c] Control no. 5511, Reheis Chemical Company, Berkeley Heights, New Jersey.
[d] Control no. 2001, Reheis Chemical Company, Berkeley Heights, New Jersey.

TABLE 1

Material	Atomic ratio[b] of Al to Cl	Percent Al[c] (EDTA method)	Percent Al[d] pyrocatechol violet	pH[e]
5/6 Basic	1.98 (2.0)	24.4	24.8	4.64
3/4 Basic	1.36 (1.25)	22.9	22.9	4.32
2/3 Basic	1.07 (1.0)	20.8	20.8	4.23
Zr-Al Trichl.[a]	1.38 (1.33)	17.7	18.4	4.26

[a] Atomic ratio of Al to Zr as measured by Reheis Chemical Co. to be 4.18; theoretical value for trichlorohydroxide is 4.0.
[b] Values provided by Reheis Chemical Co.; theoretical ratios are given in parenthesis.
[c] EDTA complexímetric method used; values supplied by Reheis Chemical Co.
[d] This study.
[e] Measured for a 1% solution.

Analytical

Aluminum was analyzed by a modification of a colorimetric method developed by Dougan and Wilson (1974). In order to prevent interference by traces of ferric ion, 1.0 ml of a 1,10-phenanthroline solution[e] was added to the samples to be assayed. The samples were agitated and allowed to react at room temperature for 5 min. Next, 2.0 ml of pyrocatechol violet solution[f] were added. Immediately after the addition of the organic ligand, the sample was adjusted to a pH of 6.2 ± 0.1 using a hexamine buffer solution[g]. The time between addition of the 1,10-phenanthroline solution and that of the buffer was always less than 8 min. Optical densities were measured[h] against a freshly prepared control approximately 1 hr after addition of buffer. Preliminary studies and those of Dougan and Wilson (1974) indicated that beyond this time, changes in optical density were negligible.

A standard curve was prepared using both aluminum chloride hexahydrate ($AlCl_3 \cdot 6H_2O$)[i] and a certified aluminum reference solution[j]. Excellent linearity was found between the measured optical density and concentration of aluminum from 0.100 mg/l to 0.320 mg/l (correlation coefficient = 0.996). The estimated error in any determination of aluminum was on the order of 5%.

Dougan and Wilson (1974) did not supply any information concerning the interference of zirconium with their assay. Since one of the aluminum chlorohydrate materials studied contained zirconium it was necessary that this be tested. Using zirconyl chloride (36% Zr)[i] and aluminum chloride hexahydrate, samples were prepared containing zirconium to aluminum ratios of approximately 0.5, 1.0, and 1.5 by weight at an aluminum con-

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[e] 0.1% (w/v), 1,10-phenanthroline, 10.0% hydroxylamine hydrochloride in water.
[f] 0.0375% (w/v) pyrocatechol violet in water.
[g] 30.0% (w/v) hexamine in water.
[h] Optical density measurements were made in 10 mm cuvettes at 585 nm, using a Hitachi Perkin-Elmer 139 UV-VIS Spectrophotometer.
[i] J.T. Baker Chemical Co., Phillipsburg, New Jersey.
[j] Certified atomic absorption standard (1 mg/ml) Fisher Scientific Company, Fairlawn, New Jersey.

centration of 0.128 mg/l. When the zirconium to aluminum ratio was 0.5 there was a positive interference of 1.5% in the measured aluminum concentration. The interference increased to +3.8% and +5.9% when the ratios were 1.0 and 1.5, respectively. From this data and the Al to Zr ratio of the material under study (see Table 1) it was felt that interference due to zirconium was negligible compared to other experimental errors and was, therefore, ignored.

Analytical grade reagents were used throughout.

Hydrolytic studies

Solutions of the antiperspirant materials that varied in pH were prepared by transferring appropriate volumes of freshly prepared concentrated aqueous solutions of the chlorohydrate to vessels containing different concentrations of hydrochloric acid. The chlorohydrate concentration of the final solutions was always 1.0 mg/l. The solutions were stored in a constant temperature bath maintained at 25° ± 0.1°C and agitated. Samples were withdrawn at various times and assayed for aluminum content as described above. Throughout the study the time between sample withdrawal and optical density measurement was constant.

