The corona discharge causes short destruction that has bad influence on a power switching circuit.

Hitoshi Narusawa, Adphox Corporation

1. Introduction

While the existence of corona discharges has been known for a long time, recently they have been quickly becoming a problem as the needs of advanced electronics and energy conservation have quickly increased the use of inverter circuits.

Corona discharges occur with even with direct current or 50/60Hz. However, any deterioration could be ignored because the energy level was so small (several picocoulombs per cycle)

A switching frequency of 50 kHz consumes one thousand times the discharge energy of 50 Hz.

Stated more clearly, a part that can be used for 100 years at 50 Hz can lasts about one month at 50 kHz at the same voltage.

2. Corona discharges hidden in products that use inverters

Many people are familiar with the word *corona*, but even electric engineers don’t seem very concerned about corona discharges.

Still, the advancements of inverter circuits to conserve energy are a breeding ground for corona discharges. Corona discharges deteriorate the insulation and affect the lifetime of various items including backlight inverters and transformers of liquid crystal televisions, high voltage printed circuit boards, connectors, cables, projector lights, the stroboscope circuit of digital cameras, high voltage switching power sources, and the inverter-fed motors of refrigerators, air conditioners, washing machines.

Particular care is required with parts that have a voltage of 300 V or higher, such as the input and output of photo couplers, contact points of high voltage relays, isolation transformers, PCBs and connectors.

Moisture absorption by insulators and defaced surfaces can cause creeping discharges. Photo 1 shows creeping discharge from a defaced surface.

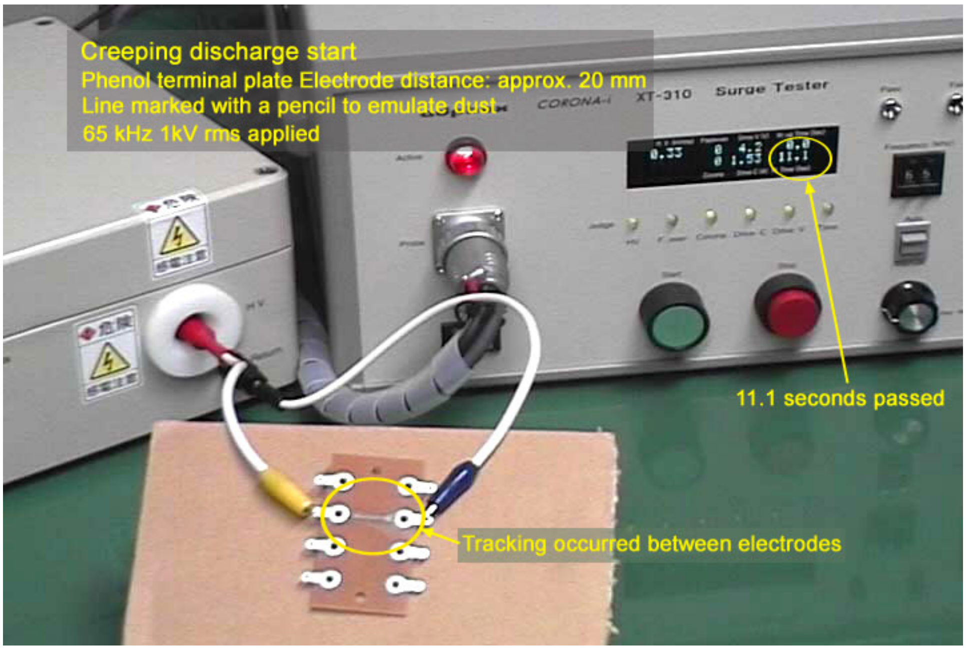


Photo 1 (a)

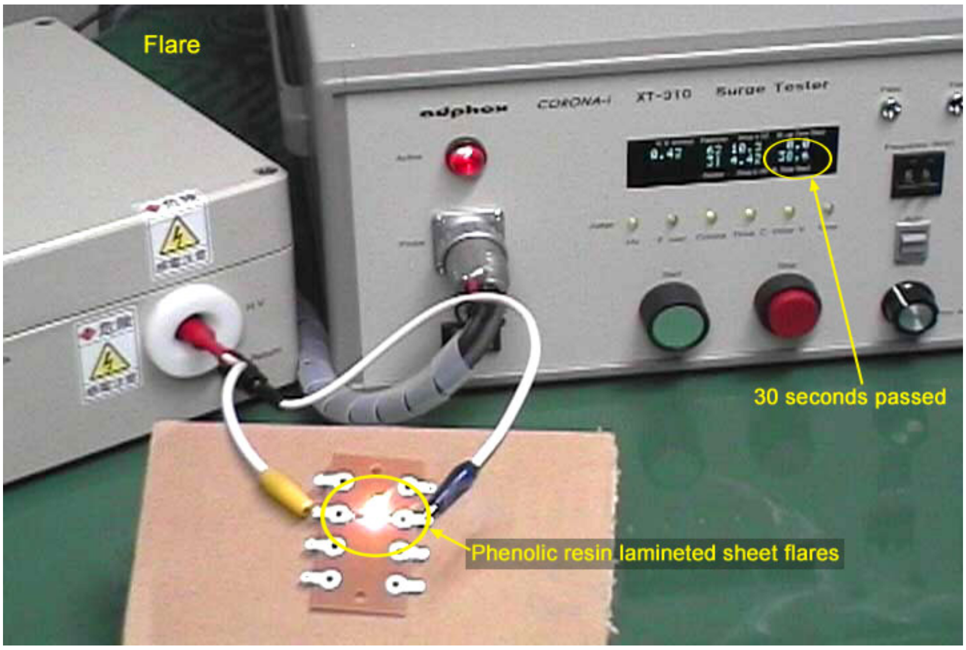


Photo1(b)

As seen in Figure 1, creeping discharges are discharges along dielectric surfaces without direct connection through the atmosphere when there are two poles on insulating plates.

