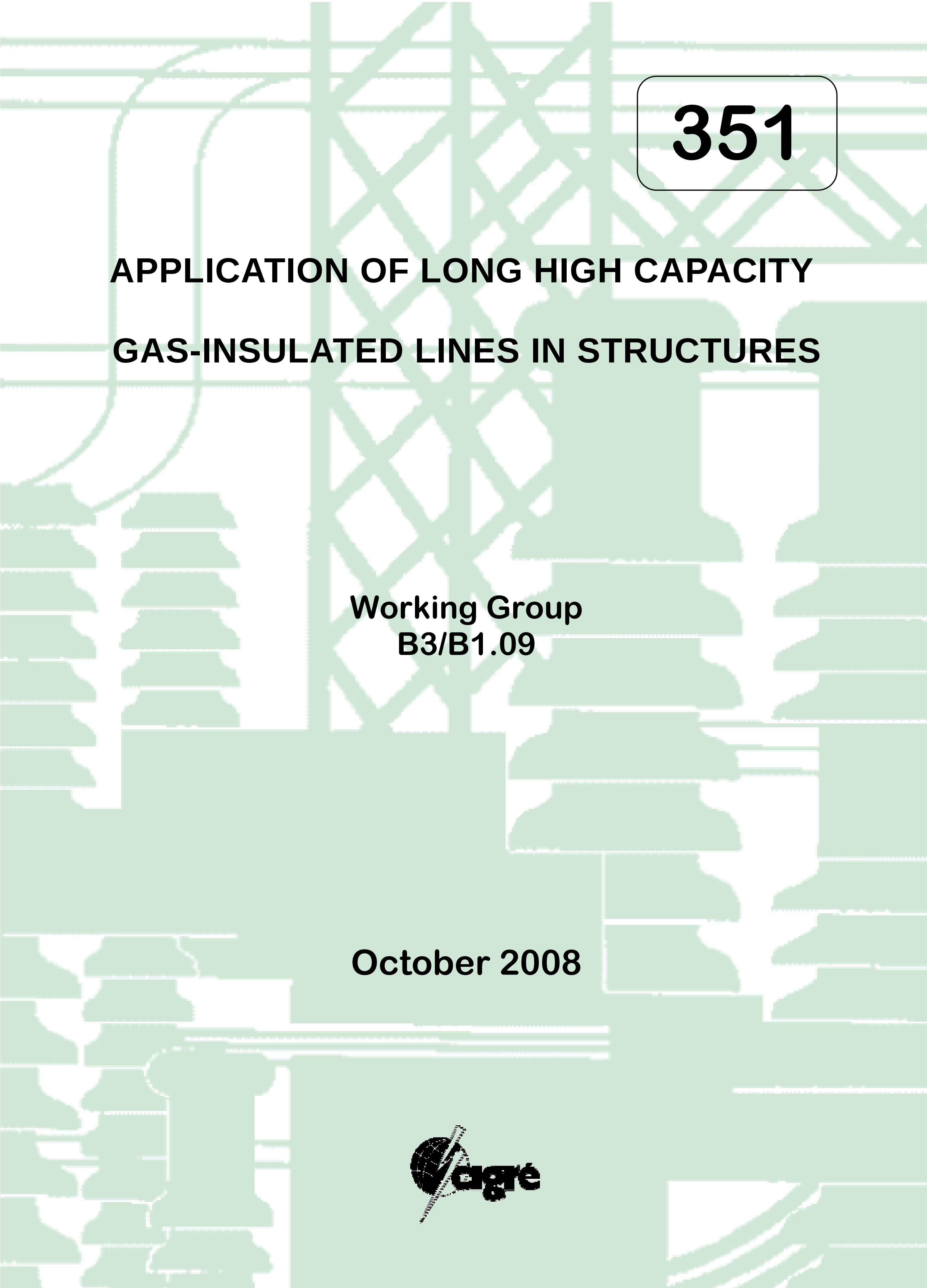

351

APPLICATION OF LONG HIGH CAPACITY GAS-INSULATED LINES IN STRUCTURES

Working Group
B3/B1.09

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Application of Long High Capacity Gas-Insulated Lines in Structures

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Summary

The need of high power transmission systems is increasing in the near future. Power Supply of large metropolitan areas like New York, London, Shanghai, Tokyo, Sao Paulo, just to name some, will ask for increasing power concentrated in a densely populated area where no overhead line will be accepted. Remote resources of energy generation using renewable sources will be installed in large amounts of Giga Watt all over the world. Wind will be the leading renewable energy resource, and the installations will be far away from the user of the wind energy. Some will even be offshore.

High power underground transmission technology is needed to transport bulk power over long distances. The gas insulated transmission line offers this opportunity. The underground laying like oil or pipelines will avoid long durations of getting permits by the authorities as it is seen today with overhead lines. New overhead line routings are often blocked by public interests and will cause delays of 10 or 20 years, which is unacceptable for the solutions needed in the power networks.

The Gas Insulated Line - GIL offers the technical possibility to solve the problem but has until today mostly been used in substations with relatively short lengths of installation.

The longest installation today has single pipe lengths of about 20 km where most installations are in the range of a few kilometres. In total about 250 km GIL are installed world-wide and in operation today.

CIGRE prepared a brochure in joint work of the substation committee B3 and the cable committee B1 under the title: "Application of long high capacity Gas Insulated Lines in structures".

Long high transmission capacity Gas Insulated Lines were studied by a JWG 23/21/33 from 1997 to 2002, which published a Technical Brochure 218 in 2003. The issue of installing a GIL in tunnels or bridges has been now addressed by this JWG and it the result covers practical project information about the use of GIL in conjunction with long structures like bridges and tunnels.

This CIGRE brochure includes:

GIL installed in specific or shared structures (tunnels, bridges) and structures with or without other services (road and railway traffic, piped services, other utilities). In the brochure information is collected on existing GIL installations in structures. It is identified what are the needs to be considered when installing GIL in specific or shared structures and information are given how to handle large scale projects and to define what “long GIL” means.

In the study mechanical and thermal design, ambient conditions, laying, installation, gas handling, testing, commissioning, quality control, repair process, safety risks, and life cycle analysis are covered.

A combination of large tunnels and bridges with GIL electric power transmission is recommended. The multi-use of traffic tunnel projects in Europe is also recommended by the European Union. The share of such expensive structures like tunnels or bridges makes projects more economical for both sides.

Although a comparison between GIL and cables is not the task of this brochure, it is worth noting that for long structures (e.g. the Brenner Tunnels with 65 km length of the tunnel) GIL does not require shunt reactive compensation (rather problematic inside and at the ends of tunnels), has null fire load and assure safety of personnel in case of internal arc (no external effects).

Contents

1 Introduction

This brochure gives information on the application of long high capacity Gas-Insulated Lines (GIL) in structures like bridges or tunnels, especially in cases where it can be used for high power transmission. It is written as a guide for technical experts involved in all aspects of GIL, but also can be used for general information to get an overview of GIL technology.

Basic information is included about published documents, the properties of insulating gases, technical data, and standard design dimensions and specifications.

The brochure explains the planning steps and requirements concerning route planning and the possibilities and limits given by the GIL.

In a world-wide search the existing GIL in structures have been identified for tunnels, above ground installations, directly buried installations, and bridges.

For tunnels and bridges specific requirements, e. g. seismic, electromagnetic fields, and grounding are explained and are discussed for different types of bridges and tunnels.

One big field in the brochure is covering the project execution and the handling of large scale projects including the operation, maintenance and repair process.

Life cycle assessment, safety analysis and finally a detailed cost analysis is included in the brochure.

2 Scope

Long high transmission capacity Gas Insulated Lines were studied by a JWG 23/21/33 from 1997 to 2002, which published a Technical Brochure 218 in 2003. Due to the lack of time and to the wide scope of work involved, the issue of installing a GIL in tunnels or bridges was not addressed by this JWG and it was therefore suggested that a new JWG is set up to cover this important issue.

Scope of work:

- GIL installed in specific or shared structures (tunnels, bridges)
- Structures with or without other services (road and railway traffic, piped services, other utilities)
- The voltage range shall be HV and EHV AC

Terms of reference:

- To collect information on existing GIL installations in structures
- To identify the issues that need to be considered when installing GIL in specific or shared structures
- To give information how to handle large scale projects and to define what “long GIL” means

The study shall be limited to:

- Mechanical and thermal design,
- Ambient conditions,
- Laying, installation, and gas handling
- Testing, commissioning, and Quality control,
- Repair process,

- Safety risks,
- Life cycle analysis.

As aspects of interactions with other services in multipurpose or shared structures during construction, operation or dismantling are studied by WG B1-08, it is foreseen that this JWG will give relevant technical input about GIL to WG B1-08 and will share information by participating in this group.

This brochure aims at describing those installations where transmission line has a common arrangement with different purpose structures.

Public access like on a bridge, trench or above ground.

Not included

The brochure does not include technical, economical, ecological and other criteria of overhead lines, cables and GIL. For this a separate investigation would be needed in a JWG of B1, B2, and B3.

This brochure also does not include the technical basics for electrical, mechanical, and thermal layout of the GIL which was widely covered by Technical Brochure 218.

3 Definitions

Tube

A tube is a single element of a GIL.

Pipe

A pipe is a longer length of the GIL.

Enclosure

An enclosure is the outer metallic pipe containing the insulating gases, conductor, and internal supporting media.

Conductor

A conductor forms the current carrying circuit of the GIL.

4 What is a Gas Insulated Line (GIL)?

4.1 Explanation for the Public

GIL is a transmission system that can be used as an alternative to conventional cables when overhead lines are not a practical solution.

The first generation of GIL is using pure SF_6 for insulation. For long distance GIL applications N_2/SF_6 gas mixtures will be used.

GIL has an essentially co-axial structure in which the conductor at high voltage is supported centrally within an earthed, conducting enclosure by solid support insulators. The space between the conductor and enclosure is filled with an electrically insulting gas under a pressure of a 0.7-1.0 MPa.

For a 400 kV transmission line the diameter of one GIL pipe is approximately 500 mm, whereby three pipes are needed for a one three phase electric system. For two systems the tunnel dimension is approximately 3.5 m diameter if it is circular, or 2.5 m height and 2.8 m width.

GIL components have been optimized for laying over long distances. Conductor and enclosure lengths together with support insulators are transported to site where they are assembled in-situ. The enclosure lengths are usually joined by an automated welding process.

The conductor usually consists of an aluminium tube, to achieve a high electrical conductivity. The enclosure, which retains the internal gas pressure, is usually made from an aluminium alloy.

The insulating gas contains sulphur hexafluoride (SF_6), an inert, non-toxic, non-flammable gas. The dielectric strength of SF_6 is approximately three times that of air at a given pressure and is widely used in high-voltage equipment where its insulating properties allow a compact structure to be obtained. In GIL, the SF_6 is used in a mixture with nitrogen. The addition of 20 % by volume of SF_6 to nitrogen results in an insulating gas mixture, which, with an increase in pressure 45 %, is comparable to that of pure SF_6 [55, 56].

The conductor current induces a reverse current of the same current level to the enclosure, so that the electromagnetic field outside the GIL is negligible (see Annex B). Therefore no special shielding is required even in areas which are critical with respect to EMC, e.g. airports or computer centres.

If an insulation failure would occur inside a GIL, the fault arc remains inside the enclosure and does not influence any outside equipment or person. The GIL is fire resistant and does not contribute to fire load. This means best protection of persons and environment. This fact is of particular importance where the connection between overhead line and high voltage switchgear goes through tunnels and shafts.

This has been tested in design tests and in long duration testings simulating the life time of the GIL in cooperation with French and German utilities. The results have been published in "Electrical and Mechanical Long-Time Behaviour of Gas-Insulated Transmission Lines" CIGRE SC 21/23/33-03, 2000 [24] and will be the basis for the revision of the GIL standard IEC 61640.

5 Basics Information

5.1 Main Documents Published

There are many publications on GIL available today on very different aspects, please see clause 15 Bibliography.

The most basic and fundamental publications are the following:

Cigré Brochure 218: "Gas Insulated Transmission Lines (GIL) ", see [1].

Cigré Brochure No 260: “N_2/SF_6 Mixtures for Gas Insulated Systems”, see [53].

CIGRE Publication at Paris Session 2000 "Electrical and Mechanical Long-Time Behaviour of Gas-Insulated Transmission Lines", see [24].

IEC report 61640: "Rigid high-voltage, gas-insulated transmission lines for rated voltage of 72,5 kV and above", see [2].

5.2 Properties of Insulating Gas

It is well known that the insulating gas in GIL is constituted by a mixture N_2/SF_6 (80%/20%).

The insulating gas mixture will be filled to a specified filling pressure and then operated in a bandwidth of operation pressures. The minimum and maximum operation pressure is depending on the gas temperature and will be fixed specific to each installation.

It is trivial that the nitrogen N_2 is a wholly inert, very steady and a-non-toxic gas.

With regard to sulphur hexafluoride (SF_6), it is necessary the following in-depth analysis.

SF_6 is used in power apparatus as an insulating and arc quenching medium because of its excellent insulating and arc extinguishing properties [53]. Due to its global warming potential SF_6 substitutes such as N_2/SF_6 mixtures are preferred in applications where large gas quantities are used and where dielectric performance is of most interest.

Today no other gas than SF_6 is available for insulation with the same electrical properties.

5.2.1 Chemical-physical Properties of SF_6

SF_6 is a synthetic gaseous dielectric with excellent dielectric insulation and arc quenching properties.

SF_6 is practically insoluble in water. It is non flammable, non toxic and odourless.

It has a very high chemical and thermal stability.

It decomposes into noxious products (e.g. monofluoride, difluoride, tetrafluoride, decafluoride) when the temperature is higher than *800°C* or when an electrical discharge occurs.

The abovementioned products, in presence of water or humidity, are subjected to hydrolysis and combine themselves to create hydrogen fluoride that is toxic and corrosive.

In presence oxygen and strong electrical discharges, sulphur hexafluoride forms decomposition products (e.g. SO_2F_2, SOF_2; these ones are subjected to hydrolysis forming noxious products) [53].

In gas mixtures the individual components are used at their partial pressures, e.g. in a N_2/SF_6 gas mixture with 20% SF_6 the partial pressure of SF_6 is 20% of the total pressure.

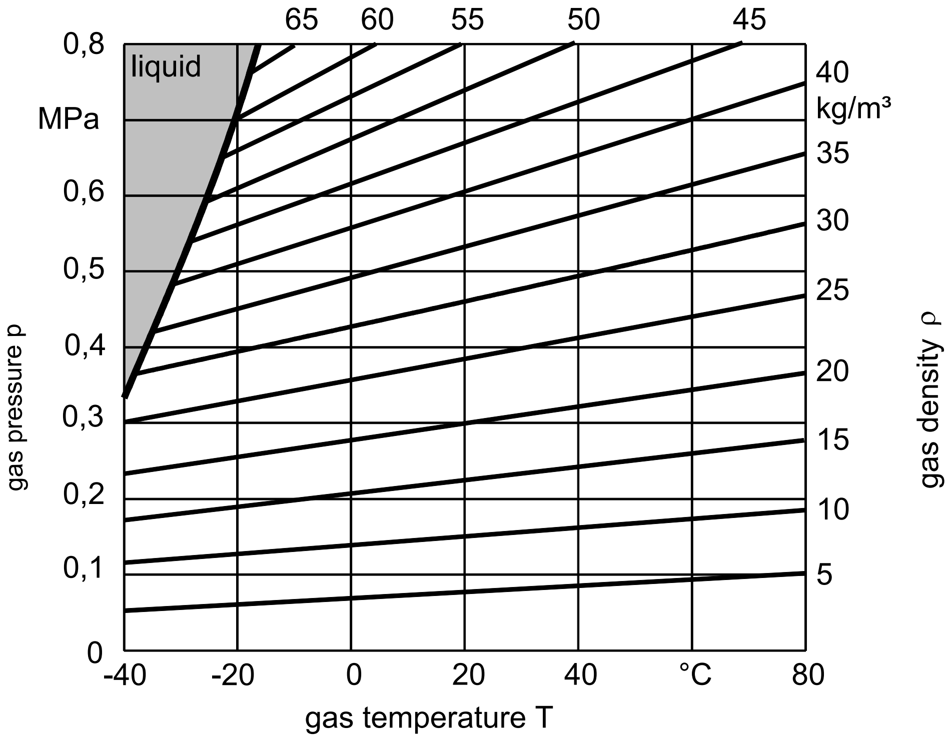


Figure 1: State Diagram of SF_6 [51]

Liquefaction of N_2/SF_6 mixtures is linear related to percentage of N_2 and SF_6. With a liquefaction temperature of pure SF_6 at 7 bar of about - 20 °C and of Nitrogen (N_2) of about - 150 °C the mixture has a liquefaction temperature of about - 130 °C.

At high pressures and very low temperatures SF_6 may become liquid. The state diagram for pure SF_6 shows at what combinations of pressure and temperature, the transition between gaseous and liquid state takes place, see Figure 1. In gas mixtures the individual components are used at their partial pressures, e.g. in a N_2/SF_6 gas mixture with 20% SF_6 the partial pressure of SF_6 is 20% of the total pressure. For N_2/SF_6 gas mixtures for use in GIL a liquefaction of either gas component is unlikely under normal operating conditions.

5.2.2 Electrical Properties of N_2/SF_6 Gas Mixtures

The electrical properties of a gas mixture are determined by the electrical properties and the partial pressures of its components. The molar concentration x_i of the i^{th} component in a mixture of ideal gases is given by

$$x_i = \frac{V_i}{V} = \frac{p_i}{p},$$

whereby V and p are the total gas volume and the total gas pressure, respectively, and p_i is the partial pressure of the i^{th} gas component. Supposed that N_2 and SF_6 perform as ideal gases the ratio of a gas mixture can be adjusted by the partial pressures of its components [52].

The intrinsic dielectric strength of the gas mixture, not affected by roughness or defects at surfaces of ambient solid material, is the main basis for the choice of the mixture ratio, the gas pressure and the design of an insulation system [53].The effective ionisation coefficient $\bar{\alpha}$ takes into account ionisation and attachment processes and governs the electron multiplication and discharge development.

According to the SF_6 content x and the N_2 content $(1 - x)$ in the mixture both gas components contribute to the effective ionisation coefficient through their individual effective ionisation coefficients ($\bar{\alpha}_{SF6}$, $\bar{\alpha}_{N2}$) [53]. The electric field strength at which the effective ionization coefficient equals zero, i.e. $\bar{\alpha} = 0$, is called critical electric field strength E_{cr} or intrinsic dielectric strength of a gas or a gas mixture [53]. As the critical electric field strength depends on the gas pressure p it is usually expressed as critical related field strength $(E/p)_{cr}$. From the critical related field strength the intrinsic dielectric strength can be calculated by $E_{cr} = (E/p)_{cr} \cdot p$.

The intrinsic dielectric strength E_{cr} of the mixture refers to its strength under ideal conditions, but can be applied for quite accurate estimations of practical properties when normalized values are used. The normalized intrinsic dielectric strength $E_{cr}^0 = \left(E/p\right)_{cr} / \left(E/p\right)_{cr\,SF6}$ of N_2/SF_6 mixtures as a function of the SF_6 content x indicates that mixtures with relatively low SF_6 content exhibit a relatively high dielectric strength. For example, a mixture with only 20% SF_6 content has 69% of the dielectric strength of pure SF_6 at an equal gas pressure (Figure 2).

To determine the optimum SF_6 content, mixtures of equal intrinsic dielectric strength Ecr are considered. The normalized pressure p0 of such mixtures can be calculated according to $p^0 = 1/E_{cr}^0$. For example, with a gas mixture containing 20% SF_6, a moderate pressure increase of about 45% is necessary to achieve the dielectric strength of pure SF_6 (Figure 2). Furthermore, the total amount of SF_6 required for a given application is given by the normalized quantity $q^0 = x\,p^0$ of SF_6 in a gas mixture of equal intrinsic dielectric strength. For example, with a gas mixture containing 20% SF_6 the required amount of SF_6 is reduced by 71% compared to pure SF_6 of equal dielectric strength (Figure 2). The SF_6 leakage rate is also reduced.

In GIL, large amounts of insulating gases are needed. For example, a 420 kV GIL with a diameter of 500 mm, would require about 13.9 tons of SF_6 per km when filled with pure SF_6 at 0,55 MPa. A N_2/SF_6 gas mixture of 80% N_2 and 20% SF_6 at a pressure of 0,8 MPa giving equal dielectric strength would require only about 4.0 tons of SF_6 per km, i.e. 29% of SF_6.

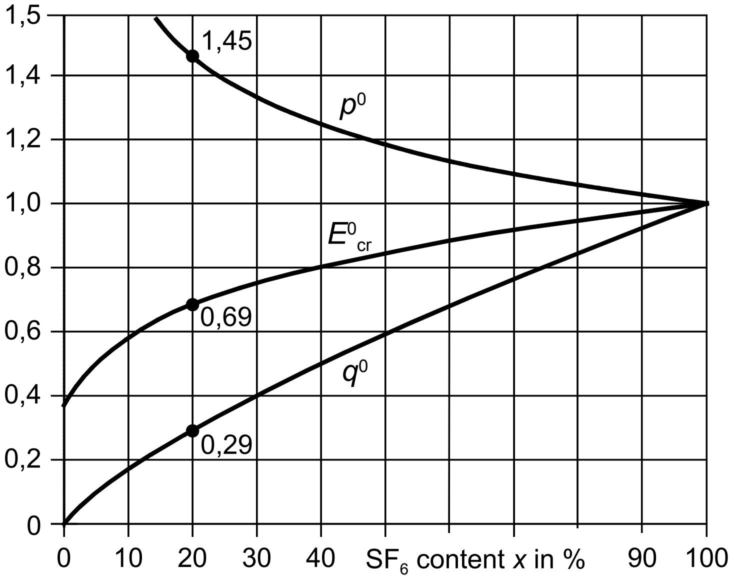


Figure 2: Normalized intrinsic dielectric strength E^o_{cr}, normalized pressure p^0 required for equal strength and resulting normalized quantity q^0 of SF_6 as a function of the SF_6 content x in a N_2/SF_6 mixture

Lowering the percentage of SF_6 could reduce the overall amount of SF_6 further, but may require the introduction of special pressure vessels, since the total gas pressure would have to rise accordingly. Using pure N_2 would require a pressure of more than 1,5 MPa. This rather high pressure would necessitate a special construction for the enclosure, and this might conflict with the relevant pressure vessel regulations. Adequate dielectric properties for GIL applications can be achieved by N_2/SF_6 gas mixtures containing 10 to 20% SF_6 when technical, economic and environmental aspects are considered [53].

Experience has shown that for N_2/SF_6 mixtures of equal dielectric strength, the voltage-time-curves are identical for such mixtures and SF_6 of equal dielectric strength, and can be applied for insulation co-ordination as usual [53].

Similar to pure SF_6 field enhancement caused by surface roughness of the electrodes may cause a considerable reduction in the discharge inception and minimum breakdown voltage. For mixtures of equal intrinsic dielectric strength (E_{cr} = const) the reduction factor is constant, i.e. it is independent of the SF_6 content in the mixture [53].

Defects on the surfaces of insulating components affect the insulation properties of mixtures in a manner similar to SF_6 of equal intrinsic dielectric strength [53]. In the case of defects like a needle shaped protrusion on electrodes, the strongly inhomogeneous field results in a considerable reduction of the discharge inception voltage. Whereby, for gas mixtures of equal intrinsic dielectric strength the discharge inception voltage U_i is equal. For a breakdown the criteria for leader inception have to be fulfilled in addition. At higher pressures there will be immediate leader inception and breakdown once streamer inception has occurred, while at lower pressures (i.e. in gas mixtures with higher SF_6 content) the leader inception voltage is significantly higher than the streamer inception voltage.

In general, in N_2/SF_6 gas mixtures with a minimum SF_6 content of 5% the discharge currents of fixed protrusions are quite similar to those of pure SF_6. Discharges of electrodes with floating potential are usually very severe, and can easily be detected by all methods independent of the gas mixture. In the case of free particles, the dominant process is charge exchange during the mechanical impact with the enclosure. Voids in solid materials (e.g. epoxy resin spacers) often contain a gas that originates from the casting process and is different from the insulation gas. Consequently, the nature of the PD signals is not affected. Therefore, the use of a gas mixture has little influence on the potential for PD detection and PD diagnostic systems developed for equipment filled with pure SF_6 can be applied in the same way for equipment containing N_2/SF_6 mixtures, in principal [53]. However, when considering gas mixtures of equal intrinsic dielectric strength it must be noted that at higher gas pressures breakdown may occur already at streamer inception voltage level so that diagnosis by PD measurement would not be possible. For this reason, N_2/SF_6 gas mixtures with a SF_6 content of 10 to 20% are used for practical applications in GIL.

5.2.3 Environmental Aspects

The majority of the insulating gas is with 80% N_2. This gas has no environmental impact, as it is naturally available in the atmosphere. N_2 is not toxic and non flammable. N_2 can suffocate.

In addition to being a more economical solution, the use of a gas mixture addresses environmental concerns, since SF_6 has a global warming potential. The GWP_{100} is 23900 times that of Carbon dioxide. However the absolute contribution by today's amount of SF_6 in the atmosphere to the global warming is 0.7%. The majority of SF_6 in the atmosphere is originated from SF_6 use outside the electrical industry. Most of such use has been banned (e.g. Isolated Windows, tires, shoes). The welded enclosure structure ensures that a high level of gas tightness is maintained throughout the life of the GIL. At the end of life, the gas mixture can be recovered, recycled, and reused. [56]

The use of N_2/SF_6 gas mixture is recommended for long distance applications of GIL. Today, most applications are in conjunction with GIS and the use of pure SF_6 because of the arc distinguishing capability of SF_6.

The use of pure SF_6 and N_2/SF_6 gas mixtures in the same substation is not wished by the users of GIL to avoid double gas handling devices and control.

For long distances application, when high power transmission is required the GIL offers the lowest CO_2 equivalent of all transmission systems in a life time view when transmission and installation losses are evaluated. Even if the SF_6 loss of total section of the GIL is taken into account once in the life time of 40 years, which has not happened in the last 40 years of GIL history world-wide.

5.2.4 Maximum Allowable Concentration in Working Areas

Experimentally, sulphur hexafluoride behaves as an inert gas and is non-toxic.

It can only give rise to asphyxiation with some concentrations in air. It is worth remembering that the TLV (threshold level) is the concentration value which a worker can breathe eight hours a day job-life long without having detrimental effects. With regard to SF_6, the TLV: TWA 1000 ppm that corresponds to 6000 mg/m^3.

According to a practical rule, the maximum value breathable by a person in a short time (some minutes) is hundred times more than TLV. In this case, it yields 100000 ppm equivalent to $6\ 10^5$ mg/m^3.

Handling and working with SF_6 is explained in IEC 62271-303 "Use and handling of sulphur hexafluoride (SF6)" and in Brochure CIGRE 276 [53, 56, 77].

6 Technical Data of the GIL

The GIL for the application in long structures has been developed on basis of first generation of GIL starting in 1974 where pure SF_6 has been used for insulation. In a development process from 1994 to 2000 the second generation GIL has been designed for the long distance applications using the laying procedures of pipe line laying and the N_2/SF_6 gas mixture for insulation without switching.

The main goal of this development was reached: cost reduction of more than 50% compared to the first generation.

The main reasons why GIL has been developed as a second generation GIL are: high power transmission rating, very high reliability, low transmission losses, low external electro-magnetic fields, high operation safety, high overload capability, and more than 30 years of experience with GIL.

See also annex A.

6.1 Electrical Characteristics

6.1.1 Standard Values on Voltage Levels and Currents

The values given are related to 80% N_2 and 20% SF_6 gas mixtures at 0,8 Mpa pressure.

The rated current is based on temperature of the ambient air without wind (40°C, IEC 62271-1), the maximum allowed design temperature of the conductor (maximal 105°C, IEC 62271-1), and the touch temperature of the enclosure (70°C for accessible GIL and 85°C for non accessible GIL, IEC 62271-1).

For long tunnels and bridges the ambient condition (temperature of air or rock, wind, sun radiation, tunnel ventilation) influence the rated current.

Details for rated currents, power losses, current in enclosures and voltage drop are explained in Annex A.

Table 1: Electrical characteristics by voltage level

Voltage Levels		**110kV**	**220kV**	**345kV**	**380kV**	**500kV**	**800kV**
Highest Voltage for Equipment U_m	kV	123/ 145/ 170	245/ 300	362	420	550	800
One Minute Power Frequency Withstand Voltage	kV	230/ 275/ 325	460/ 460	520	650	710	960
Lightning Impulse Withstand Voltage	kV	550/ 650/ 750	1050/ 1050	1175	1425	1550	2100
Switching Surge Insulation Level	kV	NA	NA/ 850	950	1050	1175	1425
Rated Current	A	2500	3000	3500	4000	4500	5000
Short Circuit Current	kA	63	80	80	80	80	80
Open Air Power Loss per Single-phase Meter at Rated Current	W/m	117	150	170	170	232	262
Capacitance per Single-phase Kilometre	nF/km	60	53	53	54	54	45
Surge Impedance	Ω	56	63	63	63	62	74
Inductance per Single-phase Kilometre	mH/km	.187	.211	.210	.215	.205	.247

Note: For 380 kV and 500 kV GIL 80% N_2, 20% SF_6 has been used, all other voltage levels currently use pure SF_6.

6.1.2 Transmission Losses

The power transmission losses of the GIL are low. This is related to the large cross sections of the electrical conductor, which is an aluminium pipe of electrical aluminium for high conductivity. The wall thickness of the conductor pipe is in the range of 6 to 15 mm, depending on the required transmission capability. With diameters of the conductor pipe in the range 150 to 250 mm total conductor cross sections of 5000 – 10000 mm^2 are typical. See line ‘open air power loss per single phase meter at rated current’ in Table 3.

6.1.3 Voltage Drop

For GIL applications in spite of the high power transfers, voltage drops are very low (always lower than 2.5%) and active losses (always lower than 1%) are satisfactory.

The wide load range of GIL allows for an effective power factor correction at the sending-end (source).

The capacitive reactive power at the sending-end only becomes an issue at very low current loadings.

The influence of voltage drop along the GIL is investigated in detail in Annex A "Detailed investigations on GIL application in long structures".

6.1.4 Phase Angle Compensation

In practical applications of GIL, the transmission network phase angle compensation is not needed when transmission length of several 10 kilometre segments are installed. Phase angle compensation is needed when the GIL length is longer than 200 - 300 km depending on the network conditions. In any case network system studies are recommended.

In Annex A the theoretical background of the low capacitive load of GIL and transmission properties of long length installations are discussed.

6.2 Mechanical Characteristics

Mechanical characteristics have been discussed in CIGRE Brochure 218 and IEC Standard 61640.

For the application in long structures like bridges or tunnels special care needs to be taken concerning the impact of vibrations and resonances to the GIL. Calculations are recommended for the specific layout of the design of structures and the possible use of damping elements.

Fatigue analysis for sensitive components like insulators and compensation bellows are recommended to meet the requirements coming from long structures and the related vibrations from traffic, wind or other structure related impact.

