Improving the Safety of Urban Underground Transport Areas due to the Use of New Energy Carriers

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ABSTRACT: To save resources and reduce CO_2 emissions, alternative vehicle drive systems based on New Energy Carriers (NEC), i. e. different types of purely electric, hybrid, gas and bio fuels are increasingly used. These NEC change the risks in transport, especially in enclosed underground areas. Nevertheless, current guidelines do not cover the changing risks as only few scientific studies on the impact of NEC on safety issues are available. This gap is addressed by the German SUVEREN project, which investigates phenomena that may occur in connection with the use of NEC in underground urban traffic areas. The research project examines the impact of battery and gas fuels on the safety of enclosed car parks, delivery areas, bus depots and tunnels. The given paper provides insight in this project and its upcoming results leading to a safety concept for appropriate treatment of NEC in underground structures.

1 BACKGROUND AND MOTIVATION

To save resources and reduce CO_2 emissions, alternative drive systems for vehicles have been developed and increasingly used worldwide. Manufacturer offer a wide range of vehicles, which can be powered completely electrically, as hybrids i.e. with a combination of internal combustion motor and electric power, or by gas.
The development of New Energy Carriers (NEC) differs worldwide from country to country depending on various parameters like technical innovation, price development of NEC and conventional energy carriers. Environmental constraints regarding sustainability and pollution, e.g. nitrogen oxide exposure in cities lead to political decisions regarding funding or prohibitions (e. g. Directive 2008/50/EC on ambient air quality and cleaner air for Europe). Accordingly, different scenarios are existing, how the future deployment of NEC will look like [Shell, 2015]. One option limits to an extrapolation of the past situation; the opposite option is a prediction of a massive change due to deterioration of environmental constraints. Independent of the wide scope all scenarios have in common, that NEC will increase significantly. In Germany, due to political consensus e-mobility is expected to prevail, but drive systems based on gas will also be used in a relevant number beside conventional fuels. As a result, NEC as drives and loads for vehicles will increasingly be used also in public and private underground (confined) urban transport infrastructures, so that their impact on safety aspects needs to be considered.

The use of new energy sources can cause different hazards compared to conventional fuels, such as battery fires, jet flames from relief valves of pressurized gas containers or the spread of highly flammable gases. Nevertheless, current safety concepts, guidelines or standards for the planning and operation of tunnels and underground spaces (in terms of design basics like heat release rates), rescue concepts and fire-fighting measures) are based on the risks of conventional energy sources, and NEC are not considered yet.

Figure 1. Charging station for e-mobility in an underground parking garage.

2 PROJECT SUVEREN

2.1 *General Approach*

To tackle the above-described situation the German Federal Ministry of Education and Research (BMBF) funded the research project SUVEREN in the thematic area "Future Security in Urban Spaces".

Figure 2. Logo of the research project SUVEREN

Its main goal is to investigate the risks resulting from increased use of new energy carriers (NEC) in vehicles in order to derive suitable safety concepts and to update the safety in underground urban areas. NEC vehicles and the associated risks, e. g. the fire behavior of batteries, pressurized gas containers, and composite materials are investigated. To achieve this goal the project is dealing with the following main tasks:

- Literature studies of past incidents
- Analytical and numerical studies
- Analysis of existing traffic facilities
- Risk analysis of new energy sources
- Development of case studies and reference scenarios for simulation of hazards regarding the use of new energy sources
- Modelling the release of substances and energy from new energy sources
- Modelling of extinguishing processes
- Analysis of hazard scenarios
- Performance of large-scale fire tests to validate the analyses and models

Project partners are the Federal Institute of Materials Research and Testing (BAM), Berlin (coordinator), FOGTEC fire protection, Cologne and STUVA, the Research Association for Tunnels and Transport Facilities in Germany. Associate partners are DB Station & Service AG, Berlin; City of Munich, Fire Directorate; CETU Centre d'Etudes des Tunnels, Bron (France); and INERIS, Verneuil-en-Halatte (France).

2.2 *New Energy Carriers (NEC)*

The term „New“ in NEC in the given context refers to changing potential consequences and market share that results from substituting conventional energy carrier petrol/diesel. Following this definition, NEC embrace alternative energy carrier (non-fossil), hydrogen gas and natural gas and liquefied petrol (LPG), even if they have a long history in the traffic sector and are of a fossil origin. Further, composite materials are taken into consideration, as these innovative materials also may lead to a change of constraints and resulting risks.