Each hydrolytic study was carried out at least twice at each pH for the various chlorohydrates. The pH of each solution was monitored during the course of each experiment and found not to change by more than 0.05 units from the initial value. The molar ratio of hydrogen ion to aluminum varied for each acidified solution but was in no case less than 100.

Throughout the studies special precautions were taken to ensure that aluminum contamination was minimized. Deionized water was used to prepare all solutions and reagents. Tests on the water showed it to be free of aluminum and other trace metals which might interfere with the assay. All vessels and pipettes were washed in concentrated hydrochloric acid, and rinsed in deionized water. This was critically important.

X-ray diffraction

X-ray diffraction patterns were measured[k] from powders of the materials using Ni-filtered Cu Kα radiation.

RESULTS AND DISCUSSION

When aluminum chlorohydrate solutions were acidified and assayed for aluminum using the colorimetric procedure, the apparent aluminum concentration determined was found to be dependent on time. The apparent aluminum concentration at time t (Al_t) for the acidified solutions was initially less than the total aluminum concentration (Al_∞), but increased to this value with time. Only in the case of chlorohydrate solutions studied at pH 3.05 were we unable to reach the expected aluminum concentrations. In part, this was due to the duration of the study. Fig. 1 is typical of the data obtained for the materials.

The concentrations of apparent aluminum measured in aqueous solutions (no acid added) of the chlorohydrates were always less than 24% of the total aluminum present

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[k] Model ADG-301 'DIFFPET' X-ray diffractometer, Tokyo Shibauro Electric Co. Ltd., Japan.

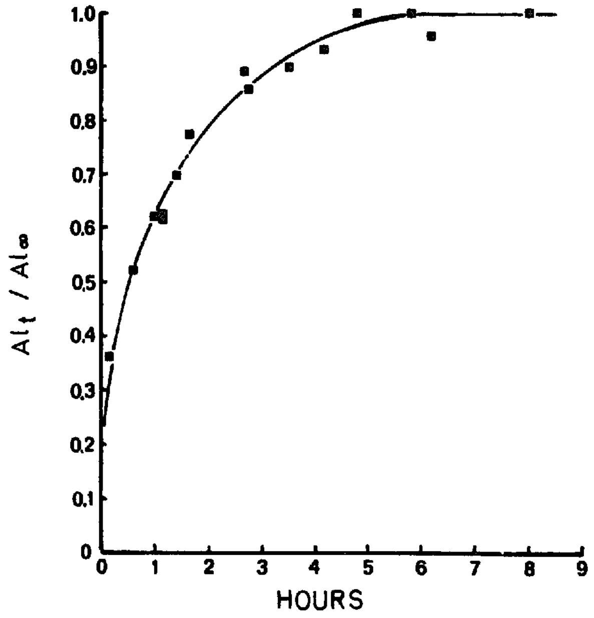

Fig. 1. Fraction of the total aluminum measured in the system as a function of time for the 5/6 basic aluminum chlorohydrate at pH = 1.13 and 25°C.

(last column of Table 2). The measured concentrations of apparent aluminum were not found to alter when these solutions were aged for one week. When a solution of aluminum chloride equivalent in total aluminum concentration was analyzed in the same fashion a much greater intensity of color developed, which corresponded to the total aluminum in solution. This may be attributed to the monomeric nature of the ions produced in aluminum chloride solutions. This acidic aluminum salt (pH of a 1% solution 3.36) is known to exist in a number of ionic forms. According to Smith (1971) and Turner (1969) these types of ions react much more rapidly with the organic ligands used in colorimetric procedures than the large polynuclear species that form when the salt is partially neutralized. In view of these data, it appears that the small concentration of measurable aluminum present in aqueous chlorohydrate solutions may be considered primarily fast reacting species, i.e. monomeric and other small ionic types. It is assumed that the analytical procedure used in this study measures these small moieties almost exclusively. Though there is a possibility that the developed color is in part due to the attachment of pyrocatechol violet to polymeric aluminum species, this was assumed to be negligible. The data collected in our studies have been treated satisfactorily according to this assumption.

