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# INTERNATIONAL STANDARD

# NORME INTERNATIONALE

## Electrical insulating materials – Determination of the effects of ionizing radiation –
## Part 5: Procedures for assessment of ageing in service

## Matériaux isolants électriques – Détermination des effets des rayonnements ionisants –
## Partie 5: Procédures pour l'évaluation du vieillissement en service

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# ELECTRICAL INSULATING MATERIALS – DETERMINATION OF THE EFFECTS OF IONIZING RADIATION –

## Part 5: Procedures for assessment of ageing in service

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This third edition cancels and replaces the second edition published in 2011. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) added recent references in 7.4 showing that some electrical condition monitoring methods show promising correlations with ageing;
b) updated recommendations for implementation of a sample deposit in 9.2, installation of a sample deposit in 9.3 and testing of samples from the deposit in 9.4;
c) updated list of references.

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The text of this International Standard is based on the following documents:

| Draft | Report on voting |
|---|---|
| 112/523/CDV | 112/553/RVC |

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60544 series, published under the general title *Electrical insulating materials – Determination of the effects of ionizing radiation*, can be found on the IEC website.

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# INTRODUCTION

Organic and polymeric materials provide a significant proportion of the insulation used in electrical systems. These materials are sensitive to the effects of irradiation and the response varies widely between different types. It is therefore important to be able to assess the degree of degradation of these insulating materials during their service lifetimes. This part of IEC 60544 provides recommended procedures for assessing ageing of insulating materials in service.

There are a number of approaches to the assessment of ageing of polymer-based components exposed to radiation environments [1], [2], [3], [4][1]. These are based on the better understanding of the factors affecting ageing degradation which has been developed over several decades. In nuclear power plants, qualification programmes are normally used for the selection of components, including those based on polymeric materials. These initial qualification procedures, such as IEEE Std 323™-1974[2] [5] and IEEE Std 383™-1974[2] [6], were originally written before there was sufficient understanding of ageing mechanisms. Most of the methods discussed in this document are therefore used to supplement the initial qualification process.

This document is the fifth in a series dealing with the effect of ionizing radiation on insulating materials.

IEC 60544-1 (Radiation interaction and dosimetry) constitutes an introduction dealing very broadly with the problems involved in evaluating radiation effects. It also provides guidance on dosimetry terminology, several methods of determining exposure and absorbed dose, and methods of calculating absorbed dose in any specific material from the dosimetry method applied.

IEC 60544-2 (Procedures for irradiation and test) describes procedures for maintaining seven different types of exposure conditions during irradiation. It also specifies the controls that should be maintained over these conditions so that when test results are reported, reliable comparisons of material performance can be made. In addition, it defines certain important irradiation conditions and test procedures to be used for property change determinations and corresponding end-point criteria.

IEC 60544-3 has been withdrawn and incorporated into the second edition of IEC 60544-2.

IEC 60544-4 (Classification system for service in radiation environments) provides a recommended classification system for categorizing the radiation endurance of insulation materials.

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[1] Numbers in square brackets refer to the Bibliography.

[2] IEEE Std 323-1974 and IEEE Std 383-1974 are now withdrawn and have been superseded by more recent revisions.

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# ELECTRICAL INSULATING MATERIALS – DETERMINATION OF THE EFFECTS OF IONIZING RADIATION –

## Part 5: Procedures for assessment of ageing in service

## 1 Scope

This part of IEC 60544 covers ageing assessment methods which can be applied to components based on polymeric materials (e.g. cable insulation and jackets, elastomeric seals, polymeric coatings, gaiters) which are used in environments where they are exposed to radiation.

The object of this document is aimed at providing methods for the assessment of ageing in service. The approaches discussed in Clause 5 through Clause 9 cover ageing assessment programmes based on condition monitoring (CM), the use of sample deposits in severe environments and sampling of real-time aged components.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60544-2, *Electrical insulating materials – Determination of the effects of ionizing radiation on insulating materials – Part 2: Procedures for irradiation and test*

IEC TS 61244-1, *Determination of long-term radiation ageing in polymers – Part 1: Techniques for monitoring diffusion-limited oxidation*

IEC TS 61244-2, *Determination of long-term radiation ageing in polymers – Part 2: Procedures for predicting ageing at low dose rates*