Nevertheless the GIL is a pressure vessel operating at low pressure, typical up to 7 bar over pressure. The GIL is designed according to the related EN pressure vessel standards taking into account that only non corrosive, dry insulating gases are used inside the aluminium pipe. Based on these design criteria no specific requirements to the tunnels and bridges are needed.

Standard Values on Dimensions

Table 2: Dimensional characteristics by voltage level

Voltage Level		110kV	220kV	362kV	380kV	500kV	800kV
Highest Voltage for Equipment U_m	kV	123/ 145/ 170	245/ 300	362	420	550	800
Enclosure Inside Diameter	mm	226	292	362	500	495	610
Conductor Outside Diameter	mm	89	102	127	180	178	178

Note: For 220 kV, 380 kV and 500 kV GIL 80% N_2, 20% SF_6 has been used, all other voltage levels currently use pure SF_6. The diameters are typical values.

6.3 Route Planning

Route planning for GIL is very similar to those of oil and gas pipelines.

The main planning parameters are:

- Accessibility of the terrain (e. g. transport, machinery, assembly tent)
- Underground condition (e. g. rock, water, clay)
- Obstacles to be passed (e. g. river, highway, railroad)

Based on the requirements of GIL:

- transport of 10 - 20 m long pipes
- assembly of laying units close to site
- bending radius 400 m limit
- space for preassembly of laying units

The routing needs to be optimized, which has a large impact on the cost.

The permission process to build underground, in tunnels or on bridges laid GIL are easier to get, because the impact is only during the construction period. Nevertheless, the official and public permission to build GIL has to be considered during route planning.

6.3.1 Adaptation to Routing by Elastic Bending

The elastic bending of the GIL allows a minimum bending radius of 400 m. This makes it possible to follow the bending of a tunnel or bridge without using bending elements, which are more costly.

In most cases the bending radii of 400 m is sufficient to follow the routing. Typical bending radii for railroad routing are > 2000 m and most bridges are almost straight.

6.3.2 Adaptation to Routing by Angle Units

In cases when the routing requires lower bending radii than 400 m so-called angle units are used. These angle units are able to serve any angle at any location along the route.

6.3.3 Vertical and Slope Routing

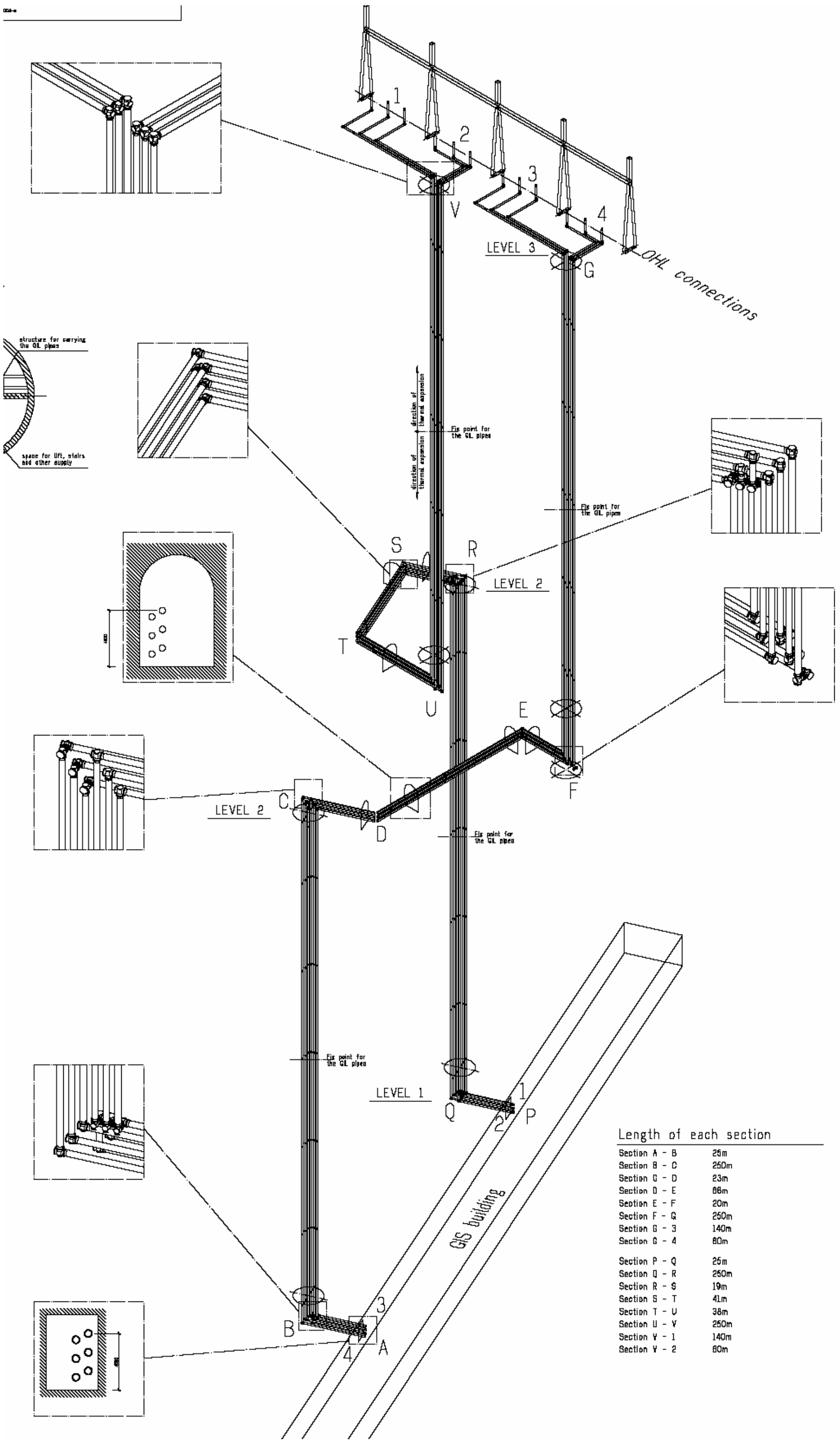
The modular design of GIL with enclosure pipe, conductor pipe, insulator and insulating gas mixture (N_2/SF_6) can be applied to solve any vertical height. Each section in itself is mechanically fixed from conductor pipe via the insulator, via enclosure pipe to the steel structure fixed to the tunnel or wall.

Vertical GIL applications of 115 m at Ruacana in Namibia, 300 m at Balsum Meadows in USA are in service. A 220 m at Laxiwa in China is under construction and 500 m at Xiluodu Hydro Power Plant in China is planned.

The number of hydro power plants (HPP) is increasing all over the world in order to avoid further negative impacts on the green house effect due to power generation. However, many of the projects currently in the planning stage will require a reliable bulk power transmission segment between high voltage switch gear and overhead line for the reason of impossible OHL access to the equipment. This is typically the case in hydro power plants where the generation equipment is located at dam level inside the valley limiting mountains and where the shores of the river or lake are very steep. Figure 3 shows a typical design which covers a difference in height between the main equipment level inside the mountain and the OHL-interface on top of it. The total height is app. 500 m and the power is transmitted by 4 GIL systems on each side of the river.

Test results of the past show that even under the conditions of vertical GIL routing the gas mixture maintains its bi-component structure within the vertical gas compartments. Once two gases are mixed, there is no spontaneous tendency of the individual gases to de-mix. For example in case there would be such a spontaneous de-mixing, the more heavy carbon dioxide would replace the oxygen at the earth surface. However, it is a matter of fact that the gas mixture of the atmosphere changes for other reason in the height of some km above sea level. As such gases which have been mixed once do not tend to de-mix without being significantly supplied with energy from the external. The heat developed by the conductor current as well as the energy of the electric field do not form a sufficient supply of energy to the gas mixture which would support a spontaneous de-mixing of the insulating gas. On the other hand the heat developed by the conductor current gets transferred to the nearest volumes of the gas, increasing the temperature there and as such keeping the gas mixture in continuous movement which supports the permanent mixing. Considering the above, the gas compartment length of inclinated or vertical GIL installations is not determined by a tendency of the gas mixture to spontaneously separate into their components. It is driven by other factors such as the difference of the pressure due to the difference in height at the bottom and the top of the compartment.

Depending on the gas used (gas mixture or pure SF_6), the length of the vertical gas compartments varies in the range of up to 100 to 250 m.



Length of each section

Section A - B	25m
Section B - C	250m
Section C - D	23m
Section D - E	86m
Section E - F	20m
Section F - G	250m
Section G - 3	140m
Section G - 4	80m
Section P - Q	25m
Section Q - R	250m
Section R - S	19m
Section S - T	41m
Section T - U	38m
Section U - V	250m
Section V - 1	140m
Section V - 2	80m

Figure 3: Conceptional design of vertical GIL installation of about 500 m shaft height

7 Existing GIL in Structures

Split between special structures, made for the GIL, and shared structures (GIL with rail or road).
Status about exiting projects in structures.
Technical data, project explanation

GIL application with Bridge and Tunnel projects must start during the project planning sequence, once the decision is made later changes are almost impossible.

The GIL world installations amount today roughly to 150 km and the longest line length is 3.3 km even if much longer runs are under study [2]. The installations can be of three different kinds: tunnel or gallery ones, outdoors ones and directly buried ones.

Table 3 shows examples of characteristics of GIL installations in structures.

Table 3: Examples of existing GIL (Part 1)

<table>
<tr><th colspan="7">Examples of existing GIL (Part 1)</th></tr>
<tr><td>OWNER</td><td colspan="2"><i>Energie Ouest Suisse</i></td><td colspan="2"><i>RWE Net</i></td><td colspan="2"><i>Chubu electric power company</i></td></tr>
<tr><td>DATE OF COMMISSIONING</td><td colspan="2"><i>2001</i></td><td colspan="2"><i>1975</i></td><td colspan="2"><i>1998</i></td></tr>
<tr><td>INSTALLATION PLACE</td><td colspan="2"><i>GENEVA, Switzerland</i></td><td colspan="2"><i>WEHR, Germany</i></td><td colspan="2"><i>SHINMEIKA-TOKAI, Japan</i></td></tr>
<tr><td>TYPE OF INSTALLATION</td><td colspan="2"><i>TUNNEL</i></td><td colspan="2"><i>TUNNEL</i></td><td colspan="2"><i>TUNNEL</i></td></tr>
<tr><td>LENGTH OF LINK</td><td colspan="2"><i>420 m</i></td><td colspan="2"><i>670 m</i></td><td colspan="2"><i>3300 m</i></td></tr>
<tr><td>NUMBER OF SYSTEMS</td><td colspan="2"><i>2</i></td><td colspan="2"><i>2</i></td><td colspan="2"><i>2</i></td></tr>
<tr><td>NOMINAL VOLTAGE OF NETWORK</td><td colspan="2"><i>220 [kV] rms</i></td><td colspan="2"><i>380 [kV] rms</i></td><td colspan="2"><i>275 [kV] rms</i></td></tr>
<tr><td>HIGHEST VOLTAGE FOR EQUIPMENT U_M</td><td colspan="2"><i>300 [kV] rms</i></td><td colspan="2"><i>420 [kV] rms</i></td><td colspan="2"><i>300 [kV] rms</i></td></tr>
<tr><td>RATED CURRENT PER SYSTEM</td><td colspan="2"><i>2000 [A]</i></td><td colspan="2"><i>2500 [A]</i></td><td colspan="2"><i>6300 [A]</i></td></tr>
<tr><td>RATED FREQUENCY</td><td colspan="2"><i>50 [Hz]</i></td><td colspan="2"><i>50 [Hz]</i></td><td colspan="2"><i>60 [Hz]</i></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">INSULATING GAS</td><td><i>pressure absolut</i></td><td><i>0.7 [Mpa]</i></td><td><i>pressure</i></td><td><i>0.49 [Mpa]</i></td><td><i>pressure</i></td><td><i>0.54 [Mpa]</i></td></tr>
<tr><td>N_2/SF_6</td><td><i>80 /20 [%]</i></td><td>SF_6</td><td><i>100 %</i></td><td>SF_6</td><td><i>100 %</i></td></tr>
<tr><td>CONDUCTOR</td><td colspan="6"></td></tr>
<tr><td>OUTER DIAMETER</td><td colspan="2"><i>180 [mm]</i></td><td colspan="2"><i>150 [mm]</i></td><td colspan="2"><i>170 [mm]</i></td></tr>
<tr><td>WALL THICKNESS</td><td colspan="2"><i>5 [mm]</i></td><td colspan="2"><i>5 [mm]</i></td><td colspan="2"><i>20 [mm]</i></td></tr>
<tr><td>MATERIAL</td><td colspan="2"><i>Al alloy
EN AW 6101B
E-Al/MgSi0,5 T6 W19</i></td><td colspan="2"><i>E-AlMgSi0,5</i></td><td colspan="2"><i>Al alloy</i></td></tr>
<tr><td>IACS*</td><td colspan="2"><i>61 %</i></td><td colspan="2"><i>48-54 %</i></td><td colspan="2"><i>59,5 %</i></td></tr>
<tr><td>CONDUCTIVITY at 20°C $m/\Omega \cdot mm^2$</td><td colspan="2"><i>35.3857</i></td><td colspan="2"><i>27,84÷31,32</i></td><td colspan="2"><i>34,5185</i></td></tr>
<tr><td>RESISTIVITY at 20°C $\Omega \cdot mm^2/m$</td><td colspan="2"><i>0.02826</i></td><td colspan="2"><i>0,032÷0,036</i></td><td colspan="2"><i>0,02897</i></td></tr>
<tr><td>ENCLOSURE</td><td colspan="6"></td></tr>
<tr><td>INNER DIAMETER</td><td colspan="2"><i>500 [mm]</i></td><td colspan="2"><i>520 [mm]</i></td><td colspan="2"><i>460 [mm]</i></td></tr>
<tr><td>WALL THICKNESS</td><td colspan="2"><i>6 [mm]</i></td><td colspan="2"><i>5 [mm]</i></td><td colspan="2"><i>10 [mm]</i></td></tr>
</table>

MATERIAL	*Al alloy EN AW 5754 AL Mg3 W19*	*AlMg2Mn0,8*	*Al alloy*
IACS*	*52,565%*	*35 %*	*51%*
CONDUCTIVITY at 20°C m/Ω·mm^2	*30,4878*	*20,3*	*29,5858*
RESISTIVITY at 20°C Ω·mm^2/m	*0,03280*	*0,050*	*0,03380*
Connection method of enclosures	*welded*	*welded*	*welded*

IACS = International Annealed Copper Standard (IACS=100 % ⇒ Copper Standard Conductivity = 58,108 m/Ω·mm^2)

Table 3: Examples of existing GIL (Part 2)

Examples of existing GIL (Part 2)			
OWNER	*National Grid UK*	*Entergy*	*BC Hydro*
DATE OF COMMISSIONING	*2004*	*2001*	*1981*
INSTALLATION PLACE	*Hams Hall, United Kingdom*	*Baxter Wilson Power Plant USA*	*Revelstoke Hydro Power Plant Canada*
TYPE OF INSTALLATION	*Above Ground / Trench*	*Above Ground*	*TUNNEL*
LENGTH OF LINK	*545 m*	*1250 m*	*400 m*
NUMBER OF SYSTEMS	*1*	*1*	*2*
NOMINAL VOLTAGE OF NETWORK	*400 kV*	*500 kV*	*500 kV*
HIGHEST VOLTAGE FOR EQUIPMENT U_M	*420 kV*	*550 kV*	*550 kV*
RATED CURRENT PER SYSTEM	*4000 A*	*4500 A*	*4000 A*
RATED FREQUENCY	*50 Hz*	*60 Hz*	*60 Hz*
INSULATING GAS	*Pressure 1.03MPa N_2/SF_6 80/20 %*	*pressure 0.379 [MPa] SF_6 100 %*	*pressure 0.345 [MPar] SF_6 100 %*
CONDUCTOR			
OUTER DIAMETER	*512-520 [mm]*	*178 [mm]*	*178 [mm]*
WALL THICKNESS	*- [mm]*	*12.7 [mm]*	*12.7 [mm]*
MATERIAL	*Al alloy*	*Al alloy 6061-T6*	*Al alloy 6061-T6*
IACS*	*-*	*59.5%*	*59.5%*
CONDUCTIVITY at 20°C m/Ω·mm^2	*-*	*34,57*	*34,57*
RESISTIVITY at 20°C Ω·mm^2/m	*-*	*0,0289*	*0,0289*
ENCLOSURE			
INNER DIAMETER	*500 [mm]*	*508 [mm]*	*508 [mm]*
WALL THICKNESS	*6-10 [mm]*	*6.35 [mm]*	*6.35 [mm]*
MATERIAL	*Al alloy AlMg3*	*AlMg3*	*Al alloy 6063 T6*

IACS*	*- %*	*35.0 %*	*53.0 %*
CONDUCTIVITY at 20°C $m/\Omega \cdot mm^2$	*-*	*20,3378*	*30,797*
RESISTIVITY at 20°C $\Omega \cdot mm^2/m$	*-*	*0,0492*	*0,0325*
Connection method of enclosures	*Welded*	*Flanged*	*Welded*

IACS = International Annealed Copper Standard (IACS=100 % ⇒ Copper Standard Conductivity = 58,108 $m/\Omega \cdot mm^2$)

7.1 Tunnels

7.1.1 Wehr, Germany (Schluchsee)

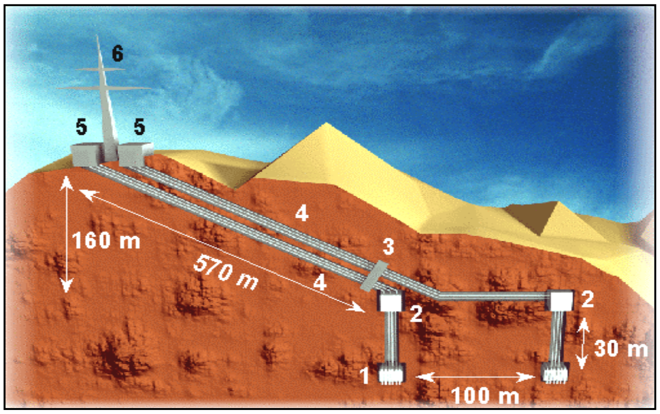
GIL technology was developed in the 1970's in parallel with the Gas Insulated Switchgear (GIS) for applications up to 800 kV. One of the first GIL installations was in the Black Forest in Germany, commissioned in 1975 at Wehr Pump-Storage Power Plant. This installation is still one of the longest 420 kV GIL connections all over the world and it represents an installation with a noteworthy inclination of the route.

Table 4: Ratings of Wehr, Germany (Schluchsee)

Rated voltage	420 kV
Lightning impulse withstand voltage	1425 kV
Rated normal current	2500 A
Short time-withstand current	35 kA, 1 s

The first GIL tunnel installation realises the connection of the pump storage power plant with the overhead 420 [kV] grid at Wehr (Black Forest in Southern Germany) (see Figure 4).

In the cavern (1) the generated energy is transformed to the high voltage transmission value of 420 kV and connected to the GIL. Following into a transfer cavern (2) encapsulated surge arresters limit the overvoltages. With transfer switches the GIL is then led into the tunnel with two three phase systems of 570 m length. The tunnel has a width of approximately 2 m and a height of 2.5 m. The GIL aluminium conductor and enclosure pipe sections of 18 m length are welded (4). See also small photo on the right. At the end of the tunnel open air surge arrestors (5) are limiting overvoltages coming from the connected overhead line (6).



MANUFACTURER	SIEMENS AG
1) 600 [MVA] Transformer	Rated voltage 420 [kV]
2) Encapsulated surge arresters	Rated current 2000/2500 [A]
3) Transfer switching units	Rated short-time current 35 [kA] (0,5 sec)
4) GIL connection	Rated impulse withstand voltage 1640 [kV]
5) Open air surge arresters	
6) Overhead line	

Figure 4: GIL double-circuit arrangement in Wehr tunnel (in service since 1975) (Siemens)

The GIL has been commissioned in 1975, after commission testing with rated impulse withstand voltage of 1640 kV. The total route length is 700 [m] and the total single phase length is (6×700) =4,2 [km].

The conductor is an aluminium alloy (E-AlMgSi0,5) pipe and its conductivity is 48÷54% of Copper Standard ($\rho_{20°C}$=32.4÷36.4 [$\Omega\cdot mm^2/km$]); the enclosure is an aluminium alloy (AlMg2Mn0,8) and its conductivity is 35% Copper Standard ($\rho_{20°C}$=50 [$\Omega\cdot mm^2/km$]). Figure 4 shows the double circuit arrangement in the above-mentioned tunnel. This is an example of the first generation GIL with pure SF_6 as insulating gas.

The operation of the GIL is in two ways: pumping by taking the energy from the overhead line system and generation of peak load energy by using the pumped water in the upper water lake. Since more than 30 years now this installation is now in service without any system failure. The revision of the GIL planned after 25 years of operation has been postponed for another 10 years to be checked then again if revision will be needed. The expectation is then under normal service condition also then a revision is not needed.

7.1.2 Geneva, Switzerland (PALEXPO)

Table 5: Ratings of PALEXPO, Geneva, Switzerland

Rated voltage	420 kV
Lightning impulse withstand voltage	1425 kV
Rated normal current	2500 A
Short time-withstand current	35 kA, 1 s

Another installation of 300 [kV] (operation voltage 220 kV) GIL in tunnel is in Geneva (see Figure 5; manufacturer Siemens AG). This is the world's first gas insulated high voltage transmission line of the second generation (i.e. insulating medium N_2/SF_6). This installation is in the outskirts of Geneva under the Palexpo exhibition halls.

MANUFACTURER SIEMENS	
Line 220 kV VERBOIS – FORETAILLE 1+2	
Max. short circuit current	50 kA, 3 sec
Lightning impulse withstand volt.	1050 [kV]
AC withstand voltage	460 [kV]
Route length	approx. 420 [m]
Total length (6x420m)	approx. 2.5 [km]
Gas volume per tube	approx. 84 [m^3]
Weight of SF_6 per tube	approx. 690 [kg]
Weight of N_2 per tube	approx. 560 [kg]

Figure 5: 300 [kV] GIL in a tunnel, PALEXPO

In 1999, the city of Geneva decided to construct a new hall at Palexpo, near the Geneva-Cointrin international airport. The presence of an overhead line (see Figure 6) linking Verbois to Foretaille constituted a major obstacle in the way of the future exhibition hall. An underground tunnel over a length of approximately 420 [m] between two towers was the solution chosen. The gas insulated line solution was preferred rather than another technology, because of its low magnetic interference level, its high transmission capacity and reduced heating effect (because of lowest power losses), as well as the capacity to be operated in a similar way to overhead lines (auto-enclosure). Erection of Palexpo GIL started in September 2000 and was completed within three months; the units were assembled into the tunnel. This GIL is in operation since February 2001 and replaces the overhead line between pylons 175÷176 (see Figure 7) and it is composed of 162 pieces of straight GIL-units each 14 [m] long.

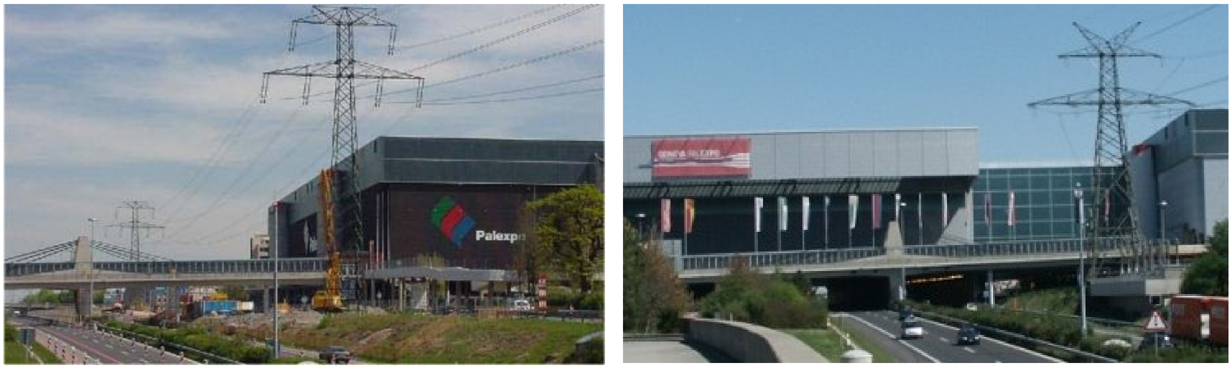


Figure 6: Span view to be replaced by an underground GIL and after the replacement

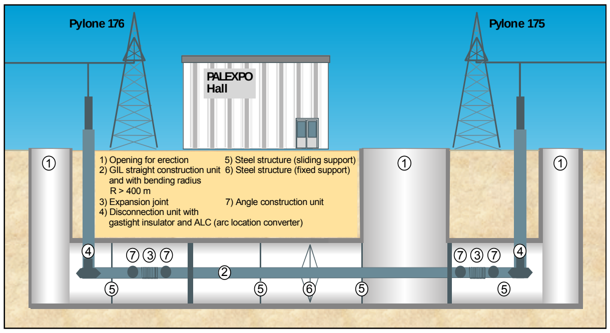


Figure 7: Sketch of OHL replacement

At both ends of the GIL, air to gas bushings close the GIL and form the connection to the overhead line (see Figure 8). Surge arresters are used at the GIL terminations. For monitoring and control of the GIL there are firstly a PD (partial discharge) UHF equipment to prevent insulation faults that can seriously damage the equipment and secondary equipment is installed for measurement of the gas density.

Figure 8: GIL connection to the overhead line

7.1.3 Shinmeika-Tokai Line

Table 6: Ratings of Shinmeika-Tokai Line

Rated voltage	275 kV
Lightning impulse withstand voltage	1050 kV
Rated normal current	6300 A
Short time-withstand current	50 kA, 2 s

Another very important installation is the Shinmeika-Tokai. The GIL route length is 3.3 [km] and the total length is 3.3×6=19.8 [km]. This transmission line connects a large-scale thermal power station (Shin-Nagoya power station named Shinmeika) with the Tokai substation. The construction was completed in February 1998 by CHUBU ELECTRIC POWER CO. The tunnel is constructed at a depth of about 30 [m] under public roads. It has four curves, with minimum radius of 150 [m] (see Figure 9). The tunnel with inner diameter of 5.6 [m] is divided into upper and lower storeys. Two GIL circuits are housed in the upper storey, and LNG pipes for supplying fuel to the power station are laid in the lower storey. The power transmission capacity of the line is currently 1300 [MW] without forced-cooling and will be increased up to 2850 [MW] when the tunnel will be cooled. The conductor is supported with epoxy insulators; insulating gas is pure SF_6 at a pressure of 0.44 MPa (first generation GIL). The unit basic element has a length of 14 [m] and the GIL is anchored by fixed support every 56 [m]. For the GIL characteristics, see Table 6.The distance between each thermal expansion-contraction section and gas section is 56 [m]. The following structure and installation techniques describe below have been specifically developed to joint as many as 1500 GIL units in a tunnel where space for assembly is limited and atmosphere is dusty.

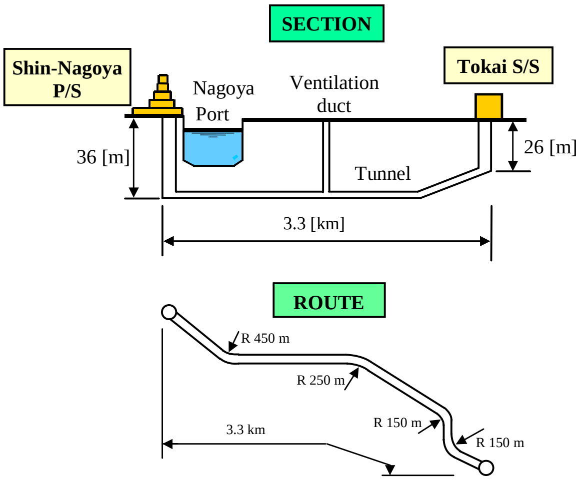
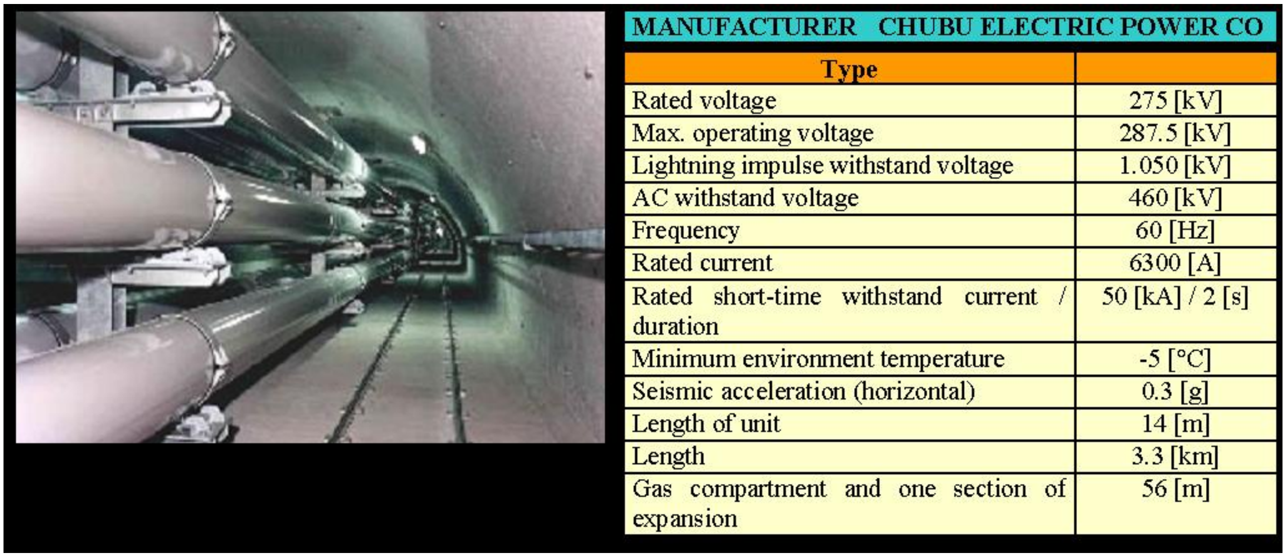


Figure 9: Section of Shinmeika-Tokai GIL (Chubu electric power CO)



MANUFACTURER CHUBU ELECTRIC POWER CO	
Type	
Rated voltage	275 [kV]
Max. operating voltage	287.5 [kV]
Lightning impulse withstand voltage	1.050 [kV]
AC withstand voltage	460 [kV]
Frequency	60 [Hz]
Rated current	6300 [A]
Rated short-time withstand current / duration	50 [kA] / 2 [s]
Minimum environment temperature	-5 [°C]
Seismic acceleration (horizontal)	0.3 [g]
Length of unit	14 [m]
Length	3.3 [km]
Gas compartment and one section of expansion	56 [m]

Figure 10: Shinmeika-Tokai Gas Insulated Transmission Line (Chubu electric power CO)

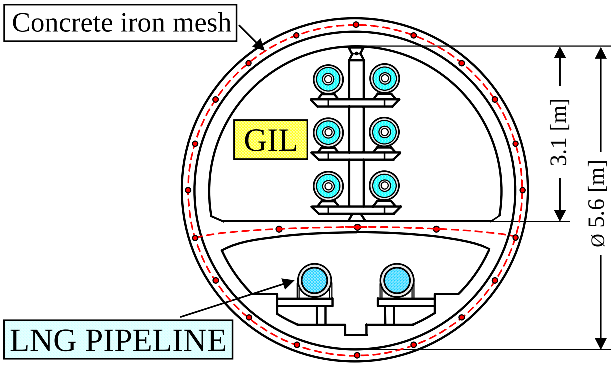


Figure 11: Cross-section of the tunnel (Chubu electric power CO)

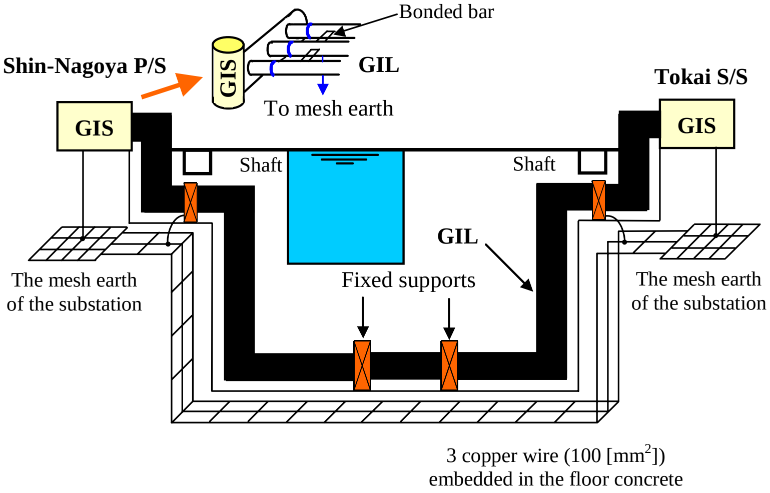


Figure 12: Grounding system of Shinmeika-Tokai GIL (Chubu electric power CO)

The grounding system of the Shinmeika-Tokai line is shown in Figure 12. An aluminium-bonding bar is used for interconnection of the enclosures. The enclosures are systematically bonded together and with the steel reinforcement of the gallery at very short length intervals; this ensures equipotentiality between the tunnel wall and the GIL enclosures and constitutes a very good distributed earthing; moreover, the steel reinforcement is solidly connected at both ends of the GIL with the mesh earth of the substation. This ensures that inside the gallery touch voltages are zeroed even during a single-phase fault. The GIL is fixed to supporting structures at intervals of 4 units (56 [m] length, see Figure 13), which constitutes one section for expansion absorption. The length of one section for expansion absorption is such that thermal expansion and contraction of the enclosure and conductor and the displacement due to an earthquake with an acceleration of *0,33* [g] can be absorbed by bellows and plug-in contacts respectively. These bellows and contacts are designed to have large strokes of movement so that errors in support mounting, in unit manufacturing, and in unit jointing at site can be absorbed. The *56* [m] unit section for expansion absorption mentioned above is identical to a gas compartment for gas treatment and for gas sampling in case of accidents. Gas pressure is monitored for three gas compartments, *168* [m] in length with fibre-optic gas density sensor. Each phase has *20* gas compartments, so *120* sensors are needed in this system. Six optical fibres, one for each GIL phase, are used for monitoring sensors. No rupture disk and relief valve are adopted because the gas volume in a gas compartment is large enough to make a pressure rise negligibly small due to a line-to-ground arc fault.

