Paper ID 10957
B1 – Insulated cables
PS 1 - Learning from Experiences

Session 2022

Formation of Potentially Harmful Shrinkage Cavities During Operation of Mass-Impregnated Non-Draining HVDC Cables

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SUMMARY

Power cables experience temperature variations due to load variations or ambient temperature changes. Thermal contraction of the impregnation compound (the "mass") in mass-impregnated non-draining (MIND) cables causes the internal pressure in the cable to drop when the load is reduced, in some case to such low levels that shrinkage cavities form. These constitute weak points in the insulation, prone to partial discharging that may cause permanent damage and eventually lead to a dielectric breakdown. Experimental and numerical modelling work has been carried out to understand the internal pressure behaviour of MIND cable insulation, and to determine under what operational and ambient conditions cavities will be created, and how large the combined cavity volume becomes. From this, recommendations are given on how MIND HVDC cables should be operated to reduce the risk of cavity-induced aging. As expected, a complete and instantaneous turn-off of the full rated current while still applying voltage, is the most hazardous case. Moderate load reductions of short durations do only lead to small and short-lived cavities. If possible, it is advantageous to keep the average loading high and reasonably constant as this causes the insulation to remain warm and without cavities. It is not advisable to operate the cable at a low load over extended periods, and especially not in the wintertime and in shallow waters or on land where no external pressure suppresses cavity formation.

KEYWORDS

Mass-impregnated non-draining cable; Subsea cable; HVDC; Cable insulation; Shrinkage cavities

1. Introduction

It has for long been generally accepted that the difference in thermal expansion coefficient between the impregnant (the "mass") and the paper in mass-impregnated non-draining (MIND) HVDC power cables will under certain conditions cause shrinkage cavities to form in the insulation [1], [2]. The cool-down after a large load reduction or turn-off is the prime example of such a condition.

The dielectric strength of such cavities is lower than in the surrounding impregnated insulation, so when exposed to high electrical fields, partial discharges (PDs) will ignite in these cavities [3]–[5]. It is also generally recognized that the PDs may or may not be powerful enough to cause local and permanent damage to the insulation, presumably because the size and shape of the cavities may vary.

It should be emphasized that the service record of MIND cables in general is good. Over the years design improvements, better quality control during manufacturing, and ramping speed restrictions appear to have reduced the risk of cavity-induced breakdowns, but the understanding of when and how shrinkage cavities become critical remains incomplete. Moreover, these cables were originally designed and used for relatively stable bulk power transmission. Today—in a deregulated electricity market—they operate with much more dynamic loading patterns than in the past. Identifying under what conditions cavities will be present in the insulation and how large they become, are natural first steps for understanding the risks involved. Such knowledge is necessary to be able to specify safe operational principles for MIND cables in today's more dynamic deregulated market, and to understand how to fully exploit the real capacity and operational flexibility of MIND cables.

During the cable manufacturing process both paper and mass are carefully treated to remove gaseous components [1]. Consequently, cavities will only be created when the internal pressure in the insulation is low, ostensibly well below atmospheric. The risk of having cavities formed is thus clearly related to the internal pressure in the insulation, which for a given cable design is determined by a large number of environmental and operational factors. Moreover, since large cavities are assumed to be more dangerous than smaller ones, the combined cavity volume (the "mass deficit") in the insulation should be an indicator of the associated hazard.

Extensive experimental and modelling work has recently been carried out aiming at understanding the internal pressure behaviour of MIND cable insulation. Four-meter-long samples of state-of-the art 1400 A / 500 kV MIND cables were subjected to current cycling [6], different ambient temperatures [7] and pressures [8], while recording the pressure on both sides of the 20-mm thick insulation layer over periods of weeks and months.

In parallel, a numerical model for the internal pressure dynamics was developed using a "multiphysics" finite element modelling software package [9]. The MIND cable was modelled as 1-D axial symmetric geometry with the different layers (conductor, insulation, Pb sheath, PE sheath, steel bands, steel wire armour, and yarn/bitumen outer serving) described by their thickness and electrical, thermal, and mechanical properties. The 1-D cable model was located inside a 12-m wide and 6-m deep 2-D area simulating the surroundings. By changing the material parameters of the 2-D part, all relevant environments can be considered, including a cable directly exposed to seawater or to air, or buried in mud at the seabed or in soil on land.

