



# Exploring and modeling how partial discharge phenomena impact the lifespan of power transformers and high-voltage bushings

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## Abstract

Transformers are essential for the transmission and distribution of electrical energy, making their insulation issues critical. Failures in insulation can lead to power supply interruptions, which may have severe consequences. One of the primary causes of insulation failure in power transformers is partial discharge (PD). The IEC standard sets a limit for acceptable PD levels; if these discharges are not accurately monitored or identified, they can damage the transformer's insulation. Even short-lived discharges can produce misleading readings from measuring devices, further decreasing the transformer's lifespan. Assessing partial discharges is crucial as it offers valuable insights into the reliability of high-voltage power equipment. PDs often occur in areas of weakness within the insulation, such as voids, cracks, and imperfections, and are considered a major factor in long-term insulation degradation and failure. In this paper, we delve into the definition of partial discharge and its effects on transformers and high-voltage bushings. We analyze simulations of partial discharge in a single void, assess relevant equations, and discuss diagnostic methods. Finally, we present conclusions and strategies to minimize the impact of this phenomenon on transformer performance.

**Keywords:** Partial Discharges, Insulation, High voltage bushing

## Introduction

In today's industrialized world, the seamless operation and ongoing supply of electrical power are essential. Transformers are crucial components in the transmission and distribution sectors, linking power systems that operate at varying voltage levels. Consequently, when transformers fail, it can lead to significant disruptions in the power supply, resulting in serious consequences. One of the primary culprits behind insulation failure in power transformers is partial discharge (PD), which can be understood as tiny sparks occurring within insulating materials [1]. Electrical insulation, often considered the most critical yet vulnerable part of high-voltage (HV) equipment, plays a crucial role in determining the integrity and reliability of these systems. PD is a localized electrical discharge that only partially bridges the insulation between conductors and can occur near or far from those conductors. These discharges generally result from localized electrical stress concentrations within or on the surface of the insulation and typically manifest as brief pulses lasting less than one microsecond [2]. As the applied voltage increases, the stress across the insulation rises, leading to discharges in cavities once the breakdown voltage is exceeded. This process weakens the insulation over time, ultimately resulting in failure during normal operations [1]. Over time, PD deteriorates the insulation's strength, potentially causing complete or partial breakdowns. Evaluating PD in high-voltage equipment, such as the epoxy resin used in rotating machines, provides valuable insights into areas of high stress and manufacturing defects. In this article, we will categorize the various types of discharge phenomena based on their occurrence and delve deeper into the implications of these findings [3].

## Insulation

Insulating materials are designed to prevent current flow, but in reality, they allow a small amount of current to pass through. This current can be made up of several components, including capacitive flux current, polarization current, surface leakage current, and internal leakage current. While insulators are primarily non-conductive, some materials, like semiconductors, fall outside this discussion [4]. Electrical insulation is a critical component of transformers, tasked with withstanding high voltages. The condition of a transformer's insulation is vital for ensuring the reliability of electrical distribution networks, enabling timely repairs, and preventing both human and financial losses. Over time, the quality of electrical insulation—primarily made up of oil and oil-impregnated paper—deteriorates due to factors like high temperatures, elevated voltages, and mechanical stress [4]. As insulation quality declines and the transformer ages, the likelihood of failure increases. To ensure optimal performance in the devices they are used in, electrical insulators must possess specific electrical, thermal, mechanical, and chemical properties [5].