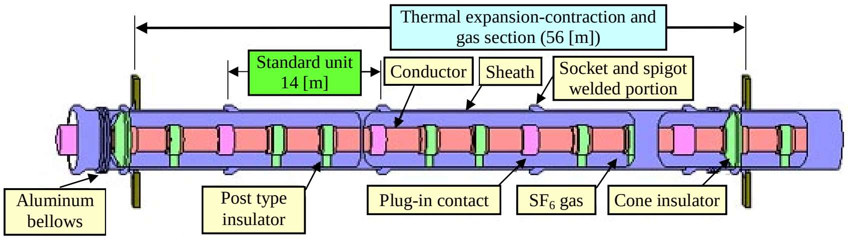


Figure 13: Basic layout (Chubu electric power CO)

7.2 Above Ground / Trench

7.2.1 Hams Hall

Table 7: Ratings of Hams Hall GIL

Rated voltage	420 kV
Lightning impulse withstand voltage	1425 kV
Rated normal current	4500 A
Short time-withstand current	63 kA, 1 s

As part of a project to reinforce the UK transmission system in the West Midlands area, National Grid needed to complete a connection at 400 kV between the final tower of an overhead line circuit and a new feeder bay at the far end of the associated substation. The route of the connection crosses a number of incoming overhead line circuits and a solution using conventional cables or GIL was sought. The continuous current rating for the circuit of 3190 A would have required the use of two cables per phase and, in this particular application, GIL was found to be the more economic solution.

The connection is around 545 m in length, approximately half of which is located within the substation boundary and the remainder on land owned by National Grid external to the substation. Within the substation, the GIL is installed above ground with the axes of the three phases arranged vertically one above the other. Outside the substation, the GIL is laid in a concrete trench in horizontal flat formation and protected by trench covers. The GIL is terminated at both ends with standard gas to air bushings.

The basic design of the GIL has been described in [57]. The enclosure lengths were joined on site using an automated orbital welding process. The conductor lengths were joined by means of plug in connectors. The insulating gas is a nitrogen based gas mixture at a pressure of 10.3 bars absolute. The enclosures are solidly bonded at both ends and at the mid point of the GIL and are earthed at intervals along the length. The GIL is provided with an electronic gas density monitoring system and UHF couplers to permit partial discharge monitoring. The GIL ratings are summarised in Table 7.

The GIL was commissioned in November 2004.

Figure 14: Transfer point above ground to trench installation

Figure 15: Above ground installation inside the substation

7.3 Bridges

7.3.1 Ecoelectrica Penuelas Power Project

Figure 16: 362 kV GIL , nominal voltage of 230 kV and continuous current of 3000 Amps

As part of the construction of a new power plant in Puerto Rico, the clients Prepa/Enron needed access a new overhead line located across another transmission corridor, under existing overhead lines and across a river bed area from the substation.

One obstacle was how to cross over the environmental sensitive area containing the dry river bed. The existing soil conditions prohibited under ground installation below the river bed while existing overhead lines prohibited use of standard over head line connections.

To resolve this issue the design team opted to cross the river bed utilizing 362 kV GIL installed on a specially designed truss bridge. The truss bridge was constructed to hold the GIL run from the station out to where the line could be terminated to the overhead line connection as shown during the construction period.

The use of bridges has many applications within the architecture of infrastructure e.g. gas pipelines, water pipelines, railways, voltage lines, and roadways. In this instance the requirements and limitations of the project do to overhead line clearances and a wetland crossing made the case for the construction of a bridge to support the GIL as the most feasible application. The application of a utility bridge is shown in the above Figure.

In determining GIL routing of this nature several possibilities should be considered, for example bridge availability and proximity to the GIL crossing, cooperation with municipalities in providing right of away for GIL on pre-existing bridges and the maximum allowable bridge loading limits for a pre-existing bridge prior to GIL loads.

To consider pre-existing bridges also provides new obstacles to consider. The bridge may not be easily reached with the planned routing for the transmission corridor. Rerouting of the corridor needs to be planned in the early stages to avoid costly extensions to the intended route.

With older bridges it will also necessitate a comprehensive mechanical analysis of sustained, occasional and expansion load cases for the structural design of the bridge and GIL to ensure the added weight is within the limits of the load factors, but also interaction between the bridge and the GIL is coherent when additional factors are involved, i.e. railway & roadway traffic vibrations and thermal expansion & contraction of bridge sections and GIL zones.

Requirements that should also be considered are maintenance provisions for access to GIL when repair work becomes necessary following an internal failure and installation considerations for easy of installation.

One fundamental problem is the ownership of installations on other infrastructure like bridges, as they may be operated and regulated under different guidelines and operated by multiple utilities.

In many cases the alternative is to completely separate the ownership of the two systems but coordinate the overall design, load analysis and installation between the two owners to assure the integrity of both systems is maintained.

7.4 Total GIL Installations World-wide

GIL is widely used in high voltage installations world-wide. Most applications are in substations, power plants or with some specific problem of crossing lines or hydro power plants.

In Table 8 the added length of GIL installed world-wide in all high-voltage levels is given. A GIL is then counted when the purpose is power transmission only without any switching element as it is usually used in GIS.

Table 8: GIL applications world-wide, status year 2000

Ur kV	Cumulated length m
1200	420
800	1200
550	52.650
420	63.600
362	10.107
242/300	32.900
72/145/172	37.100
73 to 1200	198.000

8 Specification Rules

8.1 Requirements to Structures

GIL needs 3 pipes per each electrical system. Usually two systems are used, that means a total of six single pipes. Also a 4 pipe system, with one pipe as a reserve, can be used.

Each pipe has a diameter of appr. 500 mm. The total weight including anything (conductor, gas etc.) of a single pipe for 400kV and 3150 A is appr. 30 kg/m.

The elastic bending radius is 400 m. Smaller curvatures can be done by prefabricated elbow elements. The distance between fixing points on the tunnel wall is appr. 25 m.

The thermal expansion of a GIL pipe depends on the temperature differences during operation. With a thermal heat up from 20°C to 60° C the thermal expansion of a 400 m long section is appr. 200 mm.

The configuration of a 3 pipe system and the minimum distance between each pipe depends only from maintenance logistic and repair equipment.

The corrosion protection of the Al-pipes needs to be adapted to the requirements along the tunnel. Permanent water penetration in contact with minerals e.g. chlorides needs to be avoided. Safety measures are passive corrosion protection e.g. painting, coating, water protection roofs and/or active corrosion protection. Also the chemical composition of the shotcrete for the primary tunnel lining should to be specified to prevent corrosion effects.

The sensitivity of the GIL toward vibration from rail or road traffic is low. Vibrations from sources around the GIL installation may be damped by the support structure using of dampers, if needed.

If a GIL is laid on a bridge where permanent swing from traffic and wind forces applies the vibration values need to be specified.

If the GIL is laid in a separate tunnel (pilot tunnel) then there is no vibrational influence from the traffic tunnel.

Tunnels with GIL-systems in seismic active regions have to reinforce the fixing points to avoid displacements of the pipes. In highly active zones, where displacements of the tunnel itself can not be excluded, flexible tunnel cross- and longitudinal sections may be installed.

The electric and magnetic fields in the vicinity of the GIL are negligible. Due to the solid grounding of the enclosure the electric field is practical zero, and to the induced current in the enclosure the magnetic field in the surround of the GIL is low.

There are no acoustic noises coming from the GIL.

The grounding of the GIL to limit touch voltage needs to be planned with the structure. In the case of a tunnel the GIL grounding shall be connected with the wire mesh. Special attention needs to be paid on the connecting points at the ends, and when other infrastructure is getting close e.g. railway, Gas pipelines and medium voltage lines.

Although GIL requires little maintenance provisions need to be made for access when repair work becomes necessary following an internal failure. The repair time includes not only the direct repair work on a pipe but also the time for gas handling (taking out the gas, storage and refilling).

In the case of very long tunnel structures the transport time from the tunnel entrance to the working place inside the tunnel and retour can be very decisive for the total repair time. To reduce time for transport and also for safety reasons the transport is done normally on rails. See clause 11.4.

Repair work requires access for gas handling equipment and gas storage containers. A replacement section of GIL will be installed and pressure and dielectric tests will be performed. The safety issues associates with performing the pressure test in the vicinity of shared services must be managed and consideration must be given to how the high voltage test equipment will be connected. In order to return the GIL to service within a short period, gas handling plant and spare components must be available. See clause 11.

Existing tunnels always have strong obstacles against adding a GIL: space, responsibility, ownership, maintenance, safety, fire protection, cooling, and heat

Although GIL requires little maintenance, provision needs to be made for access in the event that a repair following an internal fault becomes necessary. The implications for any shared structure must be considered.

Safety distances around the GIL structure are not needed when the GIL is sufficiently grounded, therefore it is also possible to work in the GIL structure without restrictions The GIL installed in a tunnel or on a bridge is usually only accessible by instructed experts.

8.1.1 Seismic

Underground structures (tunnels) are very stable buildings in relationship to the seismic impact of earth quakes. Normally only minor damages are reported from tunnels even in the case of highly energetic earth quakes. Damages are concentrated near the portals, especially along the contact of loose material to the rock surface, due to earth quake induced land slides or rock fall.

Special tunnel design is required, if the tunnel alignment crosses an active fault zone with creep movements. This extraordinary situation is found p.e. along the San Andreas Fault in California or along some fault zones in the Himalaya and the Andes. In such cases the tunnel is designed like a flexible tube with segmented lining to resist the creep movements almost longer.

The same design principles are used for tunnels in unstable soil conditions.

In any case the GIL must be planned and executed flexible between the fix points.

8.1.2 EMF

The growing public concern of possible harmful effects caused by human exposure to electromagnetic fields in the 50-60 Hz (extremely low frequency fields) and the difficulties in assessing, or excluding, the risk associated with long term low level magnetic field exposures, has led several national (Italy, Switzerland, etc) bodies to set on prudentially restrictive limitations on the permitted exposure levels, with particular emphasis on the magnetic field component.

GIL has a low external magnetic field due to the high screening effect of enclosures in which (see Appendix A) can flow opposing currents almost equal in magnitude but opposing in phase angle to those of phase conductors.

Because of the grounding of the enclosures at both ends the induced current in the enclosure has about the value as the current in the conductor which is 180° phase shifted due to the inductive law. The superposition of both currents results in a very low magnetic field outside the GIL.

With regard to GIL and structures, this feature is of paramount importance.

In fact, the lowest external magnetic fields ensure high electromagnetic compatibility with other neighbouring systems even if with a great proximity. This is the very case of close presence of other devices (sensible to magnetic disturbances).

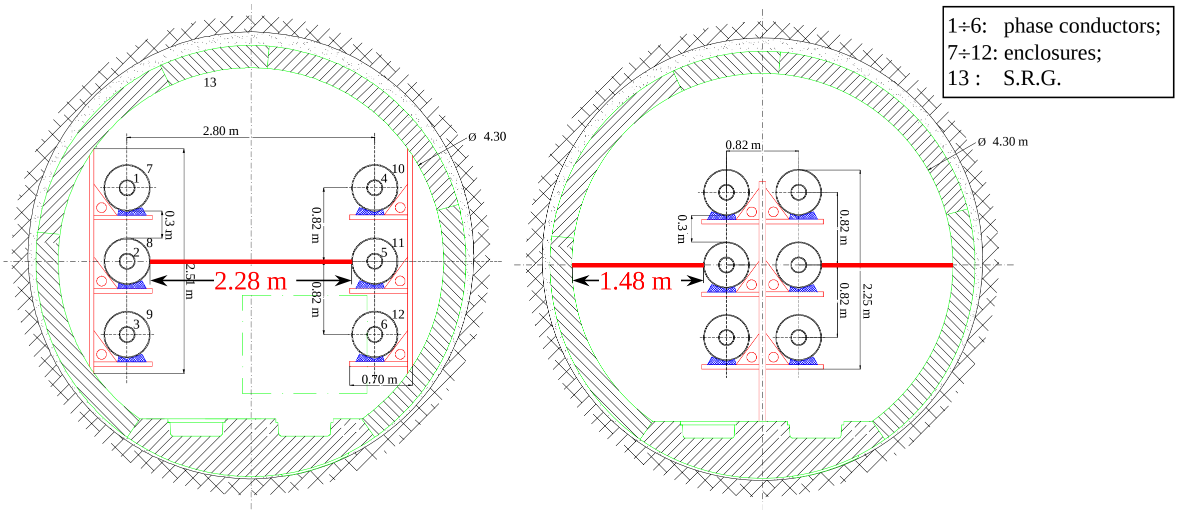
Furthermore, GIL solution can play a key role when the transmission line installation requires extremely low magnetic field levels i.e. in sensible zones, for EMC apparatus immunity or in Countries with highly restrictive magnetic field Laws.

In the following in order to give an idea of the very good intrinsic screening effect of GIL, a double-circuit GIL arrangement in dedicated tunnel is presented.

The vertical arrangement can be performed with the two circuits very close each other or with the two circuits diametrically opposing.

The former can be named "compact-placed arrangement" (CPA) on the contrary the latter "distant-placed arrangement" (DPA).

Figure 17 shows these two different kinds of vertical installations. The investigated GIL characteristics are reported in Appendix A.



DISTANT-PLACED ARRANGEMENT (DPA) COMPACT-PLACED ARRANGEMENT (CPA)

Figure 17: Possible arrangement installations of double-circuit GIL

It is worth remembering that the enclosures should be systematically bonded together and with the steel reinforcement of the gallery (S.R.G.) at very short length intervals; this ensures equipotentiality between the tunnel wall and the GIL enclosures and constitutes a very good distributed earthing.

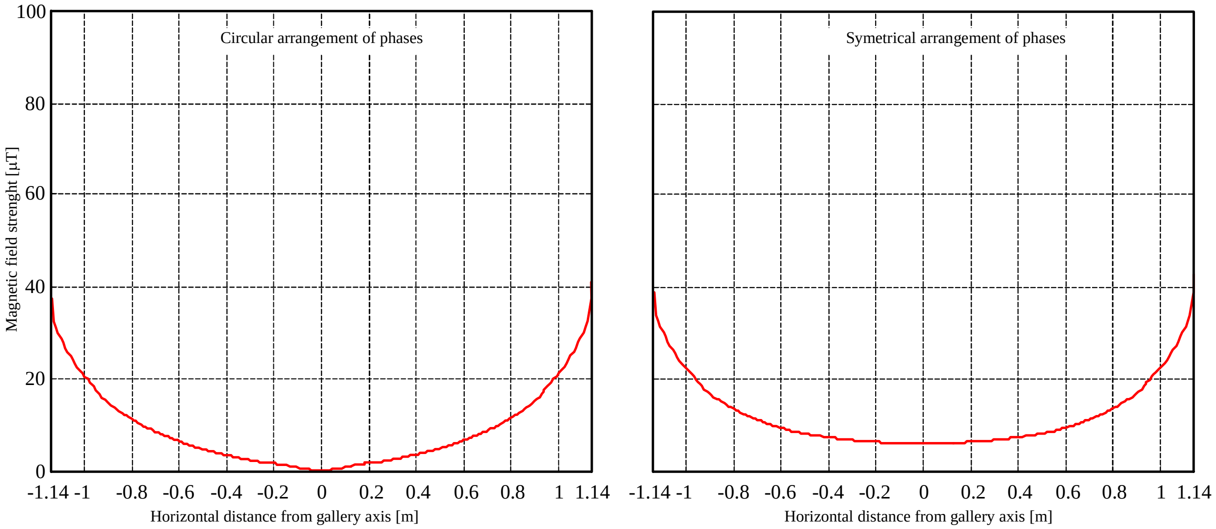


Figure 18: Magnetic field strength inside the tunnel in the zero position of the vertical axis when at total load of 2000 MVA is transmitted via two GIL.

8.1.3 Grounding

The important aspects of grounding for GIL can be illustrated by using the example of the Geneva Palexpo installation. The GIL site is located in a very dense zone of activities, including the exposition centre as well as the Geneva international airport, a railway station and an important highway. The ground network of all these elements is connected and it was practically impossible to galvanically insulate the GIL from the other infrastructures. Figure 19 presents the principle of the grounding scheme installed

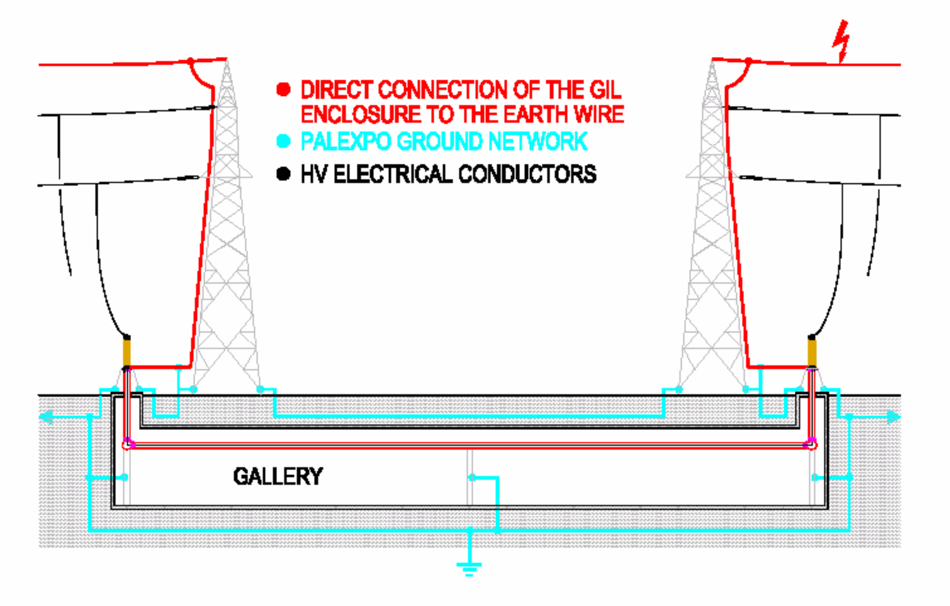


Figure 19: Grounding realisation principle

Each phase of the GIL enclosure is rigidly connected to the local ground network at both extremities and along the gallery. The overhead-to-underground transition substation equipments (outdoor bushings, surge arresters, steel structures) are also grounded and for security reasons for the personnel, special attention was given to the connection of the fences. Therefore, in order to ensure an optimal flow of any possible fault current, the GIL enclosure is directly connected by a cable to the earth conductor of the transmission line, at each end of the underground section. To prevent the ground potential from reaching an unacceptably high value in the event of a fault and excessively high currents flowing into the local ground network, the transmission line earth conductors were replaced with conductors having a larger cross-sectional area. Post commissioning ground measurements undertaken on site confirmed that the maximum values satisfied the design specification of the grounding scheme.

8.1.4 Requirements to Secondary Equipment

Precautions shall be taken to prevent adverse environmental conditions, like moisture causing corrosion.

8.2 Tunnel

In its normal state, SF_6 is non-toxic. However, in common with other gases, if released in a confined space such as a tunnel it can cause oxygen depletion and the associated risk of suffocation. Control measures such as provision of forced ventilation to ensure that the oxygen level remains sufficient in the event of a release of gas should be considered.

As described in section 6.4, GIL has a natural flexibility that allows it to follow the curvature of a tunnel route down to a radius of curvature of about 400 m without difficulty. Where the radius of curvature is significantly less than 400 m, special angled sections may be used. It is often convenient to assemble the GIL at a shaft location, where more space is available and welding fumes may more easily be extracted. The enclosure lengths are welded at the shaft position and the assembled GIL is advanced into the tunnel as each new enclosure joint is completed. Since it is not possible to feed the assembled GIL past a bend with low radius of curvature in this way, at such a bend the GIL must be assembled at its final position.

The environment of GIL installation can bring water or water steam in contact with enclosure aluminium (or aluminium alloy) causing possible corrosion.

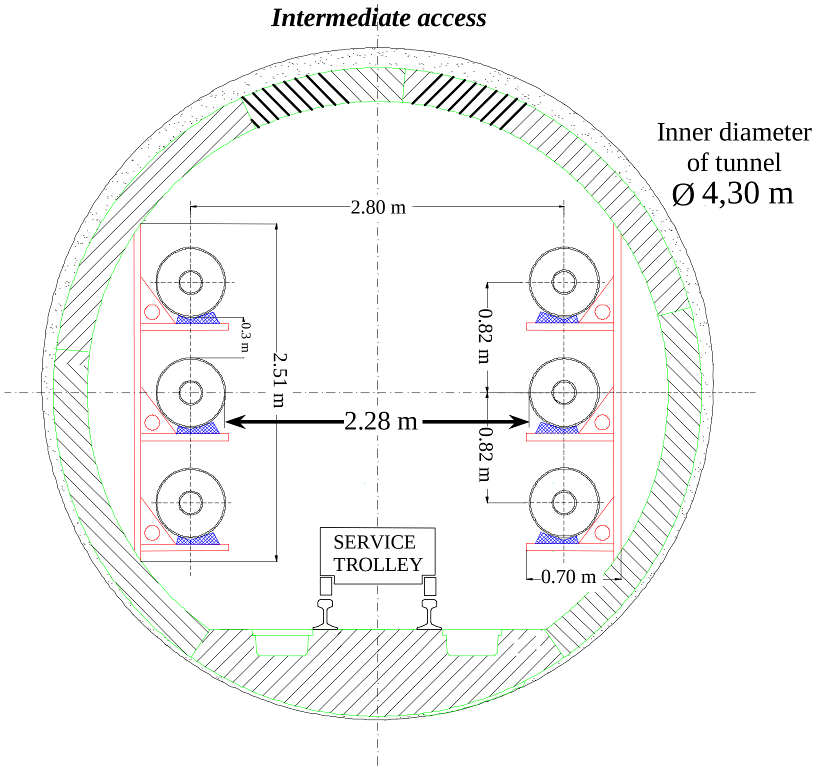
By virtue of the fact the expected lifetime of a transmission line is rather long (e.g. 30÷40 years), the behaviour of aluminium alloys exposed to environmental water deserves a very careful consideration.

The scientific literature on chemical and biological behaviour of aluminium products following exposure to environmental media is wide and comprehensive. The literature agrees on this fact: the formation of oxide layers on aluminium and its alloys has a protective function. Due to this protective layer, aluminium products are not significantly corroded under environmental conditions (pH 4,5 ÷ 8,5), unless corrosion takes place through localized formation of elements caused by chemicals and natural substances.

Ventilation, humidity, temperature, leaking of insulating gas management, non burn able, and non toxic insulating gas, repair concept after internal fault, explain the type of gas (usually if the word gas is used then natural gas is meant, which is highly burnable), tolerances of tunnel dimensioning (diameter, straight alignment, gradient), bending radius (400m), elbow elements, possibility to follow the route, power supply, transportation of spare parts,

Out of these requirements the minimum space for long tunnels can be determined. See Figure 17.

Inside service tunnels of long structures in certain distances e.g. each 500 m or 1000 m widening e.g. technical caverns directional changes of the GIL are needed, which may done by elbow elements.



Pilot tunnel with double-circuit GIL

Figure 20: Typical tunnel arrangement

8.2.1 The Use of Tunnel Structures for GIL

If a GIL is planned underground it will be necessary to use a tunnel structure. Principally there are two possibilities:

- Using existing tunnels

- Building new tunnels

Existing tunnels:

Most of the tunnels are used for road and railway traffic, water transport and pipelines (oil and gas). Due to safety reasons long tunnels for public affairs are planned in a two tube system. In the case of emergency one tunnel tube can be used as a rescue tunnel, where travellers can be evacuated safely.

The use of GIL in a tunnel tube with regular road or railway traffic should be excluded due to safety reasons when installed in the same tunnel. In the case of a traffic accident, the GIL can be damaged severely, and also the consequential damages are to be considered.

As an alternative, separation in the tunnel of physical compartments could be used.

But normal maintenance or repair work on a GIL in the segmented tunnel should not affect the traffic.

Therefore also problems of legal rights exist, if a tunnel is used multipurposely by two or more owners with different interests, see WG B1-08. As a consequence the chance to use existing tunnels for a GIL is small and more or less only restricted to tunnels out of operation.

New Tunnels:

The building of new tunnels respecting the special requirements of a GIL would be the best technical solution, but also the most expensive. To reduce costs it could be a good compromise, if the new built GIL-tunnel has also the function of a pilot or exploratory tunnel for other tunnels (traffic tunnels) to investigate the geological and hydrological situation in advance to minimize their risk of costs. The main problem in such a case is the coordination of time and interests of the two owners.

8.2.2 Specific GIL Tunnel Bored or Excavated by Drill and Blast Method

For tunnels with circular profiles due to static requirements (p.e. pressure tunnels for hydroelectric power plants or traffic tunnels in groundwater conditions) tunnel boring machines (TBM) are widely used.

Under favourable rock conditions TBM can be very effective. Daily advancement up to 100 m and more are reported. If the TBM must pass fault zones or any other unstable ground conditions the performance is reduced dramatically.

Under such circumstances the conventional drill and blast method could be the only excavation method to overcome such difficulties. Drilling and blasting can be adapted to the local ground conditions, to different tunnel profiles and to tunnel alignments with sharp bendings.

To stabilize the rock mass after excavation the so called New Austrian Tunnelling Method (NATM) is a very effective and economic method. Shotcrete, reinforced by wire mesh, steel arches and anchors, is sprayed immediately after excavation on the rock surface. This primary shotcrete lining reduces the danger of rock fall, stabilizes the rock mass and reduces the concentration of stresses. If necessary a secondary shotcrete layer can be installed to increase the stability of the rock mass.

Figure 21 shows a tunnel boring machine (TBM) used to bore round tunnels. For traffic tunnels the level below about one third of the tunnel is filled to provide a platform for roads or rail tracks. The space could be used for one or two GIL systems.

Figure 21: Tunnel boring machine

Figure 22 shows the Innsbruck Nordumfahrung Tunnel is a double track tunnel. This tunnel is built using drill and blast excavation techniques, which is called the ‘New Austrian Method’.

Figure 22: Innsbruck Nordumfahrung Tunnel, Austria, double track rail tunnel

8.2.3 Specific GIL Tunnel in Open Excavation (Gallery)

In the case that the GIL must not be laid too deep under the surface (till five meters), it could be an advantage to dig an excavation from the top instead to drill a tunnel. The excavation is concreted and covered in order to build a gallery. Additional access openings are used to bring in several straight units, angle units, disconnection units and compensator (expansion joint) units. The Figure 23 shows a typical square shape for a two systems line, the inner dimensions are 2.6 m wide and 2.4 m high.

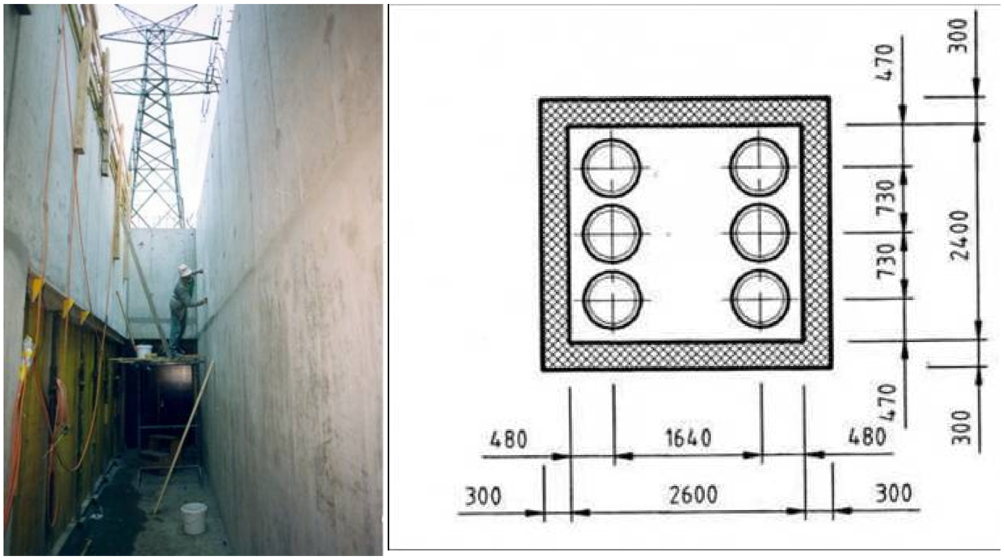


Figure 23: Square gallery of Geneva (in construction and dimension [mm])

8.2.4 Road Tunnel

The profile of street tunnel is typically a half circle. For traffic tunnels the level below about one third of the tunnel is filled to provide a platform for roads or rail tracks. The space could be used for one or two GIL systems.

