# UNEXPECTED AND UNUSUAL FAILURES OF POLYMERIC MATERIALS

*Myer Ezrin and Gary Lavigne*
*Institute of Materials Science*
*University of Connecticut*
*Storrs, Connecticut 06269-3136*

## 1.0 Abstract

Some failures are predictable, such as due to exposure to environmental conditions. In this paper the focus is on failures that there was no reason to expect. While they may become obvious, they are unpredictable. Some are unusual, involving a cause and effect on the plastic that are not obvious. Examples are cracking of nitrile rubber, contamination of GPC samples by a filter syringe, and PVC plasticizer used for many years being declared unsafe.

## 2.0 Introduction

Polymers and products therefrom are designed and produced with the expectation that they will process satisfactorily and perform as intended successfully, i.e., that they will not fail. Yet polymeric materials, including additives, do fail sometimes. The failures are often completely unexpected or unusual and the causes may not be easy to determine. This paper brings together such failures under five categories of causes:

1. In production or processing of polymers
2. Assembly of polymers into products
3. Unauthorized or unexpected change in composition
4. Service conditions
5. Synergistic effect of two stresses acting simultaneously

We do not include in the unexpected and unusual category failures that occur within an expected lifetime due to stresses such as fatigue and environmental exposure. Many of the examples can be found in reference [1].

## 3.0 Failures Originating in Production or Processing of Polymers

### 3.1 Residual unreacted monomer

It is practically impossible to convert a monomer to polymer so as to leave no unreacted monomer. It may be at the ppm (parts per million) level and considered acceptable, but not in all cases.

**3.1.1 Polycarbonate and other polymers made with bisphenol A.** The level of bisphenol A (BPA) is very low. Nevertheless, PC has come under fire for its hazardous effects. An example is baby milk bottles. Hazardous effects of polymeric materials may not be a problem if the users were only adults. But if the user is a very young baby, the danger of hazardous effects of even trace materials in polymeric materials may increase. Such problems have been claimed for products, like PC baby bottles, that have been in use and accepted for many years. The failure is in incomplete polymerization, down to <ppm level, of unreacted monomer.

**3.1.2 Vinyl chloride monomer in PVC (polyvinylchloride).** During the 1970s OSHA (Occupational Safety and Health Administration) put into effect a regulation limiting the residual unreacted vinyl chloride monomer content to 1 ppm. Previously it had been 50 ppm. The change was due to deaths from cancer caused in PVC polymerization workers. The cancer, angiosarcoma of the liver, was unequivocally attributed to VC monomer. The reduction to 1 ppm particularly affected producers who could not meet the 1 ppm requirement.

Just as in the PC/bisphenol A case above, there is a benefit to consumers in lowering the risk of harmful effects of the polymeric material. It is an unexpected failure because the materials may have been in use for many years and may be terminated due to health concerns not realized or enforced previously.

### 3.2 Plasticizer content of PVC used for floor tiles

The PVC contained a phthalate plasticizer and an alkyl ester plasticizer [2]. The latter has good compatibility with PVC; the alkyl ester type has lower compatibility, so that the formulation called for about 2X the level of the phthalate as the alkyl ester.

Floor tile bonded with cement to flooring lost adhesion after a time causing the tile to have to be replaced. Analysis of the problem tile vs. normal material found that the failed tile had 2X the amount of alkyl ester plasticizer relative to the phthalate ester. The plant operator weighing out the components for the formulation had inadvertently reversed the amount of the two plasticizers. The result was that there was too much of the one with lower compatibility, so that some of it migrated to the surface, softening the adhesive and causing loss of adhesion. It was an unexpected failure caused by an operator error.

### 3.3 PE (polyethylene) molding defect in an electrical application exposed to water

There was a barely detectable minor defect in PE molded over electrical components of an electrically charged system exposed to water. After considering other possible causes of electrical failure that occurred, it was concluded that the small opening in the PE insulation probably caused water, under pressure, to enter the system and cause failure. It was unexpected because it is rare for the PE insulation in the application to have even a small defect. It may not have contributed to failure in other materials, but water under pressure was the cause of water reaching energized locations that were not designed for water contact.

