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Hazards From Thermodecomposition of Epoxy Resins

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Introduction

Epoxy resins are among the most versatile of modern plastics. They have been employed extensively in industry for surface coatings, high-strength adhesives, durable laminates, cold solders, and lightweight foams. Several types of the higher molecular weight epoxies have found application in the potting, encapsulating, and sealing of electrical equipment, particularly electric motors. Here their high chemical resistance, bond strength, and mechanical and electrical properties can be used to advantage, especially in severe environments.[1] However, with potted electrical equipment, the danger of pyrolysis of the plastic through overheating or its combustion in open fires is always present. In certain military situations, several motors ranging from fractional horsepower to the 10- to 100-horsepower size range may be found operating in relatively confined spaces. The thermodecomposition of epoxy resins may produce an inhalation hazard to personnel working in such areas.

The epoxy resins are polyethers prepared by the interaction of epichlorhydrin with a dihydroxy compound such as bis-(4-hydroxyphenyl)-dimethylmethane (Bisphenol A). The reactive unsaturated epoxide rings permit polymerization reactions in the presence of various curing agents to form molecules of high molecular weight. The uncured thermoplastic resins are thus transformed readily into tough, hard, thermosetting solids. Depending on the type of resin desired, the

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curing agent may be a polyamine, a phenolic resin, or an acid anhydride. The irritant properties, to the skin, eyes, and respiratory tract, of the uncured epoxy resins, their components, and of the curing agents also have been attributed to the volatility and causticity of epichlorhydrin, the phenolic compound, or the strongly alkaline amines. These materials have been shown to be dermatitis agents and potent sensitizers.[2-8] Systemic intoxication from these starting materials and uncured resins has been reported.[9-11] The cured resins are generally regarded as innocuous, although machining operations may produce a fine dust or small amount of vapor that may affect a sensitized person.[12] Direct studies to evaluate the inhalation toxicity of either the pyrolysis or combustion products of cured epoxy resins have not been found in the literature.

The present report described experiments in which rats have been exposed under static conditions to both the pyrolysis and the combustion products of a cured epoxy resin of the type commonly used for potting the windings of electric motors. In the dose ranges examined, only the pyrolysis products proved to be lethal, and estimates of the L(Ct)50 and mean survival time have been computed for these products. A description has been provided of the characteristic types of damage produced in the respiratory tract. In addition, microscopic examination of kidney and liver tissue from representative animals has permitted assessment of systemic toxic effects. The findings have been discussed in terms of the potential human hazard to be associated with the inhalation of these thermodecomposition products.

Materials and Methods

Plastic.—The epoxy resin used in the trials was a commercially available product supplied as two components, the uncured resin and a curing agent. These contained the diglycidyl ether of Bisphenol A, an alkyl derivative of maleic anhydride, a plasticizer, inert mineral fillers, and colorants. These reactants were mixed, poured onto flat metal trays or into a metal tube, and cured by baking for 16-24 hours at 250 F. Thin sheets of cured resin from the trays were broken into small chips for the pyrolysis studies, and fine turnings from the solid cylinders of cured resin were employed in the combustion trials.

Exposure Equipment.—A detailed description of the exposure equipment has been provided previously.[13] The only modification was the use of a wire mesh basket instead of a trough in the combustion trials.

Exposure Technique.—Male rats of the Wistar strain, weighing 115-150 gm, were employed throughout. A total of eight trials, corresponding to eight different concentrations, were carried out with the pyrolysis products in two sets of experiments. In each set, 48 rats were assigned at random to four groups of 12 rats. A single sample weight was chosen for examination in the combustion trials; 12 rats were exposed in each of duplicate runs. The animals were housed in a compartmented basket during the exposure period in the chamber. The amount of thermodecomposition products distributed in the 300-liter chamber was obtained from the difference between sample weight and weight of residual ash. In all trials, the temperature in the chamber was recorded every minute for the first ten minutes and at ten-minute intervals thereafter. The behavior of the animals was noted during the 60-minute exposure period. At the end of a trial, the rats were transferred carefully to individual cages for observation during the following ten days, and the survival time of each animal was recorded to the nearest hour for the first 72-hour period.