Figure 3. Hydrogen-Bus

NEC are either used as fuels for internal combustion engines and fuel cells or in the form of batteries as electrical energy. From a safety point of view, new challenges of NEC are chemical processes. Further, in terms of batteries energy densities are rapidly increasing from generation to generation. This leads to new hazard scenarios during operation, parking, recharging or refuelling of NEC.

3 IMPLEMENTATION OF THE PROJECT SUVEREN

3.1 *Risk Analysis*

NEC are very much in the public focus. In case of a burning electric vehicle or an incident with a jet flame from a gas-driven vehicle, the major news report in detail. As a matter of fact, multiple more conventional cars are burning every day but these are mentioned in best case in the local papers. This leads to a public perception that suspects NEC as more dangerous than vehicles with conventional fuels. To clarify this gap of knowledge SUVEREN scientifically researches the level of risk due to NEC compared to conventional fuels.

Risk is defined as the product of the probability of occurrence of an incident and its amount of damage. To quantify the risk due to NEC the first step is to research statistics and critical accidents that took place in the past. Reduced to one sentence the result of the recherché executed in SUVEREN [SUVEREN, 2018] can be summarized, that only few critical accidents have occurred in underground facilities. Single cases are documented, but no overall picture is given. The statistical population is too small to provide a scientifically evaluable base and no reliable statement about the risk of NEC based on the past is possible. Consequently, the identification of relevant scenarios for a reliable prognosis is getting more important.

As second step to calculate the risk the extent of consequences needs to be estimated. NEC as drive or load may cause different risks, e.g. due to battery fires, jetting flames from relief valves of gas pressure vessels, the spread of toxic or highly flammable gases [Gehandler, 2017]. These effects need to be determined within SUVEREN in a qualitative and if possible quantitative way. In this context, the environment of the incident plays a major role for the resulting damage. SUVEREN addresses this question by specific case studies, in which NECs in characteristic environments are examined and possible effects are determined.

3.2 *Case Studies and Fire Scenarios*

SUVEREN addresses all reasonable NEC to provide general safety concepts for current challenges. Each energy carrier has specific characteristics. To handle the extensive task within the project the NEC are categorized regarding common characteristics into three main groups.

The first category are gaseous energy sources. Although some of the gases differ significantly regarding properties and application, they react in case of fire comparable. Stored in pressure vessels, during a fire the gas expands to a large extent and blows off via the pressure relief valve. Without ignition, this can generate an explosive gas mixture in the environment. In connection with up to 15-20 m long jet flames [Dutch Safety Board, 2012], depending on pressure and housing, may occur. Apart from different combustion temperatures, storage pressure and physical properties, the overall hazard potential of jet flames is in the same range.

The second category is battery-powered vehicles, where the battery represents a source of danger. Currently, due to best energy storage properties, most car manufacturers use Li-Ion batteries [Zhang, 2017]. This type of battery is vulnerable to damages resulting from overheating or mechanical damage. If the battery management system fails or is not able to cope with the damage a thermal runaway of the Li-Ion battery results.

The third category is biofuels used as substitutes for conventional fuels. As biofuels have very similar properties as gasoline or diesel this category has low priority in research.

NEC are present throughout the whole transport sector. To cover the most unfavourable condition SUVEREN refers to underground urban infrastructures, as the confined conditions increase the critical effects (heat, smoke, toxic gases). As underground infrastructures have well defined but very limited escape routes, in the event of fire and smoke – following the concept of self-rescue – users must be able to reach safe areas within a reasonable time. These more critical conditions for users, rescue forces and buildings lead to higher importance of safety measures than above ground. For battery-powered vehicles, relevant factors can be, besides heavy smoke also gas formation, which may occur if Lithium-Ion batteries are mechanically damaged or overheated. The release of different toxic gases, depending on the chemical composition of the batteries, and the associated risks with regard to chemical reactions (hydrogen fluoride) in combination with used extinguishing agents is hard to oversee. Further, a problem for firefighting is the battery housing, which makes access for extinguishing agents very difficult or even impossible.