### 3.4 Erosion of mold used with injection molded flame retardant nylon [3]

A common type of flame retardant is halogenated hydrocarbons containing chlorine or bromine. These may be organic compounds, or chlorine-containing polymers like chlorinated polyethylene. It is characteristic of such materials that the halogen splits off from the compound or polymer as HCl or HBr, very acidic volatile compounds. This occurs at temperatures as low as 150°C, i.e., within normal processing temperature range, exposing the metal processing machines to acid. In a case of this type, acidic volatiles produced during molding, together with abrasive fillers, caused wear of the mold surface. Gradually, the mold dimensions changed due to abrasive wear enhanced by corrosion. The wear reached a point that the molded part dimensions were out of specification and the mold had to be replaced.

## 4.0 Assembly of Polymers into Products

### 4.1 Small EPR O-rings

Black ethylenepropylene rubber O-rings of ca. 3.175-4.7625 mm diameter were fed by an automatic feeder to an assembly point where the O-rings were placed at a certain location of a plastic part. The O-rings had a slightly wet surface due to a high content of hydrocarbon oil used as plasticizer. The oily surface was the cause of O-rings sticking together at the assembly point rather than feeding into the machine one at a time. The solution was to reduce the content of oil to no more than was needed to have the desired modulus and ease of feeding singly to the assembly machine.

### 4.2 Hydrogen evolution in a two-part silicone adhesive

A two-part silicone adhesive was used as a potting sealant for an electrical product. The whole unit was placed in a PE box. Some lots of the two-part silicone caused the PE container to bulge, making the circuit in the box unacceptable. To determine the cause of the bulging, a blister was sampled and analyzed by mass spectroscopy. Hydrogen was confirmed. It was also confirmed by making small experimental mixes in a plastic bag and analyzing the gases. By proving that hydrogen was evolved from silicone mixes, the formulation was altered to prevent such effect.

### 4.3 Failure of a two-part silicone adhesive to bond to phenolic resin [4, 5]

In the assembly of a clothes iron a two-part silicone adhesive was used to bond a molded phenolic resin base part to a polypropylene top part. Failure to bond to the phenolic resin portion was experienced. These parts had been stored on the plant floor uncovered for long periods of weeks and months before being assembled. Analysis of the surface of the phenolic parts revealed a high content of hydrocarbons (Fig. 1) that were not present below the surface. The hydrocarbons had been absorbed from the plant air, from sources such as the exhaust of material handling equipment, as well as from environmental air, which contains hydrocarbons from vehicle emissions and other sources. The hydrocarbons on the surface were a contaminant preventing adhesion to silicone adhesive.

## 5.0 Unauthorized and Unexpected Changes in Composition

### 5.1 Silicone oil on titanium dioxide pigment [6]

In a case of poor bonding and printability of PE coextruded film, extraction isolated silicone oil, which had originated on the pigment. The company that had purchased the pigment was not aware that it contained silicone oil. While this additive might not cause problems in many products, some applications can not tolerate even small amounts of interfering substances. The oil was on pigment for easy flow.

### 5.2 Change of plasticizer without authorization

Electronic cable used in military applications may contain a flexible polymeric material to fill the empty spaces between twisted conductor strands. The objective is to prevent water from entering the cable if it is exposed to water. The cable had to meet a specification of liquid contained in the filler not dripping out when held vertically. The filler was a plasticized vinyl polymer with a high content of plasticizer. Thus compatibility of plasticizer and polymer was important. The cable had met the no-drip specification in earlier cables, but failed it with current product. Analysis of old (good) and new (bad) filler found that the plasticizer had been changed without authorization. That unauthorized change threatened the acceptance of a large order of cable.

### 5.3 Unauthorized use of a mold lubricant

Injection molded parts were unacceptable due to obvious defects on the surface. The cause was unauthorized use of a mold lubricant. The lubricant was not compatible with the plastic and adversely affected the part; clarity and uniformity of the surface suffered. 50,000 parts had to be rejected. Analysis identified the offending lubricant, helping to trace it to the operator who used it.

### 5.4 Two-part adhesives with an initiator in one part [7]

For this type of adhesive to function properly, the initiator has to be well dispersed into the other portion where the bond is to be made and to be present at the required level. Sometimes the bond, such as metal to metal, fails. Thermal desorption GC/MS can detect initiator in a virtual "needle in a haystack" situation. In some cases it was absent or present at a very low level so that the adhesive did not develop its intended bond strength.