In other words, discharges occur at voltages lower than the voltage at which flashovers (which starts corona discharges) occur. This flashover voltage is referred at as Vs (and will be described below).

Creeping discharge is considered a type of corona discharge. The electrical discharge advances like it is licking the surface of insulators, such as transformer bobbins.

There are cases where tracking occurs after creeping discharge, even when the high and low voltage terminals are separated by 15 mm or more.

The higher the permittivity of the insulation, the lower the creeping discharge voltage drops. Furthermore, if there is a back electrode (Figures 1 (b) and (c)), it drops further and creeping discharge may occur even if the electrodes are separated.

Terminals on standard transformer bobbins and patterns (copper foil) on PCBs correspond to Figure 1(a). However, if there is a ferrite core on the PCB or another pattern under the pattern, conditions are like Figures 1 (b) and (c) and the discharge voltage drops.

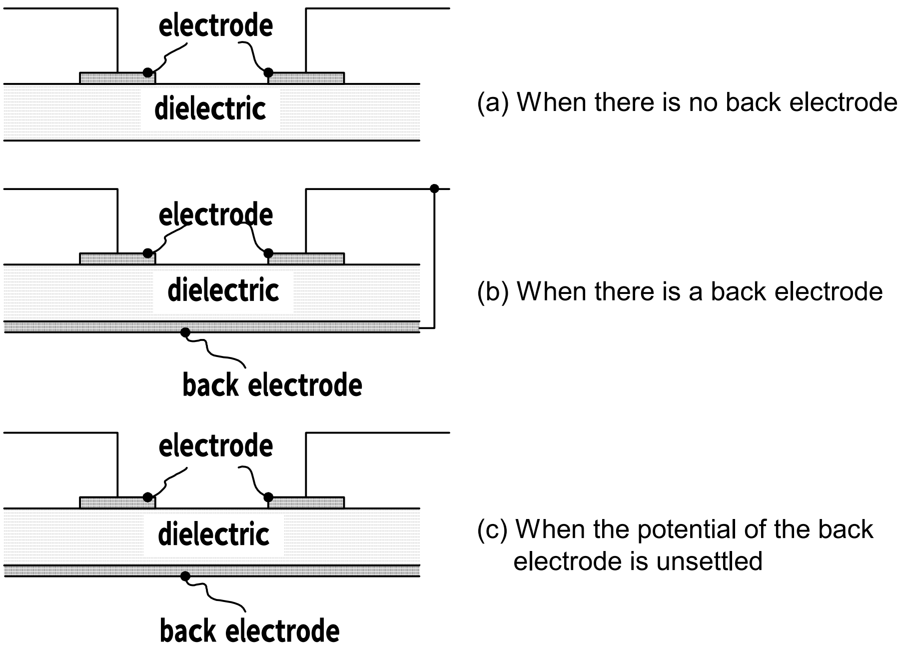


Figure 1

3. Corona discharges and dielectric breakdowns

In corona discharges, electrons are pulled by positive poles and accelerate to very high speed. They hit air molecules repeatedly and knock out their electrons, causing ionization. This has the side effect of generating ozone (O^3).

Ozone gas is a strong oxidizer and gradually oxidizes and breaks down insulators. Furthermore, high speed electrons and ions collide with the insulators and wear away at their surfaces.

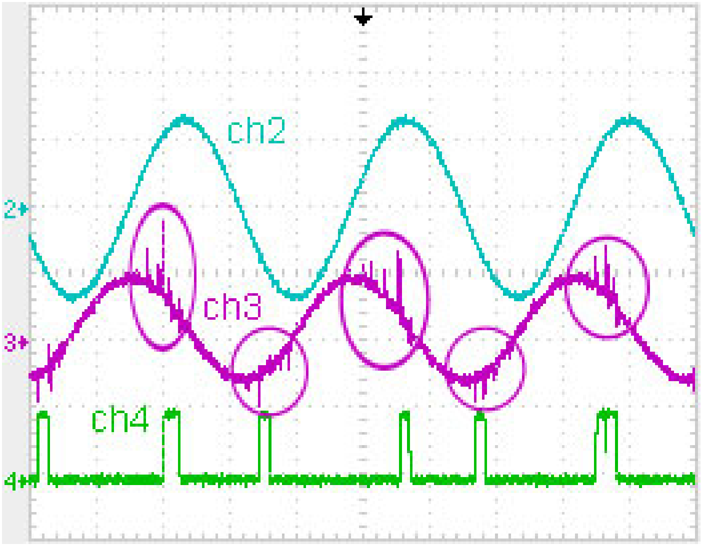
Finally, corona generates heat and the combination of these side effects gradually breaks down the insulators. Eventually, dielectric breakdowns and flashovers occur.

However, corona discharges are unusually weak electrical discharges. Furthermore, the operating waveform of most circuits is normal. As a result, no abnormalities appear and the products pass inspection.

While the energy of corona discharges is only several picocoulombs per cycle, deterioration can build up over several months.

4. Detecting corona discharges

The following events occur along with corona discharges and they can be used to detect the presence of corona discharges.



ch2; 4kV/div, ch3; 5mA/div, ch4; 5V/div, 5μs/div

Figure 2. XT-311 monitor waveform

Ch 2: Applied voltage 3.7 kV rms, 60 kHz

Even when there are corona discharges, high voltage waveforms are normal. Even with UL 3239 silicone high voltage wiring with a resistance of DC 20 kV, a corona occurred at 3.7 kV rms.

Ch 3: Current waveform

Because of the load capacitance, the current advances to a 90° phase. The circled area (○) is the corona discharge current pulse.

Ch 4: Counter waveform shows corona detection

A counter pulse occurs every time there is a corona discharge.

1. A corona discharge pulse is generated

Corona discharge pulses are random pulses with a width of several ns and a peak current of several mA. Their frequency is spread over an extremely wide range, from several hundred kHz to several GHz.