In case of gas-powered vehicles, new threats result from the emission of various gases with different densities. For gases lighter than air, this can lead to gas accumulation in the ceiling area of underground traffic systems. For gases heavier than air, this can lead to formation of a lake in low-lying areas or to further distribution of gases through drains and sewage systems. In both cases, the question in terms of gas concentration and ignitability of the resulting mixtures is relevant. Regarding the possibility of detection, the question arises which gases in what concentration are expected. Questions regarding the availability of sensors, required sensitivity and the optimum location for the measurement equipment are also addressed within the project.

Together with operators and emergency services, SUVEREN is developing NEC-specific fire scenarios which are included within case studies. The goal is to map the new hazards caused by NEC in a realistic way for five types of underground traffic facilities (case studies). From the defined bunch of scenarios, the ones with the highest reasonable risk (probability x damage) are identified to be analyzed in detail for each underground facility.

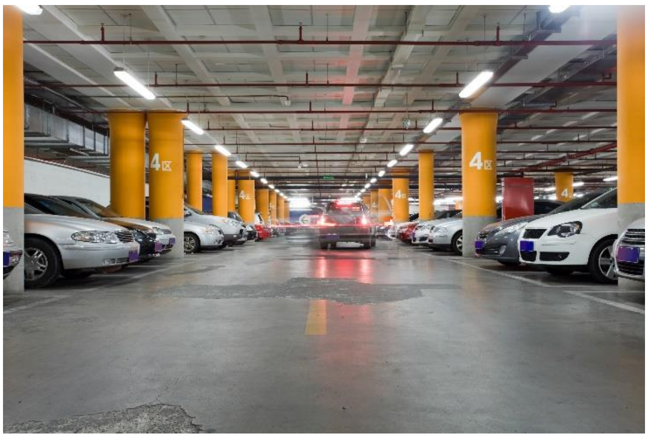

Figure 4. Underground car park.

For the detailed investigations, the following building types were identified as relevant, as they are already frequently found in the urban areas today or in the near future. Further different protection goals (self-rescue, assisted rescue and asset protection), as well as various fire risks and fire phenomena, are covered by these facilities. The project focuses on:

Underground car parks

Underground car parks are considered since they are to be found in all (German) cities and thus the total number is high. Under normal conditions, the number of people inside underground garages or enclosed parking garages is small, which eases evacuation in case of emergency. Due to the individual traffic, underground garages are used by all drive types and energy sources. In public places, with a lot of public traffic, underground car parks may be heavily frequented. The high number of vehicles parked close to each other also causes a high fire load and risk of fire spreading. In the New Year's Eve of 2017 for example, more than 1,400 cars in a Liverpool parking garage burned out completely. In case of fires for the fire brigade, the attack path is particularly difficult due to heavy smoke and fast heat development.

Charging stations for electric vehicles are already installed in many underground garages and big car parks. During charging, the battery is heavily used, which increases the risk of fire significantly.

Underground Bus Stations

At underground bus stations the danger potential is slightly different compared to the underground car parks. Bus stations are characterized by a high number of people and are usually located at main traffic junctions, which offer transfer options to other buses or trains or are connected to shopping centers. In case of an evacuation, many people could be affected. There are currently several underground bus stations around the world, e. g. in Buenos Aires (Argentina), Stockholm (Sweden), Amsterdam (Netherlands), Berlin (Germany). Most likely the number of underground bus stations will continue to increase, as lack of space in major cities lead to new city concepts based on more underground infrastructure.

Because of environmental, political and social pressure, transport companies and operators are increasingly forced to convert to alternative drive systems, which also changes the spectrum of danger for bus stations. So far, there are no uniform concepts or recommendations for dealing with NEC in underground bus stations or the construction of underground bus stations.

Bus Depots

So far only a limited number of underground bus depots are in operation, for example in Fribourg (Switzerland), Stockholm (Sweden), Barcelona (Spain), El Monte (USA), Stavanger (Norway), Singapore (Singapore). Due to limited space in city centers and growing market share of NEC Buses the number of underground bus depots is expected to grow significantly.