The analysis for initiator was done by scraping the surface of unbonded metal, providing 0.1-0.2 mg. sample. Using the University of Connecticut direct dynamic thermal desorption device, the sample was heated at 250°C/2 minutes. The volatiles thus generated were carried onto the head of the cryofocused GC column. Programmed heating at 15°C/minute produced the chromatogram of Figure 2. The initiator peak is indicated as a very small peak at a certain retention time (X axis). Figure 3 shows the mass spectrum of the peak for the initiator. Using single ion monitoring Figure 4 is the chromatogram only for mass 212 species, the major peak of the initiator. In this way initiator is detected at low levels. In the case shown initiator was present. In others none was detected and was responsible for adhesive failure of the metal to metal bond. In spite of the very small peak for initiator, the resolution and sensitivity of the analytical system make it possible to make positive identification of a compound present at very low level.

### 5.5 Failure of a servo motor in which a metal screw moves freely inside a plastic part [8]

Movement of the screw is facilitated by a polymeric grease containing plasticizers of triphenylphosphate (TPP) and a polyolester plasticizer. In service the screw "froze" and would not move freely. Analysis by IR (infrared spectroscopy), TD/GC/MS (thermal desorption gas chromatography/mass spectroscopy), TGA (thermogravimetric analysis) and SEM-EDX (scanning electron microscopy/energy dispersive x-ray spectroscopy) found that TPP had been hydrolyzed to phosphoric acid (a strong acid), that the esters of the polyolester plasticizer had been converted to the corresponding carboxylic acids by hydrolysis, and metal of the screw had corroded and the corrosion products were present in the grease. SEM-EDX of the TGA ash residue confirmed the corrosion of the metal screw.

This case illustrates how an additive (TPP) can change in service giving a new material (phosphoric acid) that can drastically affect performance. IR and TD/GC/MS were essential in revealing the chemical changes that are responsible for this failure. It is not known what caused TPP to hydrolyze to phosphoric acid. Water may have been a factor.

## 6.0 Service Conditions

### 6.1 Contamination of GPC sample solutions by the injection syringe

Solutions for molecular weight analysis by gel permeation chromatography (GPC) are injected into the instrument using a plastic syringe. The solvent used most often is THF, tetrahydrofuran. When a certain peak was obtained in the chromatogram for all samples, in the medium molecular weight range, it was considered as spurious and its origin was sought. It was determined to be suspect when solvent only injected showed it. A check of the component parts found that a soft black EPR (ethylene propylene rubber) tip at the base of the plunger was the cause. Apparently it was not crosslinked sufficiently so that THF would dissolve some of it while the solution transfer was made. Switching to a different lot of syringes solved the problem. Before it was realized that the peak was caused by contamination, it was thought to be a real component of some polymers.

### 6.2 Fracture of electric transmission power line support rod of pultruded glass reinforced polyester [9]

The rods are called guy strain insulator rods. They attach to a point near the power line at an angle. The other end goes into the ground. They provide non-conductive support for the power line. They are attached top and bottom to metal end fittings. Fracture of the rod occurred after several years of service a few inches above the lower metal end fitting.

A contribution to the problem was service condition, namely water from normal precipitation of rain and snow. An additional factor was their slightly acidic nature. Another major factor was the design of the galvanized metal end fitting (Fig. 5). The top part is shaped like a cup so that it holds liquid. The rod and end fitting are at an angle to the support post so that liquid entering the upper cup-like portion of the end fitting ran off the lower side of the end fitting. But some liquid would always remain there and evaporate to dryness. Solid matter that came with rain and snow would accumulate in the end fitting over time. Its nature was evident from the rust streak on the runoff side of the end fitting. SEM-EDX (scanning electron microscopy/energy dispersive x-ray spectroscopy) elemental analysis of the rusted streak and of the normal galvanized surface showed that the galvanizing elements were practically gone and sulfur was present. The sulfur was not present in the normal surface. It appears that acidity accompanied the rain and snow, admittedly at low concentration each individual time. However, over many years, of the order of 10-15, the accumulated acidity in the cup-like portion of the end fitting was sufficient to corrode the galvanized surface of the end fitting during the runoff.

But how does the cup-like design of the end fitting contribute to fracture of the rod? Polyester is susceptible to hydrolysis and resultant reduction of molecular weight. But the greatest weakness is the long strands of E glass fiber, which has poor resistance to water and even poorer resistance to acid. As the acidity of the solid deposit that accumulated in the lower side of the cup-like top of the end fitting increased, the pH of water that came with succeeding deposits of rain or snow became lower and lower, i.e., more acid. That led to fracture of E glass fiber, which was a major component of the polyester rod. After a time, as more and more glass fiber fractured, the rod including polyester fractured.

In addition to design (of the top part of the end fitting) and the low resistance of E glass to water and acid, a third factor is stress, which can come from differences in coefficient of thermal expansion of glass and polymer vs. metal as temperature ranges from very cold to hot. Also stress caused by wind and by installation stress.