Histological Method.—Sections of lung from representative animals dying within 72 hours were prepared from all experimental groups by the method previously described.[13] From the survivors, two rats were sacrificed on the third and the sixth days. In the case of survivors from the pyrolysis trials, sections of kidney and liver were also prepared.

Results

Observations of Behavior of Animals.—The immediate response of rats exposed to the pyrolysis products of the epoxy resin was holding of the breath with other indications of respiratory irritation. The signs of irritation soon subsided, and the animals crouched quietly. As the exposure continued, respiration became progressively more labored, and wheezing could be heard when the rats were removed from the chamber at the end of the hour. These signs persisted until death supervened.

The combustion products of the plastic appeared to be much less irritating. The rats remained quiet throughout the exposure period and exhibited minimum signs of

Cumulative Deaths in Groups of 12 Rats Exposed to the Pyrolysis Products of Epoxy Resins

Room Temp, F	Max Chamber Temp	Sample, Wt Gm	Ash, Wt Gm	% Pyrolyzed	Cumulative Deaths at Indicated Time Point: Hour 12	Hour 24	Hour 36	Hour 48	Hour 60	Day 72	Day 5	Day 10	Total Death
75	79	1.0	0.28	72.0	—	—	—	—	—	—	—	—	0
76	80	1.4	0.39	72.2	—	—	—	—	—	1	—	—	1
70	77	2.0	0.50	75.0	—	—	3	4	—	5	—	—	5
70	77	2.9	0.80	72.4	1	3	5	7	8	10	—	—	10
69	76	4.2	1.2	71.5	1	8	9	11	—	—	—	—	11
71	79	6.0	1.6	73.0	3	11	12	—	—	—	—	—	12
72	82	10.5	2.8	73.7	8	9	11	—	—	12	—	—	12
72	83	16.0	3.3	79.4	12	—	—	—	—	—	—	—	12

respiratory distress. On removal from the chamber at the termination of the exposure, normal behavior and activity were quickly resumed.

Dosage-Mortality Results.—In pyrolysis studies with the epoxy resin, two sets of four trials each were performed. Sample weights in the first set were 1.0, 1.4, 2.0, and 2.9 gm; and in the second set, 4.2, 6.0, 10.5, and 16.0 gm. The observations on temperature changes, sample weight loss, and mortality are presented in the Table. It will be noted that a fairly constant fraction of the resin, about 72%-75% in most cases, disappeared as volatile pyrolysis products which formed dense grayish-white fumes throughout the chamber. The temperature rise varied from 4-11 F above room temperature, depending on the size of the sample. No deaths were observed during the one-hour exposure period with any sample. However, with the largest sample, 16 gm, the first animal died approximately one hour after removal from the chamber, and all the rats in this group were dead after four hours. The rate of dying was slower and deaths were more evenly distributed with the smaller sample weights. No deaths occurred in the group exposed to the pyrolysis products from the smallest sample, 1.0 gm. In the case of the remaining groups (sample weights from 1.4 to 16.0 gm), no deaths occurred after the third day up to the tenth day when observations were terminated.

Only one sample weight, 20 gm, was tested in combustion trials with the epoxy resin, but the experiment was repeated. Approximately 65% of each sample was consumed when burnt, yielding a quantity of thermodecomposition products slightly greater than that produced when 16 gm of the resin was pyrolyzed. All animals survived throughout the exposure and during the observation period. A mean rise of 39 F over room temperature was recorded in the combustion trials.

Histological Findings.—Lung Tissue: In the pyrolysis experiments, a correlation was evident between the dose of products to which the animals were exposed and the extent of damage seen in the lung tissue. The microscopic appearance of lung tissue from rats exposed to the lowest doses (1.0, 1.4, and 2.0 gm samples) was essentially normal. No accumulation of fluid in alveoli or bronchioles was noted, and bronchial walls were intact. However, there were clumps of mucous material mingled with the cilia of the bronchial epithelium, and the blood vessels were slightly congested.