## High Voltage Bushings

Bushings are essential devices that allow high-voltage conductors to pass through the grounded walls of transformers, electrical panels, and substation structures. They must meet various electrical, thermal, and mechanical requirements to ensure safe operation. For instance, bushings provide reliable electrical insulation both internally (to prevent failures) and externally (to guard against sparks) for conductors exposed to rated voltage, even during maintenance in contaminated environments. They also need to support the conductor and all external connections, especially during short circuits and seismic events. Additionally, bushings must be thermally designed to prevent overheating and the aging of insulation materials during normal operations and short-circuit conditions [1-3]. This discussion draws on previous articles from INMR and highlights recent collaborations with Professor Stanislaw Gobanski from Chalmers University of Technology in Gothenburg, Sweden, focusing on alternative bushing projects. It also explores future trends shaped by changing market demands and competitive factors. Bushings are similar to insulators or surge arresters in that they are relatively inexpensive components that play a crucial role in protecting valuable equipment. Although bushings typically account for less than 5% of a transformer's cost, their failure can result in catastrophic losses, not only of the transformer but also of other expensive machinery [2, 5]. The design of bushings is fundamentally straightforward: they consist of a cylindrical conductor surrounded by a solid insulating cylinder, which is equipped with a ground barrier. However, the electric field distribution within this structure is uneven, with the highest stress occurring at the "triple junction" where the ground wall, insulating cylinder, and the external gas or liquid chamber meet. This concentration of stress can lead to partial discharge. These partial discharges, often called "gliding discharges," have a strong capacitive connection to the inner conductor and tend to occur along the insulating cylinder's surface. They can create traces on the bushing and even cause sparks. When the insulation capacitance increases (for instance, along its thickness), it can lead to discharges that propagate based on the ignition voltage, which is influenced by this parameter. In contrast, other discharge types are typically controlled by the distance between electrodes. Therefore, improving the electric field distribution along the bushing's surface is key to enhancing its resistance to spark voltage. This can be achieved through various methods, particularly capacitive control for AC applications and resistance control for DC applications at higher voltage levels [4]. Capacitive control involves placing metal plates inside the solid insulator of the bushing, effectively creating a series of capacitors whose configuration and geometry determine their effectiveness. A common and effective approach is to align these series capacitors at the same level. In the manufacturing of paper-insulated bushings, metal sheets are inserted between the layers of paper to optimize capacitance [2, 3]. For DC bushings, enhancing electric field distribution often involves adding semiconductor layers near the electrode to increase resistance by extending the distance from the ground electrode.

While high-voltage bushings are critical components, they can develop defects. Although these defects may not pose immediate risks, minor issues can compromise insulation over time. Therefore, monitoring for partial discharges and assessing their impact on the longevity of bushings and other high-voltage elements is vital for maintenance and safety.

### Partial Discharge

we will now define the PD in more detail and identify its types: It is not always possible to prevent the formation of inhomogeneities and impurities in insulating materials in the manufacture of insulating parts. When the desired insulation is placed between the electrodes and voltage is applied, the intensity of the electric field will be high in the points of insulation where there are impurities and are weak. As a result, a very rapid local electrical discharge may occur, which is called a partial discharge. Partial discharge is the local discharge inside an insulating system that is limited to only one part of the dielectric material and partially bridges the electrodes. Partial discharge may have started directly from one of the electrodes or without contact with any of the electrodes in a hole in the insulation on the head. also we can consider it considered as a wire. The partial discharge start is directly related to the voltage applied to the device. The voltage at which the partial discharge starts is called the partial discharge voltage. In cases of transient overvoltage, the applied voltage may be higher than the partial discharge voltage. Care must be taken to turn off the partial discharge when the voltage drops to its nominal limit. In fact, a partial discharge has a residue, ie it turns on at a higher voltage and turns off at a lower voltage. The voltage difference between the partial discharge on and off depends on the insulating material. The following are some common types of partial discharges using simple insulation structures, including:

- 1 Corona evacuation
- 2 Surface discharge
- 3 Discharge in composite insulating materials
- 4 Partial emptying in pores and cavities
- 5 Electric discharge in Turing channels

When the deterioration bridges the high voltage electrode to that of ground electrode leads to the complete failure of the insulation.

### Understanding Partial Discharge Types: Corona and Surface Discharges

Partial discharge (PD) can manifest in various forms, with corona and surface discharges being two notable types.

**Corona discharge** occurs in areas where the electric field is particularly intense, such as at sharp points on conductors, high-pressure equipment, and around power transmission lines. This phenomenon typically happens at sharp edges or points that are at high potential or near ground potential within an electric field. While corona discharge on transmission lines doesn't significantly affect their lifespan, it can lead to energy losses and interference with telecommunications. However, sharp points in high-pressure equipment near electrical insulators can cause damage to those insulators.

