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Liquid Insulation of IGBT Modules

Long Term Chemical Compatibility and High Voltage Endurance Testing

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***Abstract*— To facilitate operation of power electronics for subsea operation at ambient pressure components have to be submerged in a liquid. Equipment and schemes for testing of long term properties have been developed. Several techniques were used to investigate compatibility between a silicone gel and various insulation fluids. Equipment for electric endurance testing of power electronic components at dc stress under controlled temperature and humidity was developed. Performance of high voltage diodes covered with various insulation liquids, coatings and gel covering were studied.**

Keywords - IGBT, Insulation, Liquid, Gel, Coating, Chemical compatibility, Voltage endurance test, Humidity

I. Introduction

In offshore sub-sea oil exploitation variable speed drives are used for supporting production. The power electronic components can either be located top-side or at the seabed. Today's technology for seabed location applies 1 bar air filled tanks for environmental control of the power electronics. These tanks become heavy and large. This results in problems for cooling of the power electronics. An alternative technology would be to put converters at ambient pressure at the seabed. To achieve this, all components have to be placed in a liquid environment. This would reduce tank size and result in more flexible tank design.

There are various ways of protecting power electronic components as e.g. IGBT's. One technique is to cover them with a silicone gel. This increase withstand voltage compared to putting them in air, and keeps dirt away from delicate highly stressed parts like trenches between copper islands on substrates and high field areas around transistors and diodes. Obviously, the possibilities of water ingress poses possibilities for reduced performance [1].

When submerging power electronics in a liquid environment, one can either submerge the gel-covered substrates in a liquid, or alternatively use a liquid as the basic insulation instead of the silicone gel. Either way both short term and long term dielectric performance of materials have to be studied. This work is a part of a large study aimed at facilitating possibilities for power converters at subsea ambient pressure. Short term dielectric performance of various liquids stressed in the trench of a substrate models under pressure was studied [2, 3] and showed that high pressure improves partial discharge inception voltages.

For the long term performance, influence of humidity and material compatibility, it was decided to test this at ambient pressure in the lab (1 bar) as a first screening as enhanced pressure would improve performance (dielectric performance) or have little influence (chemical compatibility).

Long term dielectric performance was studied for high voltage diode chips. Contrary to the trenches, these cannot be overstressed as chip then would suffer from internal breakdown. During operation, the chip edges are stressed either with dc when the converter is idle, or with fast rising and falling voltage steps when switching.

The chemical compatibility between the gel and the liquid is crucial for the long-term efficiency and functionality of the chip. In this study, various minerals oils, synthetic and natural esters and fluorinated (perfluoropolyether) fluids are tested. The latter and some natural esters seem to be the best candidates since no interaction between these oils and the gel are observed. In addition to the pure compatibility investigation, high voltage long term experiments on diode chips (representative for IGBT insulation) objects covered with gel and insulation liquids were performed in wet and dry environments. The experiments were performed at elevated temperature and nominal DC voltage until failure. The continuously monitored leakage currents from the objects were used as failure indicator. As mentioned earlier, the chips are usually protected by silicone gel and insulating liquid. Other material combinations, including protective layers, were also investigated. Methods were developed preparing the objects and cleanness became the critical element in general. The failed objects were investigated using a microscope.