Examination of the lungs of rats that died between the 1st and the 25th hour after exposure to intermediate concentrations (2.9 and 4.2 gm samples) revealed a few foci of fluid-containing alveoli. The bronchioles were patent, and their walls remained intact. However, the cilia of the epithelial cells were either eroded or mingled with thick mucous material to form clumps. Blood vessels, particularly the pulmonary veins, were quite congested, and perivascular edema was noted in several instances. Some of the survivors in these groups were sacrificed on the third day. The general appearance of the lung tis-

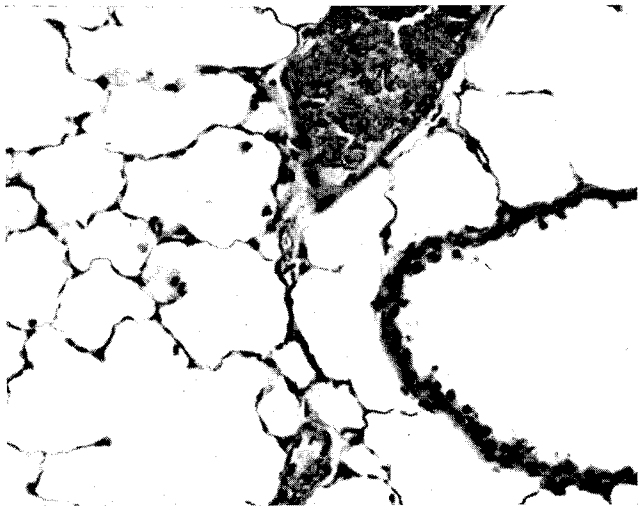


Fig 1.—Section of lung of rat sacrificed three days after exposure to pyrolysis products of epoxy resins (4.2 gm sample). Note: normal alveolar structure; active phagocytosis. Approx × 750.

sues was normal, and no fluid was present in the alveoli. The bronchial walls were thickened, and degenerated epithelial cells and debris were being disposed into the lumen, forming a kind of membranous "budding" on the intact epithelium. Active phagocytosis was evident. Vascular congestion was not a prominent feature of these sections (Fig 1).

Lung sections from the animals exposed to the highest doses (6.0, 10.5, and 16.0 gm samples) of the pyrolysis products showed more pronounced and drastic changes. Both the alveoli and bronchioles were filled with a granular exudate forming patches of consolidation. The bronchial walls were partially desquamated. Lesions similar to those described were seen in animals that died in these groups, except that the edema and general congestion were more overwhelming (Fig 2).

Fig 2.—Section of lung of rat which died four hours after exposure to pyrolysis products of epoxy resins (16 gm sample). Note: desquamated bronchial wall; pulmonary edema; perivascular edema. Approx × 550.

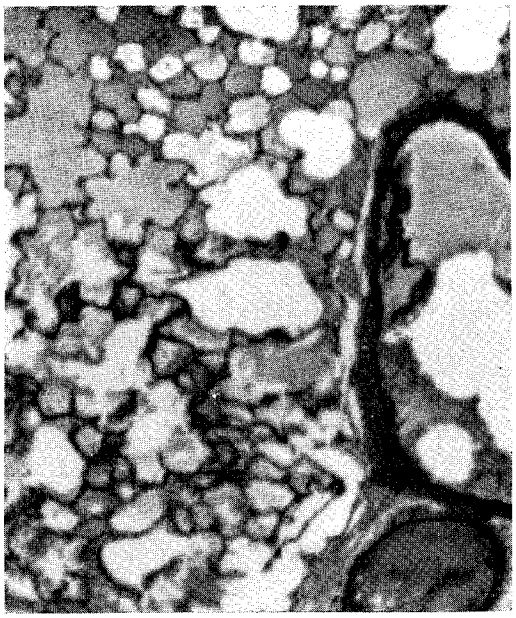


Fig 3.—Combustion of epoxy resins (20 gm sample). Lung section of rat sacrificed immediately after exposure. Note: heavy deposition of carbonaceous material on the bronchial wall; normal alveolar structure. Approx × 900.