**Surface discharge**, on the other hand, happens on the outer surfaces of solid or liquid insulation. It typically occurs at the junction of two different insulating materials, where the electrical resistance at the interface is lower than the dielectric strength of either material alone. This means that if the joint between the two insulators aligns with the direction of the electric field, the risk of partial discharge increases. Conversely, positioning the joint in line with the electric field can create vulnerabilities. If aligning them at the same potential level isn't feasible, it's ideal to orient the joint at a significant angle to the field lines to reduce stress. In some cases, such as the spacing between windings in dry-type transformers with air-to-air insulation and epoxy resin, the voltage may disproportionately stress one of the insulators, leading to partial discharge. Another significant type of partial discharge arises from small cavities within solid insulation. The high electric field strength in these voids can lead to a unique form of discharge that erodes the insulation from the inside, often resembling tree or shrub-like structures—commonly referred to as "treeing." This process can be quite unstable, causing the tree-like formations to grow rapidly. Initially, there may be no visible signs of deterioration, but once the growth begins, it can escalate quickly, potentially leading to complete insulation failure. To prevent such catastrophic outcomes, it is crucial to reduce the voltage when signs of treeing appear. In summary, understanding these types of partial discharges is vital for maintaining the integrity and reliability of electrical insulation systems.

### Results Discussion

The design of insulation systems must fulfill several essential requirements, including assessing the electric stresses that insulation can tolerate and understanding how the insulating medium behaves under those applied stresses. Insulation coordination involves ensuring that the electric stresses experienced by the insulation align closely with the dielectric strength of the insulating material. When considering solid insulation that contains flaws or voids, partial discharge (PD) can be represented using an equivalent circuit model. In this model, the capacitance of the void is denoted as  $C_c$ , while  $C_b$  represents the capacitance of the insulation that is in series with  $C_c$ . Additionally,  $C_h$

symbolizes the capacitance of the healthy portions of the insulation that are free from voids and are connected in parallel with the void. As the applied voltage increases, a critical threshold is eventually reached across  $C_c$ , leading to a discharge occurring across this capacitance. It's important to note that the voids within the insulation are filled with gas, which typically has a breakdown strength that is lower than that of the solid insulation itself. This discrepancy makes the voids more susceptible to breakdown under electrical stress, resulting in partial discharge events that can compromise the integrity of the insulation over time.

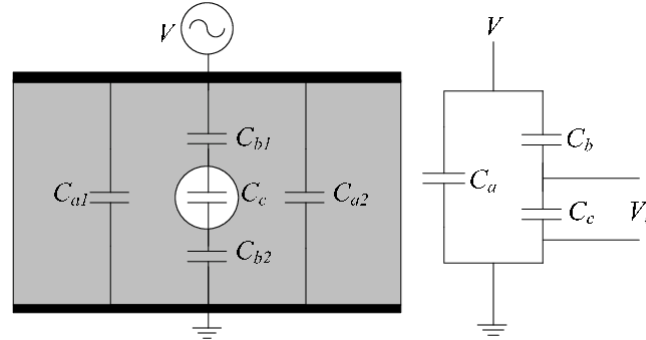


Figure (1) Capacitance model of a cavity in solid insulation[3]

In the capacitance model illustrated in Fig. 5, the following condition should be met:  $C_c \ll C_b \ll C_a$ . The total capacitance  $C_a$  can be calculated using the formula in equation (1):

$$C_a = \epsilon_0 \epsilon_r A / D \quad (1)$$

In this equation:

- $\epsilon_0$  is the permittivity of free space, valued at  $8.854 \times 10^{-12} \text{ F/m}$ .
- $\epsilon_r$  is the permittivity of the solid insulating material,
- $A$  is the area between the electrodes,
- $D$  is the distance between the electrodes.

Since the gas inside the void has a relative permittivity of 1, the capacitance of the void can be calculated with equation (2):

$$C_c = \epsilon_0 A / t \quad (2)$$

Here,  $t$  represents the thickness of the void. The capacitance of the insulation that is in series with  $C_c$  is given by equation (3):

$$C_b = \epsilon_0 \epsilon_r A (d - t) \quad (3)$$

Now, to determine the voltage across the cavity, we can use the equation (4):

$$V_c = C_b / (C_c + C_b) V_a \quad (4)$$

It's important to note that the apparent charge  $q$  from a partial discharge pulse is a significant factor influencing the lifespan of high-voltage insulation systems. According to the IEC standard 60270, this charge—the "apparent charge"—is defined as the amount that, if applied instantaneously between the terminals of a testing object in a specified test setup, would yield the same measurement on the measuring instrument as the partial discharge current pulse itself. The apparent charge is typically quantified in picocoulombs (pC). It's crucial to understand that this apparent charge does not equal the actual amount of charge involved at the discharge site, which cannot be directly measured. The apparent charge during a discharge can be expressed by equation (5):

$$q_a = C_v \Delta V_c \quad (5)$$

where  $\Delta V_c$  is the voltage across the void.