Another possibility is to tie the GIL to the ceiling of the tunnel when separation is practical.

Influences coming from traffic in the tunnel such as dust, pollution from cars or trucks have no dielectric effect on the GIL because of a complete enclosure of metallic aluminium pipes. It might have an impact on long term thermal characteristics requiring cleaning.

Vibrations from road traffic should be considered in the GIL design and the fixing method in the tunnel.

For maintenance it is not necessary to interrupt the traffic or to cause long delays. The GIL needs little routine maintenance; most can be done by remote control and visual inspection on site.

Tunnel or GIL washing should not affect the GIL performance since it is a completely closed enclosure. Only continuous water impact to the aluminium enclosure needs to be avoided to prevent corrosion.

Traffic management, cost impact and revenue compensation for GIL maintenance should be planned in advance.

Driver uneasiness, effects to eyes or epileptic effects for persons using the tunnel need to be considered and visual measures may be needed.

Electromagnetic compatibility (EMC) of the GIL towards the traffic and traffic control systems needs to be studied. Because of the solid grounded metal enclosure of the GIL the interferences are very low. For the same reason disturbances to electronic equipment in the tunnel coming from the GIL and influences of wireless installations in the tunnel to the GIL are not critical.

Figure 24 shows a two lane road tunnel at Laerdal in Norway. This tunnel is in a half cycle form excavated into the rock. It can be used to insert a GIL on the ceiling with separation.

Figure 24: Laerdal Tunnel, Norway

Figure 25 shows a tunnel with two lanes connecting Tirol to Vorarlberg in Austria. The tunnel is relatively straight, typical for road tunnels, with slight bending at the ends. The GIL could be fixed on the tunnel ceiling with separation.

Figure 25: Arlberg Road Tunnel between Tirol and Vorarlberg, Austria

8.2.5 Railroad Tunnel

Railroad tunnels are an excellent chance to be combined with GIL. In a single tunnel system with two tracks or a double tunnel system with one track in each tunnel or a pilot tunnel the GIL can be added when segregation can be achieved.

The GIL is a closed system where the high voltage part has no direct contact to the surrounding. The solid enclosure of the GIL also protects the tunnel from impact of the GIL even in the case of an internal arc.

The potential for stray DC currents of the electric rail system needs to be considered, to prevent electrolytic corrosion. The electrical interferences coming from the train are shielded by the grounded metallic enclosure of the GIL. The same shielding is active toward the electric power supply of the trains with DC, 16 1/3 Hz, or 50 Hz systems.

Vibrations coming from the rail traffic can be damped by the steel structure and dampers. The profile of the tunnel allows the use of GIL on the side, the top, or the bottom, depending on the space and the possibility of segregation.

The pollution coming from the train breaks does not affect the GIL, because of the complete enclosure.

The heat from trains and GIL in the tunnel should be part of the project engineering evaluation. A heat transfer calculation needs to be completed.

A coordination agreement for GIL maintenance in conjunction with train traffic and train operation schedule is needed. The GIL needs very little maintenance because of its complete enclosed electrical system. The GIL has no active parts which need continuous maintenance.

Railroad traffic management, cost impact and revenue compensation for GIL maintenance should be planned in advance. The safety issues concerning track closure and the decrease of rail capacity should also be considered in the case of an exchange of a piece of GIL in the tunnel. This repair concept is also part of the project engineering.

Electromagnetic compatibility (EMC) of the GIL towards the rail traffic and rail traffic control systems needs to be studied. Because of the solid grounded metal enclosure of the GIL the interferences are very low. For the same reason disturbances to electronic equipment in the tunnel coming from the GIL and influences of wireless installations in the tunnel to the GIL are not critical.

The grounding concept of the GIL is to have as often as possible low impedance connections to ground potential. Therefore, the GIL enclosure, the steel structure, the steel reinforcement of the tunnel and the grounding rods in the soil are used to form a distributed earthing system.

Step and touch potential are therefore also low because of the distributed solid grounding. A check of the grounding resistance is required.

For communication purpose the tunnel can be used by wireless systems without disturbing the GIL.

Figure 26 shows the view into the Gotthard railroad tunnel under construction. The front area is made for two railroad tracks which are running into separate tunnels in the back. The GIL could be fixed to the ceiling, the side or the bottom when segregation is possible.

Figure 26: Gotthard Tunnel, Switzerland, double rail track tunnel

In Figure 27 the Seikan tunnel in Japan is shown. This tunnel runs under the Ocean to connect the island of Honshu with Hokkaido in Japan. Here also a GIL could have been added on the side or the ceiling when segregation is possible.

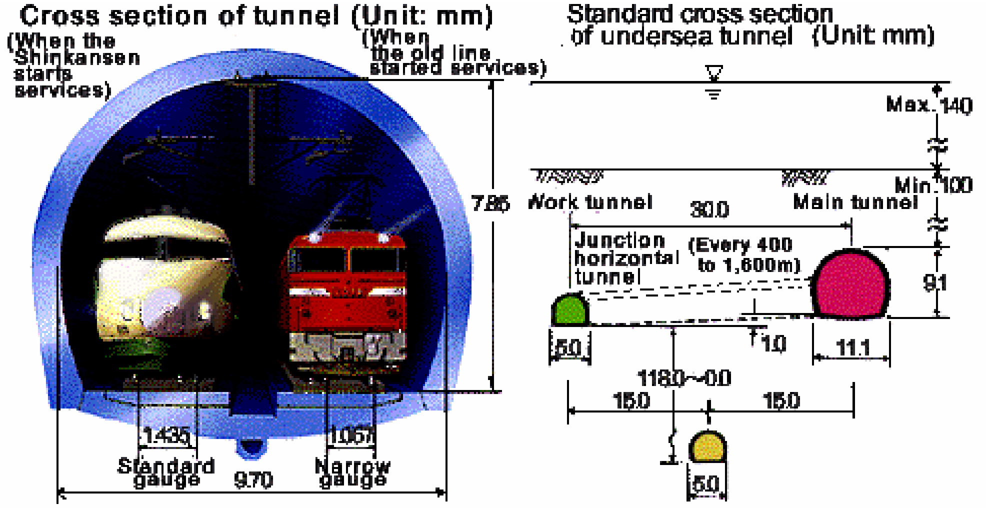


Figure 27: Seikan Tunnel, Japan, under the sea: Honshu-Hokkaido

In Figure 28 a double track railroad tunnel is shown as built in Brixlegg, Austria, to cross the river Inn. In this tunnel a GIL may also be placed on the roof, sides, or bottom when segregation is possible.

Figure 28: Railroad tunnel of Unterinntaltrasse Brixlegg Tirol, Austria, a double track railroad tunnel

8.2.6 Rescue Tunnels

Consideration will need to be given to how the GIL sections are to be introduced to the tunnel, assembled and tested.

The welded enclosure joints must be subjected to a routine pressure test. Since a hydraulic test is not possible, a pneumatic test must be performed and the safety issues associated with the stored energy during the test must be managed. Safety measures might include exclusion zones for personnel and protection of adjacent equipment from any disruptive failure.

Following assembly, the GIL will be subjected to a site dielectric test. Means of connecting the high-voltage test equipment to the GIL will need to be considered. The maximum capacitive load that the generator can provide might impose a limitation on the maximum length of GIL that can be tested and consideration may need to be given to dividing the GIL into electrically isolated sections.

Tunnel diameter, access, dimensioning of support structures (gas pressure, mechanic), elbow element, space for disconnecting unit, vibrations from rail traffic, profile of the tunnel, position of GIL tubes in the tunnel, pollution from service traffic, maintenance issues (not to influence the traffic), co-ordinate the maintenance of rail and GIL, safety issues (who the people can get out), electro-magnetic compatibility, structure to be used for earthing (distributed earthing, touch voltage, coordinate with B1-08 Ken Barber), electronic influences, wireless communication (radio telephone), gas handling in the tunnel, power supply, transportation of spare part,

In case of emergency in the train tunnel the service tunnel must be useable for rescue activities (switch off the power), separation of GIL might be needed, long tunnel need a service road (larger diameter), influences to the tunnel use coming from maintenance work, access to the GIL,

Pilot tunnel is sold to grid operator after completion, the service tunnel is the same as special GIL tunnel, see 8.1.2.1

Rescue tunnels might possibly be used for GIL if the safety requirements of the people and rescue teams e.g. fire fighting cars, emergency medical cars can be satisfied.

8.2.7 Service or Pilot Tunnels

Pilot tunnels, which are not used later for rail traffic, are the best use for GIL.

Service or pilot tunnels are usually needed for the time of the construction of the tunnel and after that they are not or only partly needed.

These service and pilot tunnels offer a good opportunity to insert a GIL when planning the use of the service tunnel is done well in advance with the tunnel planning itself.

In Figure 29 a supply tunnel is shown. This tunnel gives access during the building period and can be used for GIL after the completion of the tunnel.

Figure 29: Service or pilot tunnel

8.3 Bridges

In the following some examples are given for bridges of a certain type. This is not because there are projects or plannings of the mentioned bridges are already on the way, it is only to explain the possible GIL installation on such a type of bridge. The types considered are:

- steel grider bride

- suspension bridge

- steel bow bridge

- steel multistructure bridge

To consider using a bridge for GIL it is recommended the GIL be incorporated into the planning of the bridge design.

The use of existing bridges for GIL needs evaluation of the initial bridge design to accommodate the additional GIL requirements.

The weight of the GIL is about 30 - 50 kg per metre per phase. This weight is low in comparison to the carrying capability of a bridge and should not be a limitation to the bridge construction but needs to be considered in the bridge design.

The enclosure needs to be fixed to the bridge only in relatively long distances (e.g. 10 - 20 m). The mechanical withstandability of the enclosure allows such long distances of the fixing points. The total weight to be taken by the fix points is mainly the weight of the length of 10 - 20 m GIL which is 300 -

1000 kg. Vibrations coming from the bridge to the GIL should be considered critical because of the rigid design consisting of aluminium pipes, epoxy resin insulators and insulating gas. The vibrations can be dampened by the design of the steel structure and fixing points. To prove the long term stability a fatigue analysis is required. See 6.2.

Accessibility of the GIL shall allow visual inspection and in case of a repair the exchange of a section. In normal service the GIL needs no frequent service and checks by operation personnel.

In service the bridge and GIL will expand and contract, due to temperature changes. Thermal expansion units of the GIL will take care of these movements. Only little impact by the friction of the movement of the GIL will affect the bridge. Safety regulations concerning the GIL will take care that even in case of an electrical failure in the GIL no critical impact is affecting the bridge. The forces coming from the electromagnetic field during operation (short circuit currents) are taken by the steel structure, and in case of an internal electrical fault the metallic enclosure prevent influences to the surrounding. To prove the functioning of bridge and GIL thermal expansion a fatigue analysis is required. See 6.2.

Ambient conditions like wind and ice load, solar radiation, seismic conditions, high humidity, and ambient temperature are service conditions as defined in IEC 61640 that are considered in the design of GIL applications. The effects of these ambient conditions need to be considered as part of the bridge design.

8.3.1 Motorway Bridge

Modern motorway bridges are usually concrete structures, called steel girder bridge. The wide body of the bridge that carries the road lanes are hollow inside, like a tunnel and could be used for GIL.

The bending radius of such a bridge is usually very wide so that the 400 m bending radius of the GIL does not give any limitations.

The local environmental conditions impact the GIL and bridge design and are part of the decision process for each particular application.

In Figure 30 the Europe Bridge is shown connecting a highway over a valley, a typical application. It can be seen that the bending is low, the route is almost straight.

Figure 30: Europe Bridge, Austria 185 m height,

This detail shows the body of the bridge (green) which could be used to insert a GIL, see Figure 31. The dimensions are large enough to take 1 or 2 GIL systems.

Figure 31: Europe Bridge, Austria 185 m height, detail

The Gschnitztal Bridge in Austria in Figure 32 is an example of a bended bridge. The design with the hollow body of the bridge under the street lanes is the same.

Figure 32: Gschnitztal Bridge, Austria approx. 80 m height, bended

The Brenner Pass Motorway is also bended (Figure 33) and it is the longest slope bridge in Austria. The body of the bridge is hollow and made of concrete. This body could also be equipped with a GIL.

Figure 33: Brenner Pass Motorway, Luegg Bridge, Austria longest slope bridge, bended

Figure 34 shows the famous Golden Gate Bridge. This bridge is a suspension bridge where the GIL could be attached to the side or under the road lanes.

Figure 34: Golden Gate Bridge

Figure 35 is the Öresund Bridge which connects Denmark with Sweden. About half way the bridge goes into a tunnel. The GIL could be attached to the bridge and then continue to the tunnel. This multiple use of such structures is much recommended to increase efficiency.

Figure 35: Öresund Bridge, Denmark-Sweden

Figure 36 shows the Bosporus Bridge which connects Europe with Asia in the city of Istanbul. This large suspension bridge also could be used to add a GIL hanging underneath the road lanes.

Figure 36: Bosporus Bridge, Istanbul, Turkey

Figure 37 shows the suspension bridge over the Street of Messina to connect Calabria with Sicilia in Italy. The combined use with a GIL connected to the bridge at the side or under the lane would increase the efficiency of the installation.

Figure 37: Messina Bridge, Calabria-Sicilia, Italy

8.3.2 Railroad Bridges

Railroad bridges are usually steel bow or suspension bridges and would allow bringing the GIL to the bottom or on the sides. These applications would be very similar to the usual applications form of GIL in substations mounted on steel structures. Figure 38 and Figure 39 show the Trisanna Railroad Bridge in Tirol, Austria. This type of bridge is made of a steel structure on pylons of stone or concrete.

Figure 38: Trisanna Railroad Bridge, Tirol, Austria

Figure 39: Trisanna Railroad Bridge, Tirol, Austria

8.3.3 Multi-use Bridges

The Tsing Ma Bridge in Hong Kong is a very good example how GIL could have been installed within the bridge structure. The engineering of the GIL application should be made together with the bridge to meet all requirements.

To combine functions in one is normal practice. Consideration must be given to the additional requirements resulting from vibrations and deflection due to trains, cars, trucks or wind, thermal expansion of the bridge, the GIL, and electrical interferences during the design.

Figure 40: Aero-view

Figure 41: Sectional View: 8 Lanes of Road Traffic and 2 Rail Lines Plus Utility Services

Technical Data of the bridge:

Built:	1992 - 1997
Location:	Between **Tsing Yi**, and **Ma Wan** of Hong Kong, China
Structural Type:	Suspension bridge gravity-anchored
Function / usage:	Motorway bridge / freeway bridge and railroad bridge
Technical information	
▪ **Construction materials used**	steel
▪ **Cables towers**	Reinforced concrete
▪ **Dimensions**	main span 1377 m
	total length 2160 m
	span lengths 63 m - 76.5 m - 355.5 m - 1 377 m - 355.5 m - 4 x 72 m
	Clearance 62 m
▪ **No. of cables**	2
▪ **Height of pylons**	206m
▪ **Uniform Distributed Load**	20kN/m/lane
▪ **Wind Gust Speed**	85 m/s
▪ **Traffic Speeds**	100 km/h for automobiles and 135 km/h for trains
▪ **Deflections**	4.7 metres vertical; 4.4 metres lateral due to wind; 1.3 metres due to temperature changes
▪ **Longitudinal Movement**	at ±835 millimetres at one end of the bridge

Apart from the main function as a motorway / railway bridge, Tsing Ma Bridge is also designed to cater for utility services. The original design of the bridge has not taken into account the accommodation of high voltage GIL. At the moment, 11kV power cables and communication cables are installed in designated area on the lower deck of the bridge. Installation of 132kV power cables on the bridge is feasible but agreement has not been reached between the utility and the operator. The following depicts a brief exploration of the possible application of high voltage long GIL in a long suspension bridge.

Deflections of a long suspension bridge are high as compared to other types of bridge. The major challenge is how the GIL design copes with the design deflection limits of the bridge to ensure that the GIL will not be damaged or disconnected under the adverse conditions e.g. typhoon. Special connection units to allow the GIL to adapt to these deflections may be required to be used at specific locations along the route. Under steady state, the bridge will still exhibit some small vibrations, expansion / contraction arising from wind load, rail and road traffic, and thermal changes. The integrity of the GIL has to be sustained and maintained at all times under small deviation from nominal position of the bridge. To accommodate the GIL, segregated compartment(s) for utility services from the rail / road traffic on the lower deck of the bridge can be provided as with the case of Tsing Ma Bridge. The segregation is to prevent the GIL from collision by the moving vehicles. Access to and from the compartment for GIL delivery, installation, testing, operation, maintenance and emergency escape can be made at two ends of and appropriate locations along the bridge. Transport rails can be provided in the compartment to facilitate GIL movement. Relative weight of the GIL is small as compared to the weight of the bridge and loading of vehicles and trains, is generally not a concern to the bridge design. The maximum GIL span and distance for fixing are subject to a number of economic and technical factors like production, transportation, installation, maintenance, and the deflections limits and longitudinal movement of the bridge. Cooling for the GIL in general may not be required if the at least one side of the compartment is open to the atmosphere. This is usually the case for a long suspension bridge.

9 Interconnection Points

Depending on the position of the GIL in the network, the interconnection points can be a liaison with an overhead line or the introduction in a GIS or AIS substation.

When the GIL is part of a line, the interconnections are very simple substations with the air to gas bushings and protected by surge arresters, in the event of disturbance on the overhead line; no other high voltage equipments as circuit breaker or measurement transformer are needed. See Figure 42. Usually, the stations are protected with fences and gates and any access in it (regular or with infraction) are registered and monitored.

Figure 42: GIL termination, transition to overhead line.

9.1 Environmental Requirements

Installation GIL can be exploited under conditions of typical ambient temperature located between -30°C and +40°C. Case in case it will be necessary to envisage particular installations of heating or cooling, even technical amendments to observe the environmental conditions.

The extremity stations (conversion GIL - air) can be regarded as very simplified usual electric stations (no circuit breaker, disconnecting switch or measurement transformer) and must realized according to usual standards.

9.1.1 Temperature Calculations

In principle the GIL has a very good heat transfer using thermal convection. In long tunnels the layout of the GIL concerning rated current is part of the thermal study for the tunnel conditions. Usually ventilation of a tunnel is sufficient to be within the limits of the allowed temperatures. In all cases a thermal study needs to be done. In Annex D an example of a thermal calculation is given.

9.1.2 Influences on Tunnels or Galleries

For the achievements in tunnel, it is necessary to take into account the risks of heating due to the location and the crossed geological conditions.

Generally it is sufficient to envisage a system of ventilation, permanent or temporary, to maintain the ambient air below the limiting values. If necessary, it is possible to install equipment of air conditioning for all or part of the gallery.

Although it is not necessary to install the GIL in a tight gallery, it should be prevented that water run directly on the tubes, indeed with this water can be mixed products being able to attack the envelope chemically. In the same way it is necessary to avoid the too wet environments which would have a corrosive effect on the equipment.

9.1.3 Influences on Bridges

Although without experience feedback for the achievements of GIL on bridges, it is possible by analogy with stations GIS in the open air to take guard with the constraints due to the strong daily or seasonal variations in temperature. Similarly the near environment (salt and sand at the seaside, snows and freezes in mountain) will not be without influence on the protection of the tubes and its accessories.

Certain type of bridge (for example a suspension bridge) can present important natural movements which must also be absorbed by the GIL.

10 Handling Large Scale Projects

10.1 On Site Assembly Concept

The overall project logistics is a key factor in particular of long GIL installations. This is mainly related to the large number of components which are to be handled in a proper manner. The principle however remains the same regardless of the project size: The GIL components get delivered to the pre-assembling site which is usually a temporary installation as close as possible to installation location or to the access point which may be the entrance of a gallery or a cavern. At the pre-assembling area a temporary workshop facility gets erected where the individual pieces are put together to components ready for the final assembly procedure. It is clear that one of the most important requirements is to maintain the cleanliness inside the pre-assembling workshop. Once the components have been completed, they are transported to the assembly location. The latter is the place where the “endless” tube is put together. This can be done using flanges or welding. The latter is the more economic solution for longer lengths, flanges are mostly used for frequently diverting routings or very short installations. The progress of the installation is determined by the final assembly procedure. This means that the planning consists of two major steps: First the number of assembling crews and locations has to be determined in order to meet the project time schedule. Upon this the capacity of the pre-assembling facility and the logistical details for the transportation between the two locations are determined. This in turn defines the delivery details for the sub-suppliers of the different bits and pieces. A storage facility adjacent to the pre-assembling site is of advantage.

Important for GIL and for all high voltage systems is that those areas exposed to high voltage equipment need to be clean to fulfil the requirements which are given by the GIL standard IEC 61640.

The testing is divided into two main steps: The ongoing quality assurance during installation and the after-laying tests. The quality assurance during installation covers amongst other things the ultrasonic inspection of each individual site weld and the appropriate documentation in accordance with international and local pressure vessel code requirements. The tests after laying are mainly the pressure test of the entire system, the dielectric test and the test of the conductor resistance. Details of the site testing activities are prescribed in IEC 61640.

Due to the nature of the GIL installation works and mainly related to the requirements of cleanliness it is obvious that apart from the required Health & Safety issues a couple of other prerequisites of the site shall be fulfilled before installation can start. The most important of them is that the civil works in the vicinity of the assembling area must be completed and permanent, unimpeded access for the GIL installation crew.

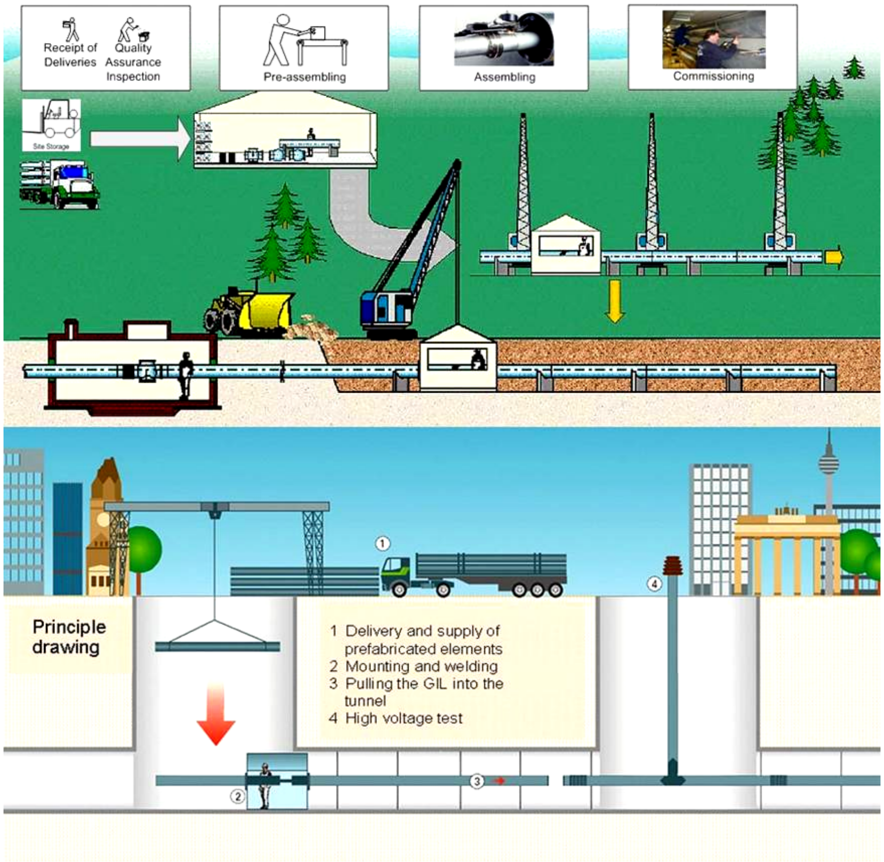


Figure 43: Site logistics scheme for GIL installation in tunnel, above and below ground

10.2 Factory Preassembled Concept

Another concept used by GIL manufacturers, who deliver GIL components to other manufacturers to build the GIL on site, allows for preassembled sections shipped directly from the GIL assembly factory. This allows for manufacture and pretesting of all shipping assemblies of up to 18 meter sections ready for installation into the tunnel area. The principle however remains the same regardless of the project size or assembly concept and needs to be evaluated as to the most beneficial alternative for any given project.

The busbar system is made in fully assembled and factory tested sections up to 18 meters in length. Changes in direction are accomplished with elbows which are pre-assembled to individual shipping sections in the factory.

Each shipping section is tested before delivery from the factory to insure the standards of reliability. Routine testing includes high voltage power frequency electrical tests, partial discharge tests of each insulator and each shipping assembly, and gas leakage tests on all shipping assemblies.

High voltage power frequency electrical tests, partial discharge tests of each insulator and each shipping assembly, and gas leakage tests on all shipping assemblies are done before shipping the section of busbar for installation.

Figure 44: High voltage test at the factory

After the pre-testing is complete GIL sections are ready to be shipped to the installation site for final testing and commissioning.

Figure 45: Shipping of the pre-assembled section of busbar

The utilization of flanged GIL sections makes the installation process simplified on site and an expeditious installation program can be accomplished. It also does not require any on-site assembly and testing area. The installation of the section of busbar into the tunnel does not require any clean area.

The longer section lengths decrease the number of connections required during installation and lowers the risk of gas leakage during operation.

Installation and commissioning of sections up to 18 meters can be completed easily due to short assembly time resulting from no extensive protection from weather or dirt to do the flange connections.

Figure 46: Installation of section of busbar on site

10.3 Handling of Deliveries

Each part shall be delivered in a packing adapted to the transport from the factory to the building site (by road, rail, sea or air) and accompanied by the instructions necessary to its handling and its storage. Transport to the building site and on the building site must be carried out according to regulations' of the supplier.

By the reception it is necessary to check that the delivery is complete, conform to the order and not damaged.

The following sub-chapters give a not-exhaustive list of the principal equipments having to be delivered to carry out a connection GIL, as well as a short description. The elements and photographs described are mainly based on the realization of Geneva.

10.3.1 Pipes (Enclosure and Conductor)

The tubes are delivered on the site in section from 14 to 18 meters (limitations due to the possibilities of transport, by the rail or the road) and are composed of an enclosure and an inner conductor. The enclosure is generally manufactured starting from an aluminium alloy sheet rolled up in spiral and welded (diameter 512mm, thickness 6mm). The inner conductor, also out of aluminium alloy, is extruded (diameter 180mm, thickness 5mm); it is maintained in the centre of the enclosure by means of moulded resin insulators laid out all the 10 to 14 meters. At the interior of the enclosure, at the base is placed a particles trap. The tubes have a capacity of flexibility being able to support a radius of curvature until 400m.

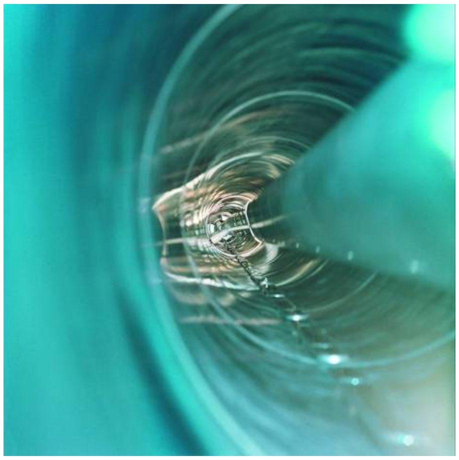


Figure 47: View inside the GIL. Enclosure and conductor are aluminium pipes. Bottom shows the particle trap

Figure 48: Design of GIL showing enclosure, conductor, post type insulator and particle trap

10.3.2 Other Components around the GIL

In addition to the GIL tubes, GIL connection is made up of other elements; to quote in particular:

- Elements bent for the important changes of direction, they are cast or fabricated parts.
- Expansion joints or compensators to absorb axial, side and angular displacement caused by thermal dilations or movements of structure.
- Valves of filling, which will must be in a sufficient number and size to handle great quantity of gas in a reasonable time, their easy access must also be assured.
- Densimeters for the permanent monitoring of the pressure of the gas mixture in the tubes.
- Antennas at the ends of the tubes being able to be used initially for the measurement of the partial discharges (at the time of the tests of reception), then like sensors for the arc locator system.
- Elements of crossing for the connection with the air line by bushings. These elements may have a separation from the GIL tubes, their gas volume is relatively small and they are thus equipped with a rupture plate.

Figure 49: Angle units, expansion joints, valves for filling

Figure 50: Density meter for gas mixture monitoring

Figure 51: Antenna for arc location system

Figure 52: Disconnecting unit with connection to the outside of the tunnel

Fig. 53: Connection to overhead line by bushing with parallel surge arrester

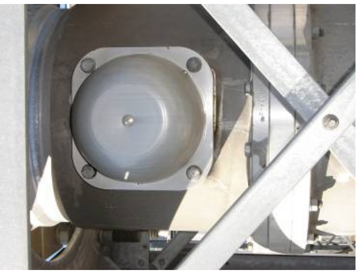


Figure 54: Rupture disc, only used for small gas compartments, e. g. at the connection point to overhead lines or substations via bushing

Peripheral components of the GIL:

- Supports of fixing every approximately 15 to 20 meters; the tube can slip axially on the supports in the event of dilation due to the variations in temperature.
- Elements of anchoring placed all few hundreds of meter allowing to fix the tubes rigidly.

Figure 55: Structures for supporting the GIL in the tunnel

Figure 56: Structure for fix point of the GIL in the tunnel

For a realization in gallery or tunnel:

- Various sensors of monitoring of the environment, such as presence of oxygen, presence of SF_6, presence of water;
- Fire protection detectors, even the extinction in certain critical buildings;

- Equipment of ventilation which can activate itself automatically in the event of rise in the temperature or manually at the time of visit of installation;
- Partial discharge measurements are used during commissioning, and pd sensors are available for measurements during operation, if needed.
- In case of overload operation it is recommended to monitor the temperature of the GIL.

Room of monitoring with secondary equipments (electricity supply, monitoring and alarms station, ...), the central processing unit and the monitor of the arc locator system, a chronological printer of events, etc.

Figure 57: Monitoring the air quality by measuring oxygen and SF_6 including a water sensor in the tunnel for safety

Figure 58: Monitoring room for the data connection to the operation centre

10.4 Assembling at Site

10.4.1 On Site Assembly Concept

GIL sections, place for preassembly tent, storage area, environmental conditions, weld preparation, delivery logistics.