Because of reluctance by some people to believe that the failure was due to "acid rain," a study was conducted of the effect of stress, air, water and acidity. Rods were stressed by bending over a curved metal part and held down at the ends. In the central stressed area liquid was applied in a flexible plastic holder that surrounded the rod. The time to fracture was recorded. Clearly the rod is susceptible to water and stress, but much more so for acid and stress. The effect is an example of failure due to two stresses acting synergistically and simultaneously, i.e., mechanical stress and acid.

Possible solution to prevent failure is to modify the end fitting to eliminate the open cup-like feature so that liquid does not evaporate and concentrate there. Another is to have a redundant rod, i.e., a second one so that if one fails, the other will hold the load.

## 6.3 Dioctyl phthalate (DOP) plasticized PVC [10]

DOP (di 2-ethylhexyl phthalate) has been a favored plasticizer for PVC for about 60 years. DOP is the plasticizer in PVC blood bags and in medical tubing. Recently DOP has come under fire for possible health risks due to trace amounts that may be ingested. A key one is for PVC baby nipples, the concern being the vulnerability of babies to any kind of health risk. Europe has banned DOP for use in PVC and in other polymers. Similar concerns may lead to a ban on DOP in this country.

## 6.4 Degradation of nitrile rubber in power supply for x-ray equipment

Nitrile rubber degraded severely in an application in which it had not degraded before. Whenever a butadiene type rubber degrades one considers possible corona discharge. Corona generates ozone, which reacts across C=C carbon double bonds of butadiene causing surface degradation and ultimately cracking throughout. There was no motor or other cause of ozone near enough to cause the failure. On further examination a high voltage lead had come in contact with the rubber. Ozone from that source was the cause of the problem.

## 6.5 Fracture of low voltage cable insulation

PE insulation of ca. 3.175 mm diameter cracked after ca. 10 years. The fractures were limited to certain lengths, while others were unaffected. The difference between normal and cracked PE was if it was near fluorescent lights. Apparently UV from fluorescent lights, together with oxygen in air, exhausted the antioxidant content of the PE. Cracking then followed. Cracked PE had zero OIT (oxidative induction time), a DSC (differential scanning calorimetry) test in oxygen which effectively measures the antioxidant content. When it is exhausted (zero OIT) the polymer is vulnerable to oxidative degradation. The failure was to not realize fluorescent lights emit UV, which can accelerate oxidative degradation.

## 6.6 Damage caused by water from uncontrolled leaking of fractured plastic tubing and other water systems containing plastics

Damage by water is a major cause of property damage, involving millions of dollars. Two such systems are tubing (pipes) in houses and outside up to houses, i.e., municipal water system and PP cold water inlet in hot water heaters.

**6.6.1 Polybutylene water pipes in houses.** The confidence level that failures would not occur in service was so high that pipes were buried in walls where they could not be reached for repair or replacement without literally breaking down a wall. Failures did occur in which water under pressure burst out of weakened pipe locations through walls. Property damage was considerable. Part of the problem was that small diameter pipe bent easily causing kinks due to its easy flexibility. Kinks sometimes were sites of fracture initiation.

Another contribution to failure was that plumbers who installed the system tended to do what they are accustomed to do with copper systems, i.e., tighten down hard at fittings and junctions. The result was sometimes that the tightening cut into the pipe, setting up that location for subsequent fracture under water pressure.

A third cause of failure was chlorine content of water, especially systems with high chlorine content to control high bacteria count. Levels as low as 1 ppm had the potential of contributing to failure. The plastic parts that were susceptible to this failure cause were acetal polymer injection molded parts.

Unfortunately, wide scale failures of water pipes in homes and in municipal water delivery systems are the recipient of very bad publicity in news media. The CBS news program "60 Minutes" had a segment on plastic pipe failures that was anything but complimentary. Such failures carry over to all plastics in the eyes of the public. Clearly there is a need to ensure that plastics in all applications, but especially those wherein there can be substantial property damage, are held to the highest possible standards and assurances of non-failure. There can also be personal injury. A man who slipped and fell in his flooded office sued for damages.