## 3 Terms, definitions and abbreviated terms

### 3.1 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

### 3.2 Abbreviated terms

BWR boiling water reactor

CBQ condition-based qualification

CM condition monitoring

CSPE chlorosulphonated polyethylene

DBE design basis event

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| | |
|---|---|
| DLO | diffusion-limited oxidation |
| DRE | dose rate effect |
| EPR | ethylene propylene rubber |
| EQ | environmental qualification |
| NPP | nuclear power plant |
| OIT | oxidation induction time |
| OITP | oxidation induction temperature |
| PVC | polyvinyl chloride |
| PWR | pressurized water reactor |
| TGA | thermo-gravimetric analysis |
| VVER | water-cooled, water-moderated energy reactor (type of pressurized water reactor developed by Russia) |
| XLPE | cross-linked polyethylene |

# 4 Background

## 4.1 General

There are a number of factors that need to be considered when assessing ageing of polymeric components in radiation environments. In 4.2 through 4.5, some of these factors are briefly discussed and references made to more detailed information.

To accelerate radiation-ageing environments, the normal approach is to increase the radiation dose rate, often combined with an increase in temperature. The two most important potential complications arising from such increases involve diffusion-limited oxidation (DLO), which is described in 4.2, and chemical dose rate effects (DRE), which are described in 4.3. The implications of these factors on the use and interpretation of condition monitoring (CM) techniques are also discussed. Accelerated ageing programmes are briefly discussed in 4.4 and 4.5.

## 4.2 Diffusion-limited oxidation (DLO)

When polymers are exposed to an oxygen-containing environment (e.g. air), some oxygen will be dissolved in the material. In the absence of oxygen-consuming reactions (oxidation), the amount of dissolved oxygen will be proportional to the oxygen partial pressure surrounding the polymer (well known from Henry's Law). Ageing will lead to oxidation reactions in the polymer, whose rate will increase significantly as the dose rate and temperature of ageing are increased. If the rate of consumption of dissolved oxygen in the polymer is faster than the rate at which oxygen can be replenished by diffusion from the surrounding atmosphere, the concentration of dissolved oxygen in the interior regions will decrease with time (the oxygen concentration at the sample surface will remain at its equilibrium value). The reduction in internal oxygen concentration can lead to reduced or negligible oxidation, referred to as "diffusion-limited oxidation".

The importance of this effect is dependent on the sample thickness (thinner samples giving smaller DLO effects) and the ratio of the oxygen consumption rate to the oxygen permeability coefficient $P$, which is the product of the oxygen diffusion and solubility parameters. Accelerated radiation environments involve increases in dose rates, which increase the oxygen consumption rate. If the temperature remains constant as the dose rate is increased, the oxygen permeability coefficient will be unchanged. This means that DLO effects will become more important as the dose rate is raised. For more detail about these effects, IEC TS 61244-1 shall be consulted.

The effects of DLO may also need to be considered when carrying out CM measurements. This is not an issue for the many CM techniques which measure properties at ambient temperature, such as those based on density and modulus measurements. On the other hand, several CM

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techniques such as oxidation induction time (OIT) and thermogravimetric analysis (TGA) use quite elevated temperatures during the measurements. For these techniques, it is quite possible to have DLO effects present during measurement of the CM parameter. For this reason, detailed test methods for CM have been developed [8] to ensure that the sample preparation and test procedure avoid DLO effects. DLO shall be addressed when developing correlation curves for CM methods, to ensure that representative data are obtained for both radiation and thermal ageing.

### 4.3 Dose rate effects (DRE)

The existence of radiation dose rate effects and methods for dealing with these effects are described in IEC TS 61244-2. This standard shall be consulted for more detail about these effects. Generally, DRE are separated into two types. The first type, which is commonly observed in accelerated radiation-ageing experiments, is due to the DLO effects described in 4.2. These DLO-based effects represent a physical, geometry-dependent DRE.

The second type of interest to the current discussion concerns chemical DRE. Such chemically based DRE are much less common. A documented case of chemical DRE is found in PVC and low density polyethylene materials, caused by the slow breakdown of hydroperoxide intermediate species in the oxidation reaction [9]. The existence of such chemical DRE shall be checked at the start of any accelerated ageing programme. If there are no data available in the literature for the specific materials of interest, this can be checked by including tests at low dose rates in the ageing programme.