Traditional partial discharge testers and our ***CORONA-i*** XT Series detect this pulse signal.

Figure 2 shows the monitor wave of a corona discharge current from the **XT-311** Corona Tester.

This test is a of silicone insulation wire with a withstand voltage of DC 20 kV. However, corona discharges occur at 3.7 kV rms.

2. Electro-magnetic waves are generated

Electro-magnetic radiation occurs along with pulse currents so coronas can be detected by receiving the electro-magnetic waves by antenna.

Coronas can be detected without contact but the directions of the electro-magnetic waves and the antenna must meet.

Mitsubishi announced the existence of such an antenna (at the 2009 National Convention of The Institute of Electrical Engineers of Japan 2-012).

3. Faint light is generated

The light generated is very faint but it can be seen in a dark room.

Portions of coronas can be identified but internally occurring coronas cannot be seen.

4. Ozone (O_3) is generated

Ozone has an identifiable smell that can be used to detect coronas. This was an effective method in the past when the necessary equipment had not yet developed.

However, ozone is a strong oxidizer and is believed to cause cancer so it must not be inhaled.

5. Sounds are sometimes generated

Coronas can be detected by acoustic oscillation. However, there are cases when coronas do not generate noise, which limits the reliability of this method.

5. Forget the common wisdom about insulators

5-1：Don’t trust DC resistance voltage

In general, DC resistance voltage and the voltage at which corona discharges start is greatly different. As shown in Figure 2, a corona of 60 kHz and 3.7 kV rms occurred with UL 3239 wires with a DC 20 kV resistance voltage.

Don’t trust DC resistance voltage. Items must be first measured with a corona tester.

5-2：The withstand voltage test and the corona discharge test are different.

Photograph 2 shows the corona discharge test of the twisted pair of the magnet wire.

This magnet wire had the resisting voltage of 3kVrms or more in the withstand voltage test done by 50Hz.

The corona discharge started by 700Vrms when the corona discharge test was done by 70kHz, and it was short-circuited at 3 seconds when 990Vrms applied.

Therefore, the withstand voltage test done by direct current and 50/60Hz is insufficient, and it is necessary to do corona discharge test