### Simulations

To demonstrate partial discharge in most electrical systems, a single-phase circuit is typically used. This circuit involves three capacitors, two voltage measurement devices, two resistors, a phase source, and an oscilloscope to visualize the output voltage from the measurements. A pulse generator is incorporated to create pulses that simulate discharges in oil, allowing us to observe the effects on the voltage chart. Additionally, a switch can be positioned at different intervals based on the time period we select.

In the setup, we use capacitors  $C_1$  and  $C_2$  at 1 microfarad each, while  $C_3$  is set at 1 nanofarad. The circuit operates at 50 Hz, with a pulse width of 20%. The period is calculated as 0.002 seconds, derived from  $1/50$  (which gives 0.02 seconds). This means that within each period, we can see 10 pulses displayed on the chart.

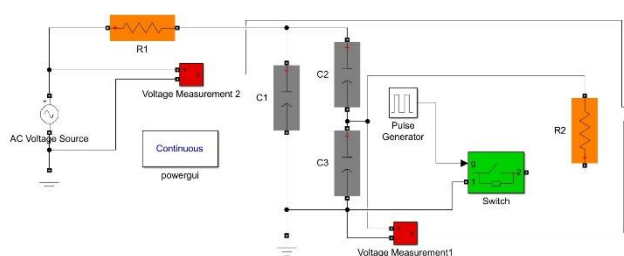
For simulating partial discharge, we utilize the pulse generator linked to the switch and the circuit. We monitor the waveforms of both current and voltage using three oscilloscopes. The power source is set at 400 kV, with a transformer that steps this down from 400 kV to 230 kv, operating at 50 Hz and rated for 250 MVA in a three-phase system. PowerGUI software aids in enhancing the realism of the circuit we've created.

Overall, the visual outputs indicate that partial discharges create some noise in the voltage and current readings, distorting the waveform display. These discharges contribute to energy losses in the circuit and introduce a bit of noise to the system.

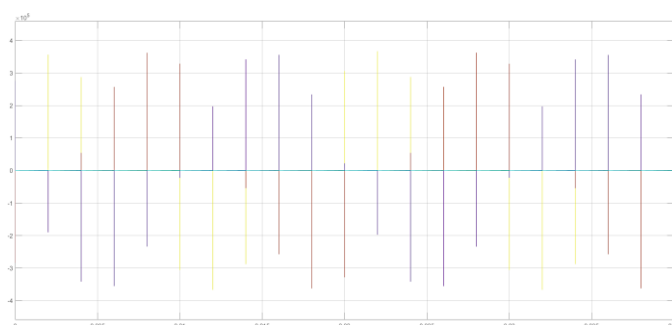
### Identified Problems:

1. **Technical Clarity:** The description contains some technical jargon that may not be accessible to every reader. Simplifying the language can help convey the message better.
2. **Sentence Structure:** The original text contains several run-on sentences and awkward phrases, making it challenging to follow. Breaking down complex sentences into shorter, clearer ones improves readability.
3. **Formatting:** Clearer formatting, like lists or bullet points, could help organize information, especially when listing components or results.
4. **Contextualization:** Providing more background information about partial discharge and why it's important would add value and context for those unfamiliar with the subject.

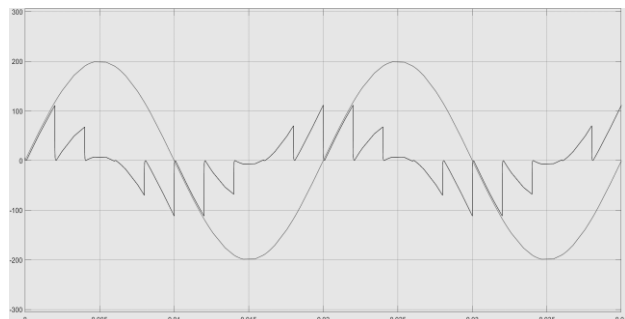
Addressing these issues would improve comprehension and clarity for a wider audience.