### 4.4 Accelerated radiation ageing

Accelerated ageing programmes in the laboratory tend to use acceleration factors much lower than are normally used in equipment qualification. This may avoid some of the problems associated with DLO and DRE. The ageing produced may then be a better simulation of the long-term ageing that occurs under service conditions. The data that are obtained in accelerated ageing tests can be used with predictive models to enable assessments to be made of the behaviour of the materials under service conditions.

Accelerated ageing programmes require a matrix of test data to be generated over a range of environmental conditions as described in IEC TS 61244-2. As a minimum, data are needed for at least three different dose rates at the normal operating temperature but additional data on thermal ageing and radiation ageing at elevated temperature enables better use to be made of the available predictive modelling methods. The dose rates and temperatures used for accelerated ageing should be selected using the principles described in IEC 60544-2 to ensure that homogeneous oxidation occurs. For each environmental condition used, test data shall be obtained at several different ageing times, the longest of which should be sufficient to introduce significant degradation. A typical test programme could take more than 18 months to complete, dependent on the radiation resistance of the materials being tested.

The data required in the test matrix are determined by the type of component being evaluated. The appropriate test parameters are given in IEC 60544-2 for various types of polymeric materials and components.

### 4.5 Accelerated thermal ageing

When carrying out thermal ageing as part of an accelerated ageing programme, it is important that an appropriate value of the activation energy is used in assessing the temperature and timescale of the accelerated test. In some materials, the ageing mechanism at high temperatures is different to that which would occur under plant conditions and in many materials the activation energy decreases significantly at lower temperatures [10], [11].

Samples which have been exposed to accelerated thermal ageing shall be allowed to stabilize before any CM tests are carried out. Some polymeric materials are hygroscopic and show a marked dependence of their properties on the moisture content [8]. This is primarily of concern

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for a few materials used in older nuclear power plants, but may also be important for those CM methods that are sensitive to the moisture content of the material.

## 5 Approaches to ageing assessment

There are a number of complementary methods available for ageing assessment as described in their respective clauses. Each of these methods has its own advantages and limitations. Selection of one or more of the methods will be dependent on the requirements of the individual users.

Several approaches to ageing assessment in-service are described in this document. These are:

- identifying components of concern to prioritize the application of ageing management programmes (see Clause 6);
- condition monitoring to assess the condition of materials which have aged for extended time periods under actual use environments (see Clause 7);
- predictive modelling to use data from laboratory based accelerated ageing programmes to estimate ageing under real-time ageing conditions (see Clause 8);
- sample deposit to provide samples for the measurement of ageing under real-time ageing conditions (see Clause 9).

## 6 Identifying components of concern

### 6.1 General

Within a nuclear power plant, there are many components containing polymeric insulating materials, for example there are over 1 000 km of electrical cables in a typical NPP. It is not practical to assess the ageing of every individual component, and many will not be exposed to significant environmental ageing conditions. It is therefore necessary to prioritize any ageing management programme by identifying those components which are of most concern.

### 6.2 Priorities for ageing management

Not all components have the same priority for ageing management. In general, those components performing safety functions during and following an accident are of most concern, together with those important to continued operation. Any components outside of these categories would initially be assigned to a low priority for ageing management activities.

The normal operating environment of the components shall be examined to identify the expected impact of the environment on their ageing. Those components identified as being subject to severe ageing are assigned the highest priority, whereas those subject to moderate ageing can then be assigned to a medium priority.

For this prioritization to be carried out effectively, environmental monitoring is essential (see 6.3), combined with knowledge of the ageing behaviour of the components. Initial assessment may make use of design calculations for temperatures and dose rates. The ageing information may come from equipment qualification data or from supplementary accelerated ageing tests carried out in the laboratory.

### 6.3 Environmental monitoring

Ageing of insulating materials in an NPP is dominated by temperature, radiation dose and radiation dose rate for polymeric materials. A major requirement for ageing management is a detailed knowledge of the actual temperatures and dose rates at locations within the plant where high priority components are situated.

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The temperature and dose rate distribution within the plant shall be obtained using temperature recorders and dosimeters. Operational fluctuations and seasonal variations shall be included by carrying out these measurements over several fuel cycles. It may be necessary to repeat such measurements when changes are made to the plant, for example power upgrades.

Small self-contained temperature recorders are available and are a practical and flexible method for localized temperature recording to supplement bulk temperature monitoring equipment that is already installed in the plant.