The polymerization of partially neutralized aluminum chloride solutions has been previously found to follow first order kinetics (Smith, 1971; Turner 1975). If the reverse reaction (hydrolysis of polynuclear aluminum species) also obeys a first order law, then

$$\frac{-d(Al_p)}{dt} = k(Al_p) \qquad (1)$$

TABLE 2

PARAMETERS OBTAINED FROM HYDROLYSIS STUDY

Materials	k (hr^{-1})			Fraction $(Al_p)_0$			Fraction [a] (Al_p) measured in water
	pH 3.05 [b]	pH 2.13	pH 1.13	pH 3.05	pH 2.13	pH 1.13	
2/3 Basic	0.007 (±0.003) [c]	0.043 (±0.007)	1.33 (±0.57)	0.66 (±0.1)	0.74 (±0.12)	0.45 (±0.39)	0.77
3/4 Basic	0.010 (±0.003)	0.016 (±0.004)	1.37 (±0.24)	0.80 (±0.12)	0.73 (±0.11)	0.68 (±0.194)	0.83
5/6 Basic	0.00 [d]	0.012 (±0.002)	0.47 (±0.09)	0.80 (±0.064)	0.85 (±0.064)	0.59 (±0.16)	0.85
Zr-Al Trichl.	0.00 [d]	0.007 (±0.002)	0.47 (±0.09)	0.76 (±0.04)	0.80 (±0.05)	0.49 (±0.14)	0.86

[a] Concentration of chlorohydrates were 5 mg/l. Estimated standard deviation in this determination was ±0.01. The pH of these solutions ranged from 4 to 5. Fraction $(Al_p) = 1 - (Al_t)/(Al_\infty) = 1 -$ fraction (Al_t).

[b] Estimated error in determination of the pH is ±0.02 units.

[c] Numbers in parenthesis represent 95% confidence intervals.

[d] The change in measurable aluminum over the time of the experiment was not highly significant.

where k is the first order rate constant and (Al_p) is the concentration of aluminum in the polynuclear hydroxy complexes. An integrated form of this equation is

$$\ln(Al_p)_{t=t} - \ln(Al_p)_{t=0} = -kt \tag{2}$$

The concentrations can be given in terms of the fraction of the total aluminum which is present in a polymeric form at any time by equation 3.

$$\text{fraction } (Al_p)_t = \frac{(Al_\infty) - (Al_t)}{(Al_\infty)} \tag{3}$$

Using these equations reasonably good linear plots were obtained for the measured data; see Figs. 2, 3, 4 and 5. The values of k and fraction $(Al_p)_0$ derived from statistical treatment of the data are presented in Table 2.

The measured rates of hydrolysis of the 2/3 and 3/4 basic chlorohydrates were not significantly different from each other at pHs 1.13 and 3.05. Neither was there a difference in the observed rates for the 5/6 basic compounds and Zr-Al trichlorohydroxide under these

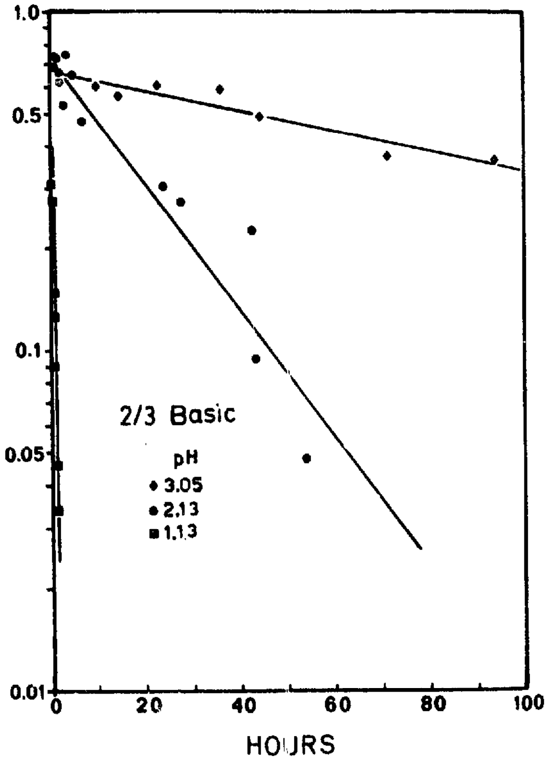

Fig. 2. Fraction of polynuclear aluminum species measured (fract $(Al_p)_t$) as a function of time for the 2/3 basic compound.