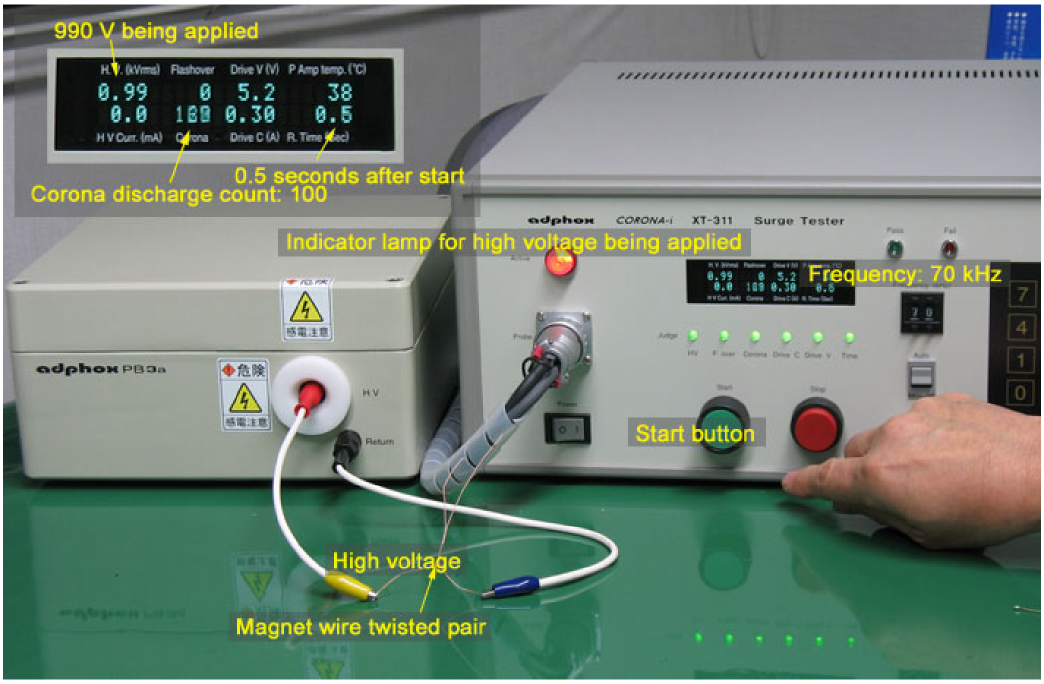


Photo2(a)
Testing

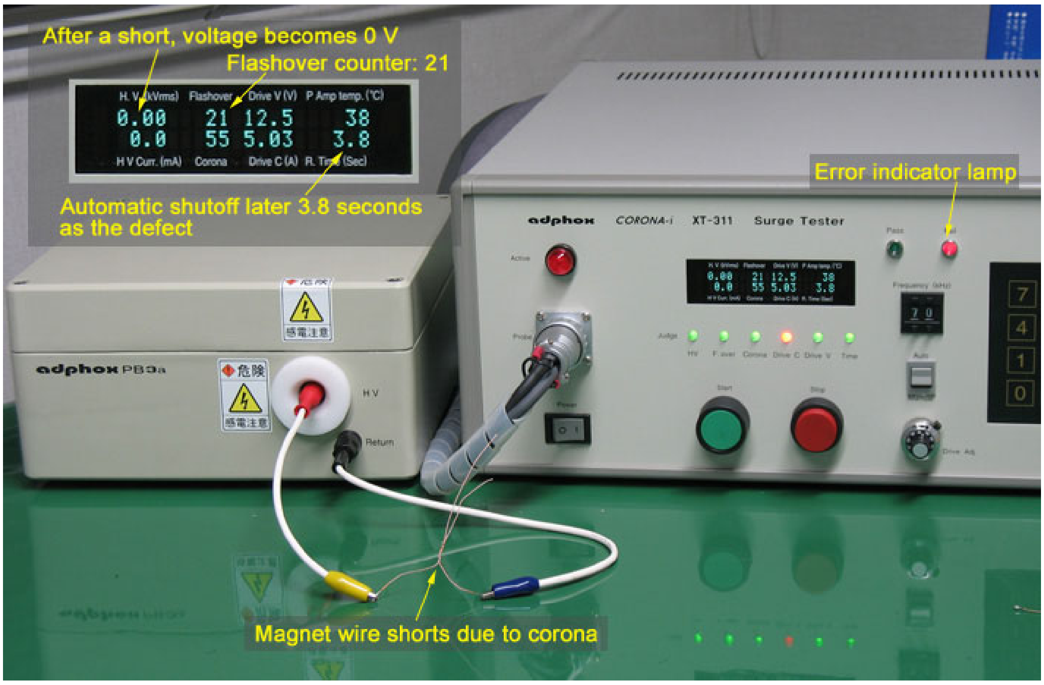


Photo 2(b) after 3.8 seconds, the magnet-wire shorts

5-3：Insulating plates do not prevent discharges

Are standard UL discharge measures effective against corona discharges?

In Photo 3(a), when 70 kHz and 6 kV rms is added in a 1.2 mm ball gap, a flashover occurs.

In Photo 3(b), a 1 mm phenolic resin laminated sheet is inserted in the gap to prevent discharges.

The withstand voltage of the phenolic resin laminated sheet is 16 kV/mm and should be a thorough, UL-compliant solution for discharges.

Flashovers are definitely stopped. However, upon close inspection, a strong corona appears at the tip of the electrode. This corona discharge is extremely strong. In a mere 10 seconds, the phenolic resin laminated sheet is burned, as seen in Photo 3 (c).

Insulation is not effective as a measure against discharges.

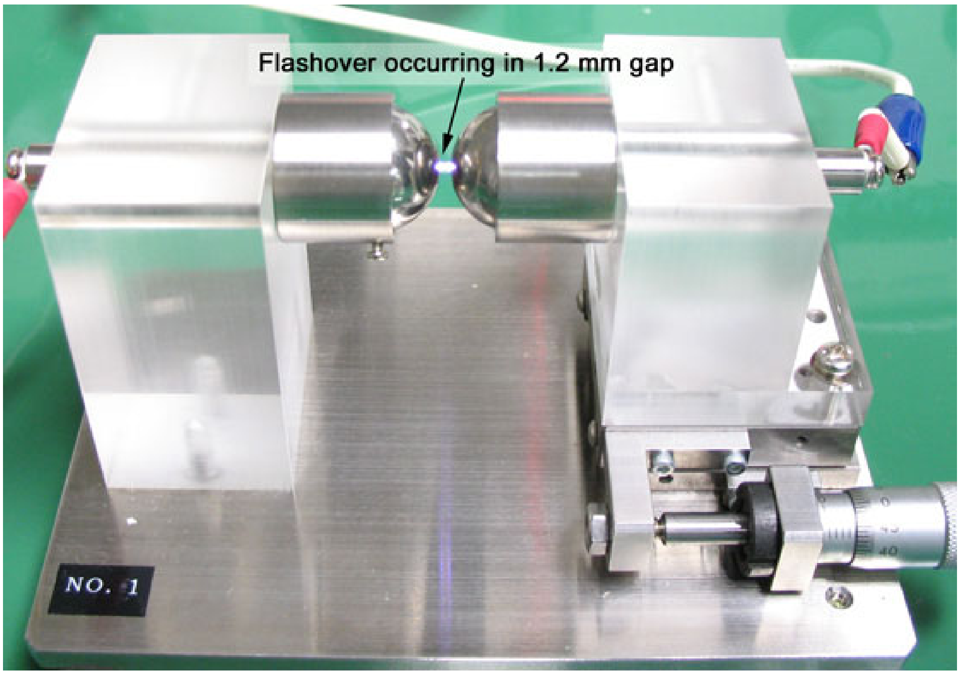


Photo 3(a) Testing

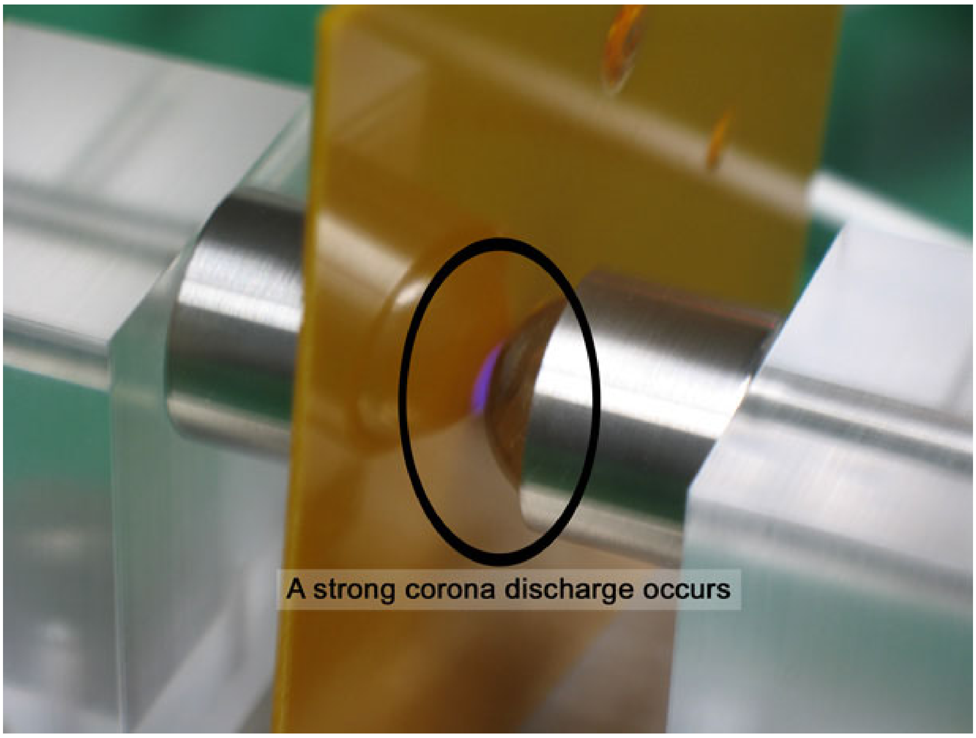


Photo 3(b). 1.0 mm phenolic resin laminated sheet was inserted in the gap to prevent flashovers

Photo 3(c)
In a mere 10 seconds, the phenolic resin laminated sheet was deformed.