**6.6.2 Polypropylene cold water inlet tubes in hot water heaters.** Hot water heaters have a long cold water inlet tube that goes to the bottom of the water being heated. Copper inlet tubes were replaced with polypropylene. The first signs of a problem were that faucets were becoming clogged with a white substance, which was PP. The hot water heaters also ceased to function normally because the PP tubes had broken off, so that incoming cold water was going to the top of the system rather than to the bottom. PP is readily oxidized and degraded to lower MW, particularly if antioxidant content is low. Replacing copper with PP did not prove to be a good replacement. The risk/benefit ratio was weighted too heavily on the risk and not enough on the benefit side.

## 6.7 Neoprene rubber cable jacket blistered in service [11]

The next case exemplifies well the completely unexpected nature of some service conditions and the resultant failure that can occur. In Figure 6, a neoprene rubber jacket for electrical cable blistered in service. In the photograph there are blistered and unblistered areas. Cuts in both were made for analysis. The question to be answered was if the blisters were due to the jacket, or to an external service condition. In one case, the manufacturer of the cable system would be liable for damages, and in the other, the user is responsible. The cable was laid on the ground in a field to operate a radar antenna. The field was used to grow corn, for which spraying was done. The cable to the radar antenna ran through the planted area. It was suspected that the blistering was due to sprayed chemicals falling on the jacket. This was confirmed by gas chromatography/mass spectroscopy of volatiles which showed the presence of at least five compounds in blisters not present otherwise. This is a service condition far beyond anything reasonable to expect. The manufacturer of the cable did not know that it would be installed in a cornfield, and so had no reason to anticipate a problem from agricultural chemicals. Possibly if the manufacturer knew that, a more chemically-resistant jacket might have been used. The jacket was not fractured, and the cable functioned satisfactorily. Nevertheless, an obviously unusual appearance is unsettling to the user of the product.

## 6.8 Temperature effects in service

**6.8.1 Effect of heating at 160°C on operation of servo motor made of PBT [12].** The servo motor consists of a PBT (polybutylene terephthalate) molded part in which a metal screw operates back and forth to control a function, such as gasoline flow. The clearance of the metal screw and PBT is small. In an endurance test the unit was operated at 160°C, which caused the PBT to crystallize further. That caused the part to shrink resulting in the screw no longer moving freely.

**6.8.2 Use of plastics at a much lower temperature than normally used [13].** Cracking of floor tile and baseboard in an area near a laboratory indoor liquid nitrogen ($LN_2$) filling station occurred. When $LN_2$ is transferred to a container, the air in the vicinity, especially directly below, is very cold. The time to fill containers may be 15 minutes or longer, so the floor and wall become very cold. The fractures are due to the thermomechanical effect of expansion and contraction over a wider temperature range than expected, and to embrittlement at very low temperature. The paint on the cinder block wall nearby peeled off due to differences in coefficient of thermal expansion. This is a totally unanticipated service condition case, well beyond any indoor thermal condition that might apply in a laboratory at that location. The $LN_2$ facility was installed after the original construction at a location where unusual conditions of temperature were not expected. Nearby areas on the same wall, away from the $LN_2$, have performed satisfactorily.

## 6.9 Explosion of five gallon polyethylene liquid waste can [14]

The can was used for laboratory solvent waste, which included toluene. Another person discarded nitric acid in the same can. Neither person was aware of the other's discarded liquid. An explosion occurred after some time of the toluene and the acid being together. To determine the cause of the explosion TD/GC/MS (thermal desorption gas chromatography/mass spectroscopy) was performed on a fragment of the PE can. Compounds detected included nitrotoluene, dinitrotoluene and an indication of trinitrotoluene (TNT). The latter compound is a high explosive. Apparently when the concentration of TNT increased to an explosive level the liquid exploded. The cause was determined because the GC/MS analytical method is very sensitive and there was enough of the compounds absorbed in the PE to be desorbed with heat and analyzed. The analytical results led to the realization that the explosion had been caused by both toluene and nitric acid being discarded separately in the same container.

## 6.10 Failure of 4000 volt cable [15]

Electrical cable, rated for ca. 4000 volts, used to operate water pumps in a power plant failed due to overheating and embrittlement. Since there was no reason to believe overheating resulted from high current carried by the conductor, the cause of failure was not immediately obvious. The insulation was EPR (ethylene propylene rubber) and the jacket was chlorinated polyethylene. Embedded in the jacket were copper shield wires. A cross-section of unfailed normal cable is in the left of Figure 7. That for failed cable is on the right, the insulation being darkest next to the jacket. Had the overheating started from the main conductor, the darkening of EPR insulation would have been greater starting at the conductor. But the reverse was true, suggesting that the source of heat was in the jacket. It was found that the shield wires carried 25 amperes, an abnormally high unintended current. Being embedded, the heat was not readily carried off and the jacket became overheated. The dark color the EPR took on was due, at least in part, to HCl (hydrogen chloride) gas evolved by chlorinated polyethylene at high temperature. Another indication of evolution of HCl by chlorinated PE is that the wires were green, due to reaction with HC1. The importance of these observations was that they proved the source of excessive heat was in the jacket, not the main conductor. Then, probing what may have caused that, the root cause of the problem was discovered as high shield current