The radial flow of mass through the porous paper insulation and the associated pressure dynamics were modelled with basis in Darcy's law, as described by Szabo et al. [10]. The permeability of the lapped paper insulation to a radial flow of mass at different temperatures was found from measurements. The cable casing, i.e., the Pb and polyethylene (PE) sheaths and the steel bands, shows a complicated mechanical behaviour when thermal expansion and contraction causes the internal pressure in the insulation to change. Such pressure changes result in immediate elastic deformations superimposed on slow plastic deformations [7]. A simple four-parameter model based on strain gauge measurements on a cable casing was implemented to model its mechanical behaviour.

The numerical model was calibrated and verified against the pressure measurements. The cavity volume, which is a quantity that cannot easily be determined experimentally, is estimated with basis in the (experimentally verified) pressure model and the properties of the materials involved. Obviously, applying a credible model allows for assessing the risk of cavity-related problems in many more combinations of loading patterns and ambient conditions than can be practically accomplished by laboratory measurements.

Hence, the concept of the work reported on here is that knowledge of the pressure dynamics or "hydraulics" and the properties of the materials involved should make it possible to indicate under what conditions a cable is expected to be prone to cavity-initiated aging. Or more precisely: i) under what operational and environmental conditions will the internal pressure stay below the levels where cavities are believed to form, and furthermore, ii) when is the combined cavity volume in the insulation becoming large.

This report contains three parts. First, the most important conclusions from the direct measurements of internal pressures on cable samples subjected to various ambient and loading conditions are presented. The second part reviews a few results from modelling of more than 7000 cases. Emphasis is here put on the combined cavity volume and how it varies during service-like load reduction situations.

The third part takes the perspective of the cable operator and recommends—with basis in both measurements and simulations—how HVDC MIND cables should be operated to reduce the risk of problems originating in shrinkage cavities.

The laboratory equipment, setups and procedures used for controlling the cable's ambient temperature and pressure, applying current and measuring internal pressures have been described in detail elsewhere [6]–[8] and will not be repeated here. Only excerpts from the measurements that illustrate the most important observations are presented. The numerical model and its ability to reproduce measured internal pressure profiles and to calculate temperature and electric field distribution and development will be described in a separate article.

2. Findings from internal pressure measurements

2.1 The internal pressure tends to asymptotically approach the external pressure

When the cable sample was kept under stationary conditions (i.e., constant, unchanged load and constant ambient temperature) for a prolonged period (weeks and months), the internal pressure slowly and gradually approached the external or ambient pressure. For a subsea cable in service this would typically be the hydrostatic pressure corresponding to the water depth where the cable is located. The orange circles in Fig. 1 indicate three cases where this happens (from left to right): i) fully loaded cable at 10 bar ambient pressure, ii) unloaded cable at 10 bar ambient pressure, and iii) unloaded cable at 1 bar ambient pressure.

In the first two cases the internal pressures in the conductor (red) and under the lead sheath (light and dark blue) stabilize on a value within some 1.5 bar from the ambient, whereas in the last case the internal pressure is still declining and will presumably end up somewhere near the 1 bar ambient. The mechanism at work here is viscoelasticity in the PE and Pb sheaths [7]. This causes the inner diameter of the Pb sheath to slowly increase and decrease, driven by the difference between the internal and external pressure.

However, MIND cables in operation do usually not experience stationary conditions lasting for weeks and months. Large load changes may typically occur within hours, and the associated thermal expansion and contraction of course also affect the internal pressure. Consequently, the important knowledge