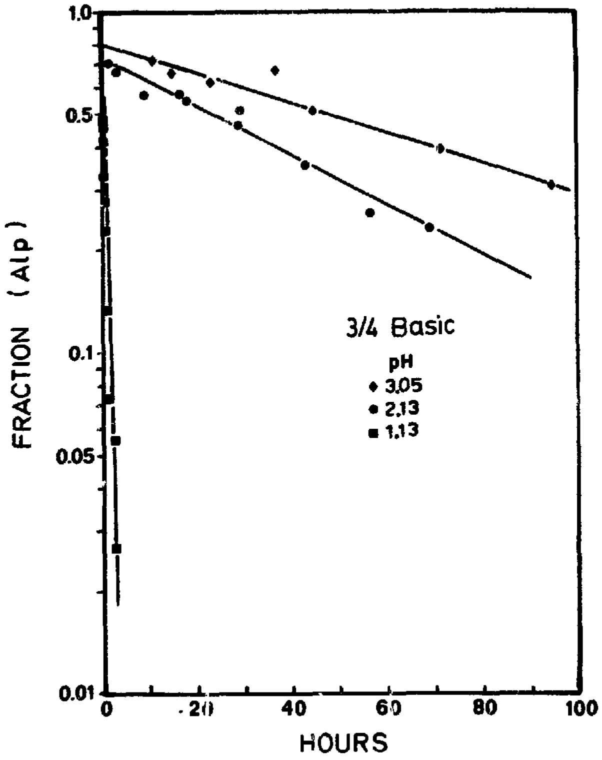

Fig. 3. Fraction of polynuclear aluminum species measured versus time for the 3/4 basic compound.

conditions. However, the rates for the latter two materials were significantly slower than the former two. At pH 2.13, each material was found to hydrolyze a rate which was statistically different from the others. The materials in order of their rates of hydrolysis at pH = 2.13 were: 2/3 basic > 3/4 basic > 5/6 basic > Zr-Al trichlorohydroxide.

One would expect the materials to hydrolyze under acidic conditions at rates which are a function of both the fraction of aluminum bound in polynuclear complexes and the molecular weight of these entities. Molecular weights of various chlorohydrates in aqueous solutions have been estimated (Bretschneider et al., 1975). The molecular weight of the 2/3 basic and 5/6 basic materials were reported to be 975 and 1571, respectively. Aluminum-zirconium chlorohydroxide complexes exhibit molecular weights which are greater than the aluminum chlorohydrates (Federal Register, 1975). As would be expected, those which exhibit a greater degree of polymerization were found to hydrolyze at a correspondingly lower rate.

Regression analysis of the kinetic data obtained for the acidified solutions of the chlorohydrates could not discern any significant difference between the fraction of polynuclear aluminum species present in these materials. When the proportion of small ionic aluminum species to the polymeric type was determined for non-acidified aqueous solutions of the compounds, small but significant differences were observed (last column of Table 2). The fraction of polymeric aluminum so obtained exhibited a rank order correla-