At both ends, additional access openings were used to bring in the straight units, angle units, disconnection units and expansion joint unit.

All the described elements must be stored inside (building or tent) in a clean place, safe from dust and moisture, what, in an environment of building site, is not always easy to obtain.

The site of assembly of the GIL must also be equipped with the several infrastructure as offices, various buildings, power supply (not to forget welded and gas treatment machines), water, etc.; without forgetting to guarantee the access to the personnel and visitors.

The rate of delivery of the material, in particular tubes is done according to the place at disposal for the storage and of the rhythm of the progress of the work of assembly. The rigorous and precise planning of the deliveries is determining on success of the building site and the final respect of the deadlines.

The thermal expansion of the conductor with respect to the enclosure will be compensated by the sliding contact system. The straight units enclosures are welded together by orbital welding machines (see Figure 63). If a directional change is needed with more than what the elastic bending of the straight units can then an angle element will be added: it covers angles from 4 to 90°. For longer GIL, disconnection units (see Figure 64) are placed at distances of about 1200 [m]. Such units are used to separate gas compartments and to connect high-voltage testing equipment for commissioning of GIL. The compensator unit is used to absorb thermal expansion of the enclosure.

Figure 59: Delivery of Transport Units at Preassembly Area

Figure 60: Preassembly of GIL Sections

Figure 61: Welding Area in the Tunnel

Figure 62: Bringing in the GIL Section into the Welding Area

Figure 63: Orbital welding machine for enclosures and phases

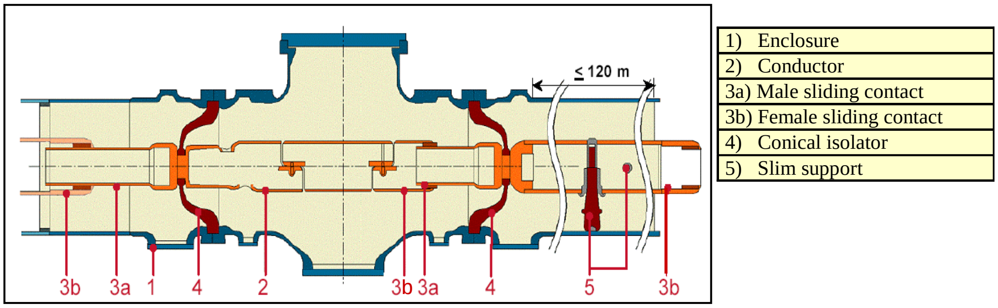


Figure 64: GIL disconnection units

10.4.2 Factory Preassembled Concept

GIL section of busbar are shipped from the factory in the largest sections allowable for transport. They are fully assembled and tested in the factory then sealed and pressurized with dry nitrogen or air for shipment.

Figure 65: Pre-assembled section of busbar at site

The various components of the busbar assembly including straight sections, elbows, tees, and crosses are factory assembled in shipping units up to 18 meters long. These assembled shipping sections are factory tested to insure the highest reliability.

At the site, the installation time is short due to the longer section of busbar with fewer joints.

During installation, centre conductors are joined together by plug-in contacts, the outer enclosure can be welded or bolted together. There is no extensive clean environment requirement for protection from weather or dirt when using the flange joints.

Figure 66: GIL installed on steel structure
Left: Placing a GIL section on steel structures
Right: Inserting a T-connector to the GIL

10.5 Laying Principle Inside the Tunnel

For the installation of a GIL there are generally two options: Welding of the pipes in one location and pulling the continuously produced pipe or moving the welding position along the route. The latter one is clearly not the preferred option due to the fact that the welding equipment and the equipment to maintain a clean welding place are not suitable for permanent movement. As such the assembly location remains in place until a certain section of the GIL has been produced. The limiting factor is the maximum length which can be pulled in position after welding. The current assumptions in this regard are based on a maximum pulling length of app. 1500m. This length in turn forms the maximum distance between two gas compartment segregations. The mechanical requirements arising out of this installation method are usually not critical as the pulling is normally done from the location of a fixed point. These fixed points are designed to absorb the forces arising out of the thermal expansion of the enclosure which comes along with force magnitudes which exceed those during pulling significantly.

The project division and planning must take account in particular long and incompressible operations which are civil work, as well as the manufacture and the delivery periods of the tubes

According to the means of transport and the place at disposal to store and weld the tubes, sections from 15 to 20 meters can be assembled. The assembly of the tubes is carried out by welding or flasks of fixing screwed between the enclosures, just as the conductors are also welded or assembled by sliding connections multicontacts.

The process of orbital welding between tubes must be extremely precise; it is carried out in a protected enclosure and requires a perfect cleanliness and the absence of draught. All the weldings undergo a control with the ultrasounds. As the weldings are carried out, the tubes are drawn on their support by a winch.

10.5.1 Duration of Laying

As an example the project of Geneva, the realization of 420 m double circuit GIL took 11 months for the tunnel and the GIL installation with the following phases:

Tunnel building

- March to September 2000 : reception of the construction authorization, digging and civil work for the gallery;

GIL Laying

- September to December 2000 : laying of the tubes and assembly of the extremity substations;
- December 2000 to January 2001 : mechanical and electrical acceptance tests;

Connecting to network

- January 2001 : connection of the overhead line;
- 9. February 2001 : release for operation;

It appears that the duration of realization strongly depends on the number of orbital welding to realize on the site. If necessary it is possible to work continuously with several teams or, if that is possible, to consider several installations of welding.

For long distance applications the project logistic will apply parallel working on the GIL to meet the total available building time. This planning is much depending from the project requirements.

10.5.2 Gas Handling

Installations GIL of several kilometres or more require to handle very great quantity of gas. To limit the gas volume the GIL is separated into gas compartments of several 100 m length. This makes the gas handling simpler. A planning of the gas handling is needed to handle storage and gas treatment. The handling instructions are defined in [77] IEC 62271-303 Gas Handling Guide and more information is given in [78] CIGRE Brochure Gas Handling. It is necessary to organise sufficient place for the tanks of SF_6 and N_2. Specialized machines are necessary to make the vacuum in the tubes before the filling, like treating the gas (drying) and making mixture N_2-SF_6 before filling. The operation of filling must be supervised permanently.

Figure 67: Gas handling device
Vacuum pump and gas mixing unit

Figure 68: Gas filling
Dilo valve to connect gas handling device

10.5.3 Testing on Site

10.5.3.1 High Voltage Test

The need to test the GIL on site after laying imposes certain requirements on the GIL and the structure in which it is installed.

The guiding rule for high voltage on site testing is not to exceed the maximum test current of about 20 A to limit the energy charged to the system. In GIL it is possible to use the accessibility to test sections of GIL through the disconnection unit, which is used as an isolation point.

One gas compartment may have a maximum length of 1500 m. This also forms one high voltage test section which needs access for the test equipment. From there the tests can be executed in two directions.

Therefore access to the GIL for high voltage testing in the tunnel from the main tunnel or from the outside is required at least any 3000 m.

Or in case of long tunnels or bridges the high voltage test equipment, using gas insulated equipment (see Figure 69), is needed to be brought into GIL tunnel or onto the bridge where the GIL is laid.

Figure 69: Gas insulated high voltage resonance test set-up
Max. voltage 680 kV, max. current 1,5 A, L = 720 mH

Figure 70: On site HV testing
Air insulated high voltage resonance test set-up

Figure 71: On site HV testing
Connecting to the bushing

10.5.3.2 Pressure Test

Pressure tests are required by the EN standards for GIS and local requirements of authorities. The EN standards on high voltage equipment are written for low pressure compartments (typical up to 8 bars), dry and inert gases (SF_6 and N_2). The EN standards are the following:

Table 9: Pressure vessel standards for GIL

EN	Title
EN 50052:1986 EN 50052:1986/A1:1990 EN 50052:1986/A2:1993	Cast aluminium alloy enclosures for gas-filled high-voltage switchgear and controlgear
EN 50064:1989 EN 50064:1989/A1:1993	Wrought aluminium and aluminium alloy enclosures for gas-filled high-voltage switchgear and controlgear
EN 50068:1991 EN 50068:1991/A1:1993	Wrought steel enclosures for gas-filled high-voltage switchgear and controlgear
EN 50069:1991	Welded composite enclosures of cast and wrought aluminium alloys for gas-filled high-voltage switchgear and controlgear
EN 50089:1992	Cast resin partitions for metal enclosed gas-filled high-voltage switchgear and controlgear

10.5.3.3 Gas Leakage Test

A gas leakage test can be made with a gas sensoring device which senses SF_6. These devices (sniffers) have been used for 30 years with GIS and have proven to be very effective for detecting leaks.

10.5.3.4 Functional Test

Functional tests are used to prove that all connections are correctly made, including the secondary systems. The secondary systems are the gas density meters and the arc location sensors.

Grounding connections along the GIL are tested in accordance with the IEC standard 61640.

For tunnel installations fire and smoke detectors and oxygen sensors might be installed and need to be tested.

10.5.4 Quality Control

Although technically not very complex, the good execution of a connection GIL depends primarily on the quality control of all the phases of the realization. The critical point is obviously to ensure the tightness of the system and any risk of escape by cracks, microscopic cracks or any kind of tightness losses must be detected as soon as possible.

A connection GIL being an installation under pressure, it must answer the standards and requirements in force in the place of its exploitation. In the same way the process of welding must be validated by official authorities.

Each component of the system must be identified and documented from its manufacture to the assembly. The tubes must be identified individually and their position known with precision.

11 Operation, Maintenance and Repair

11.1 Operation

Operation of a GIL:

Seen from the dispatching centre (control system), a connection GIL could be operated like an overhead line; their electric behaviours against the network are similar, in particular concerning the distribution of load (no production of reactive power).

The mixture of gas N_2+SF_6 allows even in the event of appearance of one electric arc in a tube to proceed to an automatic reclosure, according to uses of operation in the network, the time of pause should be sufficient for die-ionized the gas mixture if the defect is fugitive.

The overhead to underground transition substations, if they are not direct at the extremity of the line, do not need of any particular High Voltage equipment such as circuit breaker, disconnecting switch or measurement transformer, only surge arresters are installed beside the bushings, which makes connection GIL transparent for the control system and operation.

Monitoring specific to the GIL:

Each gas compartment must be equipped at least with one **densimeter**. These sensors, which are compensated in temperature, allow to monitor permanently pressure of the mixture of gas in the tubes. They are equipped with a display for visual control at the time of inspection, like several levels of alarm for minimal pressure in the case of leakage or gas loss. These alarms can to be transmitted remotely to the control system and/or to alert the personnel. The sensitivity of the densimeters and the determination of the alarm thresholds must to be carefully studied according to the important volume of gas by compartment.

Connection GIL can be equipped with one **Arc Detector and Locator System** based on the principle of a measurement of the difference travel time of wave between the place where occurs the arc and them ends of the tubes equipped with reception antennas; the precision is ensured thanks to a synchronization by GPS. In the event of fugitive defect (successful automatic reclosure) on a connection with a GIL, the dispatcher will be able to know if the defect occurred in a tube or on an overhead part.

According to the dimensioning of the installation, load flow and environment, it is necessary to proceed to **measurements of heating** uninterrupted which will be able to act on a system of ventilation.

Monitoring of the installation:

In an installation in a gallery or a tunnel it is recommended to install **gas-detectors SF_6** as well as **presence of oxygen** in the low points. This information is to be put in relation to one possible alarm of pressure drop sent by a densimeter of compartment.

The presence of water, for example related to infiltrations, can be detected by **measuring apparatus of water level** with float.

According to the principles of exploitation and the concepts suitable for each company, other monitors can be installed, such as for example:

- Fire and temperature sensor
- Extinguishing system
- Monitoring of the access
- Video camera
- etc.

Monitoring requirements and safety rules are very much related to the operator and local authorities. The technical installations and the operation instructions are not different to other high voltage installations and very similar to GIS. Technology is available on the market.

Round the clock service:

In the event of critical alarm or on request of the dispatching, personnel of the round the clock service must go in the installation. By safety measure, the personnel who reach a gallery must take a portable apparatus of detection of presence of oxygen, just as the gallery must be equipped with oxygen mask at regular intervals and escape ways.

11.2 Maintenance

GIL lines require theoretically very little maintenance actions; however the limited experience feedback concerning this technology pushes the owners with a careful attitude of preventive maintenance. The following actions of maintenances can be mentioned:

- Periodic round of inspection. The interval is to be fixed between 1x/week (at the beginning of the operation) to 1x/month. This round makes it possible to make sure that there is nothing abnormal on the level of GIL, but also on the whole of the installation and the extremity stations. In particular the pressure in the tube (densimeter) should be visually controlled, as well as the general state (water infiltration, cleanliness, etc.).
- Each year it is necessary to envisage a control of pressure with pressure gauges of precision and a measurement of the quality of the gas (humidity). This work requires an outage of the installation.
- The densimeters must be calibrated periodically, for example every 5 years. This work requires an outage of the installation.
- Gas-detectors SF_6 placed in the gallery must be calibrated periodically, for example every 5 years.
- The oxygen detectors use sensitive cells that consume themselves with the time and must thus be reloaded regularly.
- According to the environment of the installation and of the state of pollution it is necessary to clean the insulators of the bushings and the surge arresters at the extremity stations.
- It is also necessary to proceed to various actions of cleaning tubes and gallery; to note that the system of ventilation bring dirtiness (filters could be installed).
- In the event of water infiltration above the GIL, there is a risk of corrosions of the tubes according to the composition of the fluid. It is desirable to put protections or to require a waterproofed gallery by the construction.
- Various other traditional operations in electric stations must be carried out, such as checking of the tightening of connections and control by means of camera thermovision.

11.3 Internal Arc

In case of internal arc the GIL using an 80 % N_2 and 20 % SF_6 gas mixture with a minimum wall thickness of 6 mm will not burn through if the length of the gas compartment is long, e. g. 100 m. This will allow GIL to be added in traffic tunnels.

To protect the GIL no special protection system is required, see clause 11.1.

11.4 Repair Process

Even if the principle of GIL is relatively simple and include few peripheral devices, the high requirements of manufacture and of assembly, the environment where the GIL is installed and the existing experience feedback do not make it possible to exclude the assumption to have to proceed with repairs of the installation.

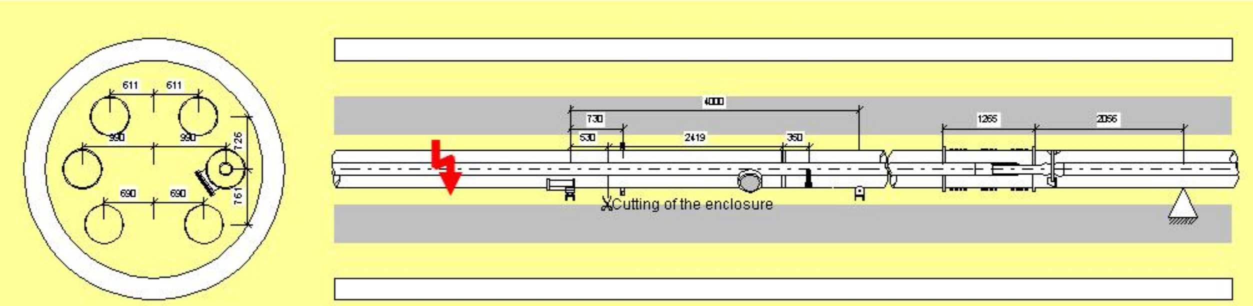
At the design of the installation it is of advantage to take account of this assumption and to apply various measurements such as:

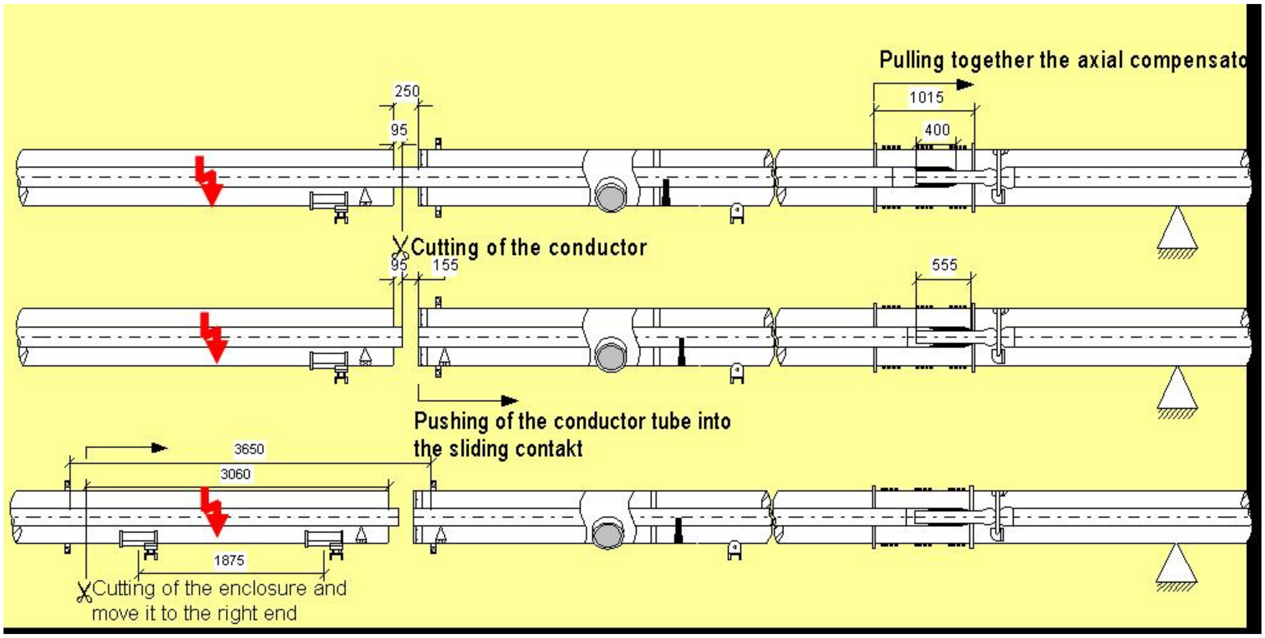
- To stock parts of reserve, for example of the tubes, near to the installation or in the gallery for an underground system.
- To ensure of the permanent or emergency access for vehicles and machines.
- To envisage to have to handle and treat the large quantities of gas, therefore to have cisterns or batteries of bottles.
- To distribute all along the GIL electric power to supply various machines (welding, treatment of gas, ventilation, light, etc.).

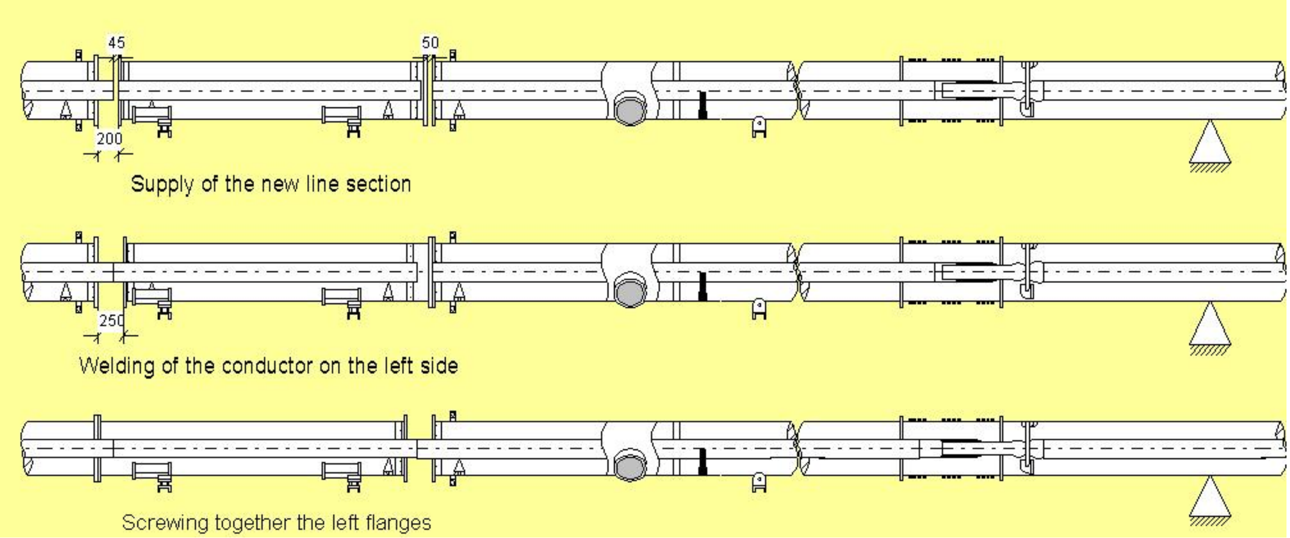
The repair process itself consists of the following activities:

- setup of the repair site
- removal of gas filling,
- cutting and removal of the encapsulation and conductor,
- installation of replacement conductor and encapsulation,
- gas-filling and high voltage test,

Figure 72 outlines the repair scheme. The entire process has been performed and proven. The duration of a potential repair is app. 2 weeks including preparation and final testing which represents a comparable value for high voltage underground transmission systems.




Pulling together the axial compensato
250
95
1015
400
Cutting of the conductor
95
155
555
Pushing of the conductor tube into the sliding contakt
3650
3060
1875
Cutting of the enclosure and move it to the right end


45
50
200
Supply of the new line section
250
Welding of the conductor on the left side
Screwing together the left flanges

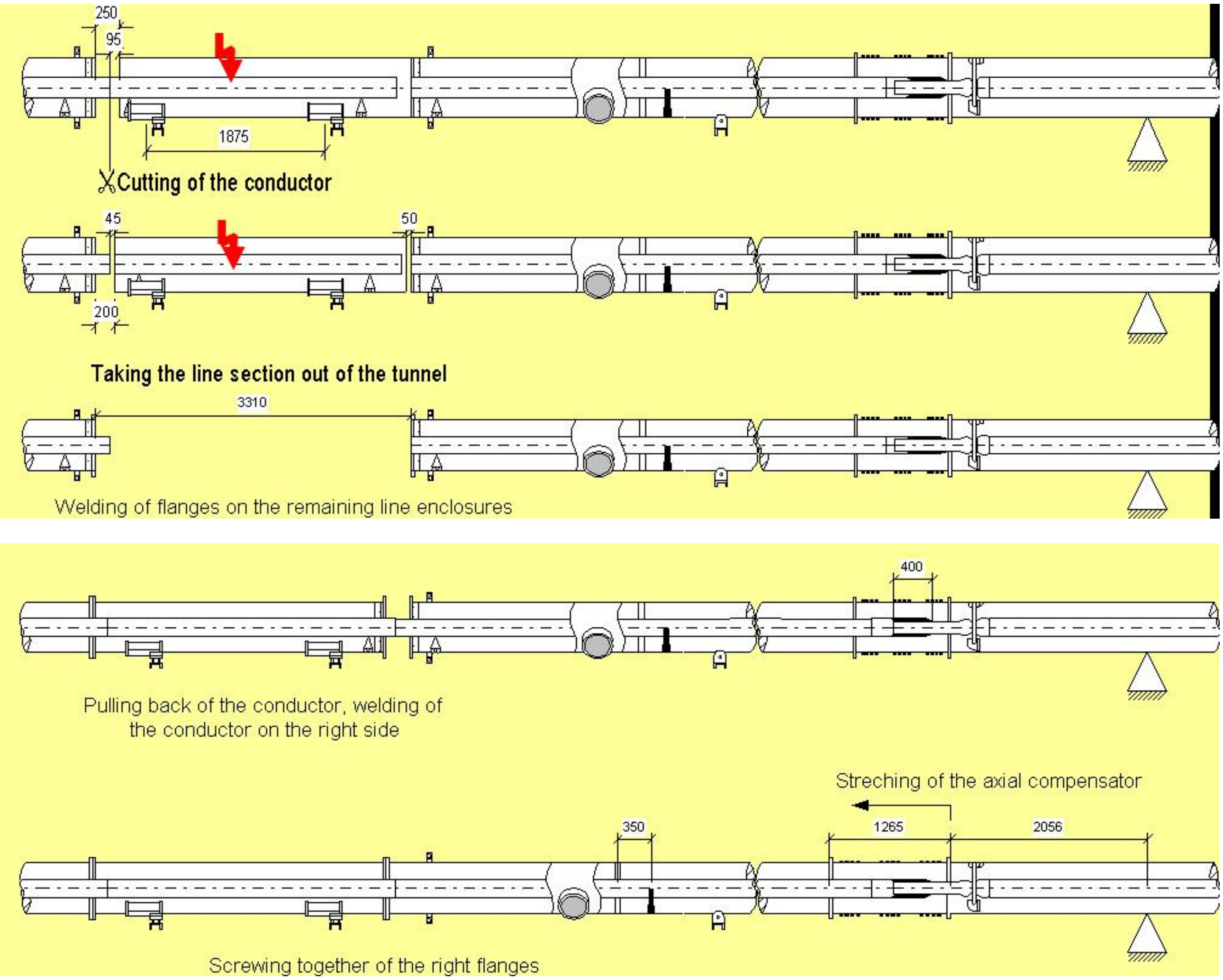


Figure 72: Repair scheme

11.5 Gas Tightness

The gas density of insulating gas mixture provides the electrical ability of the GIL. To supervise the gas tightness is therefore part of the operation and control system of GIL. In case of the gas loss below a given pressure value the GIL would be switched off.

The reason for the gas losses could be:

Damage of the outer metallic enclosure

The outer enclosure of the GIL is consisting of an aluminium pipe of several mm wall thickness, typical 8 - 10 mm. To destroy this metallic enclosure strong forces are needed.

Protective measures

To protect the GIL from such distortions the installation has to be in the way that such impact is most unlike, e. g. not in direct contact to traffic.

Failures of the welding

The weldings which are made on site or in factories do have a 100 % control of the weld quality. Nevertheless, it is possible that there might be void which could lead to gas losses. Such gas losses are low in quantity and can be repaired on schedule.

Control equipment for gas density control is installed to allow the scheduled repair of the void.

Gas quantity limitation

To limit the risk of lossing large quantities of insulating gas to the atmosphere the GIL uses gas mixture with the majority of Nitrogen (80 % N_2) as insulating gas and the total length of a GIL line is separated into gas sections of some 100 m.

A slow escape can be measured either directly by densimeters assembled on the tubes, or indirectly by the gas-detectors SF_6 installed in the low points of the installation. Localization of these leak or microscopic cracks is much more difficult and requires systematic research with detectors SF_6, or radiographic examinations and ultrasound. The experiences show that the points to be controlled in priority are the weldings:

- Spiral weldings carried out by the manufacture of tubes;
- Points of welding for the fixing of the particles trap inside, bellow, the tube. This work is completed in factory;
- Orbital weldings to assemble the sections of tube. These weldings are carried out on the site. An ultrasonic inspection of each weld being part of the quality plan during installation is recommended.

Gas escapes can be repaired on site by welding, but require a very high expertise in welding and the working conditions are particularly delicate to implement (cleanliness).

In all the cases the repair of the tubes requires to handle large quantity of gas (to empty, store, treat, fill), it needs a suitable infrastructure and generally takes much of time. To ensure the staff safety in charge of the interventions, it is necessary to envisage a system of gas extraction.

11.6 End of Life

At the end of life of a GIL the equipment will be recycled and most of the material can be reused.

Insulating Gas

The used insulating gas is a mixture of SF_6 and N_2 . Both gases can be separated by using the conventional gas handling devices and will be stored in conventional steel bottles. The SF_6 is stored in fluid condition and the N_2 is stored in gaseous condition under high pressure (e.g. 200 bar) in standards steel bottles or containers. Included in the gas separation and storage process is a gas cleaning and gas drying process. The stored gas has the quality of new gas and can be re-used under the IEC 62271-303 Gas Handling requirements.

Materials

The materials used for GIL are aluminium for the enclosure and the conductor pipes and cast resins for the insulators. Those materials can easily be separated and reused or brought into the recycling process to produce new aluminium pipes or insulators.

Recycling

Recycling of GIL is because of its nature of a gas insulated system easily possible. The used materials can be separated with the de construction process and on this way can be brought into the reuse process or into the manufacturing process of new materials.

12 Safety Analysis

The withstand of the metallic enclosure to internal arc avoid external impact like fire.

Accidents in the tunnel or on the bridge might be a danger for the GIL and separation to moving traffic is required.

There is no influence from radio activity in the tunnel expected to the insulating gas and the electrical stability of the GIL, as the metallic enclosure is shielding the inside from the surrounding.

O_2 measurements in the tunnel are recommended at low locations in the tunnel to make sure that no personnel risk is given.

When the GIL gas compartment needs to be opened care has to be taken avoiding direct contact with possible decomposition product of the insulating gas. Therefore the operations manual instructions need to be followed.

The gas handling needs to be carried out in accordance to the IEC gas handling standard 62271-303.

Touch voltages and touch temperatures are limited to values below the required values of the related IEC standards.

Tunnel inspection are recommended in time sequences which fit to possible impacts coming from water, dust or other environmental impact. Such sequences of inspections could be in a year cycle.

Requirements in earthquake situations have to be taken into account in earth quake areas.

During HV test and during pressure vessel test at the installation and commissioning process precautions as used with high voltage systems have to be taken into account.

A safety analysis needs to be made for each installation in tunnels or bridges. The requirement will vary with the use of the structure. Part of the safety analysis is the impact coming from failure in the GIL, e. g. internal arc, fire in the structure, accidents in the tunnel or on the bridge.

12.1 Fire in Tunnel or Bridge

Precaution coming from the GIL is not needed, because only metal and non burning materials are used. There is no additional fire load coming from the GIL.

12.2 Accidents with Flammable Products

In cases when fire is reaching temperatures in the tunnel exceeding 800 °C precaution of chemical-physical decomposition products is needed because of the toxicity of such products of accidents with flammable products on the bridge or in the tunnel.

13 Life Cycle Analysis (and Life Cycle Costing)

Life Cycle Analysis (or Life Cycle Assessment) is an integrated "cradle to grave" approach to assess the environmental performance of products and services.

The LCA methodology is described in detail by SETAC (Society of Environmental Toxicology and Chemistry), that gives the following definition of the methodology: “Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements.”

LCA is regulated by ISO within the following standard documents: 14040, 14041, 14042 and 14043 [42,43,44,45].

According to ISO standards LCA can be subdivided into four fundamental phases [46]:

- Goal and scope definition: definition of the aims and of the borders of the system;
- Life Cycle Inventory Analysis (LCI): compilation of an inventory of inputs and outputs;
- Life Cycle Impact Assessment (LCIA): evaluation of the potential environmental impacts associated with those inputs and outputs;
- Life Cycle interpretation: interpretation of the results of the inventory and impact phases in relation to the objectives of the study.

Inventory stage is the heart of LCA: data is required from all life cycle phases of the product, for all inputs and all outputs.

In particular the following phases need to be considered: production; installation; operation and disposal.

For example in the production phase of a GIL materials used for the realization of enclosures (aluminium alloy), conductors (aluminium alloy), insulators (plastic materials), and insulating gas (SF_6 and N_2) need to be considered.