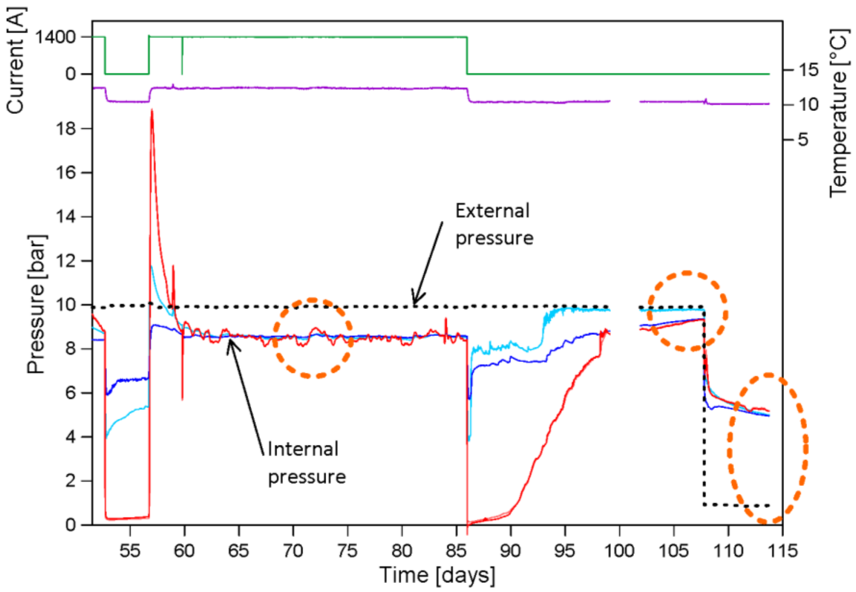

Fig. 1. Pressure profiles at two locations under the Pb sheath (light and dark blue) and near the conductor (red) in a cable sample subjected to load cycling between 0 and 1400 A (green) inside a pressure tank with the pressure (dotted black) reduced from 10 bar to atmospheric on day 108. The ambient temperature (purple)—approximately equal to the cable surface temperature—is around 10 ºC, and a few degrees higher when current is applied. (Reproduced from [8].)

gained is that the internal pressure in a cable is determined by both the long term (previous weeks and months) and short term (previous minutes and hours) loading history.

2.2 High ambient pressure and/or high ambient temperatures cannot prevent cavity formation after a load turn-off

The general belief is that MIND cables at deep waters are less prone to cavity formation, and that a high current load has the same effect. The experimental findings support these assumptions, but with certain reservations.

Fig. 1 shows the internal pressures recorded in a cable that has carried rated current for a month until the load is turned off at day 86. The external pressure is 10 bar, simulating a water depth of 90 m. Within approximately one hour after the load turn-off, the pressure at the innermost parts of the insulation (red line) abruptly falls to zero (and even below). This clearly suggests that the temperature drop causes cavities to be formed. Moreover, the pressure in these parts of the insulation stays at a very low level for several days, possibly causing the cavities to combine and grow into larger and more dangerous ones.

Apparently, a slow radial mass flow and the mechanical stiffness of the circular cable structure cause a considerable pressure difference across the insulation to be maintained over an extended time (black dotted vs red line in Fig. 1). Hence, a sea depth of 90 m is no guarantee for absence of cavities after a large load reduction, although eventually the pressure in the innermost parts of the insulation rises, and the cavities will disappear.

Fig. 2 illustrates the effect of high load and high external temperature on the internal pressure dynamics during and after load turn-on and turn-off. The most notable and surprising observation is that even with an ambient temperature (grey and black lines) as high as 35–38 °C, a load turn-off causes the pressure in the innermost insulation (red line) to fall to virtually zero. The pressure drop takes place within approximately one hour after turn-off, and the pressure remains low for many days. The conductor

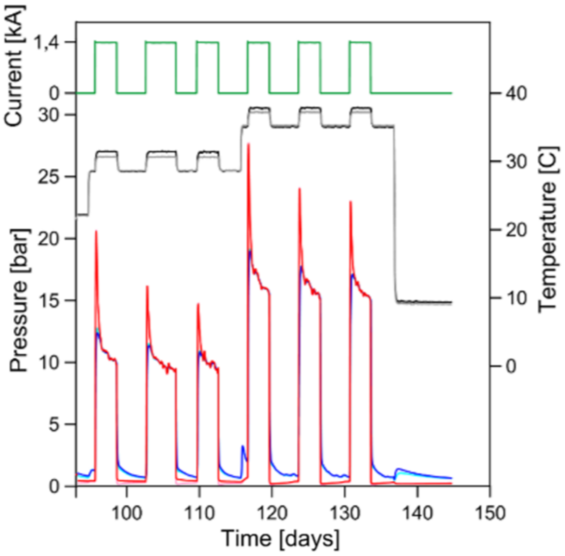

Fig. 2. Pressure profiles obtained under the Pb sheath (light and dark blue) and near the conductor (red) during load cycling at atmospheric pressure. The ambient temperature was stepped up from approximately 30±2 °C to 37±2 °C and then down to 9 °C. The current loading drove the ambient temperature some four degrees up. (Reproduced from [6].)