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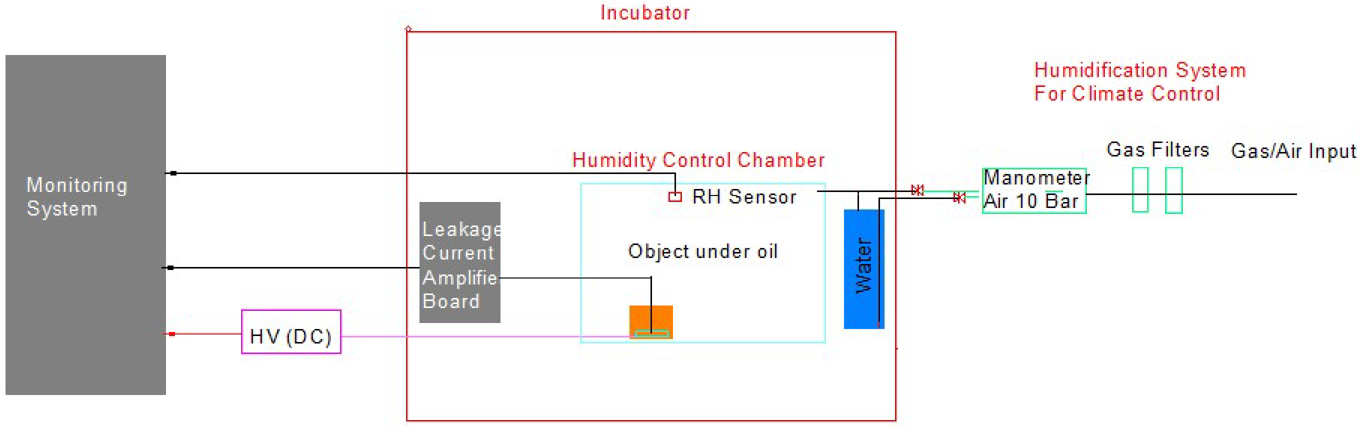

Fig. 1: Schematic setup for the long-term ageing experiments (humidity and temperature control), the object schematic in this figure is only one of many object in the humidity control chamber.

II. Experimental Section

A. Chemical Compatibility

A selection of relevant materials in a simple model system was investigated wherein the gel is put in contact with the insulation liquid using sealed glass bottles under nitrogen atmosphere for 120 days. Their interaction is followed as a function of time. After 120 days, when no difference was visually observed in the liquid phase from the beginning to the end of the experiment, a potential change of color or a potential optical inhomogeneities (scattering) from gel particles is investigated for the liquid by Ultraviolet-visible (UV-vis) spectroscopy. Structural changes within the liquid or the gel were investigated by Infrared (IR) spectroscopy and isothermal microcalorimetry (IMC). The tests were performed at two temperatures (22°C, 100°C) at ambient pressure. Nine liquids were selected based on their chemical differences, Table 1.

Table 1: Nature of the liquids

Nature of the liquids	Liquids
Mineral oils	Marcol 52, Primol 352, Nytro 10XN, Shell Diala
Synthetic ester	Midel 7131
Natural esters	FR3, BioTemp, Midel EN
Polyether fluorinated fluid	Galden HT230

B. Long Term Hivh-Voltage Functionnality Tests for IGBT Electronic Components

Components representative for power electronic converters (diodes) insulated with liquids in various ways relevant for subsea applications has been long term tested under dc stress at respectively low and high humidity level in air at ambient pressure and relative high temperature. Components are either been submerged in liquids or covered with silicone gel, polyimide, parylene and then submerged in liquid. Current was measured for each object and when current exceeded a certain level the component was considered failed. Fig. 1 shows the setup investigating the functionality of electrically stressed components. The humidity control is taken care of using a filtered air (to avoid particles) flow bubbling through a water reservoir at the incubator temperature. The humidified air is then guided into the humidity control chamber (sealed plastic box) containing the objects in operation and mixed with dry air at the appropriate rate to achieve the target humidity. This is a cheap, relatively clean and efficient method controlling the environment and useful for long term experiments. Freewheeling diode chips provided by Westcode were used as objects. The focus was primary on the guard ring area on the chips. High DC voltage is applied to each object and the continuously monitored leakage current is measured using a special in house designed amplifier board. For the diodes the high voltage and leakage current contacts was made using silver epoxy glue (Epotek TV1003) prepared in reasonably clean environments.

III. Results and Discussion

A. Compatibility

Various minerals oils, synthetic and natural esters and fluorinated (perfluoropolyether) fluids were tested with respect to their compatibility with the silicone gel. The latter and some natural esters seem to be the best candidates since no interaction between these oils and the gel was observed for the techniques used here.