Radiation monitoring is best achieved with alanine dosimeters, which are suitable for long term measurements. These dosimeters are not significantly affected by temperature, can be sealed to avoid the influence of humidity and are suitable for monitoring over a wide dose range. The radicals formed under irradiation in alanine are stable over time periods in excess of a year and can be measured using electron spin resonance. For more detail about radiation monitoring, IEC TS 61244-1 shall be consulted.

### 6.4 Localized severe environments

Identification of localized severe environments (hotspots) where high priority components are located is an important aspect of ageing assessment. Such locations can be identified in a number of ways, including interviews of plant personnel, operational reviews, review of plant layout drawings and plant walkdowns [12], [13], [14], [15]. Each will provide a different perspective on hotspot conditions. Feedback from plant maintenance personnel is an important aspect of identifying early signs of degradation.

### 6.5 Worst case components

Having prioritized the components most likely to be affected by ageing, carried out environmental monitoring and identified localized severe environments, the components will have been assigned to either a high, medium or low priority for further ageing management. All components assigned to a high priority shall be subjected to ageing management activities such as CM or planned replacement.

The evaluation process can be refined as more information becomes available. For example, if CM of high priority cables indicates that degradation is much less severe than expected, it may be appropriate to move these components to a lower priority category.

## 7 Condition monitoring techniques

### 7.1 General

CM techniques are used to assess the condition of materials which have aged for extended time periods under actual use environments, such as in nuclear power plants, accelerators, reprocessing plants. The approach makes use of test methods which have been shown to correlate well with ageing degradation.

CM in ageing assessment can be used in a number of ways, ranging from short term trouble shooting to long term on-going qualification programmes.

### 7.2 Establishing correlation curves for CM methods

In order to use CM methods effectively, it is important to develop correlation curves between the monitoring parameter measured and the prime indicator of degradation or functionality. For low-voltage polymeric cable materials, the prime indicator of degradation is generally considered to be tensile elongation at break, since changes in electrical properties are small before physical failure of the cable in many cases. In seal materials, the compression set has proved to be a useful indicator of the degradation in sealing properties introduced by ageing. Suitable degradation parameters for other components are given in IEC 60544-2.

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Correlation curves shall be determined by measurements of the prime indicator and the relevant CM parameter on samples aged under identical conditions, as shown schematically in Figure 1. The measurements shall cover a range of degradation levels, from the unaged condition to a severely degraded condition. It is recommended that at least five sets of data at different ageing times be used in establishing the correlation curve (Figure 2), preferably for several different temperatures and radiation dose rates. An example of a correlation curve for a CSPE cable sheath material is given in Annex A.

Correlation curves are normally established using accelerated testing. Such tests shall be carried out using the procedures described in IEC 60544-2. Alternatively, correlation curves can be established as part of the sample deposit procedure for ageing assessment, as described in Clause 9, or as part of the initial equipment qualification process.

### 7.3 CM methods

There is a wide range of methods which have been evaluated for CM of polymeric components, particularly for cable materials [4], [17]. Of the many methods examined, several have been identified as being potentially suitable for practical use. Measurement standards for the most developed of these methods are described in detail in the various parts of the IEC/IEEE 62582 series [8]. For these methods, data correlating the monitoring parameter with degradation of the polymeric component have been built up and the practical limitations explored. The most developed methods are

- indenter modulus;
- oxidation induction time (OIT) and oxidation induction temperature (OITP);
- elongation at break.

NOTE There are many other methods which have been investigated for CM and suitable measurement standards for some of these are expected to be developed over the next few years. A number of these are described in IAEA-NP-T-3.6 and IAEA-TECDOC-1825, together with their limitations [4], [17].

Visual inspection (including tactile and other sensory inspection) is a qualitative monitoring method which can be a valuable tool in assessing localized ageing degradation within nuclear power plants using walkdowns. The practical considerations for in-plant visual inspections (walkdowns) are described in more detail in [12], [13], [14], [15].

Electrical methods for assessing degradation in cable systems and their associated end-devices are described in IEC 62465 [18]. These methods primarily relate to cable systems (connectors, penetrations, etc.) rather than degradation of the insulating materials but some methods are showing great promise in correlating with thermal ageing degradation [18], [19].

### 7.4 Using CM for short-term troubleshooting

In short-term tests, the emphasis of CM is in identifying the extent of a problem or in demonstrating that a problem does not exist. For example, the indenter has been used to determine the extent of damage to cables from degradation arising from damaged thermal insulation on a steam line near a cable in a BWR nuclear power plant. By carrying out indenter measurements along this cable, a profile of the damaged area was obtained. This enabled replacement of a limited section of cable rather than replacing the entire cable run. Another example was the use of in-situ electrical CM methods to determine the functionality of a range of cables in an NPP that had been in operation for 40 years. The results showed that 60 % of the cables tested were not significantly aged and recommendations could be made for replacement of those that had aged significantly [20].