temperature during loading is around 50 °C which is close to the maximum permissible level for this cable. Still, a load turn-off is likely to cause cavities to be created near the conductor.

Hence, it should be recognized that rapid load reductions or turn-offs are potentially risky, even with a warm insulation or at large sea depths, which are conditions that have commonly been expected to mitigate and even fully prevent cavity formation.

2.3 Rapid internal pressure changes become superimposed on the pressure level exerted by the external pressure

Large and fast load changes, such as turning on or off the full rated load current, may result in large pressure rises and drops in the insulation. As shown in Figs. 2 and 3, the internal pressure changes in such cases are rapid, of large magnitudes, and greatest in the innermost part of the insulation (red lines). It turns out that these fast changes become superimposed on the internal pressure levels generated by the external pressure the cable is subjected to from its environment (the black dotted line). For a submarine cable this is the hydrostatic pressure. Hence, as can be seen from Fig. 3, the relative changes in internal pressure are essentially the same at 1, 4 and 7 bar ambient pressure, but the absolute pressures take different values. The load turn-off on day 17 brings the pressure in the innermost parts of the insulation (red line) down to the potentially harmful level of well below 1 bar, whereas the pressure dip after the load turn-offs at days 24, 31, 38 and 45 never reaches such low values.

Consequently, a cable at a large sea depth takes advantage of a high external pressure and is after a load reduction or turn-off thus less likely to experience pressure drops approaching the low levels where cavities form. However, under certain conditions—e.g., after a long period at full load as in the case shown in Fig. 1—pressure drops to very low levels may occur also at a considerable depth.

3. Findings from simulations of cavity volumes

By applying the numerical model, temperature and pressure distributions in the insulation, both as a function of time, have been determined for a variety of environmental conditions and loading patterns.

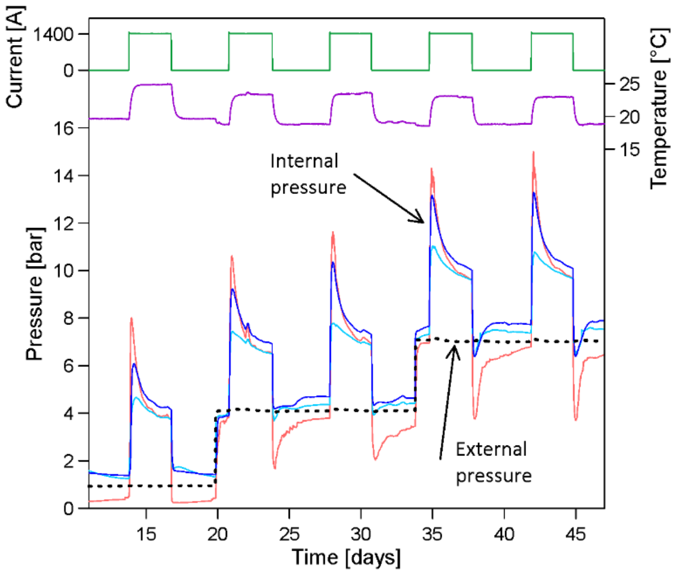

Fig. 3. Pressure profiles under the Pb sheath (light and dark blue) and near the conductor (red) in a cable sample subjected to load cycling at 1, 4 and 7 bar (dotted black line) ambient. (Reproduced from [8].)

The combined cavity volume in the insulation is then estimated by calculating the "mass deficit" that under very low internal pressures occurs as a result of the thermal contraction of the mass. Obviously, also this quantity varies with time.