An example of Infra-red spectra of Midel EN, a natural ester in contact with the silicone gel for three months at 100 ºC can be observed in Fig. 2 (top). If one compares with the pure oil, the small bands characteristic of the gel at around 2000 cm^{-1} are observed in the spectrum of the oil that has been in contact with the gel. This suggests that the gel is slowly decomposing into the oil. This phenomenon has also been observed for all the mineral oils tested and for Midel 7131, a synthetic ester. As observed with Midel 7131 and Biotemp, if one compares the spectra of the pure gels and the spectra of the gels that have been in contact with Midel EN (at room temperature and at 100 ºC), two peaks characteristic of the oil phase appear: at 1700 cm-1, a peak corresponding to an ester band and at 2700 cm^{-1}. This reveals the absorption of the ester oil by the gel. Hence Midel EN and the silicone gel are not compatible.

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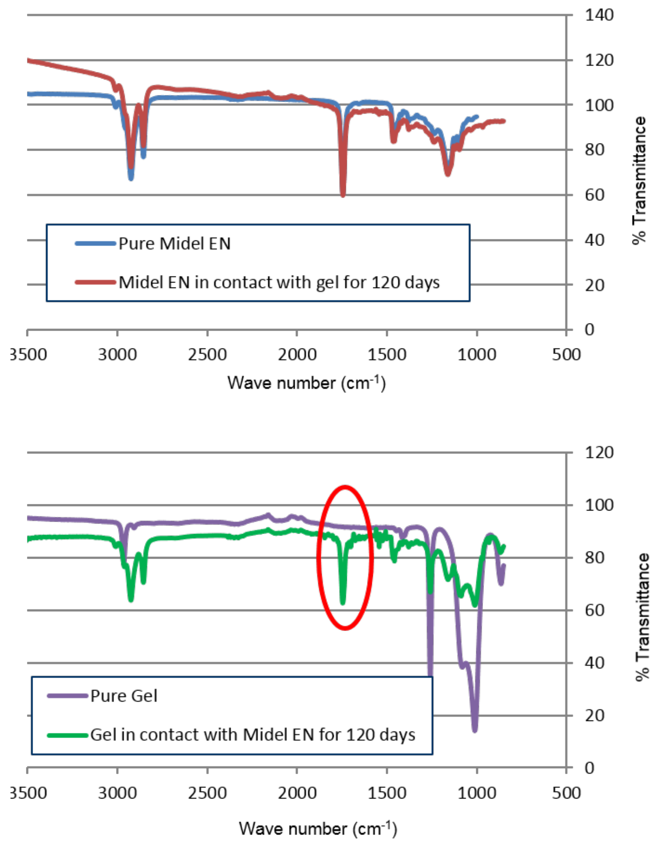

Fig. 2: Infra-red spectra of pure Midel EN and of Midel EN that have been in contact with the gel for 120 days at 100°C (top). Infra-red spectra of pure gel and of gel that have been in contact with Midel EN for 120 days at 100ºC (bottom). The red circle encloses the region of interest.

This incompatibility of the two phases was confirmed by isothermal microcalorimetry and the results obtained for the natural ester Midel EN are shown Fig. 3.

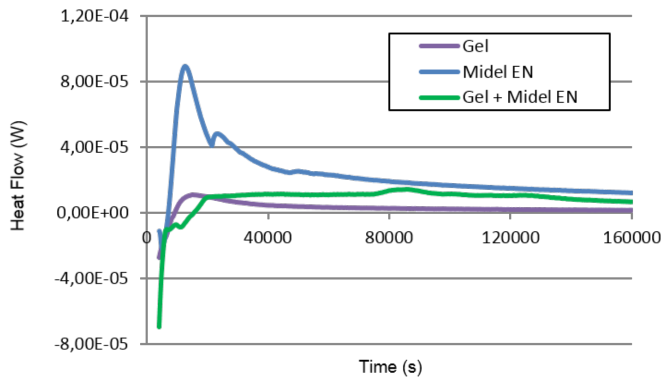

Fig. 3: Heat flow vs. time for the thermal decomposition of gel, Midel EN and a mixture of both.