## 7.0 Synergistic Effect of Two Stresses Acting Simultaneously

Either of the two stresses by itself may not be a problem. But two together can have a devastating effect. Environmental stress cracking is a well known case of this synergistic effect.

### 7.1 Environmental stress cracking [16]

An injection molded SAN (styrene-acrylonitrile) piano key had a hook end that attached to a metal spring to make the key spring back after being played. The hook end experienced fracture (Fig. 8, 9). Fracture occurred when the inside of the piano was cleaned with ketone solvent to remove adhesive from areas where it was not needed. The solvent vapor condensed on the piano keys causing fracture at the hook end spring location. The cause was sought by performing thermal reversion to observe the level of frozen-in or internal stress due to injection molding. Heating is done several degrees above the glass transition temperature for a short time. The part shrinks and distorts in response to the frozen-in stress. Parts with low internal stress will not shrink and distort much. The photos show extensive shrinking. Of particular importance is the shrinkage of the hook end (Fig. 9), which is greater than shrinkage of the whole part. It was concluded that fracture was due to condensed solvent acting as an environmental agent at a high stress point, the hook end. The stress may have come in part from the external spring tension as well as internal frozen-in stress.

### 7.2 Water treeing of PE electric distribution cable [17]

PE is a good dielectric and is water resistant. These properties were the basis for extruded underground distribution cable (of the order of 15-35 KV). When first put into service, XLPE (crosslinked PE) cable was thought to be a “marriage made in heaven” for the two key properties of high dielectric strength and high water resistance. Being underground, electric power would be less vulnerable to disruption by natural forces as is the case for overhead cables. Falling trees and limbs would not knock underground electric power out of service.

Underground cable started to fail in about 5-10 years. The PE experienced dielectric failure due to a failure mode called “water treeing” because the degraded PE resembles trees. The synergistic stresses causing failure were electrical energy and water. Oxygen also plays a role in oxidative degradation. The failure is due to the formation of a degraded area, which acts as a channel for electrical breakdown. Putting failed cable back into service may require replacement of long lengths of buried cable, which may not be readily accessible.

There always is electrical potential in a cable in service. The second factor is the ingress of water, which can cause slow, steady breakdown of PE, helped along by oxidative degradation. Without electrical potential, water is not a problem at the very low levels present. Clearly it is a synergistic effect of the two together.

The solutions include anti-treeing additives, very clean PE free of impurities, and other polyolefins that are less susceptible to water treeing, i.e., crosslinked EPDM (ethylene propylene diene monomer).

## 8.0 Summary

Examples have been given of polymeric material failure under five categories (Introduction 2.0). Failures can occur for practically any polymeric material in various ways and at various stages of manufacture, assembly and service. Often failures are unpredictable, especially for synergistic effects like environmental stress cracking and electric power cable water treeing. In some cases possibility of failure was not adequately considered, such as replacing copper tubing with PP tubing in hot water heaters and PB pipe for water service. In all cases, a risk/benefit assessment is desirable, considering even worst case scenarios with regard to risk. Not only is the reputation of certain polymers adversely affected by failures, but plastics in general receive a “black eye.” Polymers are sufficiently different than metal that they require special care in handling, such as in plumbing.

It is unlikely that all failures of polymeric materials will ever be completely eliminated. Certainly the “unexpected and unusual” ones will continue to surprise and plague us. But we can learn from the present large storehouse of failures by being alert to similar situations of composition, service conditions and all factors that together may make for success or failure with plastics and rubbers.

## 9.0 References

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17. Ref. 1, p. 32.

## Key Words

Plastics failure, unexpected failure of polymers, failure in processing, assembly, composition changes, service conditions, synergistic effects.