In order to carry out an LCA huge quantities of data need to be handled. Computer programs can handle data and relevant analyses faster, more conveniently and with better quality assurance.

A number of software packages for LCA are available (for example TEAM - Tools for Environmental Analysis and Management - made by Ecobilan).

These software packages usually contain data bank and the main categories of environmental impacts: green house effects, rain acidification, eutrophication, and depletion of the ozone layer, photochemical production of smog, loss of non renewable sources, human toxicity, and eco-toxicity for aquatic and terrestrial environments.

Other impacts on the environment that are not present in an LCA but should be taken into consideration are electromagnetic fields, acoustic noise and soil use.

Beyond to the evaluation of the impacts on the environment given by LCA, in order to achieve a complete optimization of the life cycle management of a component, it is necessary to consider the economic evaluations involved. This is possible by LCC (Life Cycle Costing).

According to IEC 60300-3-3 (2004) [48] “Life Cycle Costing is the process of economic analysis to assess the total cost of acquisition and ownership of a product”.

Fundamental to the concept of life cycle costing is the basic understanding of the product life cycle and the activities that are performed during these phases. Also essential is the understanding of the relationship of these activities to the product performance, safety, reliability, maintainability and other characteristics, and resulting life cycle costs.

There are six major life cycle phases of a product (as defined in IEC 60300-2):

a) concept and definition;

b) design and development;

c) manufacturing;

d) installation;

e) operation and maintenance;

f) disposal.

The total costs incurred during the above phases can be divided into two major areas, namely, acquisition costs and ownership costs.

From the user point of view, for a component like GIL (or analogous solutions of power lines) with well defined technology (for which it is not important to explicit concept, design and development costs), the total life cycle costs can be expressed as [49]:

$$\mathbf{LCC = CINV + CADD + CPM + COP + CUNV + CDIS}$$

In which

LCC life cycle cost;
CINV investment cost;
CADD additional costs of the user (personnel costs for installation, commissioning tests and formation);
CPM cost of programmed maintenance;
COP operation costs;
CUNV unavailability costs;
CDIS dismantling costs.

LCA and LCC (together with technical evaluations of a solution) are fundamental analyses for the multicriteria evaluation which can be applied to power lines solutions, in order to compare different possible technologies [50].

Encloses economical and environmental aspects including the whole elements involved in the process from the manufacturing over the operation finally to deconstruct the equipment.

14 Costs Analysis

The cost estimations made here for GIL are based on a feasibility study of a real application of GIL in a long tunnel. The study was financed by DG-TREN of the EU.

The real costs may differ significantly from the values specified here, depending on the specific project requirements.

14.1 General Explanation

The instinctive reluctance towards GIL chiefly due the first strong impression generated by its high investment costs does not find rational confirmation after having considered the impact of different valorisations of power losses and possible burdens on the territory.

The installation cost of the gas-insulated lines is sensibly higher than that of an overhead line. Moreover, as shown in Italian literature [59], [60], the economic convenience of the GIL compared to overhead transmission lines is highlighted when power losses and territory constraints are accounted for. These territory constraints may be different in other regions or countries, therefore, the conclusions could be different. In fact, the resistive losses are significantly lower compared to overhead lines, and the dielectric losses are wholly negligible. This could reduce the transmission costs significantly. The major role in comparative analysis is played by territory constraints owing to magnetic-field limitation imposed by law. More restrictive are the magnetic-field limitations imposed by the state as more convenient GILs are compared with other EHV transmission systems.

Any economic comparison between different transmission technologies must be based on a total cost assessment.

14.2 Economical Comparison of GIL Applications

To economically assess different GIL applications refer to [58, 61, 62, 63, 64, 65].

In these documents the cost comparisons were made between overhead lines, cables and GIL.

This included all parameters influencing the costs like: investments, losses during operation, reactive compensation, EMF and environmental requirements, cost of land and impact of the upfront approval process (time delay) for specific applications mentioned in the references.

14.3 Overall Cost structure

14.3.1 Investment Cost / Capital Equipment / Cost Driver

Until today large scale projects of the magnitude of 10 km to 100 km have not been realized. There the sub-supplier infrastructure for aluminium pipes, insulators and insulating gas are not laid out to produce such large volumes. Investments into production equipment need to be coordinated with available and new suppliers with sufficient lead times to meet project schedule and goals.

It can be expected that the cost per km can be reduced by large scale production.

Example 50 km double system GIL:

300 km of pipes	at 20 m pipe length	a total of 15 000 pipes and weldings are needed.
	at 21 m pipe length	a total of 14 285 pipes and weldings are needed.

14.3.2 Cost Drivers

Cost driver in a large scale project in a tunnel or with a bridge are related to:

Environmental conditions
Temperature, dust, and humidity are influencing the type of equipment needed (tents, heating, cooling)

Accessibility of the site
The accessibility on site will influence the length of the single pipes, and with this the building time and cost.

Transportation restriction
Transportation restrictions at sites and to tunnel access points do influence the length of pipes, and the maximum number of pipes with one truck load. The turning radius for equipment and truck has big impact.

Storage on site
The GIL pipes have a large volume requirement for storage. Storage is needed to balance the laying process with availability of GIL segments. Beside the pipes all the expandable manufacturing supplies need storage in a warehouse

Facilities on site
Warehouse, administration, and storage buildings are needed close to the tunnel access areas. Space for parking, worker and administration equipment and vehicles.

Assembly factory on site
The size of the assembly factory, where the GIL segments are prepared for laying, is much depending on the project schedule. The number of segments per day will define the labour and equipment requirements. Special consideration need to be given to on site handling under cleanliness requirements consistent with high voltage equipment.

Considerations to laying area
The laying area is where the GIL segments are finally placed.
The access and proximity to point of use.
The number of such laying areas will influence the laying speed and cost.

Organisation of the construction sequences
Where to put the welding places, how to handle the transport in the tunnel, where to work in the tunnel.

Restriction on working days / shifts
Local laws and authority rules are influencing the working time, and safety.
The total project schedule is influenced and with this the cost.

Availability of materials and skilled personal
The large amount of material may reduce the cost because of the volume ordered, but also may increase the cost if the available capacities are to low. The skilled personal needs to be trained well in advance of the project start.

14.3.2.1 Materials

Enclosure and conductor pipes
The material used is aluminium alloys, and the price is linked to the volume forecast of the London exchange material index. For the example of 50 km with two GIL Systems a total of about 6500 t is needed.
That means that early contacts to the suppliers are recommended.

Insulating gas
For the example of 50 km of two GIL systems a total of 400 t SF_6 is needed when the insulating gas mixture 20% SF_6 and 80% N_2 is used.
Today the annual world production offers a capacity of about 9 000 t, it is recommended to contact the suppliers early.

Insulators
The total volume of insulators needed is not market driving. Insulators are usually made in house of the GIL manufacturer.

Support structures
The volume of steel structures is compared to the steel marked not big, and has a minimum impact. But it is a local market driver delivered from companies in the region.

Low voltage power supply
The installation of low voltage power supply equipment.

14.3.2.2 Labour Cost

Special skilled personal is needed, e.g. welders, but the number is not so high that it will cause problems in hiring.

14.3.2.3 Handling on Site

The handling on site is dependent on the possibility of transporting the pipes by rails, hanging monorail or other transport means.

For the handling within the tunnel lifting and positioning tools are needed at assembly locations. The access to the structure to support the GIL in the tunnel will influence the work flow.

The speed of laying is dependent on the method of assembly and the organisation of the handling process on site.

The great advantage of GIL is that the handling can be carried out in parallel at many locations, which would speed up the whole installation process.

14.3.2.4 Installation Process

Supports
Support structures mounting in the structure to be scheduled in the project.
Consideration of anchoring in the tunnel walls (wall thickness is about 20 to 25 cm) shall be determinate and coordinated with the allowable mechanical loads.

Welding
Welding in the structure at mounting places for subassembly
To use the enlargements of pilot tunnel for welding and assembling the GIL segments

Laying
Laying in the structure needs to be orientated on the structure accessibility (working space) and the project time schedule.

Gas handling on site
The long structure needs special treatment of the evacuation and gas filling of the GIL.
Consideration must be taking to the size of the equipment fitting into structure.
Transportation of equipment and storage of the gas mixture.
Use of auxiliary piping for the evacuation.

14.3.2.5 High Voltage Testing

Timing schedule
The project commissioning schedule will establish the requirement for intermittent testing capabilities.

Number of testing points
The number of testing point will then define test system design.

Size of test equipment
System design will determine the size of test equipment depending on the GIL segment length to be tested. The access to the testing point has an impact on the size of the testing equipment.

14.3.2.6 Connection Points / Switching Yards

Installations
For long lines of GIL (e.g. 50 km) circuit breakers, disconnectors, ground switch, surge arrestor, ct, vt, and control equipment are needed to the possibility to separate and to operate in the network.

Grounding
The GIL is solid grounded system and will be connected to the structure grounding, and to the switchyard at both ends.

Land usage
The size is depending on the switchgear technology (air or gas insulated) and will be chosen according the local requirements.

14.3.2.7 Reactive Power Compensation

The low capacitive load of a GIL does in normal cases and with length of 50 to 100 km not require additional reactive power compensation.

Therefore no additional costs for reactive power compensation losses occur.

14.3.2.8 Planning, Commissioning and Authorisation Cost

Studies
Environmental impact studies are required by authorities.
System and network studies
Thermal studies

Commission cost
To use or rent the structure from a third party (tunnel or bridge owner)

14.3.2.9 Monitoring and Control Systems

Gas density monitoring
Each gas compartment need to be monitored.

Arc fault location
One arc fault location system for the total length of the line.

Low oxygen warning system
To protect human by entering the tunnel.

Air quality detectors
To protection of humans and to be connected to the operation system (e.g. ventilation control).

Onsite wiring
To connect all monitoring, control and communication devices.

14.3.2.10 Ventilation and Cooling

Installation cost
The cost of the equipment.

Place
The cost of the additional civil requirement for equipment installation

Operation cost
The cost for energy and maintenance to operate the ventilation

14.3.3 Communication, Operation and Maintenance

Supervision
The tunnel or bridge needs periodic visits, and inspections.
Video camera systems may be used.

Lighting
For entering in cases of emergency, inspection and maintenance.

Auxiliary Power System
To be independent for security reasons.

Communication
To connect people entering the structure to the outside in case of help needed.

Tunnel/Bridge maintenance
Maintenance cost for tunnels or bridge might be significant, e.g. drainage system.

14.3.4 Power Transmission Losses

GIL
The transmission losses of the GIL according to the transmitted power are relatively low, see Table 3.

Compensation
No compensation losses for reactive power compensation in normal cases.
Network calculation and simulations are needed in each project.

14.3.5 Repair Process

Exchange
In case of repair a segment of GIL to be exchanged, length approximately 20 to 30 m.

High voltage testing
To recommission the GIL high voltage testing is needed.

14.4 Dismantling Cost

At the end of live the main material of the GIL can be separated in aluminium, insulation gas and insulators.

These materials can be sold for recycling and reuse.

The cost of the dismantling may be covered by the price of recycled material.

15 Conclusion

This brochure shows that for the future a large scale of possibilities to apply Gas Insulated Transmission Lines are a practical opportunity to solve the need of high power transmission. The restructuring of the transmission network with large scale installations of wind farms on- and offshore, solar thermal power plants, tide power plants on one side and the replacement of old thermal power plants, which are usually larger in scale and power production and widely spread local generation with photovoltaic, small wind generation, biogas generation and district heating with power generation will change the power network. New transmission capabilities are needed and ecological and economical requirements need to be fulfilled.

Secondly this brochure shows clearly that there is a strong benefit on both sides by using traffic bridges and tunnels for high power transmission lines. Very expensive structures like high speed train tunnels crossing e. g. the Alps, Pyrenees and other mountains may be laid out in the way that also electrical power can be transmitted through the tunnel. The same can be said for large bridges e. g. the Bosporus Bridge in Turkey, the Öresund Bridge in Denmark / Sweden or the Tsing Ma Bridge in Hong Kong, China are only a few examples where GIL could have been used to solve electric power supply bottle necks.

The most important message which can be drawn from this brochure is that in any case of a tunnel or a bridge for common use with a GIL the planning has to start early. In an optimum situation both planers for the electrical system and for the traffic tunnel or bridge are planning jointly together. This is easy said but need some initiative, because the authorities and responsibilities are not the same. Strong coordination is needed and this has to be early in the process to be successful.

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Annexes

Detailed Investigations on GIL Application on Long Structures

Annex A

A1 Enclosure Circulating Currents

Proximity Effect

It is well-known that the enclosures of the three phase conductors of a GIL must be solidly bonded together and grounded at the ends and at regular intervals along the line: this yields enclosure and phase current phasors nearly equal but 180° out of phase. Due to the importance of this fact, chiefly regarding the subsequent almost null external magnetic field, a simple and evident matrix procedure is here reported [4]. Let us consider the model of Figure 73, where $\boldsymbol{i_c}$ (whose elements are i_1, i_2, i_3) is the phase conductor current vector, $\boldsymbol{i_e}$ (whose elements are i_4, i_5, i_6) the enclosure current vector, $\boldsymbol{u_e}$ and $\boldsymbol{u_e^*}$ the enclosure voltage vectors at the sending-end and at the receiving-end of the line respectively.

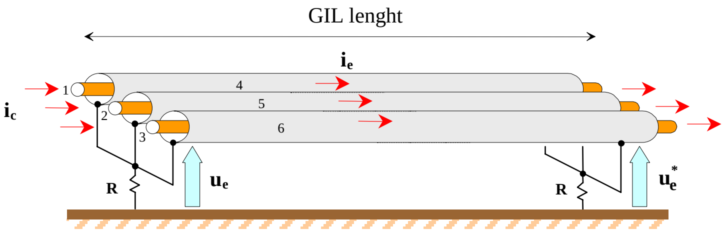


Figure 73: Simplified model of a single-circuit GIL

Considering only the longitudinal self and mutual impedances of the line, the foregoing vectors are related by the following equation

$$\boldsymbol{u_e} = \boldsymbol{Z_{ec}} \boldsymbol{i_c} + \boldsymbol{Z_{ee}} \boldsymbol{i_e} + \boldsymbol{u_e^*} \qquad (1)$$

with $\boldsymbol{Z_{ec}}$ and $\boldsymbol{Z_{ee}}$ calculated by means of Carson's theory. By noting that $\boldsymbol{Z_{ec}}$ and $\boldsymbol{Z_{ee}}$ differ only in diagonal elements for enclosure resistances r_e

$$\boldsymbol{Z_{ee}} = \boldsymbol{Z_{ec}} + \begin{array}{|c|c|c|}\hline r_e & & \\ \hline & r_e & \\ \hline & & r_e \\ \hline \end{array} = \boldsymbol{Z_{ec}} + \boldsymbol{R_e}$$

and assuming that enclosures are perfectly bonded and grounded at the line ends, so that $\boldsymbol{u_e=0}$ and $\boldsymbol{u_e^*=0}$, (1) becomes

$$\boldsymbol{0 = Z_{ec} i_c + (Z_{ec} + R_e)\, i_e} \quad ;$$

consequently

$$\boldsymbol{0 = I \cdot i_c + (I + Z_{ec}^{-1} R_e) \cdot i_e} \quad ,$$

where I is the 3×3 identity matrix. If enclosure resistances could be null it would result

$$\boldsymbol{i_e = -i_c}$$

i.e. there would be a perfect opposition between conductor and enclosure currents (hence a perfectly zeroed external magnetic field). Considering typical enclosure resistance (i.e. 2.33 mΩ/km), three different values of ground resistivity ρ_g, and imposing positive sequence currents in inner conductors, Table 10 reports the results.

Table 10: Enclosure currents for different ground resistivity values

	ρ_g=100 [Ω·m]	**ρ_g=1000 [Ω·m]**	**ρ_g=50000 [Ω·m]**
$\boldsymbol{i_c}$	$\boldsymbol{i_e}$	$\boldsymbol{i_e}$	$\boldsymbol{i_e}$
$1 \angle 0°$	$\boldsymbol{0.992783 \angle -178.741°}$	$\boldsymbol{0.992840 \angle -178.742°}$	$\boldsymbol{0.992908 \angle -178.743°}$
$1 \angle -120°$	$\boldsymbol{0.999463 \angle 61.898°}$	$\boldsymbol{0.999458 \angle 61.899°}$	$\boldsymbol{0.999453 \angle 61.901°}$
$1 \angle 120°$	$\boldsymbol{1.006592 \angle -58.713°}$	$\boldsymbol{1.006548 \angle -58.751°}$	$\boldsymbol{1.006494 \angle -58.718°}$

The high values of ρ_g chosen for the computations in Table 10 are well justified when considering a GIL installation in a mountain gallery with very high resistivity of rocks.

The results of Table 10 show that the enclosure phasors change very slightly as a function of ground resistivity ρ_g. This can be explained considering that the sum of the multiconductor currents is almost null $\sum_{k=1}^{6} i_k \cong 0$ so that the variation on ρ_g slightly affects the enclosure phasors. Moreover, it is worth nothing that the most important consequence of this current opposition is the strong reduction of magnetic field outside the line in spite of low additional losses in enclosures. This simple but elegant matrix procedure takes into account the earth return currents but it is unable to consider the current density distribution in the enclosures (i.e. proximity effects).

For a pipe with a given thickness, the proximity effects are responsible for non-uniform current distribution along the circumference whereas the skin effect for non-uniform current distribution along the radius.

There are several contributions in literature aiming at demonstrating that the proximity effects in GILs are always very slight because the external magnetic field (responsible for giving non-uniform current distribution) is always very low [5, 6].

With regard to skin effect, its incidence is negligible until the thicknesses of both phases and enclosures are less than the penetration depth (advisable choice!).

Electra 100 gives some formulae in order to calculate the conductor R_c and enclosure R_e resistances taking into account the skin and proximity effect contributions namely:

$$R_c = R'_{oc} \cdot (1 + y_c) \qquad \text{where} \qquad R'_{oc} = R_{oc} \cdot [1 + \alpha_c \cdot (\theta_{core} - 20)]$$
$$R_e = R'_{oe} \cdot (1 + y_e) \qquad \text{where} \qquad R'_{oe} = R_{oe} \cdot [1 + \alpha_e \cdot (\theta_{schermo} - 20)]$$

R_{oc} dc phase conductor resistance at 20°C $[\Omega / m]$;

R'_{oc} dc phase conductor resistance at operating temperature $[\Omega / m]$;

R_{oe} dc enclosure resistance at 20°C $[\Omega / m]$;

R'_{oe} dc enclosure resistance at operating temperature $[\Omega / m]$;

α_c phase conductor temperature coefficient $[K^{-1}]$;

α_e enclosure temperature coefficient $[K^{-1}]$;

y_c skin and proximity effect coefficient for the phase conductor;

y_e skin and proximity effect coefficient for the conductor.

For y_c and y_e calculation refer to [1] or [3].

It can be demonstrated [1], as stated before, that for usual installations the contribution of proximity effects in y_c and y_e is always very low: the same for skin effect contribution if phase conductor and enclosure thicknesses are less than penetration depth.

Minimize Electric Field

With regard to the dimensional characteristics, it should be noted that, in order to minimize the electric field, the optimal ratio between enclosure inner diameter D'_{to} and conductor outer diameter D_{ti} should be *2,72*.

In practical applications any ratio between *2,5* and *3* can be adopted since in this range the electric field increases only of *0,5%*.

Chiefly for tunnel installations (and for the other installation as well), it would be advisable to have power losses as lower as possible (even if GIL has the lowest power losses of any a.c. transmission lines) in order to minimise the cooling requirements (IEC 61640 stated that for installations in gallery or shaft forced cooling will generally be necessary): this means a GIL low per unit length resistances namely for both phases and enclosures an aluminium alloy with high IACS and a higher cross-section. In order to increase the cross-section, one could think to enlarge thicknesses but it is worth remembering that the maximum thickness must be compatible with the penetration depth. In fact, the penetration depth δ of aluminium at *50 °C* and at *50 Hz* is:

$$\delta = \sqrt{\frac{2 \cdot \rho}{\omega \cdot \mu}} = 13.045 \text{ mm}$$

So it is advisable not to exceed this thickness for both phases and enclosures. For instance, let us suppose to have the GIL in Table 11:

Table 11: Typical data of a 400 kV GIL

Cross sectional area of phase (Al IACS=61 %)	**mm^2**	*5341*
Cross sectional area of enclosure (Al alloy IACS=52.57 %)	**mm^2**	*16022*
Phase Outer Diameter	**mm**	*180*
Phase thickness	**mm**	*10*
Enclosure Inner Diameter	**mm**	*500*
Enclosure thickness	**mm**	*10*

An increase of 3 mm in phase thickness (i.e. $t_{ph}=13$ mm) would give $r_{ph\_new}=4{,}752$ mΩ/km against $r_{ph\_old}=6.286$ mΩ/km (with $t_{ph}=10$ mm as in Table 11) and hence about *17,8 %* (it can be roughly computed as $100\cdot(r_{ph\_old}-r_{ph\_new})/(r_{ph\_old}+r_{en})$ under the same current) power loss saving (it is worth remembering that r_{en} contributes to power losses as well). The same increase in enclosure thickness gives rise to fewer power loss saving i.e. (r_{en_new}=1,8 mΩ/km; $r=r_{ph\_new}+r_{en\_new}=6{,}54$ mΩ/km with only *7,6 %* power loss saving).

A2 Power Losses and Voltage Drops: Electrical Transmission Performances

The GIL unbalance (voltage unbalance ratio, meant as negative and positive sequence voltage ratio, is about *0,01 %*) is practically negligible with respect to the values 1%÷3% due to an untransposed overhead line. In order to study the steady-state regime, it is possible to refer to the single-phase positive sequence circuit (see Figure 74), with the following per unit length parameters:

- r_{ph} is per unit length phase conductor resistance;
- r_{en} is per unit length enclosure resistance;
- $x = \omega\ell$ is per unit length longitudinal reactance (with ℓ inductance of circuit phase-enclosure);
- $y = \omega c$ is per unit length shunt susceptance (with c capacitance between phase and enclosure).

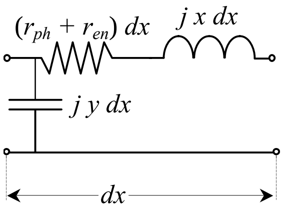


Figure 74: Single-phase positive sequence circuit of a GIL

It should be noted that the shunt conductance $g = \tan\delta\, y_\ell$ is wholly negligible being the gas loss factor $\tan\delta$ practically null. Moreover, the per unit length positive sequence resistance is given by the sum of phase r_c and enclosure r_e resistances (hypothesizing that the enclosures current phasor magnitudes are equal to those of phases). The value of per unit length capacitance is:

$$c = \frac{2\pi\varepsilon_0}{\ln\frac{D'_{to}}{D_{ti}}} = 54.45\ [nF/km] \qquad (2)$$

and per unit length inductance is given by

$$\ell = \frac{\mu_0}{2\pi} \ln \frac{D'_{to}}{D_{ti}} = 0.20 \text{ [mH/km]} \tag{3}$$

where

D'_{to} is the inner diameter of the enclosure;
D_{ti} is the outer diameter of phase conductor.

In this approach, the proximity and skin effects have been neglected (as it appears perfectly allowed in usual installations). By a theoretical standpoint, also the system steady-state regime ought to be studied as a multiconductor dissymmetric line but considering the lowest unbalance ratios, it is possible, alternatively to the multiconductor approach (the only one without approximations), to use a single-phase positive sequence circuit. Once determined the equivalent single-phase circuit, it is rather immediate to calculate the electric quantities.

In fact a sufficiently precise analysis on the behaviour of any transmission lines can be performed by means of the fundamental following relations:

$$\underline{E}_S = \underline{E}_R \cosh \underline{k}d + \underline{i}_R \underline{Z}_0 \sinh \underline{k}d \tag{4}$$

$$\underline{i}_S = \underline{E}_R \frac{\sinh \underline{k}d}{\underline{Z}_0} + \underline{i}_R \cosh \underline{k}d \tag{5}$$

where $\underline{E}_S$, $\underline{i}_S$ are the sending-end phase-to-ground voltage and current respectively;

$\underline{E}_R$, $\underline{i}_R$ are the receiving-end phase-to-ground voltage and current respectively;

$\underline{Z}_0$ is the characteristic impedance;

$\underline{k}$ is the propagation constant;

d is the line length.

In order to give a more immediate perspicuity to the results let us avoid the p.u. method using the real electric units. Once fixed the complex receiving-end power (three-phase), it is possible to calculate the receiving-end current $\underline{i}_R$ to be used in (4) and (5) with the following relation:

$$\underline{i}_R = \frac{\overset{*}{S}_R}{3 \cdot E_R} \text{[kA]} \tag{6}$$

(the symbol * indicates the complex conjugate) where $\underline{S}_R$ [MW + j Mvar] and $\underline{E}_R$ [kV] is set on the real axis i.e. $E_R = U_R / \sqrt{3}$ (U_R is the phase-to-phase receiving-end voltage).

Once calculated by means of (4) and (5), the values of $\underline{E}_S$ [kV] and $\underline{i}_S$ it yields:

$$\Delta U = \frac{\left|\underline{U}_S\right| - \left|\underline{U}_R\right|}{\left|\underline{U}_R\right|} \tag{7}$$

$$\underline{S}_S\left[\mathrm{MW}+\mathrm{j\,Mvar}\right]=3\,\underline{E}_S\,\overset{*}{i}_S \tag{8}$$

$$\Delta\underline{S}=\underline{S}_S-\underline{S}_R=\Delta P+j\,\Delta Q$$

$$\Delta_{P\%}=100\cdot\frac{\Delta P}{P_R} \tag{9}$$

For instance, let us consider a single-circuit GIL with a route length equal to *d=100 km* and the characteristics shown in Table 11.

The subsequent electric transmission parameters are reported in Table 12.

Table 12: Data and parameters of a 400 kV GIL

a			**b**				**c**			***f=50 Hz***
*Phase cross-section (Al IACS=61%)**	**mm^2**	***5341***	*d.c. resistance of phase at 60° C*	r_{ph}	**mΩ/km**	***6,286***	*Longitudinal impedance*	$\underline{z}=r_{ph}+r_{en}+j\omega\ell$	**mΩ/km**	***8,6+j64***
*Enclosure cross section (Al alloy IACS=52.57 %)**	**mm^2**	***16022***	*d.c. resistance of enclosure at 50°C*	r_{en}	**mΩ/km**	***2,330***	*Shunt admittance*	$\underline{y}=g+j\omega c$	**mS/km**	***0+j 0,017***
Phase Outer Diameter	**mm**	***180***	*Total d.c. resistance*	$r=r_{ph}+r_{en}$	**mΩ/km**	***8,6***	*Characteristic Impedance*	$\underline{Z}_0=\sqrt{\frac{\underline{z}}{\underline{y}}}$	**Ω**	***61,46 ∠ -0,07 rad***
Enclosure Inner Diameter	**mm**	***500***	*Phase-enclosure voltage*		***kV***	$400\,kV/\sqrt{3}$	*Propagation Constant*	$\underline{k}=\sqrt{\underline{z}\cdot\underline{y}}$ $\underline{k}=k'+jk''$	**1/km**	***0,0001 + j 0,001***
Phase and enclosure thickness	**mm**	***10***	*Phase-enclosure inductance*	ℓ	**mH/km**	***0,204***	*Surge Impedance Loading at 400kV*	$SIL=\frac{400^2}{\lvert\underline{Z}_0\rvert}$	**MVA**	***2604***
Insulating gas N$_2$/SF$_6$	**%**	***20/80***	*Phase-enclosure leakance*	g	**nS/km**	***negligible***	*Capacitive current related to U$_o$= $400\,kV/\sqrt{3}$*	I_{cap}	**A/km**	***3,95***
Pressure	**bar**	***7***	*Phase-enclosure capacitance*	c	**μF/km**	***0,0545***	*Ampacity*	I_a	**A**	***2400÷3000 It depends upon the installation type***

*IACS = International Annealed Copper Standard (IACS=100 % ⇒ Copper Standard Conductivity = 58,108 m/Ω·mm^2)

From Table 12 it is of note the low per unit length capacitance *c* (*54.5* nF/km) and the high ampacity, which is dependent upon the installation type, but is always very high namely from *2400* A to *3000* A. The foregoing parameters have been used in (7), (8), (9) to achieve the results reported in Table 13.

Table 13: Performance of single-circuit GIL 400 kV, 100 km calculated by means of equivalent single-phase model

U_R=400 kV (at receiving-end)							
$\underline{S}_S$ [MW] +j [Mvar]	|$\underline{S}_R$| [MVA]	$\underline{S}_R$ [MW] +j [Mvar]	cos□	|$\underline{U}_S$| [kV]	□$_{P\%}$	□P [W/m]	□U [%]
0.05 – j 311.56	0	0	0.98	399.28	//	0.8755	-0.178
490.39 – j 210.16	500	490 + j 99	0.98	400.05	0.079	6.7689	0.012
981.49 – j 103.06	1000	980 + j 199	0.98	400.82	0.152	26.1213	0.205
1473.4 + j 9.7322	1500	1470 + j 298	0.98	401.61	0.228	58.9327	0.401
1966.0 + j 128.22	2000	1960 + j 398	0.98	402.40	0.306	105.2032	0.600
2953.6 + j 382.27	3000	2940 + j 597	0.98	404.03	0.462	238.12231	1.007
3944.2 + j 659.10	4000	3920 + j 796	0.98	405.70	0.618	424.8754	1.425
4937.9 + j 958.71	5000	4900 + j 995	0.98	407.42	0.774	665.4645	1.855
5934.7 + j 1281.1	6000	5880 + j 1194	0.98	409.18	0.930	959.8907	2.296

By making a comparison with the other transmission technologies (here not reported) a conclusion can be drawn: gas insulated lines has the best transmission efficiency due to null dielectric losses and lowest Joule losses.

Other notes can be derived from Table 12:

- In spite of the high power transfers, voltage drops are very low (always lower than 2.5%) and active losses (always lower than 1%) are fully satisfactory and noteworthy in global cost evaluation;
- In a wide load range GIL gives an effective power factor correction at sending-end;
- Capacitive reactive power required at the sending-end becomes considerable only at very low loadings.
- The grey-highlighted rows can be representative of overload regimes which are well suitable for GIL. In fact GIL overload capacity is about $2,2*I_a$ for *10 min* and $1,9*I_a$ for *1 h.*

A3 Shunt Reactive Compensation

The per unit length longitudinal impedance of a GIL is lower than those of overhead and cable lines. This must be taken into account when integrating such lines in an existing grid chiefly constructed of overhead lines. Consequently for any given GIL application, detailed power flow studies and network simulations must be performed. The power flows do not depend upon the per unit length impedance but upon the total (due node to node length) impedance. Attention must be paid when there are two different parallel lines with the same length.

In order to evaluate the operating capability of Long AC EHV transmission XLPE cables and the need or less of reactive compensation, some procedures have been developed [12]: this approach is worth applying to any distributed-parameter transmission line (including overhead lines) and hence to GIL.