Isothermal microcalorimetry (IMC) is a powerful tool to investigate compatibility between two phases. It is a direct measure of the net rate of heat flow as a function of time. For two completely compatible materials, the cumulative amount of heat consumed or produced for the mixture should be equal to the sum of the cumulative amount of heat consumed or produced by the separate components. As observed 3, this is clearly not the case for the mixture of Midel EN and slicone gel since the heat flow curve obtained for the mixture (green) is not the sum of the two flow curves obtained for the separate components. The same results were obtained for all the other studied liquids at the exception of FR3 another natural ester (see below) and of Galden a perfluoropolyether. The IR spectra obtained for FR3 in contact with the silicone gel are shown Fig. 4.

Contrary to what was observed for the mineral oils, Biotemp, Midel 7131 or Midel EN, the spectrum of FR3, a natural ester in contact with the silicone gel for three months at 100 ºC is identical to the spectrum of pure FR3, revealing the fact that the gel did not seem to disintegrate into the oil phase. In order to investigate if the liquid was diffusing in the silicone gel phase, the spectrum of the gel that has been in contact with FR3 for 3 months at 100 ºC was recorded and compared to the spectrum of the pure gel, Fig. 3 (bottom). Once again, the spectra obtained are identical revealing the absence of interactions between the two phases. This was confirmed by IMC and the results are presented Fig. 5.

The heat flow curve obtained for the mixture of silicone gel and FR3 is almost exactly the sum of the two flow curves obtained for the separate components proving the total compatibility between the two phases. The same result was obtained for Galden HT 230, a perfluoropolyether.

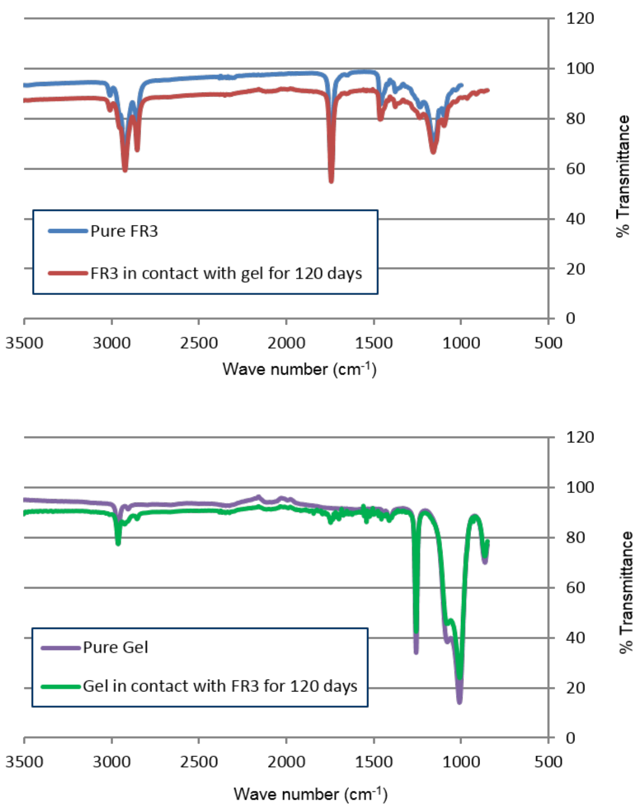

Fig. 4: Infra-red spectra of pure FR3 and of FR3 that have been in contact with the gel for 120 days at 100°C (top). Infra-red spectra of pure gel and of gel that have been in contact with FR3 for 120 days at 100ºC (bottom).