Like underground garages, these are characterized by high fire loads and a high risk of fire spreading between the buses parked close to each other. Gas-powered buses further increase the risk of spreading due to excess gas blown off by the pressure relief valve. Without ignition, this can generate an explosive gas mixture in the environment. In connection with fire hazardous jet flame may occur. For operational reasons battery-powered buses need to be charged during parking in the depot. As described above the charging process embraces a significantly higher risk of fire. Evacuation is less critical, as in bus depots only trained staff is affected in case of fire. To detect fires immediately the detection systems must be well-matched to the hazards of the NEC.

Delivery zone

Delivery zones are increasingly being built underground for shopping centers. As many transport vehicles are powered with NEC, these enter the underground delivery zones and need to be considered in the safety regulations. Adequate detection systems and firefighting systems must be adapted to the new situation so that a safe evacuation of the usually small number of people is possible and damage to the infrastructure can be prevented. SUVEREN considers case studies in real delivery zones. The aim is to develop relevant recommendations for safety technology and to highlight the importance of the NEC with regard to the load of the transport vehicles.

Road Tunnel

Even if statistics show, that tunnels are the safest sections of the roads the situation in case of a fire may be very challenging, as survival conditions may deteriorate rapidly and tunnels provide limited options for escape. For this reason, the safety regulations for tunnels, although different in each country, are very high. New threats due to NEC are likely already covered by the design fires between 30 MW up to 100 MW considered for conventional fuels [RABT, 2016] and no additional restrictions for NEC vehicles are required. However, with increasing use of NEC, the transport of batteries and other hazardous materials will increase. Many regulations are set by the ADR (the European Agreement concerning the International Carriage of Dangerous Goods by Road), but some of these are contradictory and it must be examined to what extent NEC are dangerous for the users and the structure.

First, to investigate additional hazards from NEC following fire scenarios are defined independently from the above described case studies (underground facilities). Subsequent these reference scenarios are assigned to different cases (see Table 1 to 3) concerning their potential risk and importance for each case. SUVEREN focusses on the risks of CNG (compressed natural gas, representing gaseous pressurized NEC), Li-Ion batteries (LIB) and composite materials (CM).

Table 1. Compressed natural gas (CNG) Scenarios.

CNG 1:	A vehicle starts burning inside (i.e. due to technical failure in the motor department, cigarette, arson, etc.) → the fire spreads over the whole vehicle → a temperature triggered pressure relief device is activated → gas is released, and a jet fire occurs → surroundings are affected by the jet fire
CNG 2:	Due to a rapture or a pressure relief valve gas is released → a jet fire occurs after being ignited by an external ignition source → surroundings are affected by the jet fire
CNG 3:	A heat load from an external heat source (i.e. due to external vehicle fire) occurs → a temperature triggered pressure relief device is activated → gas is released, and a jet fire occurs → the burning behavior of the vehicle is influenced by the jet fire

Table 2. Li-Ion-Battery (LIB) Scenarios.

LIB 1:	A damage occurs inside the battery (thermal, mechanical or electrical failure) → the battery management system fails → a thermal runaway inside the battery arises → the vehicle starts burning
LIB 2:	A vehicle starts burning inside (i.e. technical failure in the motor department, cigarette, arson, etc.) → the thermal load induces a thermal runaway inside the battery → the vehicle starts burning
LIB 3	A heat load from an external heat source (i.e. external vehicle fire) occurs → parts of the vehicle ignite, and the vehicle starts burning → the heat load induces a thermal runaway inside the battery → the burning behavior of the vehicle is influenced by the battery fire

Table 3. Composite materials (CM) Scenarios.

CM 1:	A heat load from an external heat source (i.e. external vehicle fire) occurs → parts of the vehicle body start burning → the composite materials influence the heat release of the vehicle fire → surroundings are affected
CM 2:	A vehicle starts burning inside (i.e. technical failure in the motor department, cigarette, arson, etc.) → the composite materials influence the heat release of the vehicle fire → surroundings are affected

By defining these scenarios as a reference, it is possible to assign them to the above described underground facilities. Combining specific types and numbers of vehicles with the underground facilities allows to determine the main goals of investigations. Table 4 provides an overview about the summarized information and the five case studies that are investigated within SUREVEN.

Table 4. Case studies and associated scenarios of SUVEREN.