It is reasonable to assume that the risk associated with cavities increases with increasing cavity volume, but also with the time a large cavity volume persists. (Many small cavities may over time coalesce to larger and more dangerous ones.) These are the main parameters considered in the modelling results presented in the next sections. Here, the load changes are not simply instantaneous as in the experimental work described above, but takes place at a rather steep ramping rate of 60 MW/min, corresponding to 2 A/s.

3.1 A complete ramp-down from full load leads to the largest combined cavity volume

Fig. 4 shows the modelled cavity volume after ramping down the current from the full load of 1400 A and down to zero at different ambient temperatures and pressures. Prior to this, the cable had carried full load for an infinitely long time, causing the pressure to become the same throughout the insulation. (Temperature differences between the inner and outer parts of the insulation and thermal expansion of the mass have caused some of the mass to migrate outwards to cancel out any pressure gradients.)

As expected, the load reduction initiated at t=0 and the accompanying temperature drop in the insulation cause cavities to form; with a combined volume calculated to reach around 6 cm^3 per meter of cable some six hours after turn-off in some of the cases presented in the figure. Assuming the cavities form in the butt gaps and that the butt gaps account for around 10% of the insulation volume, this implies that shrinkage cavities in the form of low-pressure gas bubbles in these cases make up approximately 1.4% of the butt gaps. However, the cavities are not expected to be evenly distributed; most of them are probably created in the innermost parts of the insulation where the temperature drop is largest.

The temperature of the surroundings has a surprisingly small influence on the cavity volumes being generated within the first hours. This is probably because the viscoelastic properties of the PE and Pb sheaths during the extended time at full load prior to the ramp-down have caused the sheaths to deform,

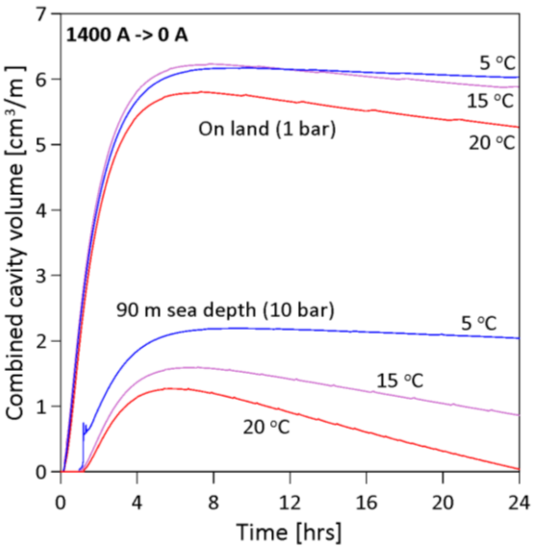

Fig. 4. The combined cavity volume per meter cable after a ramp-down from 1400 to 0 A at different ambient temperatures for a cable under atmospheric pressure (upper curves) and at 90 m sea depth (lower curves). The 2 A/s load reduction starts at *t*=0 and takes nearly 12 minutes.

so that the internal pressure over time has approached the external pressure for all temperatures. (This behaviour is seen Fig. 1 and discussed in Section 2.1.)

However, the ambient temperature influences to a considerably extent on the lifetime of the shrinkage cavities. At higher temperatures the lower viscosity of the mass causes the backflow of mass from the outer to the inner regions of the insulation to proceed faster, thereby filling up the cavities existing in the innermost insulation layers. (These experienced the largest temperature drop and the greatest thermal contraction after the load turn-off.) Hence, in the 20 °C / 10 bar case all cavities have disappeared after 24 hrs, whereas at 5 and 15 °C this process is much slower.

3.2 A high external water pressure to some extent suppresses cavity formation

The modelling results in Fig. 4 indicate that under otherwise similar conditions, a high external pressure is favourable as it causes less cavities to form. A cable on land or in shallow water will have a roughly three times larger combined cavity volume compared to the same cable exposed to the external pressure at 90 m sea depth.

As was already pointed out in Section 2.2, external pressure only to a certain extent mitigates the risk of harmful cavity formation. Even a 10-bar pressure is insufficient when turning off a fully loaded cable. Moreover, in simulations applying a 100-bar external pressure (not included in the figure), cavities are found to form after a turn-off from full load at ambient temperatures below 15 ºC, further supporting this assertion.