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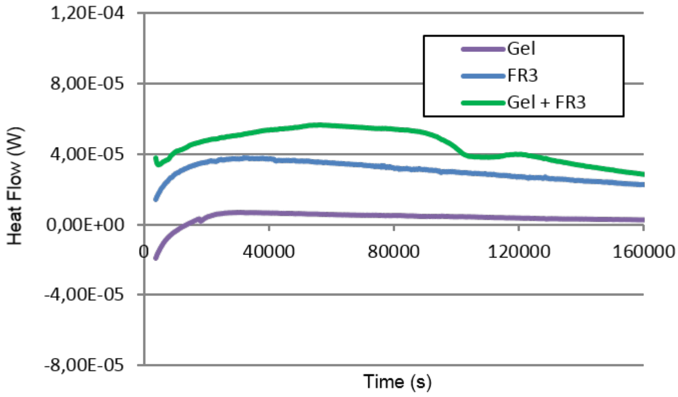

Fig. 5: Heat flow vs. time for the thermal decomposition of gel, FR3 and a mixture of both.

B. *Long Term Hivh-Voltage Functionnality Tests for IGBT Electronic Components*

In these experiments, various liquids were applied either directly on the chips, or on top of a thick silicone gel layer, or layers of parylene (applied industrially) or polymide (applied in-house). In Fig. 7**,** an overview of the long term ageing experiment of the electrically stressed objects with different material combinations and relative humidity is presented. We also observe the status of the objects. The red columns (<39 weeks) represents failed objects while the green columns represent objects still in operation (39 weeks).

Voltage was applied on all objects in parallel using only one dc voltage source (Fig. 7). Therefore, the voltage development is the same in all figures (Fig. 7 and Fig. 8). The voltage source was turned on/off and also adjusted during the testing period due to work in cabinet. Also each time one object failed voltage was shut off for all samples.

Note that for all diode type objects, there are three identical samples (i.e. Fig. 7 and Fig. 8). The three currents from the diodes are very similar (typical for most objects) so what is in reality three different curves (in each figure) may seem like one. For the dry system (i.e. Fig. 8) all of the diodes are still in operation. After 45 days one of the three diodes in the wet system (Fig. 7) experienced an increase in the leakage current ending in a drop of the voltage (Fig. 6, mauve color). This diode was reconnected after 112 days at a lower voltage (1 kV) to ensure that it really failed (there were doubts) and after 130 days it was finally disconnected again together with another diode failing (green curve). After 195 days the last of the wet diodes was disconnected (blue curve, erratic behavior with sporadic very high current not seen so well in this figure). It is difficult to draw any general conclusions but the Galden HT230 oil is evaporating (volatile liquid even though the boiling point is high) from this "open" experiment with air flow at ambient pressure. The Galden glasses with objects are all refilled with 2 months interval. The wet system leads to failure and at the moment almost all these objects have failed.

For all material combinations (Fig. 7) we observe a decreasing trend in the leakage current for the wet system (i.e. Fig. *7*) while the dry system (i.e. Fig. 8) seems stable with a slight increase in leakage current towards the end. In the first period (approximately 90 days) we also observe that the current for the wet diodes (i.e. Fig. 6) is about 20% higher than for the dry system (i.e Fig. 8).This is also observed for the other material combinations (Table 2).

Failure occurs almost always for wet diodes seen from either a voltage drop of the dc supply unable to supply enough current, or a trigging from the amplifier board used for current measurements. In this way the set-up setup functioned well.

In these experiments, we found that covering the objects with a stagnant layer (gel, parylene) avoided problems with contamination pulled to high field regions [4, 5]. Therefore, a stagnant coating is very important. Oil directly on the object could lead to transport of contamination into high field regions hence provoking a failure. In general, the 70 % RH systems is an extreme situation and leads to failure, while for the dry system most objects still are in operation after 270 days (Fig. 6). Some failures for the dry system are observed but this was caused by insufficient clean conditions during preparation and the use of oil directly on the object. Using a very highly viscous silicone insulation liquid directly on the components also resulted in failure (Fig. 7).