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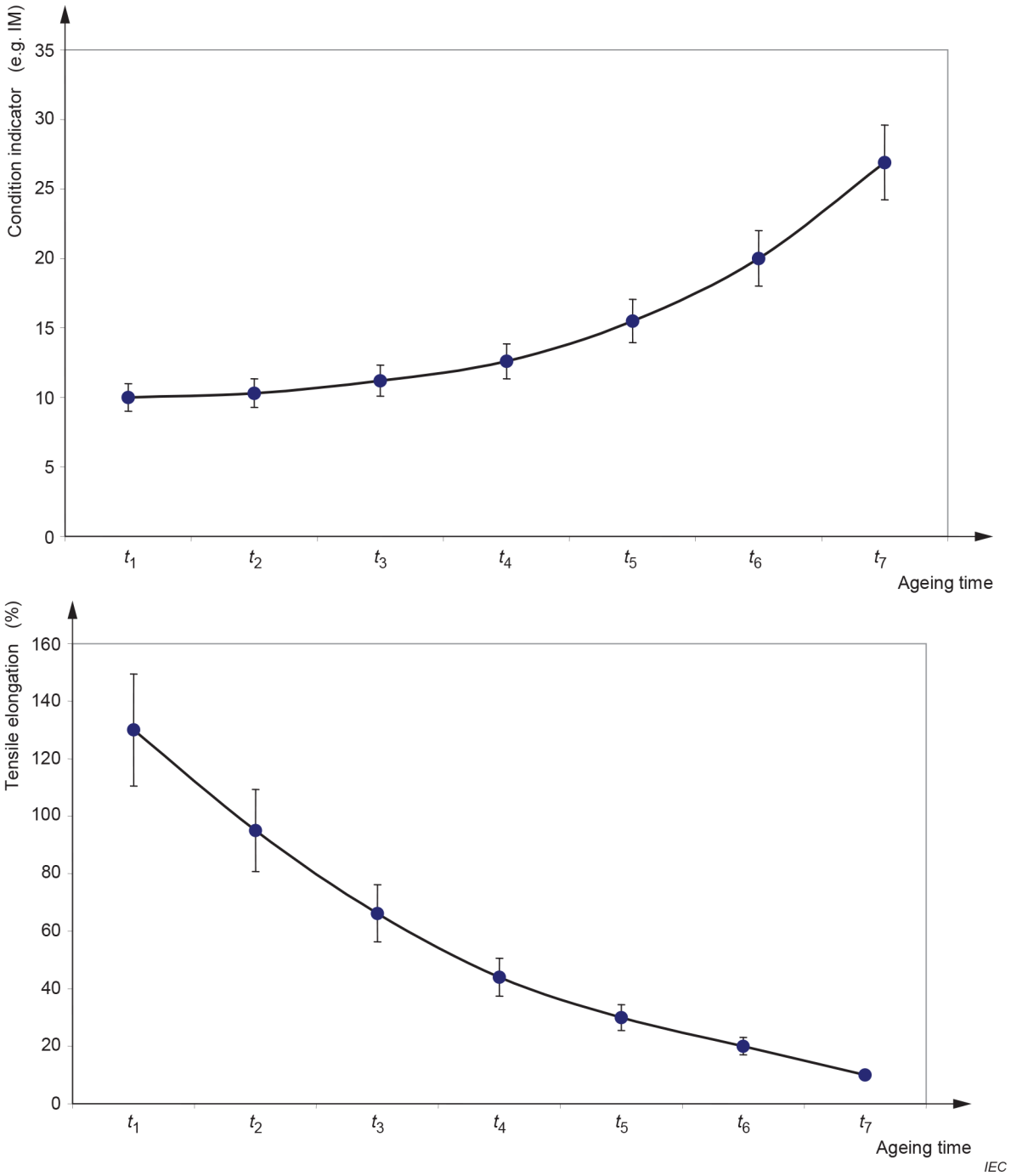


**Figure 1 – Development of ageing data on changes in tensile elongation and a condition indicator (e.g. indenter modulus) – Schematic representation**

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