Since no deaths occurred in animals exposed to the combustion products from large samples of the epoxy resin, some rats were taken and sacrificed immediately after exposure and others on the third and the sixth day. Regardless of the time of sacrifice, all lung tissue appeared normal. There was neither accumulation of fluid in the alveoli nor vascular congestion. The only distinguishable differences between the three groups were the amount of deposition of carbonaceous material and the degree of phagocytic acivity. Lung sections from rats sacrificed immediately after exposure showed a heavy deposition of charred particles along the bronchi, bronchioles, and in the alveoli, and a few phagocytes were discerned (Fig 3). Phagocytic activity was at its peak by the third day and declining by the sixth day after exposure. The amount of foreign particles present diminished with the passage of time.

Kidney Tissues: Kidney sections were prepared only from rats that survived exposure to the pyrolysis products from 1.4 to 4.2 gm samples of epoxy resin. On microscopic examination, these tissues appeared to be normal on the whole, although it was noted that the glomeruli were swollen and highly vascularized and the Bowman's capsules were filled. The proportion of swollen glomeruli was dependent on the dose. For example, in rats exposed to the pyrolysis products from the 2.0 gm sample, 30%-40% of the glomeruli were swollen (Fig 4); over 80% of the glomeruli were swollen in rats which had undergone exposure to the products from the 4.2 gm sample. These observations were made on rats sacrificed three-six days after exposure. The kidney sections from rats killed at the end of the ten-day observation period appeared to be almost normal. Only a few swollen glomeruli scattered around the cortex were found. The impression gained was that of normal recovery from a mild intoxication.

Liver Tissues: Alterations indicative of mild intoxication were observed in liver sections from animals sacrificed about three days after exposure to the pyrolysis products. Cloudy swelling of hepatic cells was seen quite generally, and several sections showed foci of mild fatty degenerative change around the center of the lobule (Fig 5). In

Fig 4.—Kidney section of rat sacrificed six days after exposure to pyrolysis products of epoxy resins (2.0 gm sample). Note: congested and normal glomeruli. Approx × 250.

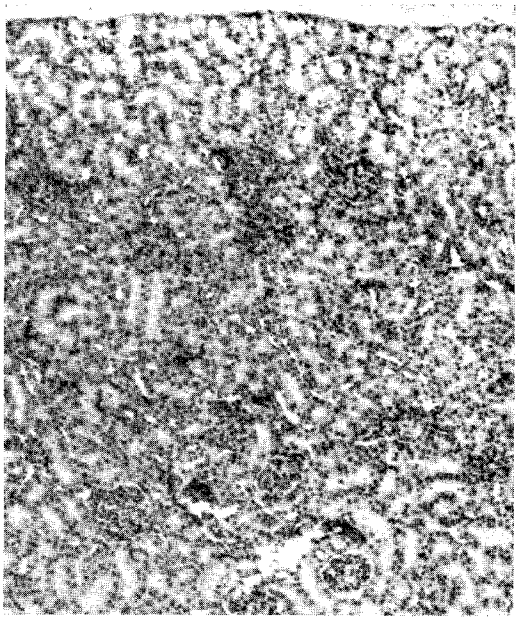
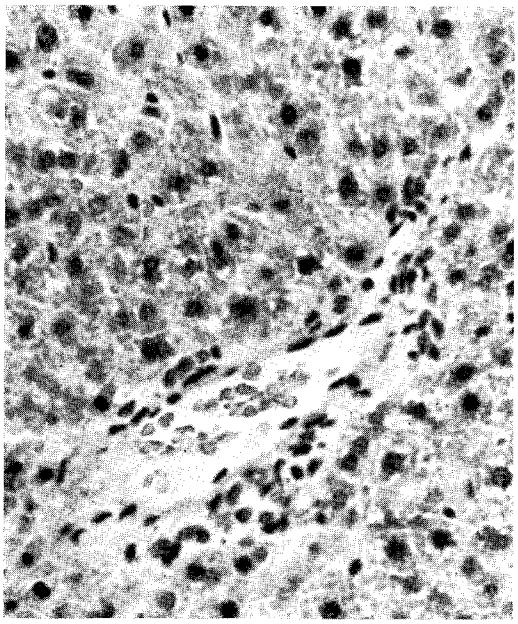


Fig 5.—Liver section of rat sacrificed three days after exposure to pyrolysis products of epoxy resins (2.0 gm sample). Note: degenerative changes around the center of lobule. Approx × 650.



animals sacrificed after a few days, slight atrophy of hepatic cells was discernible and histiocytes were present in the distended sinusoids.