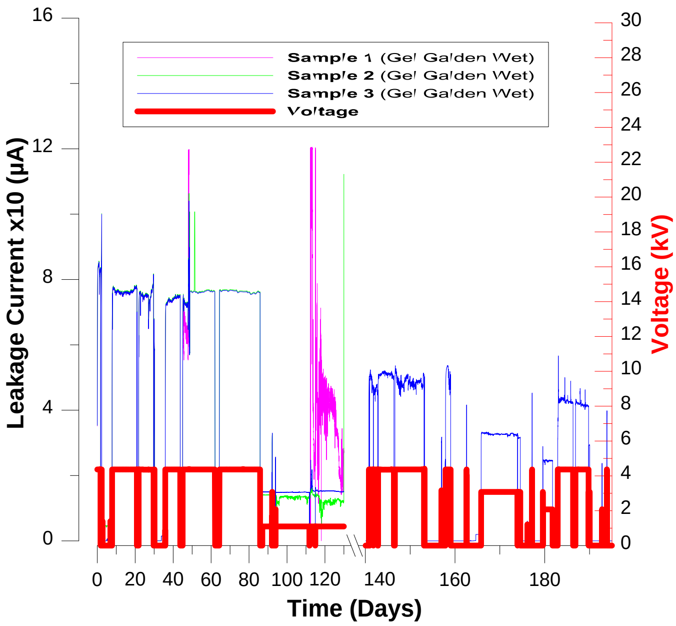

Fig. 6: Example of the current and voltage development with time for the long-term ageing experiments, wet case, Galden-gel.

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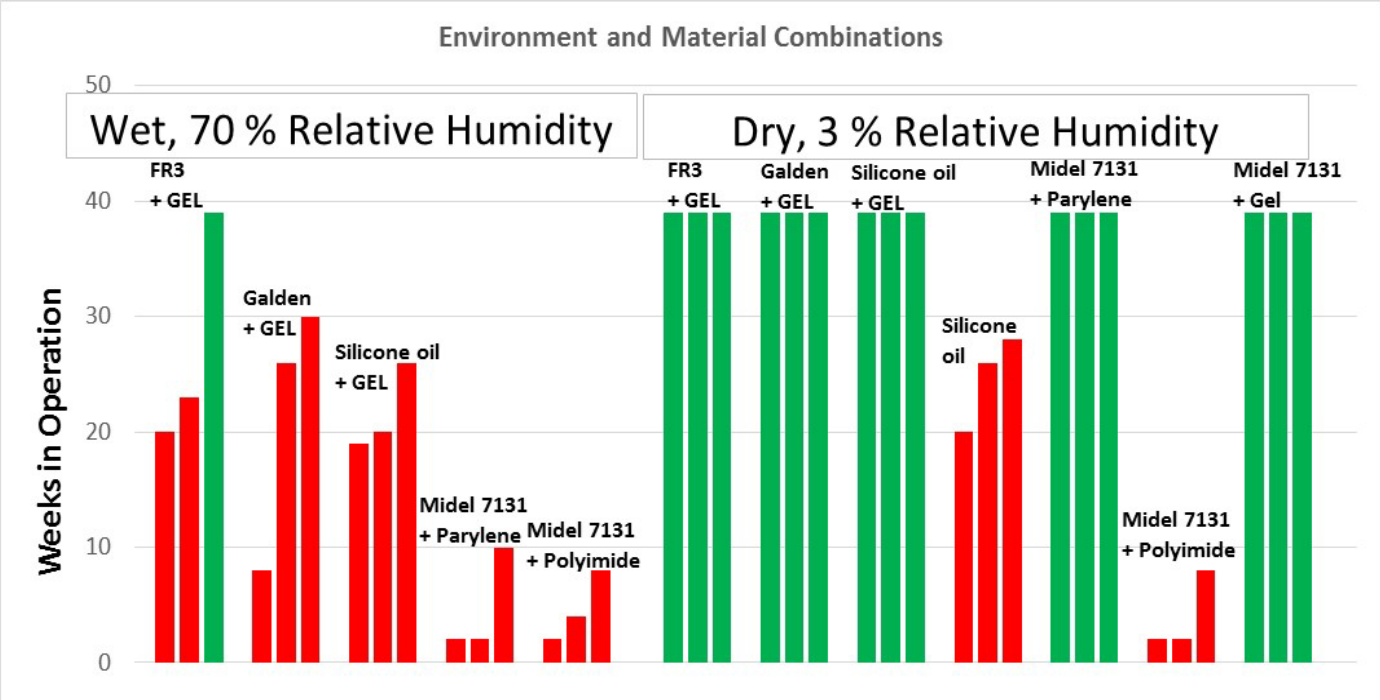