3.3 Even modest load reductions create cavities

A complete turn-off from full load, as considered in Section 3.1 and in the experimental investigation, is obviously the most severe case. Fig. 5 shows the results of simulations of three cases with more modest load reductions. Here the load is reduced by 20% from initial steady-state values of the rated load current I_0, $0.75 \cdot I_0$ and $0.5 \cdot I_0$.

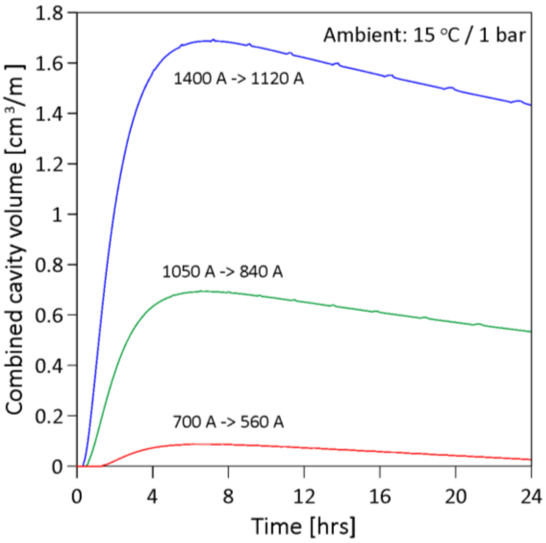

Fig. 5. The combined cavity volume per meter cable after 20% ramp-downs from 1400 A, 1050 A and 700 A. The ambient conditions are 15 °C / 1 bar. (The small ripples, best visible in the upper curve, are numerical effects.)

As can be seen, cavities are expected to be created in all these cases, but to a lesser extent than during a complete turn-off. For example, ramping down from 1400 A to 1120 A yields a cavity volume per meter cable of 1.7 cm^3 at most, whereas ramping all the way down to 0 A results in an approximately four times larger cavity volume, see Fig. 4.

The large difference observed between the three cases in Fig. 5 is mainly due to that the temperature drop across the insulation is approximately proportional to the current squared. Consequently, the temperature drop and the resulting thermal contraction after a 20% reduction become far larger when the initial load is high.

3.4 Cavities are created quickly but tend to last for long

Previously reported PD measurements carried out on a cable that had carried rated load current for an extended time showed that the first cavity-induced PDs appeared within minutes after turning off the load [4]. The interpretation is that a rapid temperature drop, especially near the conductor, caused cavities to be created without much delay when the load is reduced. For the cavities to disappear, in contrast, mass must migrate through the paper layers from the outer parts of the insulation. This a slow process, especially at low temperatures where the viscosity of the mass is high. Consequently, when cavities are formed, they tend to last.

Fig. 6 shows how the combined cavity volume develops over period of eight days following 10% and 20% load reductions from rated load. It takes almost 70 and 180 hrs before the radial mass migration has filled up all cavities in these two cases.

Hence, Fig. 6 visualizes the difference in the time constants associated with thermal contraction (causing cavities to form) and inwardly directed mass flow (causing cavities to disappear).

4. Recommendations for MIND cable operations

Before giving general recommendations as to how MIND cables should be operated to mitigate the risk of cavity-initiated aging and breakdown, a few obvious but still important matters deserve attention:

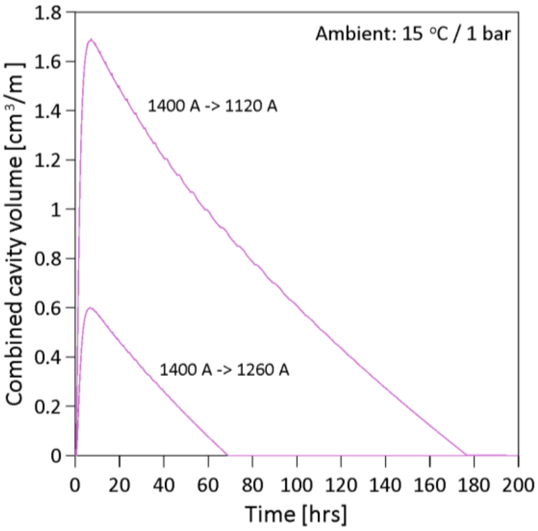

Fig. 6. The combined cavity volume per meter cable after 10% and 20% ramp-downs from 1400 A. The ambient conditions are 15 °C / 1 bar. (The first 24 hrs of the upper plot are also shown in Fig. 5.)