5-4：Insulators are dielectric material

70 kHz and 5 kV rms are added to a 3.2 mm ball gap (See Photo 4(a)). Since the gap is sufficiently wide, neither corona discharges nor flashovers occur.

Accordingly, this insulation was sufficient for flashovers and coronas. However, to further insulate the area, a 3 mm insulation plate (phenolic resin laminated sheet) was inserted in the gap. Nevertheless, a strong corona discharge occurred, as seen in Photo 4(b).

This insulation plate became a corona dielectric plate. After 30 minutes, the phenolic resin laminated sheet was burned, as shown in Photo 4 (c).

Instead of insulators, it is necessary to think about dielectric materials. When considering the bobbin of a transformer, in this, the solution is a difficult problem.

Photo 4(a)
When the gap is 3.2 mm, no discharge occurs, even when 5 kV rms is applied.

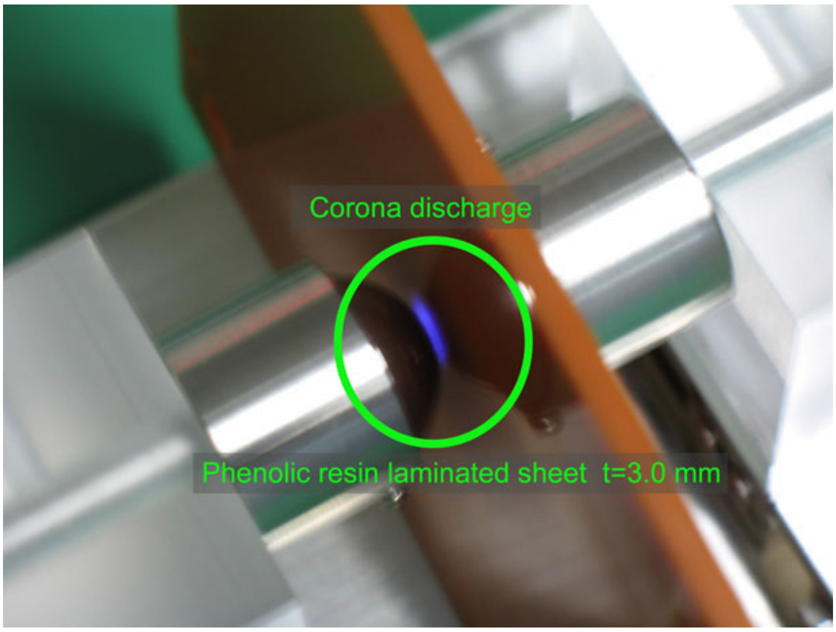


Photo 4(b)
A corona discharge started when a 3mm insulation sheet was inserted in a gap where no discharges occurred.

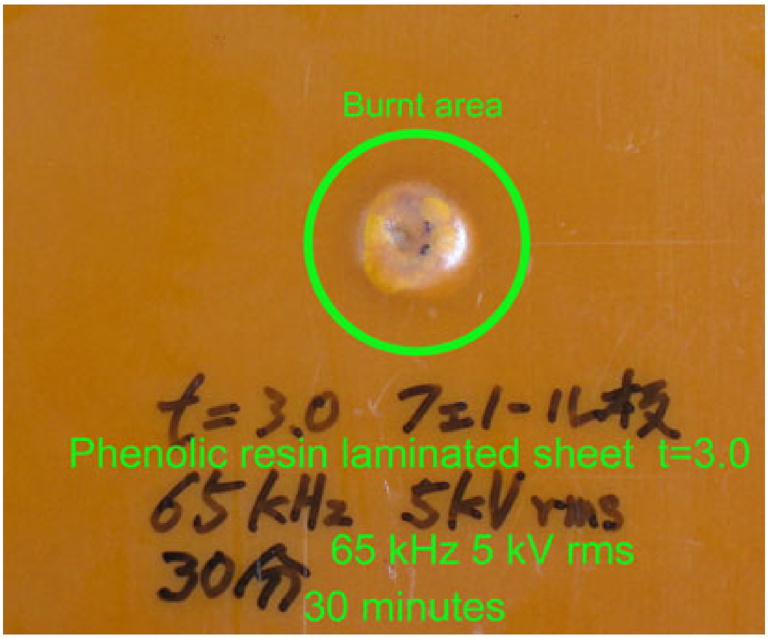


Photo 4(c)
The 3.0 mm phenolic resin laminated sheet was burned.

6. What are corona discharges?

6-1: The true identity of corona discharges is the Ionization of air

While corona discharges are not known as such, they are truly the ionization of air, like flashovers. If an electric field over a certain amount is applied to a gas, ionization occurs.

When voltage is applied to a parallel plate electrodes, the voltage that causes a flashover, V_S, is expressed as the following formula. (Masamichi Ohki : High Voltage Engineering, p.57 [ISBN 4-8375-0506-6])

$$V_S = 126pl \div \left(\log_{10}(pl) + 0.22\right) \cdots\cdots (1)$$

V_S : Flashover voltage (V_{DC})
p : Atmospheric pressure (mm Hg)
l : Distance between electrodes (cm)

Figure 3 is a graph of Formula 1 at one atmosphere. When the space between electrodes is filled with ionized air, a complete circuit discharge (flashover) occurs.