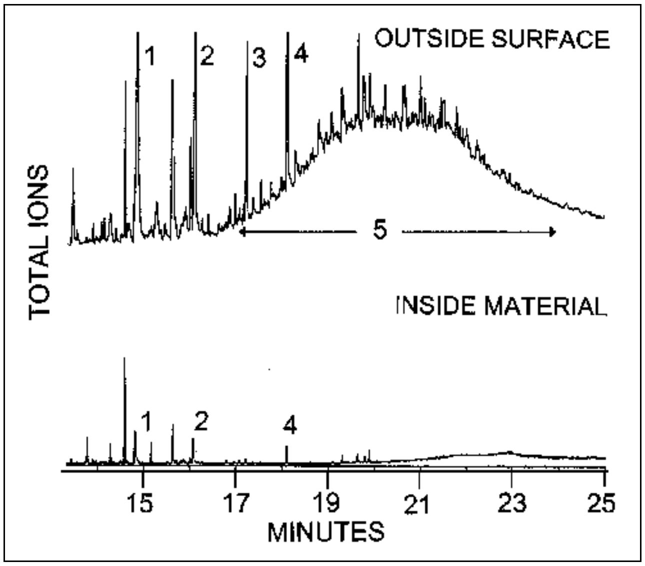

**Figure 1.** GC/MS chromatogram of outside surface (top) and material below the surface (bottom) of phenolic resin part that could not be bonded to silicone adhesive; peak 1-hexadecanoic acid, 2-octadecanoic acid, 3-octadecanamide, 4-dioctylphthalate, 5-hydrocarbons (Ref. 5. Fig. 7).