- Subsea cables have different surroundings (water, sand, mud etc.) along the route, and usually these do not change. An operation pattern that is gentle to one part of a cable installation may thus be more challenging to other parts. For example, segments directly exposed to water are more susceptible to cavity formation than segments that are buried in the seabed.
- The same largely applies for the environmental conditions (ambient temperature and pressure). For example, sections of a cable installation that experience a high water pressure are safer than sections at atmospheric pressure. Moreover, the environmental conditions are for the most—but not completely—beyond the operator's control. For example, the ambient pressure is always the same at a given location, but in a trenched section the ambient temperature is greatly influenced by the loading history.
- The environmental conditions may show substantial seasonal variations, the prime example being the water temperature. Consequently, what is considered a benign operation pattern in summer may be less so in winter.

Most HVDC MIND cables in service are subjected to large, rapid and frequent load changes at constant voltage. Presently, the current ramping rate may typically be limited to around 30–60 MW/min (corresponding to around 1–2 A/sec for a typical cable), but future demands are expected to request significantly faster and more frequent ramping. The measurements and simulations show that nearly all load reductions lead to pressure drops and will cause cavities to form. Even with today's operational patterns it is unrealistic to completely avoid internal pressures that cause formation of cavities. Limiting the time at low pressures in the insulation is, however, still advisable as this is expected to reduce any PD-induced aging and extend the lifetime of the cable. From the outcome of the present study the following general recommendations for MIND HVDC subsea cable operation can be deduced:

Recommendation	Rationale
Keep the average loading high and reasonably constant.	The cable remains warm and without cavities. Moderate (<20-30%) load reductions of short durations (up to a few hours) only have a minor impact on the average temperature. Cavities will only exist temporarily.

Under load reductions there is only a marginal advantage of applying a slow ramping rate compared to a fast.	Unless a load reduction takes days and weeks, cavities will always form since the inwardly directed flow of mass is slow because the driving force (i.e., the pressure difference) is low.
Load increases are preferably carried out at a high ramping rate.	Increasing the load always means increasing the temperature, which is never a disadvantage as it tends to fill any cavities present. A fast ramping-up, from a "cold start" reduces the time cavities exist.

A few operational conditions are identified as potentially risky and should be avoided, if possible:

Recommendation	**Rationale**
Do not operate the cable at a low load over extended periods, and especially not in the winter.	With an ambient temperature of only a few degrees (typically by direct exposure to cold seawater) and a low load, the cable insulation temperature will permanently stay at temperatures where cavities will persist. The condition will be most severe in shallow waters where no external pressure contributes. (At deep waters where temperature always is low, the external pressure tends to mitigate cavity formation.)
After extended periods (weeks) at full load, do not reduce the load to very low levels and leave the cable unloaded or nearly unloaded for an extended time.	With full load and high internal pressure, the Pb and PE sheaths gradually and over weeks deform causing the volume available for the insulation to enlarge somewhat. After a load turn-off, the temperature falls, and thermal contraction soon causes a mass "deficit" that is larger than it would have been with a lower load or a shorter loading time. Cavities form and remain as it takes weeks before the Pb and PE sheaths contract/adjust to the lower load.
A cable that has been inoperative for an extended period, e.g., a new installation or after a repair, should be energized with a high rather than a low load.	With no heat generated in the conductor, the temperature in the cable will—even for a trenched cable—approach the seawater temperature, which may be so low that cavities persist in the insulation. Applying a high load causes the temperature to rise fast in the cable (quickly filling any cavities) and eventually also in the surrounding seabed.

The internal pressure drops and accompanying phenomena such as formation of shrinkage cavities, are all caused by load reductions, or more precisely by reducing the load current. The applied voltage, which in fact is what causes electric discharging, aging and breakdowns, has been ignored in all the above discussions. Hence, a few comments related to voltage and dielectric stress are appropriate:

- After a load turn-off it is always advisable to also turn off the voltage, as this reduces the dielectric stress substantially (also when taking the electric field set up by space charges remnant in the insulation into consideration).