When an insulation plate is placed between the electrodes, the plate obstructs the current so flashovers do not occur. However, electric fields are not prevented so the air is partially ionized. This referred to as a partial discharge and is a typical corona discharge.

The point here is that the plate can stop the current but not the electric field.

In fact, inserting the insulation plate strengthens the electrical field of the air (because the permittivity of the dielectric material is greater than the air).

This is the cause of the corona discharge in **5-4**.

Vs in formula 1 is the voltage at which flashovers occur. This voltage applies an electric field that ionizes the air. Whether the ionized air becomes a complete circuit discharge (flashover) or partial discharge (corona discharge) depends on the space between electrodes. In other words, *Vs* is the same as the voltage at which corona discharges start.

The case above is for parallel plate electrodes. For needle electrodes, the electric fields focus at the tips only and corona discharges easily occur there. In practice, discharges occur at cusps like transformer terminals.

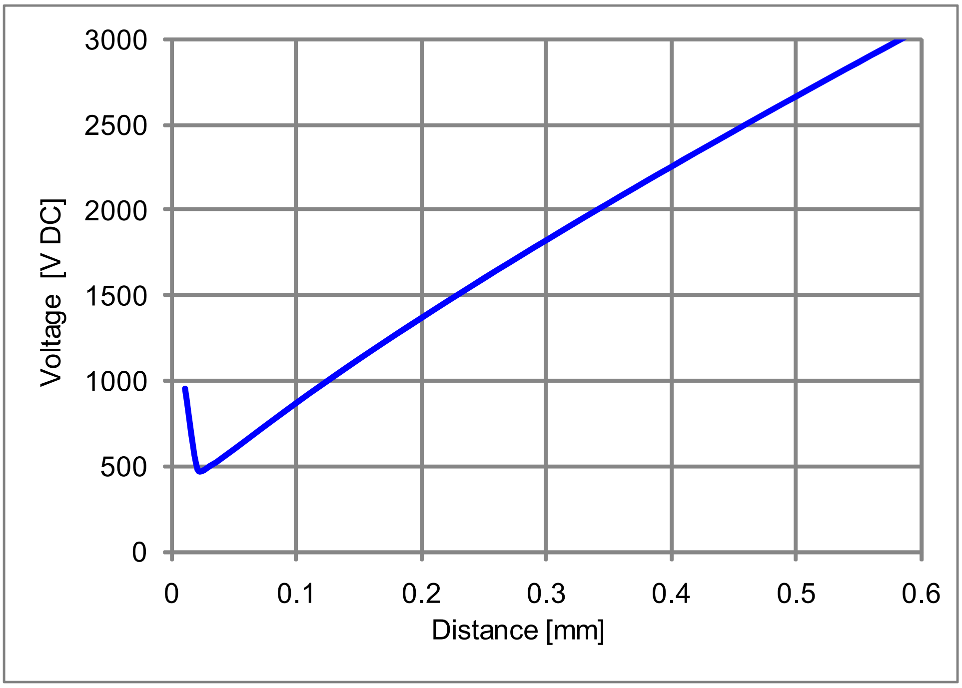


Figure 3. Flashover voltage at 1 atmosphere

6-2: Principles

Figure 4 explains the principles of corona discharges. Ultraviolet and cosmic rays create small amounts of ions and stray electrons in air.

When voltage is applied to electrodes as in Figure 4, electrons move to the positive pole and positive ions move to the negative pole.

If the electric field strengthens, the electrons move at high speed, collide with air molecules and knock out their electrons, ionizing the molecules. Electrons flow into the positive pole and positive ions flow into the negative pole. This is a corona discharge.

However, as seen in Figure 4 (b), the insulation plate is gradually electrified. This weakens the space field and stops electrical discharges.

When direct voltage is applied to electrodes, a corona discharge occurs immediately after the switch is turned on, as shown in Figure 4. However, the corona later dissipates, as show in Figure 4 (b). In this case, corona discharges do not cause much deterioration.

Let's consider when the direct voltage is on or off. Even when the added voltage is switched off, as in Figure 4 (c), the charge that electrified the insulation plate doesn't discharge. Therefore, it doesn't return to the ON condition (Figure 4 (a)) but instead alternates between Figure 4 (c) and Figure (b). This makes it difficult for corona discharges to occur.

Furthermore, this shows that repeated applications the same polarity voltage are not suitable for corona discharge testing.

When alternate current is applied to electrodes, the condition follows following pattern: Figure 4(a)→(b)→(c)→(d)→(e)→(f). The important point here is that, at the switch between Figure 4 (c) and (d), the electrons and positive ions that electrified the insulation plate suddenly rush to the electrodes that reverse voltage.

As well, electrons collide with air molecules to create positive ions (α effect) and the positive ions collide with the electrode and emit secondary electrons (γ effect).

This makes possible to understand the large corona discharge that occurs at the switch between Figure 4 (f) and (a) as well.

6-3: Separating out noise waveforms

The above explanation shows why corona discharges only occur when the AC voltage polarity reverses and when the voltage is increased from Figure 4 (a) and (d).

Corona discharges do not occur when the voltage is constant (Figure 4(b) and (e)) or dropping (Figure (c) and (f)).

Take a look at Figure 2. The corona discharge current pulse appears only when the voltage waveform enlarges.