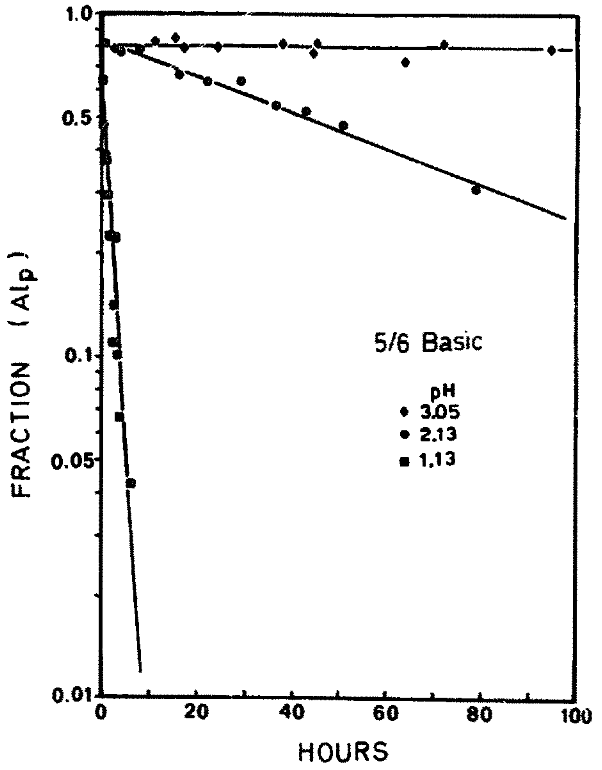

Fig. 4. Fraction of polynuclear aluminum species measured versus time for the 5/6 basic compound.

tion with the molecular weights and measured hydrolytic rates. The greater was the fraction of the polymeric species (Al_p), the lower was the hydrolytic rate and the higher was the molecular weight.

The basicity of the aluminum chlorohydrates examined tend to correlate qualitatively with their degree of polymerization and rates of acid hydrolysis. This is consistent with the findings of Ruff and Tyree (1958). They observed that the average molecular weight of aluminum aggregates increased with increasing basicity of aluminum ions in solution. The presence of a cation like zirconium in addition to aluminum in the chlorohydroxide complex appears to markedly influence the degree of polymerization and rate of hydrolysis regardless of the atomic ratio of aluminum to chlorine. The basicities of such compounds are not related in a simple manner to this ratio.

Though the fraction of polynuclear species for the aluminum chlorohydrates did not appear to be markedly different from each other, their molecular weights vary substantially. This is interesting in view of the antiperspirant efficacy of these materials. The aluminum chlorohydrates studied all exhibit approximately the same level of antiperspirant activity, but are less potent than aluminum chloride (Bretschneider et al., 1975; Shelly and Hurley, 1975; Helton et al, 1956). The lower antiperspirant activity for the chlorohydrates relative to aluminum chloride may be associated with the smaller fraction of non-polynuclear (fast reacting ions). It has been reported that zirconium-aluminum

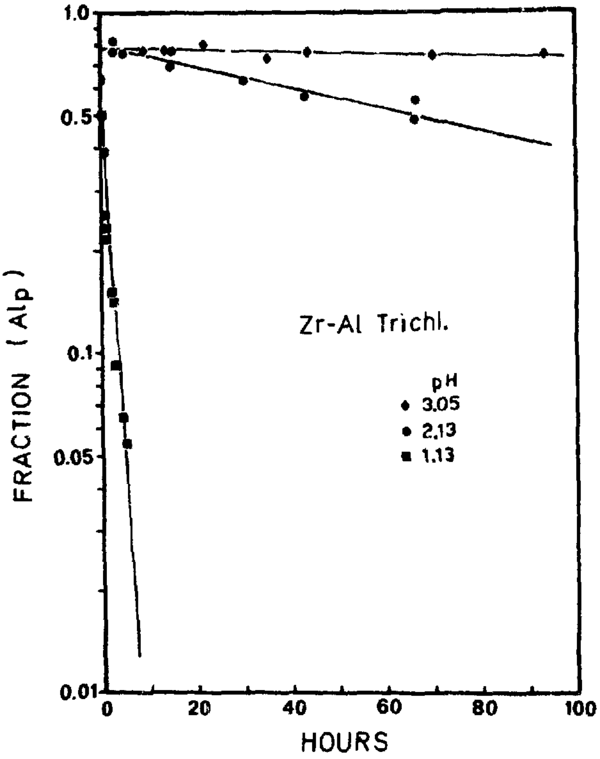

Fig. 5. Fraction of polynuclear aluminum species measured versus time for zirconium-aluminum trichlorohydroxide.

complexes are capable of retarding perspiration to a greater degree than aluminum chlorohydrate (Helton et al., 1956). It is quite likely that the activity of these materials is due in part to the properties of the zirconium cation present in the complex. Zirconyl chloride is known to be an effective antiperspirant (Shelly and Hurley, 1975). In light of these findings, it would be reasonable to assume that a formulation which markedly influences the distribution of ionic aluminum species could result in an alteration in the antiperspirant potency of the material.

