



ADVANCES IN CHEMICAL REJUVENATION OF SUBMARINE CABLES

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ABSTRACT

Submarine cables spanning two or more kilometers have proven challenging to apply conventional rejuvenation technology. Novel approaches, which include new installation methods and new materials to extend the life of submarine power cables, are described. Theory, experiments, and field results demonstrate that these new approaches address the shortcomings of the earlier technology. The technology described can be tailored to provide: (1) more rapid short-term reliability, (2) longer rejuvenated cable life, (3) an inherently safer installation, (4) a tailored formulation paradigm which adjusts the chemistry to account for significant operational variables, and (5) a process which can address any length of cable.

KEYWORDS

Submarine cable, rejuvenation, injection, life extension, radial exclusion, strand desiccation.

INTRODUCTION

Over twenty years have elapsed since the author and his colleagues introduced the first commercially significant solid dielectric enhancement technology as described in [1]. During those twenty years, this first generation technology has proven itself as an important tool to enhance the reliability of aging infrastructure, saving circuit owners an estimated US\$1B of capital, which otherwise would have been spent on replacement. Submarine cables have proven to be an engineering challenge. Since the cables are often very long, the two-decade-old approach is often incapable of fully completing the cable treatment.

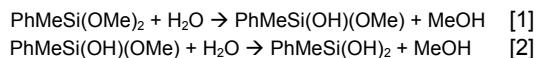
This paper describes novel approaches, including new installation methods and new materials, to extend the life of submarine power cables. Theory, experiments, and field results demonstrate that the new approaches address the shortcomings of the first generation technology. The new technology choices can be tailored to provide: (1) more rapid short-term reliability – the post-injection dielectric performance improvement slope is steeper by more than an order of magnitude as shown in [2], (2) longer rejuvenated cable life often exceeding the 40-year expected life for the highest performance modern cable designs as demonstrated in [3] and [4], (3) an inherently safer installation, including lower flammability fluids, which have flash points in excess of 94°C compared to the legacy material, which has a flash point of 0°C as per the supplier's MSDS, which can be found at [5], (4) a tailored formulation paradigm, which adjusts the chemistry of the treatment fluid to account for significant operational variables described in [2], and (5) a novel process, which can address any length of cable. The first four items in this list of advances have been explained elsewhere. The balance of this paper will examine the injection conundrum faced when treating very long cable lengths.

CONDENSATION

From 1984 to 1987 approximately 20 km of medium voltage underground power cable were treated with acetophenone. Acetophenone was a known fire retardant and life extension material. Acetophenone is present in most cross-linked polyethylene (XLPE) as a by-product to the cross-linking process. The beneficial effects of acetophenone were noticed accidentally, since it is present in significant quantities in new XLPE cables as a by-product of the cross-linking process.

There are two problems with acetophenone when it is used alone. First, its freezing point is about 20°C, which makes its injection at temperatures below that temperature problematic. Second, with a rapid diffusivity of $1.3 \times 10^{-7} \text{ cm}^2/\text{s}$ at 50°C in polyethylene, it is fugitive and would not stay inside the cable insulation for periods beyond a couple of years. The early injections with acetophenone employed permanent bottles attached to the cable to replenish the acetophenone which exuded from the cable. Although failure free and a huge technical success, the safety and maintenance issues associated with this life-time connection drove the development of a water-reactive silicone material PMDMS (phenylmethyldimethoxysilane). The properties and advantages of moderately diffusing ($D=5.73 \times 10^{-8} \text{ cm}^2/\text{sec}$ at 50°C) PMDMS are described in considerable detail in [1]. In short, a silicon atom with two water reactive groups was substituted for the carbon-oxygen double bond of the acetophenone. The two water-reactive portions of the PMDMS are methoxy groups, which readily hydrolyze with water and condense in the presence of an appropriate catalyst, to form siloxane oligomers, generally to an equilibrium mixture with degrees of polymerization between 4 and 7.

Alkoxysilanes undergo two types of chemical reactions, both of which are typically accelerated with catalysis. The first reaction type is hydrolysis. For example, PMDMS or PhMeSi(OMe)_2 hydrolyzes in two steps as follows:



An example of the second reaction type, condensation, is:



This second kind of reaction, the condensation of two monomers to a dimer in the presence of a catalyst, is but one example of dozens of condensation reactions which actually occur. The catalyst employed by the over two-decade-old technology is tetraisopropyltitanate (TIPT). For example, with TIPT present a dimer and a monomer can condense to a trimer, two dimers can condense to a tetramer, or a trimer and a monomer can condense to a