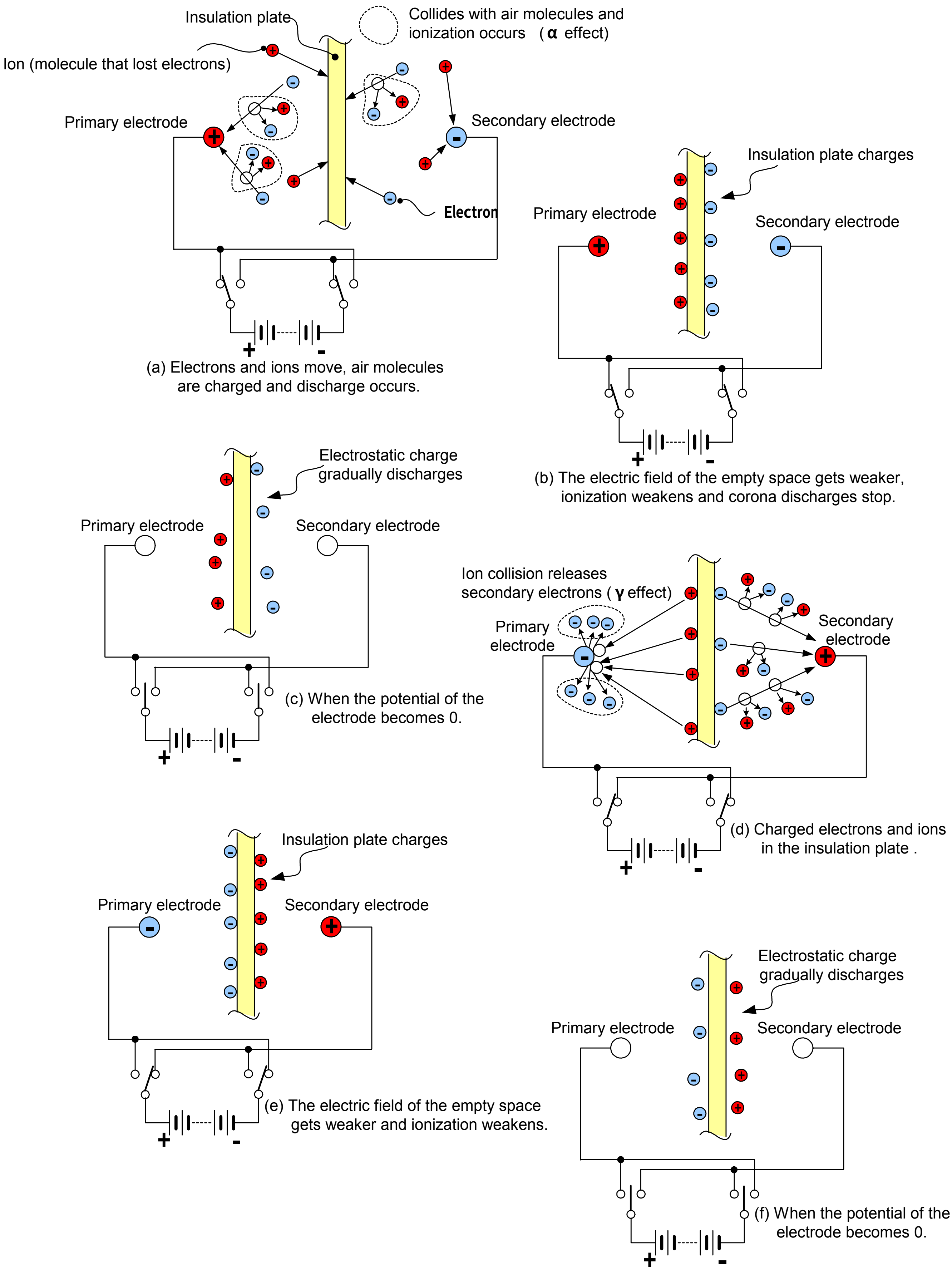
(Corona pulses appear in areas where the voltage waveform drops. This occurs because the phase of current advances 90° versus voltage because the load is capacitive.)

As seen in Figure 2, corona discharge current pulses are difficult to separate from noise. However, it is possible to confirm whether a true corona discharge current pulse is being detected or noise has been falsely detected by comparing it with voltage waveform.

Furthermore, the current of the corona discharge flows in the direction of the voltage applied to the electrodes.

If the polarity of the voltage is reversed, the direction of the current naturally reverses. However, noise is not related to applied voltage and direction and polarity are roughly symmetrical. Therefore, corona discharge current pulses and noise can be separated.

Figure4. Principles of corona discharges



(a) Electrons and ions move, air molecules are charged and discharge occurs.

(b) The electric field of the empty space gets weaker, ionization weakens and corona discharges stop.

(c) When the potential of the electrode becomes 0.

(d) Charged electrons and ions in the insulation plate .

(e) The electric field of the empty space gets weaker and ionization weakens.

(f) When the potential of the electrode becomes 0.

6-4: Corona discharge energy is proportional to frequency

The addition of AC voltage repeats as one cycle from Figure 4 (a) to (f). Corona discharge energy is the same in each cycle. Therefore, at 50 Hz, there are 50 corona discharge cycles per second. At 50 kHz, there are 50,000 cycles.

If the insulation deterioration by caused coronas is proportional to the discharge energy, then a product with a lifetime of 100 years at 50 Hz will have a lifetime of just one month at 50 kHz. Accordingly, the higher the frequency, the more attention needs to be paid to corona discharges.

7. Corona resistance test of magnet-wire

This test was performed using the twist wire shown in Photo 3.

Table 1 shows the test results at a voltage 20% higher than the corona inception voltage. These results show that while corona inception voltage appears unrelated to frequency, the lifetime shortened as the frequency increased.

Magnet-wire 2UEW, Dia. 0. 26

Test freq.	Corona inception voltage	Lifetime(test voltage 550Vrms）
17kHz	470Vrms	638s
35kHz	480Vrms	342s
70kHz	480Vrms	156s

Table 1. Corona resistance test of magnet-wire

8. Solutions for corona discharges

Corona discharges are caused by the ionization of air by strong electric fields. Therefore, it is crucial to prevent strong electric fields from occurring.

Formula 1 is basic formula for parallel plate electrodes. Actual electrodes are curved and the electric fields that occur are not uniform. Therefore, it is necessary to understand and expand from Formula 1.