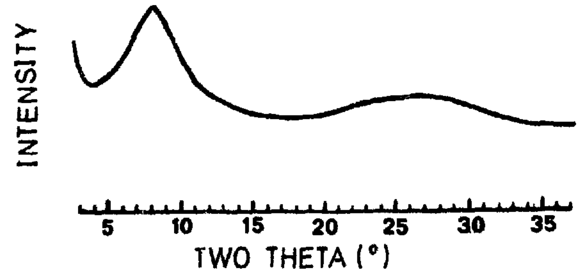

Fig. 6. The X-ray diffraction pattern of 3/4 basic aluminum chlorohydrate.

The X-ray diffraction patterns obtained for the four materials were all similar: a typical one is reproduced in Fig. 6. Each pattern exhibited two diffuse peaks: one centered at 8.5° in two theta corresponds to a d spacing of 10.5 Å and another at about 26° (d spacing of 3.5 Å). These diffraction maxima had widths at half their peak heights of approximately 3.5° and 9.0°, respectively. These diffuse powder patterns, which are characteristic of many non-crystalline substances, were not significantly altered on aging for over two years.

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REFERENCES

Bretschneider, E.S., Rubino, A.M. and Jones, J.L., Jr., Physical properties of antiperspirants as related to their efficacy. Cosmet. Perfum., 90 (1975) 27.

Brosset C., Biedermann G. and Sillein L.G., Studies on the hydrolysis of metal ions XI. The aluminum ion. Acta, Chem. Scand., 8 (1954) 1971.

Brun, R., Hunzikor, N. and Evados P., Recherches sur le mecanisme d'action des antiperspirants. Congr. Int. Dermatol. 13th, 2 (1967) 755.

Dougan, W.K. and Wilson, A.L., The absorptiometric determination of aluminum in water. A comparison of some chromogenic reagents and the development of an improved method. Analyst, 99 (1974) 413.

Federal Register 40, No. 109 (1975) 24328 (June 5). (Also information on zirconium-aluminum chlorohydroxides presented at an open meeting of OTC Antiperspirant Advisory Panel of the FDA on December 16, 1974.)

Govett, T. and de Navarre, M.G., Aluminum chlorohydrate, new antiperspirant ingredient. Am. Perfum. Ess. Oil Rev., 49 (April) (1947) 365.

Helton, E.G., Doley, E.W. and Ervin, J.C., Zirconium oxychloride, a new ingredient for antiperspirants. Proc. Sci. Sec. Toilet Goods Assoc., 26 (1956) 27.

Ruff, J.K. and Tyree, S.Y., Light scattering studies on aqueous aluminum nitrate solutions. J. Am. Chem. Soc., 80 (1958) 1523.

Shelly, W.B. and Hurley, H.J., Jr., Studies on topical antiperspirant control of axillary hyperhidrosis. Acta Derm. (Stockh.), 55 (1975) 241.

Smith, R.W., Relations among equilibrium and nonequilibrium aqueous species of aluminum hydroxy complexes. In Hem, J.B. (Ed.) Nonequilibrium Systems in Natural Water Chemistry, Adv. in Chem., No. 106, Am. Chem. Soc., Washington, D.C., p. 250.

Turner, R.C., Conditions in solution during the formation of Gibbsite in dilute Al salt solutions Z: effect of length of time of reaction on the formation of polynuclear hydroxyaluminum cations, Soil Sci., 106 (1968) 338.

Turner, R.C., Three forms of aluminum in aqueous systems determined by 8-quinolinolate extraction methods. Can. J. Chem., 47 (1969) 2521.

Turner, R.C., The equilibrium constant for the formation of $Al_2(OH)_2^{4+}$ in aqueous solutions. Can. J. Chem., 58 (1975) 2811.