Case Study (Underground Facility)	Main Goal of Investigations	Scenarios, No. of Vehicles	Measures to be evaluated
Car Park	• predict the fire spread between passenger cars • detect changes in smoke spread and releases of toxic gases • evaluate the influence of charging stations	6 passenger cars (2x3), 1 car starts burning: LIB 1, 3 CNG 1, 3 CM 1, 2	• examine the suitability of water mist systems • dedicated regulation for charging stations and/or charging areas in car parks • detection unintended gas releases in consequence of pressure relief failures • analyze early warning systems (eCall) for NEC-driven cars • examine additional smoke extraction systems
Bus Terminal	• predict the fire spread inside a bus • detect changes in smoke spread and additional gas releases	1 bus starts burning: LIB 1, 2 CNG 1, 2	• examine the suitability of water mist systems • adjustment of the PRD release direction • detect unintended gas releases in consequence of pressure relief failures • upgrading and adjustment of bus stations • examine additional smoke extraction systems
Bus Depots	• predict fire spread between several busses • evaluate the influence of charging stations • detect changes in smoke spread and additional gas releases	2 busses, 1 bus starts burning: LIB 1, 3 CNG 1, 3	• examine the suitability of water mist systems • regulation of charging stations and/or charging areas in bus depots • adjustment of the PRD release direction • upgrading and adjustment of parking spaces in bus depots • analyze early warning systems (eCall) for NEC-driven cars
Delivery Zone	• predict the fire spread inside a transporter/ truck • investigate the heat and smoke releases from transporters/ trucks	1 transporter/ truck starts burning: CNG 1 LIB 1, 2	• examine the suitability of water mist systems • consider the effect of fire detection devices inside battery packs • examine additional smoke extraction systems
Tunnel	• analytical estimation of HRR	1 truck loaded with batteries, 1 battery starts burning: LIB 1	• propose valve-controlled firefighting systems • consider the effect of fire detection devices inside battery packs

3.3 *Concept of large scale test programm*

To determine the properties of NEC in case of fire in connection to the relevant scenarios described before fire tests will be performed. As fire tests in general require severe effort and cause high costs a main goal of the project is to develop alternative methodologies. For this reason, an equivalent fire load with comparable properties shall be developed. The aim is to determine a cost-effective alternative to expensive real fire tests and to set a standard fire load for future tests.

At the end of the year 2018, fire tests will be carried out by the subcontractor IFAB in order to achieve the above-mentioned goals. Large Li-Ion batteries (30 kWh and 40 kWh) will be tested stand alone and in connection with active fire suppression systems (with and without water mist). Further tests with a gas tank set on fire will be executed to research the resulting jet flame and option for fire suppression. The fire tests are required to determine detailed parameters for CFD modelling and validation (see 3.4). In the respective test, a jet flame will be induced and sprayed with water mist to determine the interaction between the fine water droplets and the flame. The main goal is to repeat the results of the original fire tests with the equivalent fire load and to simulate the system with numerical calculations.

Figure 5. Large-scale fire testing.

3.4 *Modelling of heat and species distribution and fire suppression*

A main task of SUVEREN is the quantification of the various risks and hazards from both new and conventional energy-driven vehicles and associated infrastructure (e.g. charging station) in underground facilities. As the targeted facilities are large and complex the analysis of the consequences of a NEC induced fire will be performed using computational fluid dynamics (CFD). CFD tools are widely used in both industry and research and proven to be capable of predicting the smoke and heat distribution in large buildings especially when fire testing is impossible or very cost intensive.

The individual assessment of every scenario (e.g. based on geometry, fire size and ventilation condition) enables a performance-based design approach. Further CFD modelling of SUVEREN will include the interaction of fire with active suppression and ventilation systems and consider toxic species other than standard fire products soot and carbon monoxide (CO). To improve the quality of the numerical calculations the models will be validated against the results of the fire tests.

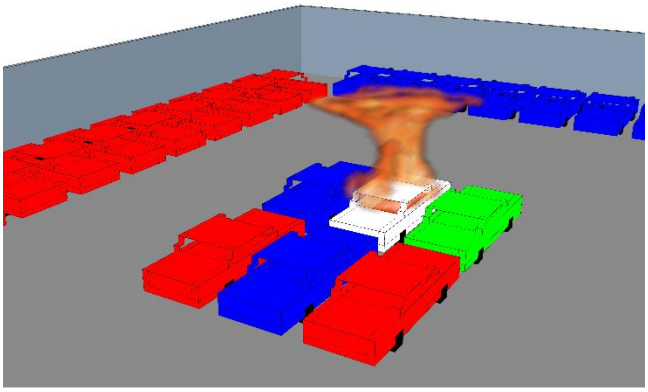

Figure 6. Flame formation during the fire simulation of a car in an underground car park.