First, start by confirming the portions where corona discharges occur using a corona discharge tester. Then surmise the causes and perform solutions for each. The main solutions are as follows.

Solution 1

The distance between electrodes must at least meet Formula 1. Be aware that if the space between electrodes is dielectric, the effects of permittivity will raise the strength of the surrounding electric field. Furthermore, if the core is conductive, corona discharges often occur via the core.

For EE cores, separate and insulate the high and low voltage areas of the core and increase the distance between the high voltage coil and the core.

Solution 2

If the electrode tips are pointed, electric fields focus at the tip and corona discharges occur. When corona discharges occur between the terminal tip and chassis, inserting an insulation plate in between is not an effective Solution (as explained above). It is necessary to cut the terminal tip or widen the attachment interval with the chassis.

Solution 3

The ionization of air causes corona discharges. Therefore, eliminating air prevents discharges.

Vacuum impregnating silicone or epoxy is a very effective. However, if even the smallest void is left inside, a corona discharge will occur in the void. It is important to consider a structure where air can easily escape.

For the sake of clarity, the vacuum was set to 1/10 atmosphere in **Figure 5**. However, even at

1/100 or 1/1000, voids did not disappear in poor structures. Make sure that the shape of the core and bobbin do not trap air.

Furthermore, if the distance between the start and end of the coil and the terminal is lengthened, the drawn out wire portion become a high electric field and corona discharges may occur. If there are such areas, potting the area with silicone may be beneficial.

Solution 4

Creeping discharges are considered a type of corona discharge and can be detected by corona discharge testers. Unfortunately, there is no useful manual for Solutions.

Even if the space between pins standing on the bobbin (dielectric material) is 20 mm or more, even 2 kV rms may cause creeping discharge. Therefore, testing with a corona tester is required.

Phenolic resin laminated sheets (Bakelite) are often used for UL compliance. However, this appears to be weak against creeping discharge so Teflon and polyacetal is recommended for measurement jigs.

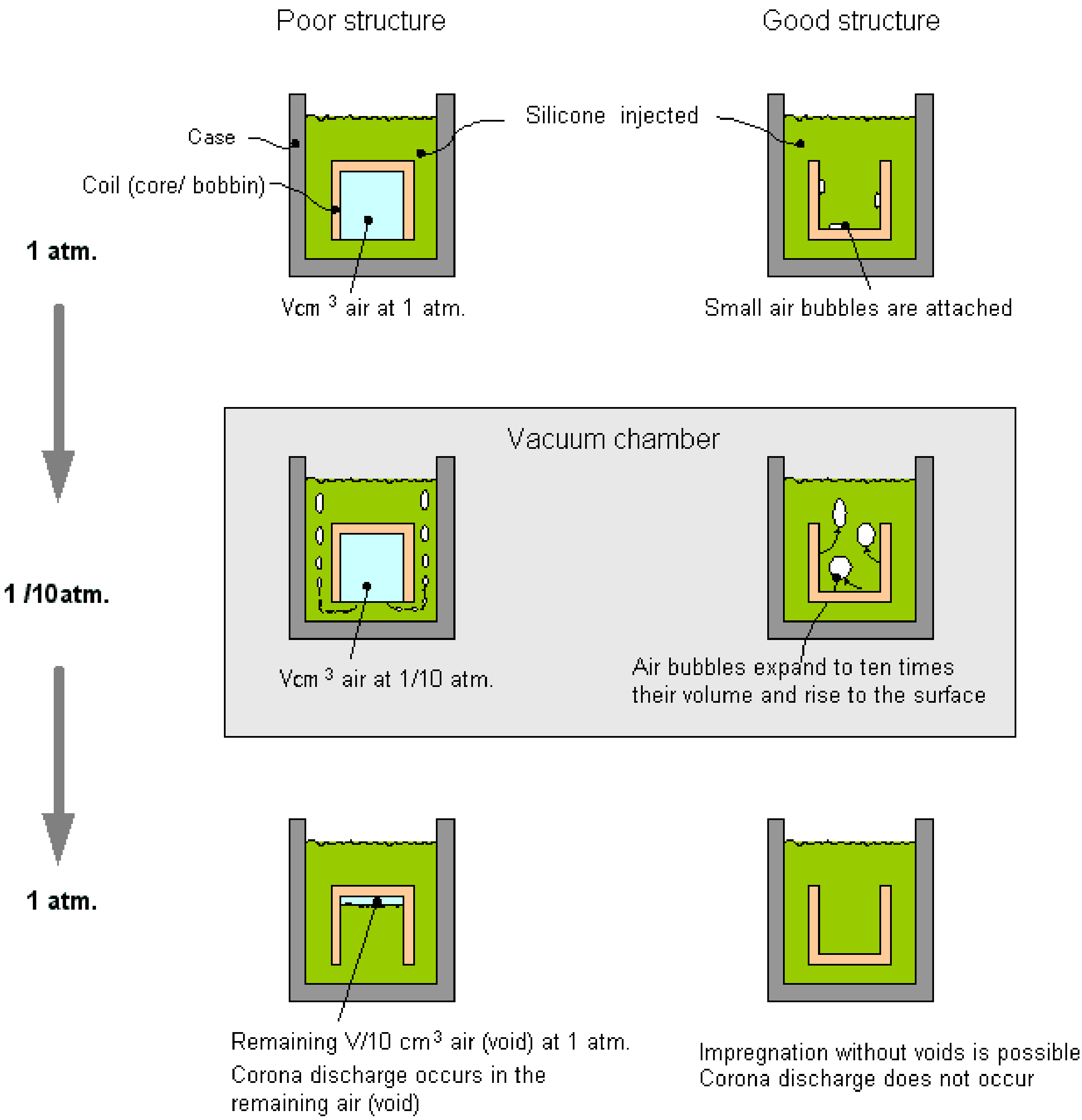


Figure 5. Considerations for structures where air can easily escape for vacuum impregnation