lead to dielectric failure. Reports of cable failures suspected to be caused by water trees about the time of the original study by Vahlstrom [39] also originated in Japan [42]. These unexpected discoveries of possible unsatisfactory service life of polyethylene and crosslinked polyethylene power cables were disturbing to the power utilities and the cable industry and led to urgent studies of the problem in many countries including Canada [43–46]. Most of the work has been carried out on HMWPE and unfilled XLPE. The quantities of EPR and filled XLPE cables in underground distribution are relatively small; furthermore the opaque nature of these materials makes the detection of trees difficult. Trees can be observed easily in XLPE and HMWPE cables because these insulations are translucent. Water treeing of dielectrics is discussed and illustrated in Chapter 2. Water trees are apparent by their characteristic dark appearance when contrasted to the translucent, thin wafers cut from the cable insulation. Because of the lack of field evidence, it is not possible to conclude that EPR cables have failure rates comparable to HMWPE and XLPE. It has been reported that the treeing susceptibility of EPR cables is about equal to that in XLPE and less than that in HMWPE [47].

Water trees, sometimes called electrochemical trees, have basic characteristics different than electrical trees. Electrical trees are characterized by the occurrence of partial discharge, require high electric stress to initiate and rapidly lead to catastrophic dielectric failure. Water trees can be initiated at much lower dielectric stress, grow very slowly, are associated with no measurable partial discharge, and may completely bridge the insulation from conductor to shield without dielectric breakdown, although the dielectric strength is much reduced, in particlar the direct current (dc) breakdown value [48]. Electric treeing, a well-known phenomenon since the early days of electrical engineering, occurs in poorly designed or overstressed insulation systems. The mechanism of failure is known and understood. Water treeing is a process studied intensively since circa 1970, but the inception and growth of the treelike structure has no universally agreed theoretical basis. The literature on water treeing is large because the investigations, although only encompassing a short time period, are intensive. Bernstein [49] in his review of water treeing theory, gives the major requirements and factors influencing the growth but suggests that the mechanism of inception is not known. It is accepted that two fundamental conditions are required: (i) a polar liquid, usually water, must be present and (ii) voltage stress. Electrical trees require only voltage stress. Other factors, listed in no particular order of importance, have been enumerated by Bernstein [49]. These are aging time, material nature, contaminants/impurities, temperature, temperature gradient, cable design, magnitude of operating voltage stress, test frequency, antioxidant, voltage stabilizers, water nature, and semiconducting layer type.

It has been shown that water in the interstices of the stranded conductor greatly enhances the tree growth even when the cable is immersed in water, particularly when a temperature gradient exists in the insulation [50]. Badher et al. proposed a physical model of aging in polymeric cables [51] and later proposed short- and long-term electrical tests based on the model [52]. Lyle and Kirkland reported on an accelerated aging test procedure for the growth of water trees and determination of cable life when subjected to various test conditions [53]. The importance of water in the strand and increased temperatures were again demonstrated.

Although the problem of water treeing has not been eliminated, manufacturers are improving processing technology to improve the service life. Cables manufactured today are improved over those that exhibited early failures circa 1970. Tape strand shielding is now unacceptable. The number of voids, protrusions, and contaminants have been significantly reduced. Tree-retardant XLPE insulation compounds are now widely used. Some experts believe that voltage stress should be reduced even though this action would increase the first cost of the cable. Hermetically sealed sheaths have been developed [54], although these designs might be economically attractive only for transmission voltages. Experience indicates that such sheaths provide good service lives for cables rated at 138 kV and higher. The great importance of keeping water out of the strand is now accepted, and several manufacturers now offer a strand filler to prevent water ingress. Modern cable design has improved markedly over the last decade, but a final solution to water treeing and premature failure in wet environments has not yet been assured. Figure 3.12 illustrates the rising trend of failure rates. Recent field investigations [55] led to the conclusions that failures in XLPE begin to intensify after 10–15 years of service and that water treeing and internal defects (inclusions) were the most often identified problems. Unfortunately, there is an unavoidable time lag between possible effective corrective measures and corroborative evidence from service failure rates.

3.5 SOLID-DIELECTRIC INSULATION TECHNIQUES

Since the 1950s there have been great advances in the techniques of insulating medium-voltage solid-dielectric cables. Formerly the insulations were the thermosetting* compounds based on butyl rubber or the thermoplastic compound, polyethylene. The butyl rubber insulant was applied by an extruder, called a tuber. The vulcanization of the insulation was a separate operation in an open steam vessel or autoclave. Semiconducting fabric tapes were utilized for conductor and insulation shielding. In

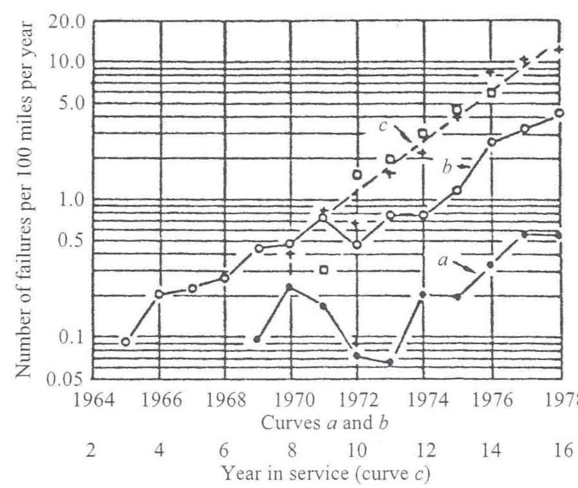

Figure 3.12 Failure rates of polymeric power cable rated 5–35 kV; after Thue [46]: (a) and (b). Average failure rate for all cables operating in a particular year: (a) XLPE and (b) PE. (c) Failure rate versus number of years in service: XLPE + PE.

*A thermoset is defined as a material, cured under heat, that does not soften when reheated. This definition is not strictly true for crosslinked polyethylene because it does soften and has lower physical strength than most vulcanized rubbers at high temperatures. However, for practical cable applications, the definition is suitable.