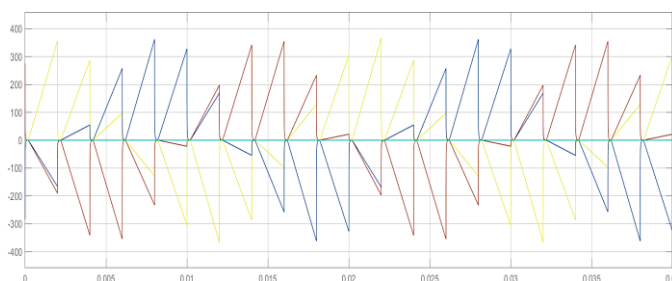
**Figure(2) Single phase PD circuit model.**



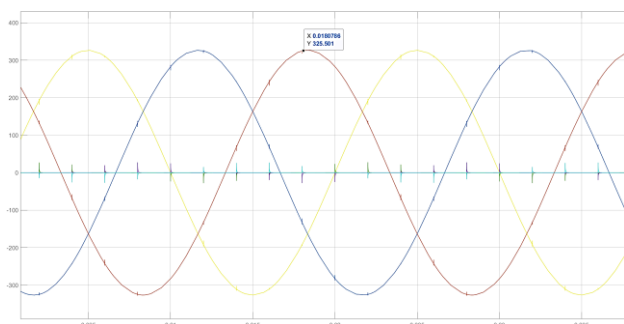
**Figure(3) Scope 2 (switches signals)**



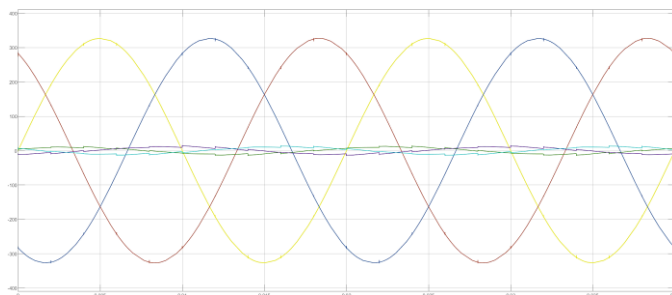
**Figure(4) PD WAVES IN 1 PHASE SITUATION**