Comment

The experiments described above have demonstrated that sufficiently high concentrations of the pyrolysis products of epoxy resin are lethal to rats when inhaled. The data of the Table permit computation of the L(Ct)50 of these pyrolysis products, and, by using the cumulative totals at 72 hours and the method of probit analysis, an estimate of 3.2×10^5 mg min/cu meter is obtained. It is also possible, after making some simplifying assumptions, to derive the mean surival time of rats exposed to the computed L(Ct)50; a value of approximately 50 hours is found.[14] It is of interest to compare these calculated values with those reported in analogous studies with the pyrolysis products of polyurethane foam and a polyurethane-coated nylon fabric.[13] An L(Ct)50 of 2×10^6 mg min/cu meter was derived for these polyurethane plastics; therefore, their pyrolysis products are only about one sixth as toxic as those produced by the epoxy resin. Another point of difference in the behavior of animals exposed to these various pyrolysis products should also be noted. With the polyurethane plastics, most of the deaths occurred during the 60-minute exposure period, and, in fact, only a few deaths were recorded during the subsequent observations period. The mean time to death in rats exposed to the L(Ct)50 was of the order of 30 minutes. This may be contrasted with the value of 50 hours given for the mean time to death of rats exposed to an L(Ct)50 of the pyrolysis products of epoxy resin.

The histological examination of lung tissues from rats that died after exposure to the epoxy resin pyrolysis products indicated that the primary cause of death was respiratory failure resulting from pulmonary edema. However, respiratory embarrassment may also have been a consequence of histotoxic anoxia, since it was observed that some animals died after exposure to low concentrations of the pyrolysis products and exhibited a negligible degree of edema. It is also possible that systemic effects of cardiac, renal, or hepatic origin may have constituted a contributing factor; some mild toxic effects on blood vessels, kidney, and liver were remarked. The role of excessive heat stress and depletion of oxygen is considered to have exerted no significant effect in causing mortality in the pyrolysis experiments for reasons which have been advanced previously.[13] Microscopic examination of the respiratory passages of rats sacrificed after exposure to the combustion products of the epoxy resin revealed no pathological change; phagocytic removal of foreign particles appeared to be proceeding normally.

The value of 3.2×10^5 mg min/cu meter, derived for the L(Ct)50 of the epoxy resin pyrolysis products, provides a basis for evaluating the hazard these products may present to the human. It will be assumed that man is at least as susceptible as rats to the action of these materials. The calculations suggest that a man confined in a room of 1,500 cu ft volume for one hour with no appreciable air change would receive a lethal inhalation exposure from the pyrolysis products derived from one pound of epoxy resin. The occurrence of such circumstances in practice is by no means impossible to envisage. Furthermore, the insidious nature of the action of these products, reminiscent of the action of the primary lung irritants, strongly suggests that adequate precautions be taken either to prevent their formation or to protect exposed personnel. However, in overt fires where combustion of the plastic with flames occurs, the hazard would appear to be greatly reduced, as was concluded in the case of the combustion products of polyurethane plastics.

Summary

The toxicity of the pyrolysis products of an epoxy resin to rats has been determined. A value of 3.2×10^5 mg min/cu meter has been estimated for the L(Ct)50 when the exposure period was one hour. The mean survival time in rats exposed to this dose has been calculated to be approximately 50 hours. No

deaths were observed when rats were exposed to slightly higher concentrations of the combustion products of the resin.

Histological sections of lungs, kidney, and liver from representative animals have been examined. It was concluded that respiratory failure from pulmonary edema was the predominant cause of death, although other effects, eg, histotoxic anoxia and systemic renal or hepatic changes, may have played a contributory role. No pathological damage was associated with exposure to equivalent doses of the combustion products of the epoxy resin.

It was concluded that the pyrolysis products may constitute a hazard to human personnel in circumstances realizable in practice.

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