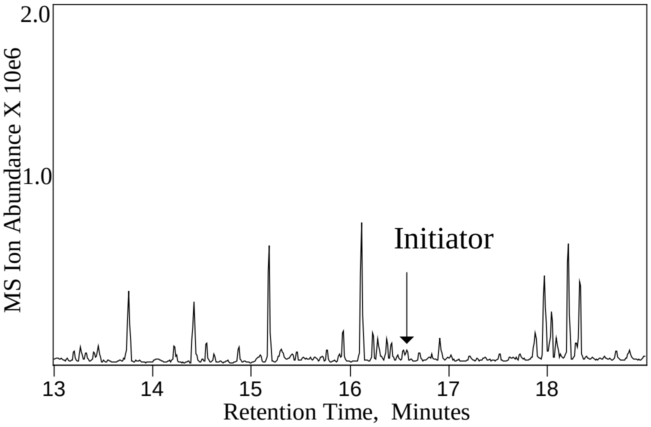

**Figure 2.** Thermal desorption GC/MS of metal surface to detect initiator in an adhesive (Ref. 7, Fig. 1).

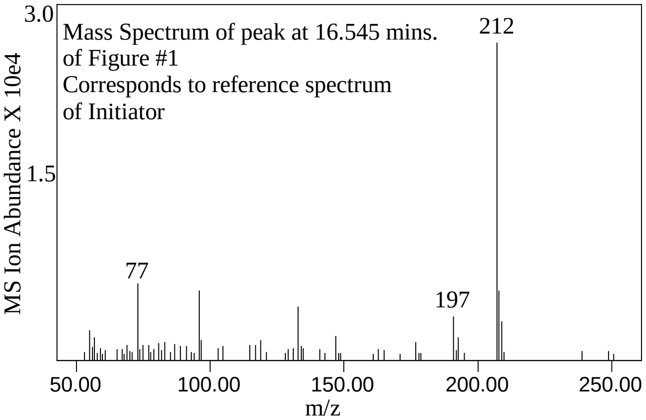

**Figure 3.** Mass spectrum of GC peak to identify initiator in Figure 2 (Ref. 7, Fig. 2a).

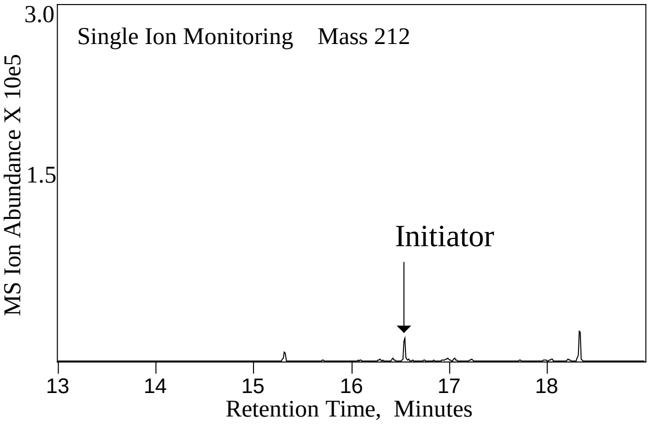

**Figure 4.** GC/MS of Figure 1 with single ion monitoring of ion mass 212 (Ref. 7, Fig. 2b).

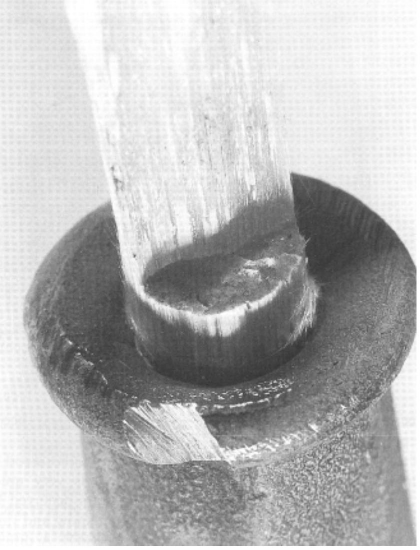

**Figure 5.** Polyester-fiberglass guy strain insulator rod fractured in electric transmission service (mechanical support rod) after 10-12 years. Note cup-like feature at the top of the end fitting where liquid is held and evaporated (Ref. 1, p. 178, Fig. 6-18).

**Figure 6.** Neoprene rubber jacket blistered due to agricultural chemicals sprayed on it in a corn field where neoprene jacketed cable lay on the ground for a radar antenna (Ref. 1, p. 177, Fig. 6-17).

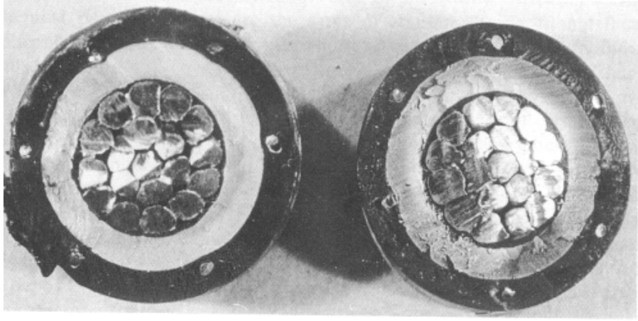

**Figure 7.** Cross-section of degraded (right) and undegraded cable showing darkening of insulation started near the outer part of the cable where the ground wires are located in the black jacket (Ref. 1, p. 163, Fig. 6-5).

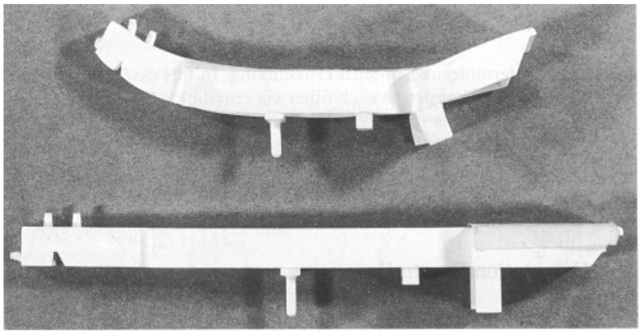

**Figure 8.** SAN piano key before and after (top) heating to release frozen-in stress (Ref. 1, p. 42, Fig. 2-20).

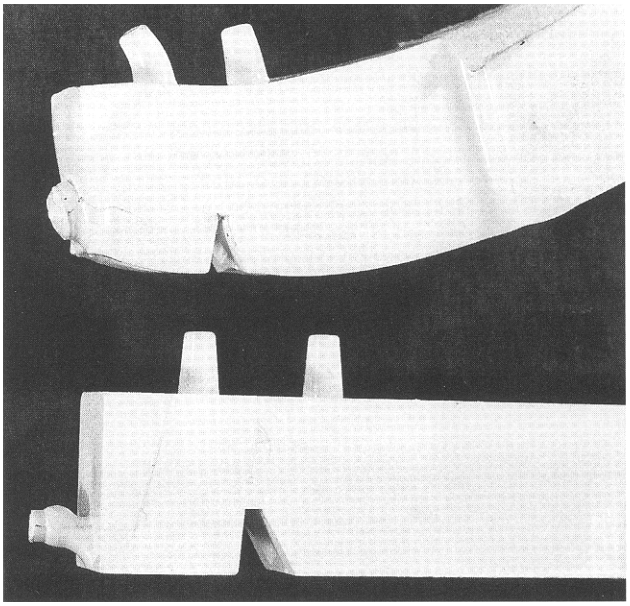

**Figure 9.** Close-up of hook end (left) on SAN piano key before and after (top) heat shrinkage (Ref. 1, p. 43, Fig. 2-20a).