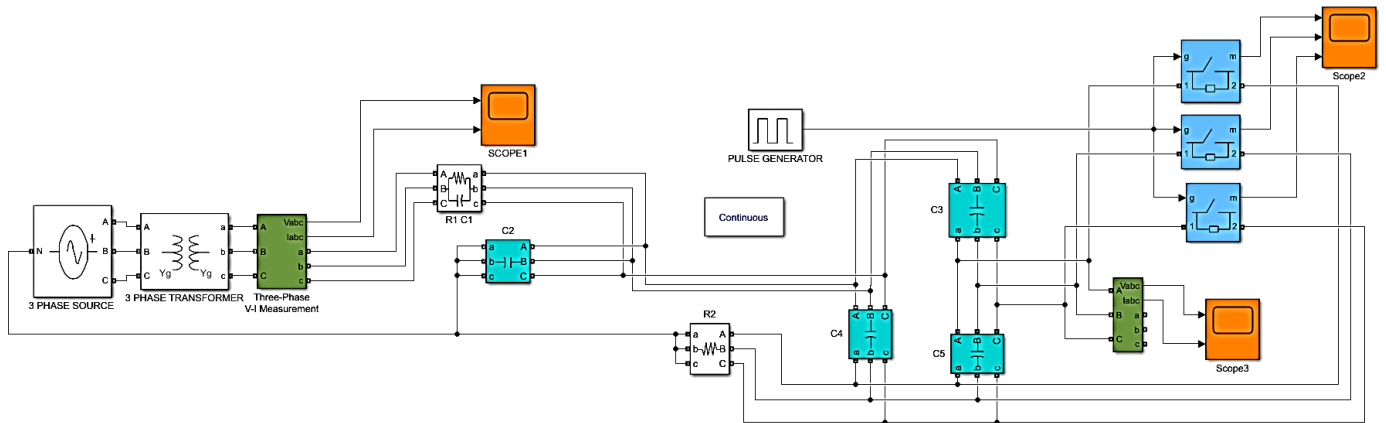
**Figure(5) PD noises**



**Figure(6) Main voltage chart**

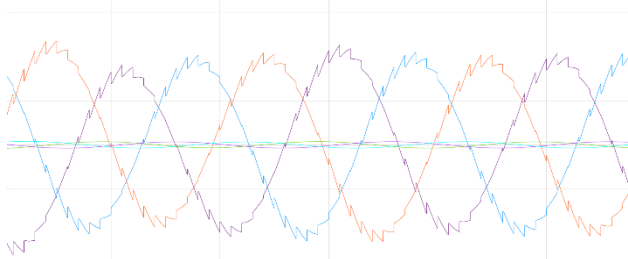


Figure(7) PD

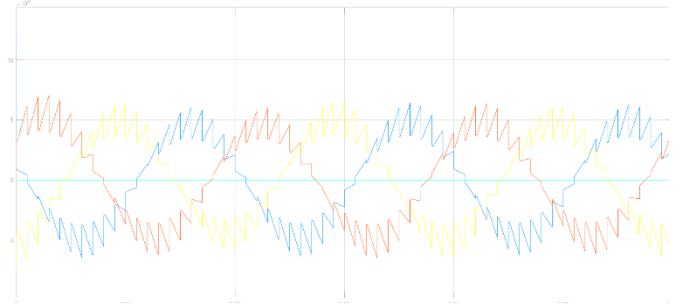


Figure(8) PD circuit in power transformers

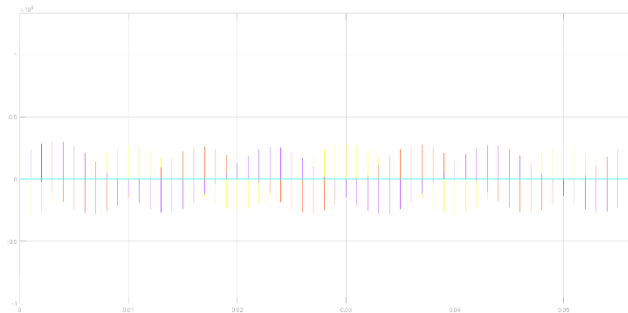
That circuit has the 0.001 second periode and pulse with is 10%. the  $c_1 = c_2 = 1 \times 10^{-7}$  and  $r_1 = r_2 = 10$  ohms ,  $c_3 = c_4 = 10 \times 10^{-5}$  ,  $c_5 = 1 \times 10^{-5}$ . in the wave picture its visible that pd has effect on the voltage and current wave face.



Figure(9) Voltage and current waves(main chart)



Figure(10) PD waves in circuit



Figure(11) Switches

## Conclusion

Power transformers play a crucial role in electrical transmission networks, serving as their core components. A substantial amount of research and funding has been directed toward these devices, so any failures can raise significant concerns for both energy providers and consumers. To appeal to potential buyers, various tests are conducted during the quality control phase of transformer manufacturing. It's been noted that around 30% of operational failures are due to electrical issues. One of the primary causes of these electrical failures is partial discharge (PD), which usually begins at weak points in the insulation—such as faulty gaskets. This process generates conductive pathways within the insulation, gradually leading to a breakdown in its protective properties and eventual failure. Therefore, understanding the characteristics and locations of these weak spots is vital for researchers aiming to prevent further damage to the insulation. Detecting partial discharge can be approached through several methods, including acoustic, chemical, optical, and electrical techniques. However, recent studies have shown that non-electrical methods often fall short in terms of efficiency and accuracy when it comes to pinpointing the nature and location of these faults. Investigating partial discharge phenomena and simulating them is essential, as they have a significant impact on the lifespan of high-voltage transformers and bushings. By improving our ability to detect and locate partial discharge, we can help extend the operational life of transformers. Additionally, modeling and simulating the behavior of partial discharges within solid insulation is beneficial for effective monitoring. Therefore, implementing on-line monitoring



for partial discharge in power plant transformers is crucial. With careful oversight during construction and continuous monitoring of partial discharge activity, we can maximize transformer lifespans. However, it's important to remember that transformers have a finite lifespan; weak points in insulation will always exist, making them susceptible to partial discharge.





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