- Most HVDC links installed in the past use LCC converters and thus change the direction of power flow by reversing the voltage polarity. Space charges present in the cable insulation cause the maximum electric field immediately after a polarity reversal to become substantially (up to around 70%) higher than under stationary operation at full load. Hence, polarity reversals temporarily but severely increase the dielectric stresses and the risk of initiating aging and breakdown in cavities, and should therefore, also be included in risk assessments of the various MIND cable operation procedures and patterns.
- Radically changing the operating principles of the converter stations in such a way that the changes in the power transmitted in a HVDC link are achieved by adjusting voltage and not current would make it possible to virtually avoid formation of shrinkage cavities. (A discussion of whether such a technology shift is technically and economically feasible is beyond the scope of the present work.)

It should be emphasised that the recommendations given above are of a general nature. When assessing the risk of cavity-induced problems for a given installation, the cable operator needs to also include several installation-specific factors, such as converter configurations, system requirements, operational history (e.g., past loading patterns and number of polarity reversals), service experience (e.g., insulation failures), etc. Moreover, it should be kept in mind that the MIND cable technology has evolved and improved considerably over the last 20–30 years. Older designs are more prone to problems originating in shrinkage cavities.

As a final remark, an attempt to identify the most hazardous operation sequence for a MIND cable is made. The "worst case scenario" for an HVDC MIND cable may be something like this: i) in the winter run a poorly trenched cable in shallow waters fully loaded for a prolonged time, e.g., a month, ii) turn off or rapidly reduce the load to zero, iii) reverse the polarity, iv) leave the cable unloaded but energized.

BIBLIOGRAPHY

[1] T. Worzyk, "Submarine Power Cables: Design, Installation, Repair, Environmental Aspects" (Springer, Germany, 2009).
[2] M. Runde, R. Hegerberg, N. Magnusson, E. Ildstad, and T. Ytrehus, "Cavity formation in mass impregnated HVDC subsea cables - Mechanisms and critical parameters" (IEEE Electrical Insul. Mag., vol. 30, no. 2, 2014, pp. 22–33).
[3] G. Evenset and G. Balog, "The breakdown mechanism of HVDC mass-impregnated cables" (CIGRÉ session, Paris, 2000, paper no. 21-303).
[4] M. Runde, O. Kvien, H. Förster, and N. Magnusson, "Cavities in mass-impregnated HVDC cables studied by ac partial discharge measurements" (IEEE Trans. Dielectrics Electric Insulation, vol. 26, 2019, pp. 913–921).
[5] G. C. Montanari, P. Seri, S. F. Bononi, and M. Albertini, "Partial discharge behavior and accelerated aging upon repetitive DC cable energization and voltage supply polarity inversion" (IEEE Trans. Power Delivery, vol. 36, no. 2, 2021, pp. 578–586).
[6] M. Runde, S. M. Hellesø, N. Magnusson, and K. T. Solheim, "Internal pressures and pressure gradients in mass-impregnated HVDC cables during current cycling" (IEEE Trans. Dielectrics Electric Insulation, vol. 27, 2020, pp. 915–923).
[7] M. Runde, E. Jonsson, E. Jonsson, and N. Magnusson, "Plastic Deformations of the Sheaths of Mass-Impregnated HVDC Cables and their Effect on the Internal Pressure" (CIGRÉ Science and Engineering. vol. 21, 2021, pp. 14–25).
[8] M. Runde, E. Bjerrehorn, E. Jonsson, N. Magnusson, "Internal Pressure Dynamics of Mass-Impregnated HVDC Subsea Cables at Different Sea Depths" (CIGRÉ Science and Engineering, vol. 2, 2022).
[9] COMSOL Multiphysics (available: http://www.comsol.com).
[10] P. Szabo, O. Hassager, and E. Strøbech, "Modelling of pressure effects in HVDC cables" (IEEE Trans. Dielectrics Electric Insulation, vol. 6, 1999, pp. 845–851).