The following calculations show that GIL has good power transmission properties concerning the physical basic data to get integrated into the grid. The study of the quality of the no-load voltage and the current limiting length shows this.

Firstly it is important to analyze the no-load regime: d_U and d_I are the no-load voltage and current limit lengths respectively, which for GIL are equal to:

$$d_U = 308\ km; \qquad d_I = 542\ km$$

It is worth noting that the limit d_U is much more restrictive than d_I.

However these length limits are merely theoretical because the network nodes which the line is linked with have infinite fault level. By means of a simplified but useful approach that allows considering the real fault level of the network source, the equivalent generator can be used (as seen at node S in a regime without the line): it is characterized by the no-load voltage (which is supposed to be U_o^+ =230 kV) and the short-circuit impedance (for simplicity it is purely inductive jX_{Sc}); the no-load regime at R deriving from the insertion of GIL at S, is completely defined by

$$\underline{U}_{oS} = \frac{U_o^+}{jX_{cc} - jX_C} \cdot \left(-jX_C\right) \qquad \underline{U}_{oR} = \frac{\underline{U}_{oS}}{A_{id}} \tag{10}$$

where $-jX_C = A_{id}/\underline{C}_{id}$ is the capacitive impedance of GIL. With regard to X_{Sc} evaluation it is possible to refer to the subtransient impedance U_o^+ / I''_{Sc}, giving the subtransient current I''_{Sc} (three-phase at *S*) the foreseen highest values (≈ *50 kA* → X_{Sc} = *4.6* Ω) and lowest (≈ *10 kA* → X_{Sc} = *23* Ω) in the *400 kV* network.

Due to capacitive nature of the load X_C at *S* and the Ferranti's effect at *R*, $|\underline{U}_{oR}|>|\underline{U}_{oS}|> U_o^+$ will be always verified so that in any case the phasor $\underline{U}_{oR}$, computed by means of (10), will not have to exceed the magnitude *242.5 kV*=$U_m/\sqrt{3}$.

The length for which this happens is the length L_e.

Figure 75 shows L_e as a function of short-circuit impedance for single and double-circuit GIL: when the network is strong the limit length is rather high both for single-circuit and double-circuit whereas when the network is weak (namely with three-phase short-circuit currents up to 15 kA) the limit length reduces considerably.

So this is the most restrictive criterion and has to be verified in each situation.

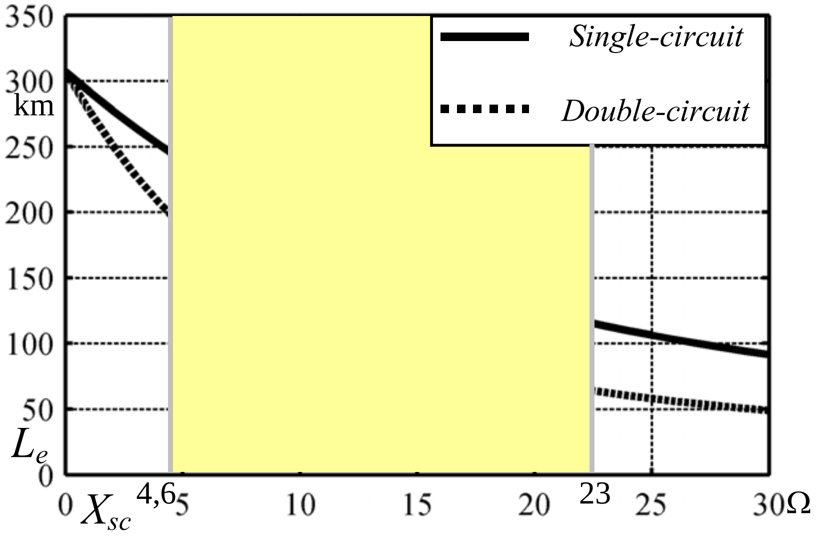


Figure 75: No-load limit lengths as a function of short-circuit impedance

Also the other criterion, which deals with the power capability, is few limiting: Figure 76 (d=120 km) highlights that GILs are suitable for bulk power transmission (chosen ampacity I_c=2400 A).

The voltage levels at node R play a key role in the network service and can be directly visualised in the "receiving-end power area" by means of phase voltage curves parameterized with $|\underline{U}_{oR}|$ constant, implementing the well-known expression of receiving-end power

$$\underline{S}_R = 3\,\underline{U}_{oR}\,[(\underline{U}_{oS} - \underline{A}_{123}\,\underline{U}_{oR})/\underline{B}_{123}]^* \tag{11}$$

Once fixed $\underline{U}_{oS} = 230\ kV \angle \sigma$ and by setting $\underline{U}_{oR} \angle \rho$ (e.g. with magnitudes *220, 225, 230, 235, 240 kV,*) it is possible to give suitable σ-ρ values such to determine complex power $\underline{S}_R$ in the "receiving-end area". In such a way, it can be clearly singled out the regimes which are not acceptable owing to excessively high or low voltage levels at *R* (even if compatible with limit I_c): for example, heavy reactive power flows or active ones on long runs.

However, the voltage level curves in Figure 76 show the very good voltage levels at receiving-end in a wide field of capability limits.

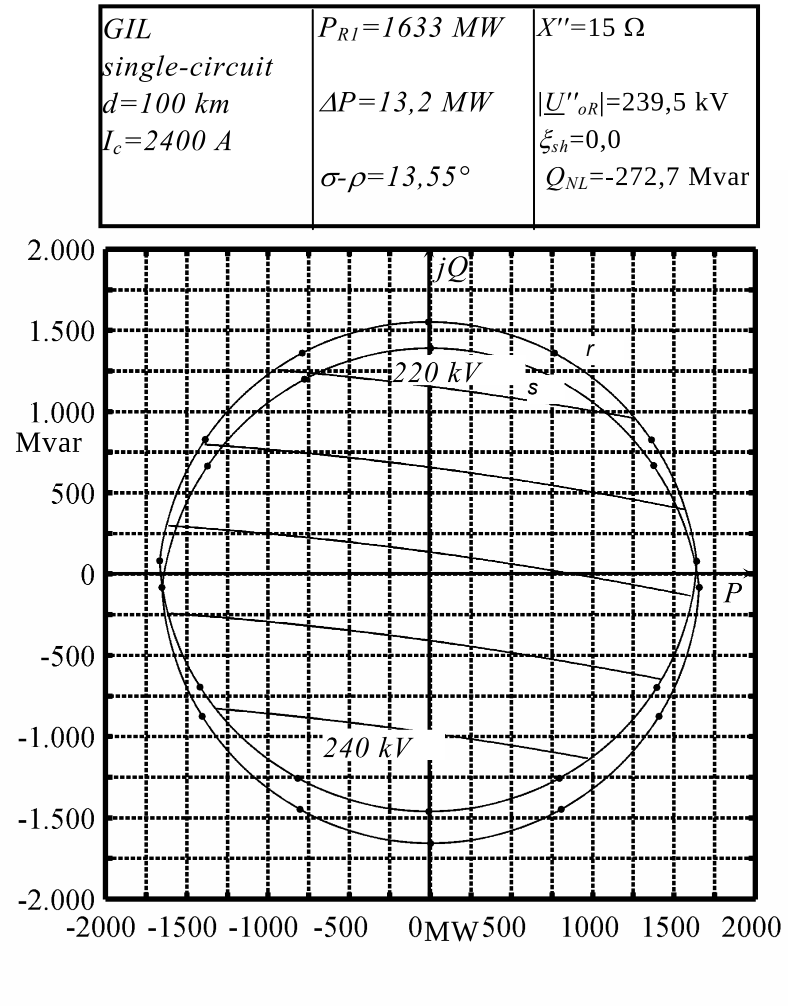


Figure 76: Power Capability Chart for GIL ; d = 100 km

If GIL is used in a mixed lines composed of a cascade connection of overhead lines, the issue is more complicated. For a thorough investigation on this topic refer to [76].

Annex B

B Magnetic Field Calculations

This annex gives very detailed information about the magnetic field in a tunnel by using GIL. It is a special application of the general statement given in clause 5.

Since the fundamental electrical quantities generating the magnetic field are the current phasors, a choice of current scenario must be undertaken.

Therefore two scenarios will be hypothesized in the following: the former is the GIL operation at 2000 MVA (cosφ=0.98) and the latter at 3000 MVA (cosφ=0.98).

Of course, any current value must give rise to an allowable enclosure temperature accordingly to IEC 61640. For tunnel installation, the maximum allowable enclosure temperature is 70°C when touchable and 80 °C when not touchable.

The multiconductor analysis [4] allows studying the variation of the phase conductor currents along the line so that a choice of the section in which studying the magnetic field must be undertaken. The choice is the receiving-end section where the phase currents are *maximum* (so for the magnetic field) in order to undertake a conservative choice.

Table 14 and Table 15 report the system current phasors for 2000 MVA and 3000 MVA loadings respectively computed by means of multiconductor procedures [4].

It is worth noting that the multiconductor procedure can exactly compute the enclosure current phasors: they are almost equal to those of phase conductors but 180° out of phase. Furthermore Table 15 has been computed for the phase sequence RST – TSR (named asymmetrical supply or low reluctance configuration, see Figure 77).

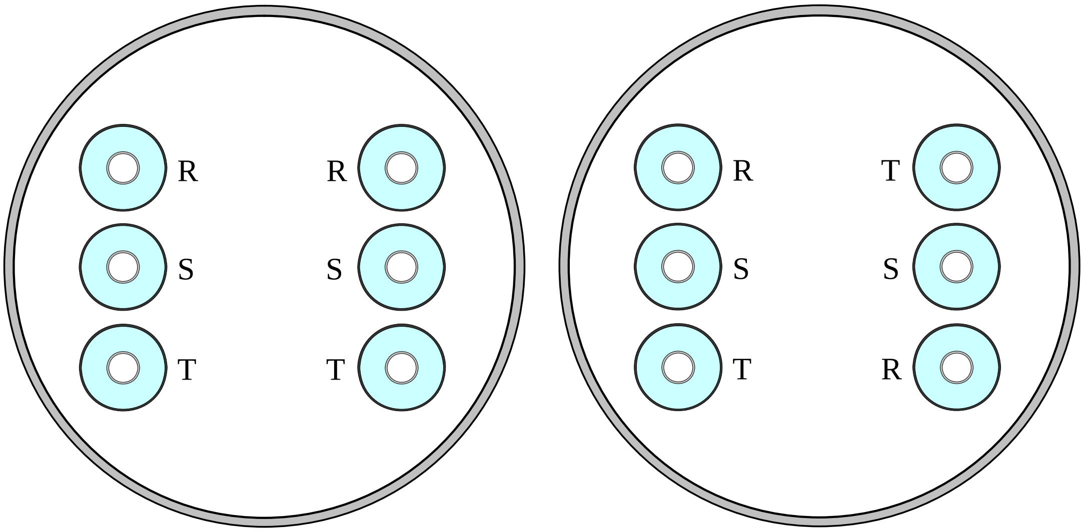
Table 14: Conductor currents for double-circuit GIL 400 kV $|\underline{S}|$=2000 MVA, d = 57 km

Receiving-end Currents [A]				
Phases			**Enclosures**	
R	**1**	|1442| ∠-4°	**7**	|1423.4| ∠169°
S	**2**	|1442| ∠-124°	**8**	|1441.7| ∠49°
T	**3**	|1442| ∠116°	**9**	|1460.1| ∠-71°
T	**4**	|1442| ∠116°	**10**	|1460.1| ∠-71°
S	**5**	|1442| ∠-124°	**11**	|1441.7| ∠49°
R	**6**	|1442| ∠-4°	**12**	|1423.4| ∠169°
Steel Reinforcement of the gallery (S.R.G.)			**13**	| 37.3| ∠144°

Table 14 shows that beyond the asymmetrical supply, also RST – RST phase arrangment (named symmetrical supply) could be possible.

Table 15: Conductor currents for double-circuit GIL 400 kV $|\underline{S}|$=3000 MVA, d = 57 km

Receiving-end Currents [A]				
Phases			**Enclosures**	
R	**1**	|2164| ∠-14°	**7**	|2135.4| ∠168°
S	**2**	|2164| ∠-134°	**8**	|2162.8| ∠48°
T	**3**	|2164| ∠106°	**9**	|2190.5| ∠-72°
T	**4**	|2164| ∠106°	**10**	|2190.5| ∠-72°
S	**5**	|2164| ∠-134°	**11**	|2162.8| ∠48°
R	**6**	|2164| ∠-14°	**12**	|2135.4| ∠168°
Steel Reinforcement of the gallery (S.R.G.)			**13**	| 56.0| ∠143°



SYMMETRICAL ONE
or SUPER BUNDLE PHASING

ASYMMETRICAL ONE
or LOW RELUCTANCE PHASING

Figure 77: Symmetrical (RST-RST) and asymmetrical (RST-TSR) supply

The authors have also studied the current density distribution [5, 6] taking into account the proximity effects: these effects are not so marked if the enclosure spacings do not lessen below 0.3 m.

However this spacing results necessary for orbital welding operation.

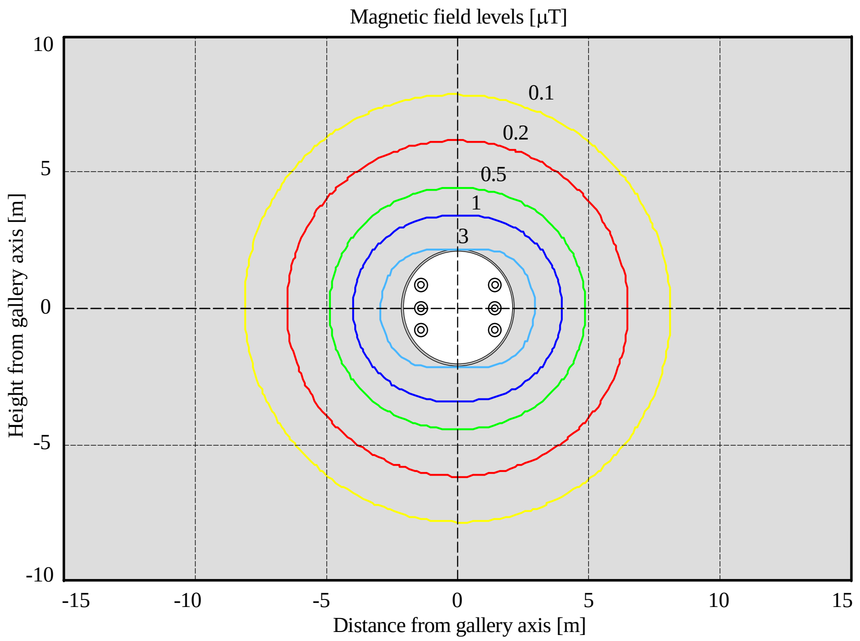


Figure 78: Magnetic fields outside the tunnel with asymmetrical supply and $|\underline{S}|$ = 2000 MVA (cosφ = 0.98)

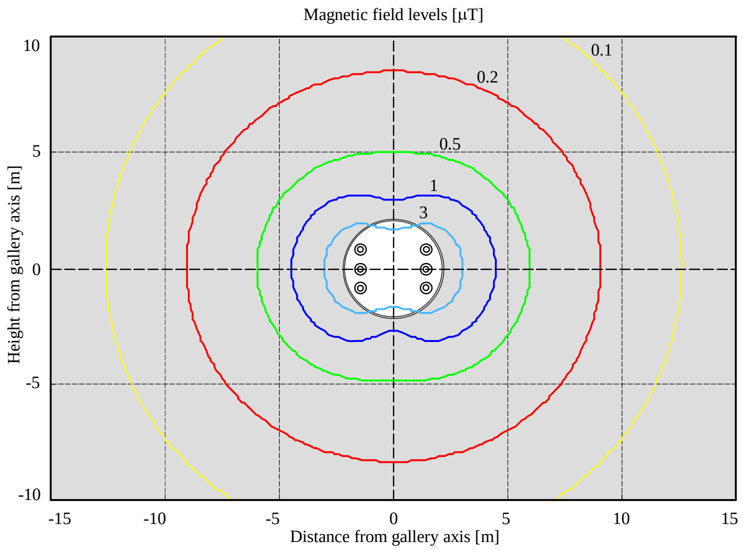


Figure 79: Magnetic fields outside the tunnel with symmetrical supply and $|\underline{S}|$ = 2000 MVA (cosφ = 0.98)

All the magnetic field computations in the following refer to current phasors in Table 14.

Figures 78, 79 and 80 show the magnetic field levels outside the pilot tunnel for different arrangements and supplies. By observing these $_{\text{Figure}}$s, the following considerations yield:

- the supply configuration that minimizes the external magnetic field is the asymmetrical one (compare Figure 78 with Figure 79);

- outside the pilot tunnel, the consideration of proximity effects in magnetic field calculation give negligible differences from not considering these effects;
- the magnetic field shielding due to the opposing currents flowing in the enclosures is very effective: in Figure 78 at the distance of *2.8* m from gallery axis the magnetic field level is below *3* μT. Hence, a great electromagnetic compatibility both with MV-LV cables, fibre optics (usually hosted in a service gallery) is reached;
- the geometrical compactness of the two circuits (see Figure 80) gives an advantageous effect on magnetic field levels: in fact the value of *3* μT is reached at *1.77* m from tunnel axis;
- the value of 100 μT is never overreached outside the pilot tunnel.

As regards the magnetic field inside the pilot tunnel, Figure 86 also shows the study line (highlighted in red colour) along which the magnetic field has been computed.

Figure 81 shows the magnetic field along the study line for asymmetrical and symmetrical supplies respectively.

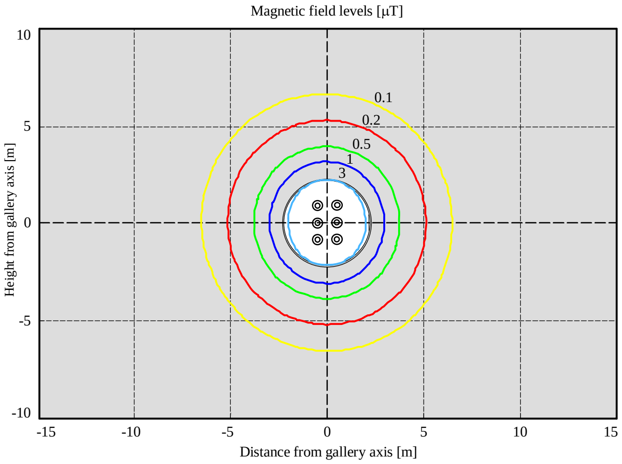


Figure 80: Magnetic fields outside the tunnel (RST-TSR) for CPA and $|\underline{S}|$ = 2000 MVA (cosφ = 0.98)

The maximum value along this line is in the proximity of enclosures; moreover, for asymmetrical supply the magnetic field at the centre of the pilot tunnel is zeroed in accordance with the magnetic field theory whilst for symmetrical supply the values are higher and the magnetic field at the centre of the tunnel is different from zero.

However, the magnetic field value does not overreach 40 μT.

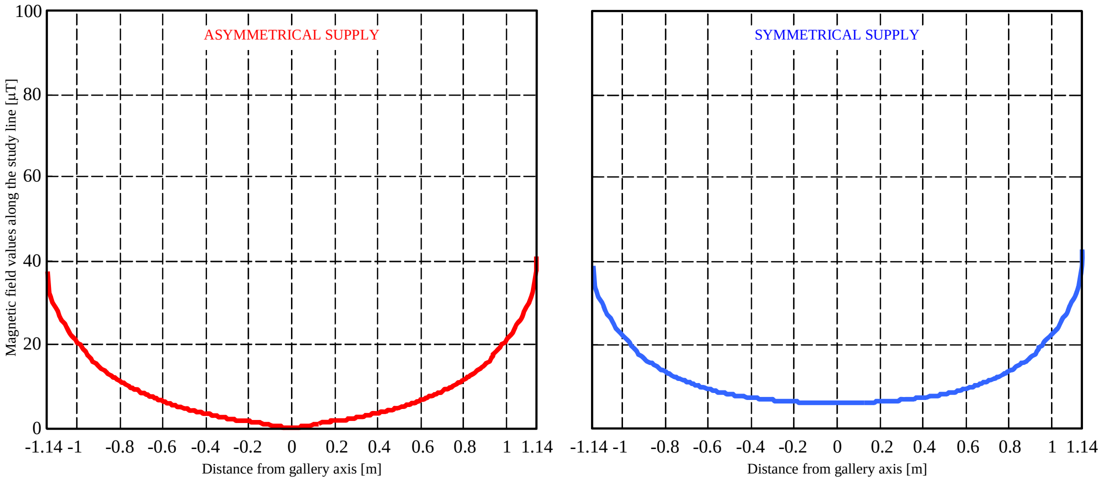


Figure 81: Magnetic field inside the pilot tunnel along the study line for asymm. and symm. supply - DPA

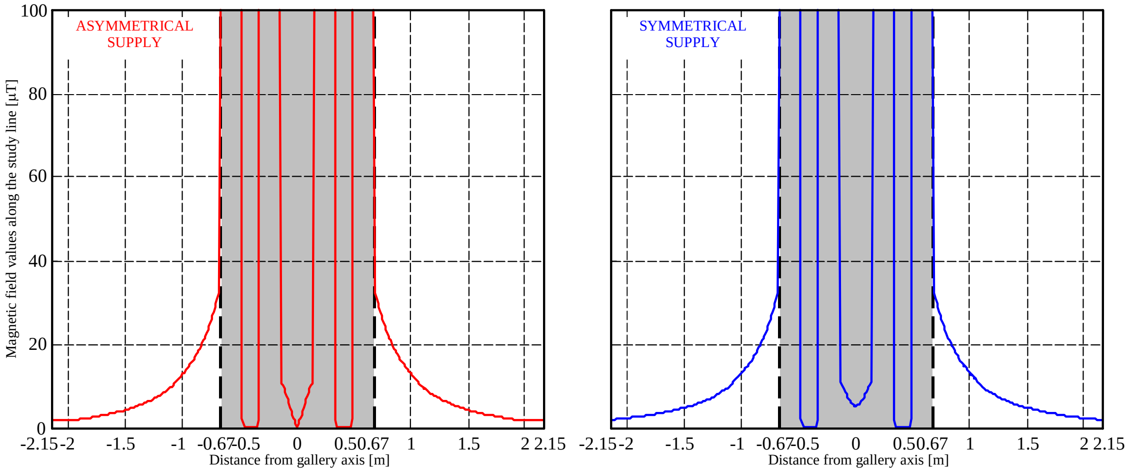


Figure 82: Magnetic field inside the pilot tunnel along the study line for asymm. and symm. Supply - CPA

With regard to this kind of installation, the consideration of proximity effects in magnetic field computation gives negligible differences outside the tunnel and slightly inside: the comparison with a FE model shows that there is a really good agreement being the computation considering the proximity effects more precise (see Figure 83).

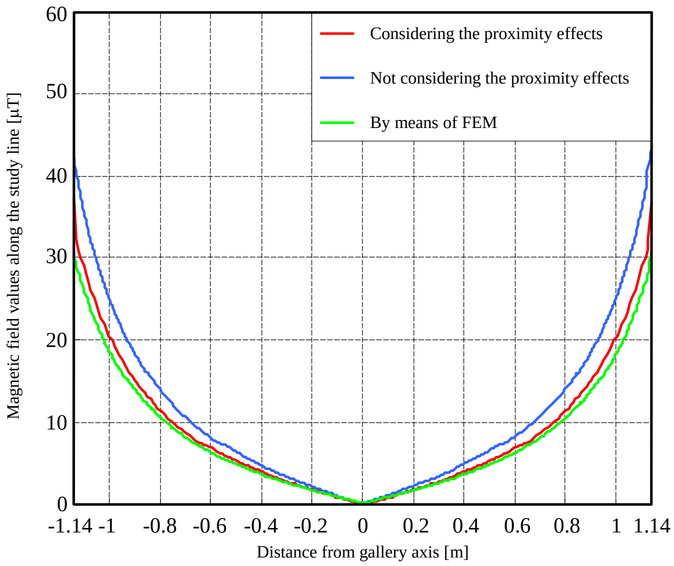


Figure 83: Comparison of the magnetic field inside the pilot tunnel - DPA

Figure 82 shows the comparison of the magnetic field computations between symm. and asymm. supplies in CPA: the shadowed zone represents the non-viable area owing to the presence of transmission line. The magnetic field values are always very low.

All the magnetic field computations in the following refer to current phasors in Table 15.

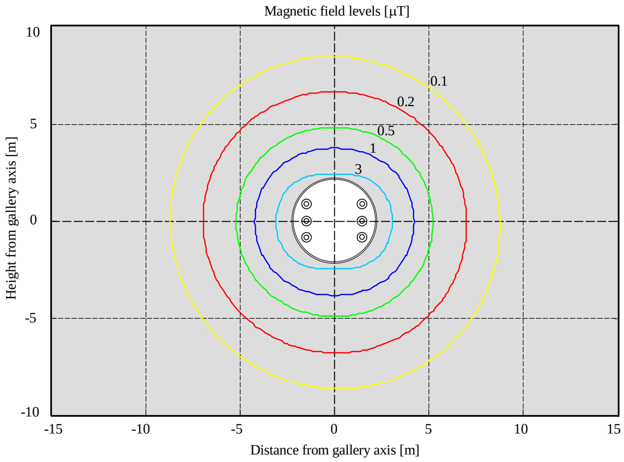


Figure 84: Magnetic field for DPA, asymm. supply and $|\underline{S}|$ = 3000 MVA (cosφ = 0.98)

Once again the supply configuration that minimizes the external magnetic field is the asymmetrical supply (see Figure 84). The differences with the previous results are chiefly on the higher magnetic field levels: the value of *3* µT is reached at *3.13* m (see Figure 31) whilst for CPA of Figure 85 the value of *3* µT is reached at *2.05* m.

Figure 86 shows the magnetic field inside the pilot tunnel: the maximum value is 50 µT.

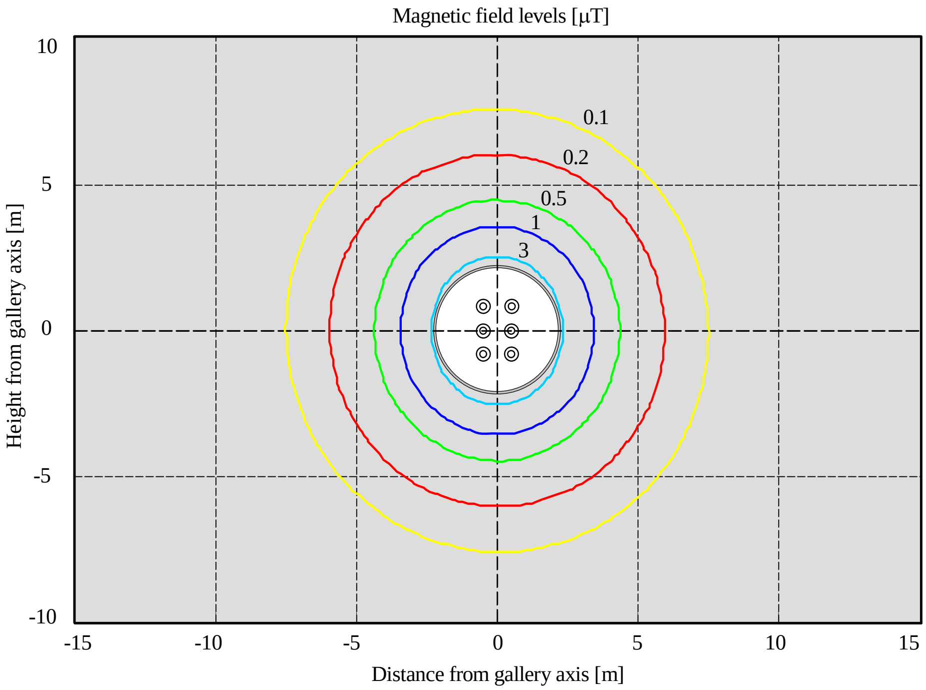


Figure 85: Magnetic field for CPA, asymm. supply

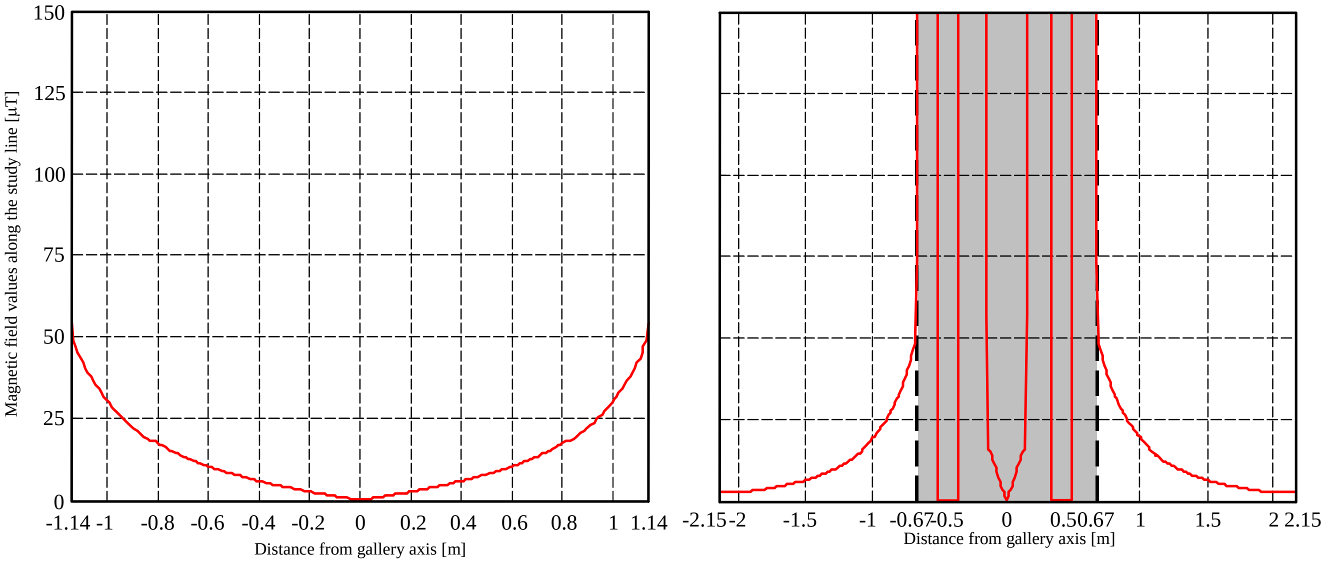


Figure 86: Magnetic field inside the pilot tunnel along the study line for DPA and CPA, asymm. supply

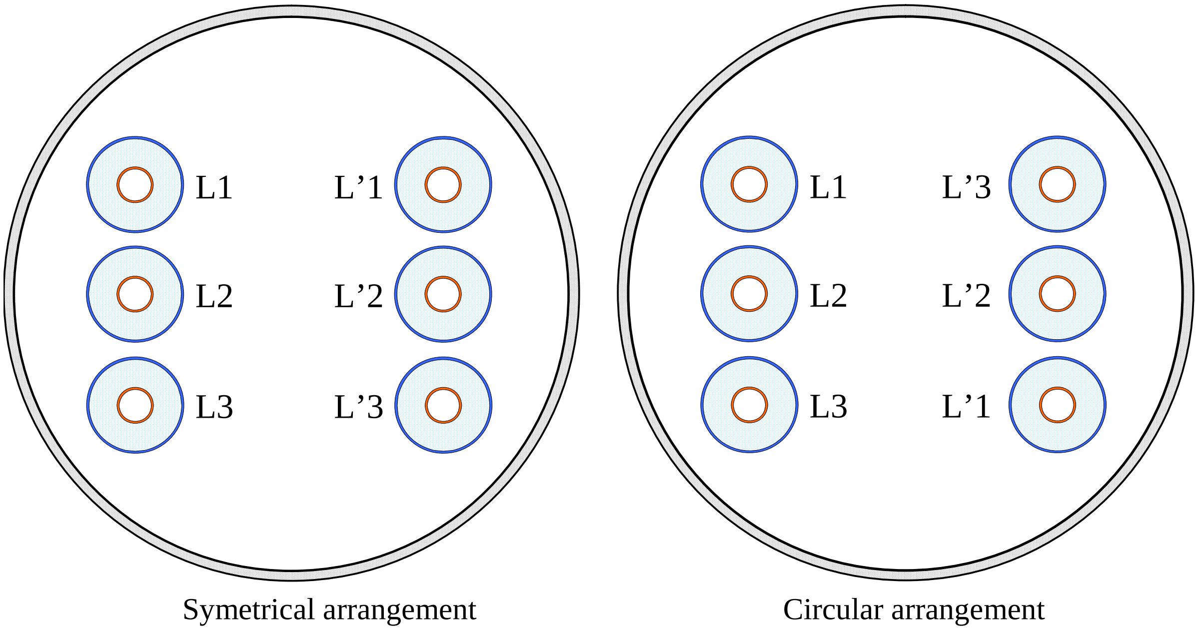


Figure 87: Phase arrangements in a tunnel

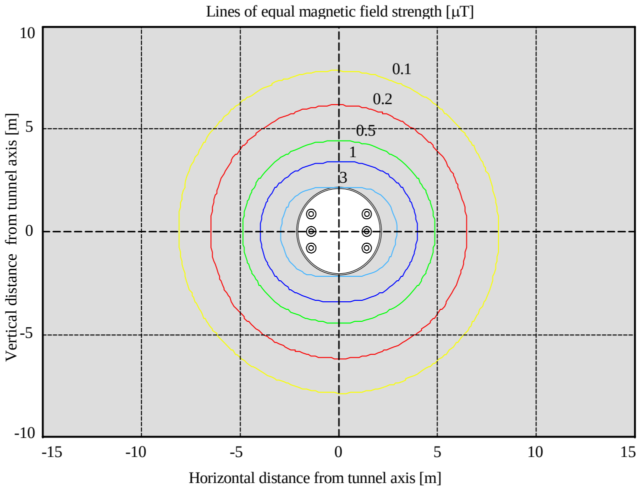


Figure 88: Magnetic field strength when at total load of 2000 MVA is transmitted via two GIL. The phase arrangement is circular (L1,L2,L3 – L'3,L'2,L'1).