Fig. 7: Time to breakdown from endurance testing of diode in various insulation systems. Test done at 60 ºC and relative humidity environment control. Diodes were operated at maximum 4.4 kV.

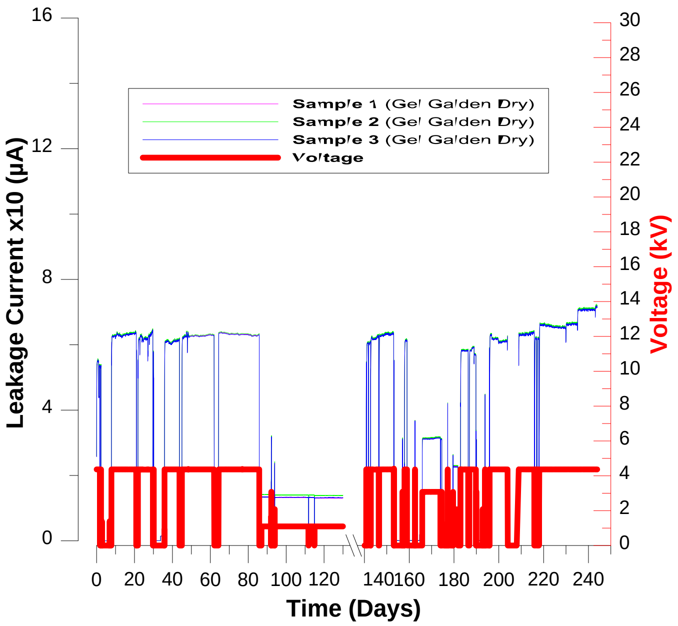

Fig. 8: Example of the current and voltage development with time for the long-term ageing experiments, dry case, Galden-gel.

For both systems, the humidity control employs air which is not ideal for natural esters used (FR3, Fig. 7). The natural ester solidifies into a gel due to oxidation [6]. However, in subsea installations the oxygen content would not be a problem. Moreover, the relative humidity environment is controlled. In Table *2*, the average initial leakage currents (first 80 days) for the wet and dry systems were compared.

Table 2: Leakage Current (LC) comparison for wet and dry system (initial period – until 90 days).

Object	LC (µA) wet	LC (µA) wet
Diode – Gel/FR3	70	60
Diode – Gel/Galden HT230	78	63
Diode – Gel/AK 10000	80	64
Diode – Parylene/Midel 7131	58	50

IV. Conclusion

Various insulation fluids were tested with respect to compatibility with silicone gel. Natural ester FR3 and Galden HT230, a perfluropolyether were found to be the best candidates among the tested liquids since no interaction between these fluids and the gel was observed by UV, IR or IMC.

Equipment for electrical testing at high temperature and humidity control of power electronic components covered with insulation liquids, coatings and gel covering has been developed. Leakage current from each component was monitored and used as functional diagnostic for each object. We observe that the extremely wet system (60 °C for 70 % RH) quickly leads to failure while the dry system (60 °C for 3 % RH) in general still is operative after 39 weeks. We observe that the initial current for the wet diodes is significantly higher than for the dry diodes but towards the end the remaining operational wet diodes have a lower current than for the dry diodes. High humidity in combination with the applied DC voltage could probably dissociate and drain ions away leading to a lower current in the long run. We do not know the critical limit for the humidity provoking failures but we have a system

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capable of investigating these issues. Clean condition during object preparation is crucial. Coating seems to improve the functionality avoiding the insulating liquid directly transporting contaminations into high field regions.

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