Annex C

C High Voltage On-site Test

An alternative high voltage on site test method in which the whole length of a long distance GIL is tested, is described below.

This alternative method has the disadvantage that with the long test length a high amount of energy is stored in the GIL, which might cause internal damage in the event of a discharge during testing.

When gas-insulated transmission lines (GIL) are installed through tunnels of railways or motorways, any interaction between the traffic and the GIL system shall be avoided. This is also related to the reliability of the GIL. To verify its correct installation, a related on-site test of the GIL seems to be a must. But is such a test of a huge GIL feasible? Let us consider the example of the 400kV GIL interconnection between Austria and Italy (65 km length 3,54µF according to Paper [58].

Paper [38] considers many aspects of such a huge 400 kV GIL (65 km, 3.54 µF), but there is not yet information about the after laying-test. An AC withstand voltage test connected with PD measurement according to the UHF sensor method seems to be necessary. Let us consider the voltage generation for the test:

If one assumes that the GIL is tested as a whole and the practice of GIL testing is similar to that of a 400 kV GIS, a 50 Hz test voltage of 515 kV according to IEC 62 271-203 should be applied. Then the tremendous test power of 295 MVA would be required. If this should be supplied according to the resonant principle, the feeding power of the resonant test system would reach the order of 2.5 MVA even if a very high quality factor q' = 120 is assumed. It is obvious that it would be practically impossible to realize such a test.

There are three possibilities to reduce the power demand:

- reduction of the test voltage possibly down to the phase–to–phase voltage (400 kV);
- reduction of the test length by a disconnector in the middle (32.5 km, 1.77 µF, testing from both ends);
- reduction of the test frequency as for after-laying test on cables down to 20 Hz

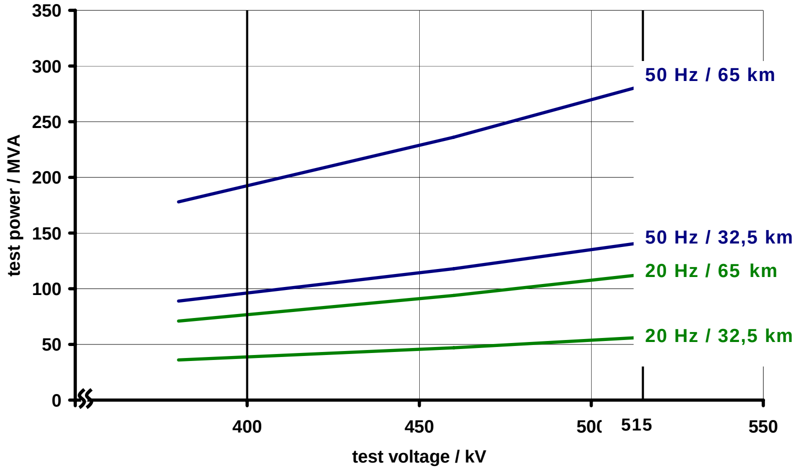


Figure 89: Test power depending on test voltage for different configurations of the GIL test

Figure 89 shows that the reduction of the test voltage alone is not sufficient, because 178 MVA test power and 1.5 MVA feeding power at 400 kV test voltage are still too high. The largest 50 Hz equivalent test power realized for the 400 kV – cable project in London has been 112 MVA. The real test power at 31 Hz has been 67 MVA. Therefore it seems realistic to plan testing with an available 50 Hz test power in the order of 100 MVA. This can be reached by a combination of voltage reduction and testing of half of the length. A test system for 400 kV test voltage, 89 MVA test power (50 Hz) can be realized with a variable frequency test system of four reactors, each 200 kV / 111 A / 50 Hz (Figure 90).

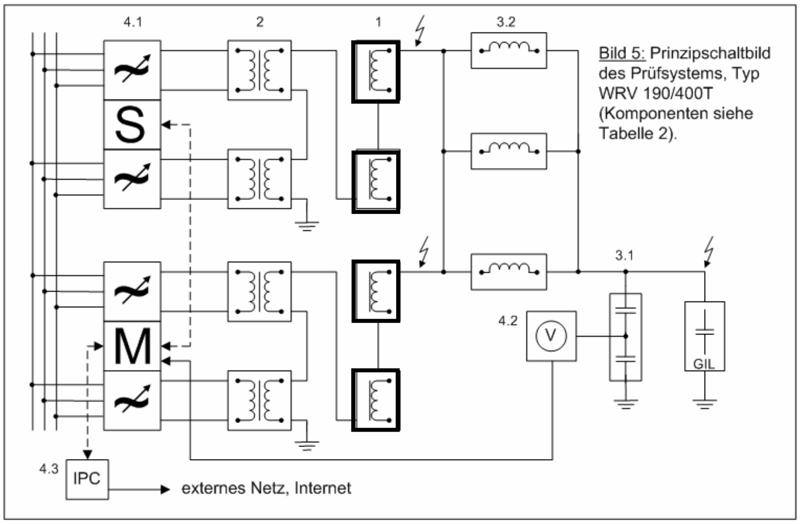


Figure 90: Combination of for reactors (1) with four exciter transformers (2) and four frequency converters (3) for a 400 kV test system. (4) – blocking impedance; (5) – voltage divider

The combination of several frequency-tuned resonant test systems of similar test power is well introduced for testing large cable system (Figure 91). All necessary components have shown high reliability in practice.

Figure 91: Combination of three variable frequency test systems as used for the London 400 kV cable system (Photo: courtesy IPH Berlin)

An interesting solution would be the combination of reduction of the frequency and reduction of the test voltage, but testing the full length of the GIL. A reduction of the frequency means a harder requirement with respect to free–moving particles in the GIL, the reduction of the test voltage a lower requirement. This means that there might be a certain compensation of the two influences. A test system for 400 kV, 71 MVA test power at 20 Hz would require the same configuration as shown in Figure 90 but with four reactors 200 kV / 90 A / 20 Hz.

Independent on the decision for the one or the other proposal, the GIL between Italy and Austria will be testable.

The conclusion is that long GIL application can be tested on site by limiting the maximum tested length to about 30 km and lowering the test voltage from 515 kV to 400 kV. If in addition to the lowering of the voltage the test frequency is lowered from 50 Hz to 20 Hz then the maximum tested length will be about 60 km.

The technical approval to lower the voltage and/or frequency without alteration of the test quality is needed, and the GIL standard IEC 61640 needs to be adapted.

Annex D

D Heat Transfer Analysis related to Buried Transmission Line Vaults

Summary

Calculations are presented for cooling buried transmission vaults. For a region characterized by granitic topography from below sea level to 300 m above sea level, overlaid with dense urban construction. Depth of burial of a nominally horizontal tunnel may range from 0 to as much as 300 m. Total length of the tunnel would be up to 8 km.

Calculations of the air temperature increase from resistive heating from the GIL show that some form of active cooling is essential at practical current levels, even considering heat transfer into the rock and to the surface. Forced air-cooling is the most straightforward, but does require periodic fan houses on the surface to exhaust hot air and introduce fresh. Chilling the tropical source air would help, but add capital costs and complication.

An alternative to air-cooling is a water cooling system. The simplest concept is water pumped through a finned pipe that absorbs the generated heat from the warmed air. Using pipe with external fins would enhance efficiency, as would forcing a relatively low volume rate of air. This system might be less costly, and minimize surface utility structures.

For maintenance operations with the high voltage power off, the tunnel would still require small level of forced air for worker comfort, to remove the lighting load, and to remove heat being conducted back into the tunnel from the surrounding soils.

With the varied terrain combinations of cooling methods for different sections may be viable.

Specifications

The following data and parameters were used for this report.

Conductors:	Power	550 kV / 4000 A
	Circuits	2
	Number tubes	6
	Enclosure O.D.	0.508 meters
	Heat gen/ph	54.3 w/ph-ft = 178.1 w/ph-m
	Heat gen total	1068 w/meter
	Lighting load	20 w/meter (only for maintenance)
Tunnel Dimensions:	Height (outside)	3 meters
	Width (outside)	4 meters
	Nom. Wall thickness	0.3 meters
	Burial depth (to top)	0 to 300 meters
	Length	3 km to 8 km
	Net flow area	6.94 sq meters
	Dh	1.31 meters
Limits:	Enclosure limit	80 °C
	T_{air} in tunnel	61 °C (at 4000 amps/ckt)
	Tamb above ground	35 °C
	Tsoil	28 °C

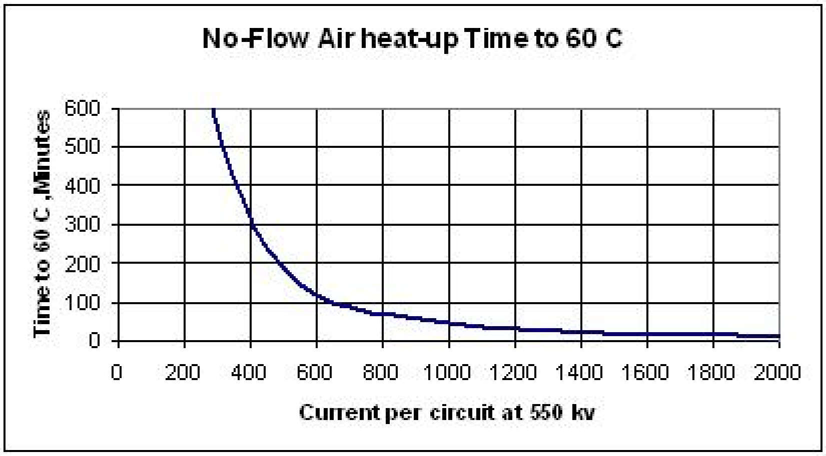
Tunnel ambient temperature vs Enclosure limit, calculated from TempCalc for 550 kV/4000 A.

T, °C	Enclosure, °C
35	55.8
40	60.5
45	65.1
50	69.8
60	79.1
61	80.1
65	83.8

Note that temperature calculations assume natural convection cooling by ambient air at the specified temperature. Enclosure cooling would be enhanced by forced convection over the surface, but there is no data available. Using these values to set the limit for the air temperature is therefore conservative. For this study, with the enclosure temperature limit specified as 80 °C, an air temperature limit of 61 °C was used.

Air Temperature Increase With No Cooling

The time for the air volume in a tunnel section 1 meter long to heat from 35 °C to 61 °C was calculated for 500, 1000, 2000, and 4000 A, taking no credit for heat transfer through the walls. The resistive heat generated was with temperature calculations for each current level. This is a straightforward calculation using the volume of air and its specific heat. The result for the maximum 550 kV / 4000 A was 2.7 minutes. Others are shown on the graph below. Heat transfer through the tunnel walls to ambient soil might mitigate this result somewhat, but by no more than a few minutes because of the high thermal resistivity of the walls and granitic soils. Clearly this system requires forced cooling for safe operation.

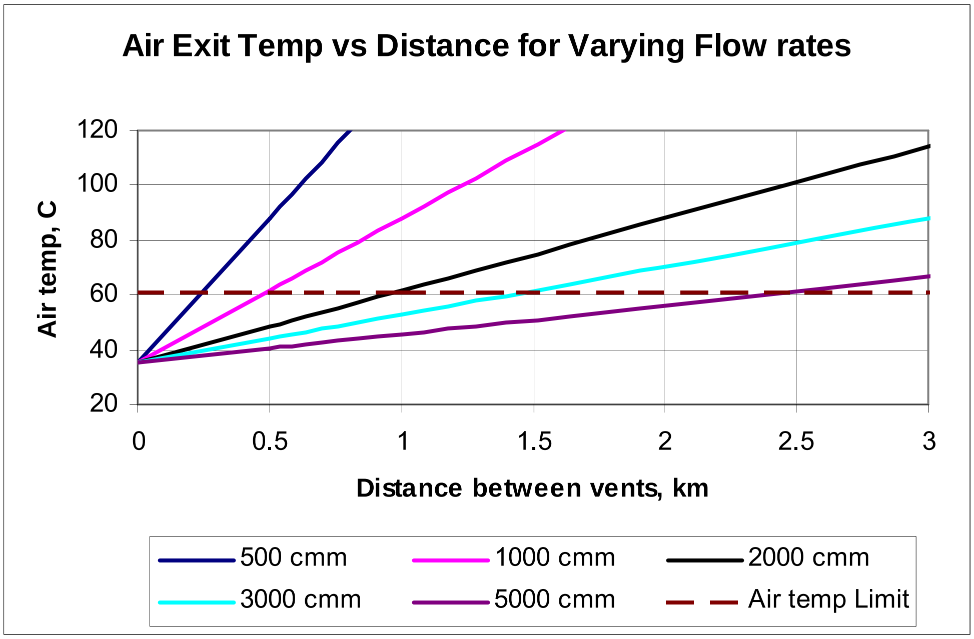


Air Temperature With Air Cooling – Adiabatic Case

a. Maximum Power Level (550 kV / 4000 A per circuit)

Temperature of a given amount of forced air (commonly measured in cubic meters/minute) at a given inlet temperature increases linearly with tunnel length, for a fixed circuit power. The word “adiabatic” in this case means that no allowance is made for cooling by heat conduction through the wall to the surroundings. This then is the most conservative model. There is, of course, a strong dependence on the air flow rate – the more air flow, the further down the tunnel before the air temperature limit is reached. When the limit is reached, then the heated air must be vented and cool air blown in.

The following chart shows the result of calculations for 550 kV / 4000 A.



For example, one could have 1 km between vent/fan stations if the flow rate were 2000 cubic meter/minute (70,630 cubic ft/min). The relation is nearly linear with flow.

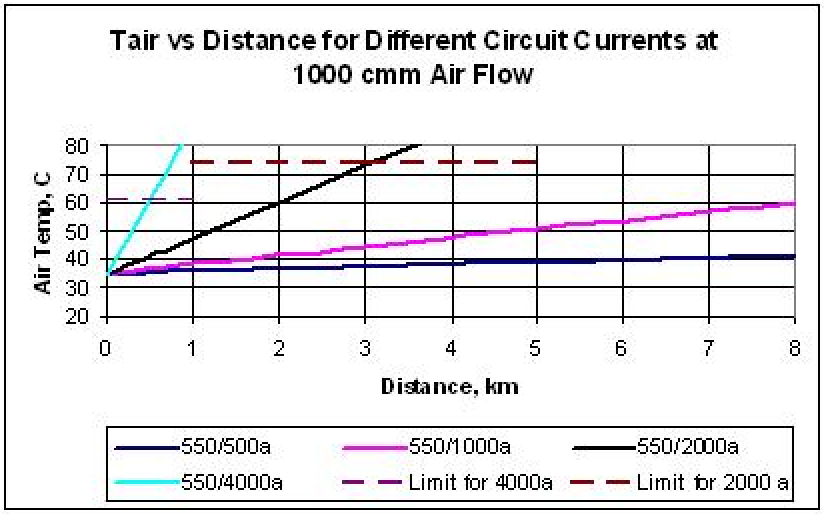
b. Power levels less than maximum

The next graph continues illustrates of the effect of lower currents. Some cooling is always essential. Varying the amount determines how long the tunnel can run without a utility station. An air flow rate was picked that offers possibilities for reasonably long runs, and air temperature calculated as a function of distance for several currents. The adiabatic assumption is used.

Two things are of interest. If the current is low enough (see 500 A/circuit curve), it is apparently possible to go the full 8 km at this air flow rate (1000 m^3/minute).

Secondly, the enclosure heat generation decreases as the current decreases. What this means is that the air temperature limit (61 °C for the 4000 A case) can be higher at lower currents, and still keep the system within the 80 °C enclosure temp limit. These are indicated on the graph.

So for example a run could go as far as 3 km with 1000 m^3/minute air flow at 2000 A/circuit.



Air Temperature With Forced Cooling – Non Adiabatic

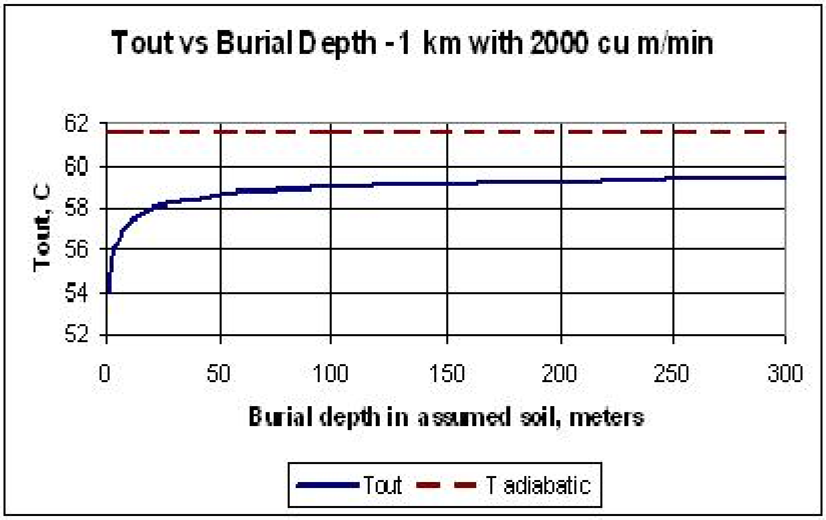
When the ambient temperatures of the surrounding soil or at ground level are less than the air temperature inside the tunnel, heat will flow via that route at a rate dependent upon the overall temperature difference and the thermal properties of the intervening materials. The overall resistance can be calculated from the resistivities of the individual materials. Like ohmic resistances, the thermal resistivities are very material dependent and usually non-linear. Soil and rock resistivities can only be approximate.

Geometry of a tunnel system also adds complication. The situation is referred to in classical heat transfer literature as a “semi-infinite” problem. While the boundary value of the ground surface is evident, heat is also transferred indefinitely sideways and downwards into the earth. That boundary is ambiguous. Mathematical treatment of simpler geometries (e.g., a round pipe) is possible, but only empirical approximations or digital simulations are available for the rectangular geometry.

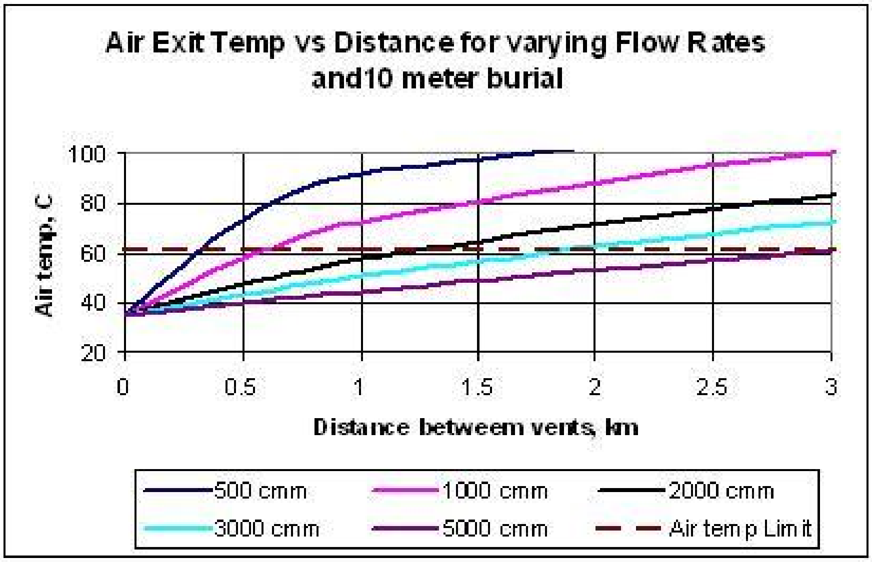
A final comment regarding heat transfer through the soils, is the time constant of the system. In some cases the thermal resistivity of the materials, particular stony soils, is quite high, quite varied, and a significant amount to be heated. A common measure of this is the thermal diffusivity $\alpha = k/\rho c_p$. For a typical soil $\alpha = 10^{-5}$ m^2/s, whereas for a metal like steel $\alpha = 1.5$ m^2/s. Small values imply slow rate of temperature rise by conduction. One would therefore expect there to be a significant time before a steady state temperature distribution is established. Studies have shown that the diurnal variation of surface temperature from solar heating is not evident below about 1-2 meters. Seasonal variations are not evident below 20 meters.

The calculations shown that take into account heat transfer into the surroundings are therefore a presumed “steady state” condition that may actually never be fully realized. The rate would be highest on the day of start-up, and probably decrease with time afterward as the surroundings heated. In shallow burial, the effect would be noticeable. A conservative approach is to assume the adiabatic results for burial deeper than a few meters.

The following chart illustrates the effect of burial depth for one particular air flow (2000 m^3/minute) at the end of 1 km distance. The improvement is about seven degrees over one kilometre at one meter depth, decreasing to about a degree at 300 meters. The curve is asymptotically approaching the adiabatic line as one would expect. Similar curves can be generated for other distances and air flows, but the result would be similar.



The next graph is similar to the one shown previously for the adiabatic case. It shows the tunnel air temperature at various distances from an inlet for various air flow rates. The additional parameter is burial depth, and as an example the depth chosen is 10 meters. It is understood that in the project the burial depth will vary widely.



The air temperature rise is initially similar to the adiabatic case because the temperature difference between air and ambient surface is low. As the air heats up a larger fraction is in fact transferred into the soil to the surroundings (at least in steady state), but this fraction only becomes significant after the air temperature is considerably above the defined temperature limit for protection of the GIL. Deeper burial only makes the situation worse as discussed previously. At very shallow burial, 0 – 1 meter, the heat transfer rate to the surface would allow lower airflow for a short distance.

The large variation in soil compositions, coupled with the wide variation (and uncertainty) in soil resistivity, suggests that a conservative design would not try to take credit for heat transfer to the soil and surroundings, except perhaps for very shallow or surface burial sections of the tunnel.

Water Cooling

Water cooling in lieu of air-cooling may be an alternative cooling method. One concept briefly explored here is to suspend a pipe in the centre/top of the tunnel shaft, with water flowing through it. The heated air generated by the GILs rises by natural convection to the top area of the tunnel and is cooled by contact with the water pipe. The cooled air descends to the floor of the tunnel, and flows out and upward over the GILs again. Alternatively, two smaller pipes, one for each circuit, could be used.

Heat transfer would be enhanced if the water pipe were finned. Typical finned pipe has circular disks about twice the pipe diameter welded to the pipe at short intervals. Fins may increase heat transfer efficiency by 2X or more over bare pipe. There are several vendors of finned piping worldwide, and their technical assistance should be solicited for detailed design. In addition, experimental studies should be done to optimize the cooling pipe location. A low airflow through the tunnel may also be necessary to promote more uniform cooling of the GILs.

The following Table 16 summarizes the theoretical water flow requirement for varying tunnel length. The requirement is based on the volume of water needed to absorb the heat generated before reaching the specified temperature limit.

Table 16: Water flow requirement related to tunnel length

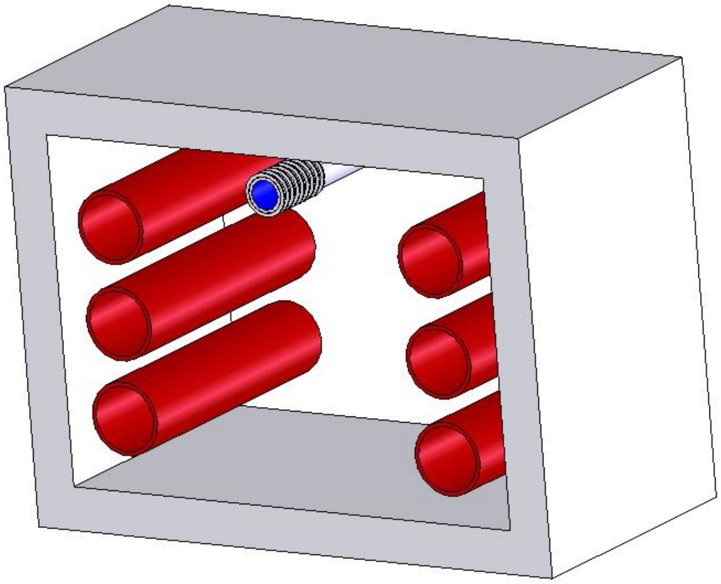
Distance [m]	Total heat generated [kW]	Volume of water [l/m]
1000	1,068	697
3000	3,205	2091
5000	5,343	3485
8000	8,548	5575

The pipe size is primarily determined by the friction pressure loss over a specified distance, as shown in Table 17. Estimates for the flows and distances in the Table above are as follows.

Table 17: Pipe size determined by friction pressure loss over a specified distance

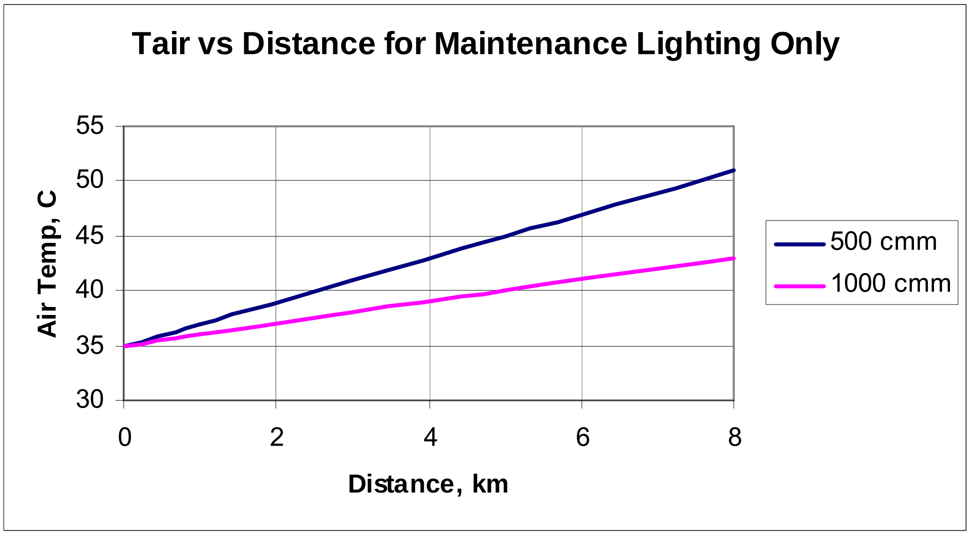
Distance [m]	Water volume [l/m]	Pipe diameter [mm]	Pressure loss [Mpa]
1000	697	75	0,689
3000	2090	150	0,545
5000	3486	200	0,438
8000	5576	200	2,241
8000	5576	250	0,758

The relative cost of air cooling versus water-cooling has not been estimated. However, with water cooling it appears possible to provide adequate cooling over much longer distances before a temperature limit is reached. This is simply due to the greater heat capacity of water over air. In addition, water-pumping stations should be smaller, quieter, and have less impact on the urban areas than the large blowers and fan houses.



Ventilation During Maintenance

A heat load of 20 W/m was specified to allow for lighting during maintenance. It was assumed in the previous calculations that the lighting would be off during normal operations. However, over the long distances involved 20 W/m would heat the air beyond worker comfort levels. In addition, long periods of operation will raise the tunnel walls and surrounding soil to above normal temperatures. Upon shutdown, this energy will be conducted back into the tunnel. Provision of forced air at some level will be required. Were a water-cooling system be employed, this same forced air might be proportionate with the need to provide air motion and turbulence for effective heat transfer from the tubes to the water pipe.



The graph below shows air temperatures vs distance for 20 W/m heating and two air flows. A maximum worker tolerance level was not specified, but would probably be on the order of 40 °C.

Conclusions And Recommendations

Cooling the tunnel is possible with either forced air or a water system. Combinations of methods could be designed according to burial depth and surface structures.

Except as noted no allowance has been made for technical uncertainties or safety factors. These need to be applied to design considerations in cooperation with the owner and other system contractors.

Air cooling is the most straightforward and would require less design study and development. Design should be based on the adiabatic case for conservatism.

Water cooling has the potential for cooling over longer stretches of tunnel, having fewer intermediate utility stations, and minimizing impact on the environment.

Water-cooling would require a more detailed design study of alternative methods, and experiments with mock-ups to maximize the heat transfer effectiveness and efficiency.

Some cooling airflow will be required to remove lighting heat, heat conducted into the tunnel from the surroundings, and provide for worker comfort.