4 OUTLOOK RESULTS

The research project SUVEREN (Duration 9/2017-8/2020) will deliver holistic safety concepts for underground, urban traffic areas, covering the challenges of both conventional and NEC fuels. This includes:

- Risk assessment methods including NEC
- Validated numerical models to identify hazards
- Recommendations for planning and equipment
- Development of appropriate mitigation technologies (active measures)

4.1 *Development of mitigation technologies*

In addition to determining the risk of NEC, one main objectives of SUVEREN is to develop and demonstrate the effectiveness of active measures to identify risks, increase the safety of users and reduce the damage. To achieve this, research is executed regarding the interaction between smoke gases and extinguishing agents as well as firefighting methods. For example, the effect of sprinklers or water mist extinguishing systems on battery fires is examined.

4.2 *Performance-based design*

For road tunnels the design and respective safety equipment (ventilation, fire protection) are defined by existing regulations (e. g. German RABT). The worst case scenario for these regulations are fires including heavy-goods-traffic (HGV) which are already dimensioned large enough to cover the impact of NEC in reasonable cases too. Consequently the use of NEC inside a road-tunnel equipped in accordance to current regulation will most likely not require additional safety equipment. Nevertheless, the rescue service must apply slightly different procedures and rescue strategies. Regarding road tunnels the situation differs considerably from underground car parks, where the fire risk increases due to NEC (e.g. charging stations for E-Mobility) and up to now prescriptive regulations apply, which may not cover the new requirements.

Car parks are equipped with different technical systems for guidance of the motorists, but also include firefighting equipment. Fire detection is mandatory in most countries; sprinkler systems in some countries. Other countries require sprinklers system only in the case that further constructions are was built above the car park. Hydrants and portable fire extinguishers are also mandatory in most countries. Car parks are typically divided into fire sections limiting the access of smoke & heat to larger areas using fire-rated barriers.

The findings of SUVEREN reveal that the materials used inside cars have changed and due to the increased use of combustible materials like plastics and composites, the fire load has changed for all current vehicles. Additionally, the fire load can vary a lot depending on car type, fuel (various NEC or conventional) and size.

To cover the wide scope of constraints a performance-based approach for dimensioning might be recommended for car parks following the success of introducing this method to assess tunnel projects. SUVEREN provides efficient tools and measure for a performance-based design approach: Risk assessment methods including NEC validated numerical models to identify hazards, appropriate and proofed mitigation technologies, and recommendations for planning and equipment.

4.3 *Guidelines*

Existing guidelines are based on conventional vehicles and do not cover changes due to increased use of NEC fuels or even changes in the fire loads of conventional vehicles due to new equipment and vehicle size or innovative materials like composites.

The results of SUVEREN are expected to be implemented in standards and regulations with reference to underground infrastructures. To offer concrete support to operators and designers of urban underground facilities a guideline with practical recommendations will be published and training programs will be offered.

5 CONCLUSIONS

The results available so far show that the increased use of NEC in underground urban infrastructures will not lead to a critical change of the safety level in general. Depending on the environment, the existing regulations and methodology cover the risks of NEC. Especially in case of road tunnels, regulations based on heavy goods vehicles (HGV) with conventional fuel and loads require little adjustments to the new situation. On the other hand, the situation in the other cases like underground car parks differs considerably, as the fire risk increases and prescriptive regulations do not cover the requirements. Here a performance-based approach for dimensioning will be investigated to embrace the large scope of constraints. SUVEREN provides efficient tools and measures to execute a performance-based approach: Risk assessment methods including NEC, validated numerical models to identify hazards, appropriate mitigation technologies, and recommendations for planning and equipment.

SUVEREN started in September 2017 and requires a duration of three years to perform the whole task. Large-scale test as an important base for the validation process will be executed end of 2018. Due to the early editorial deadline in August 2018 the given paper is limited to conceptual and preliminary results of the project. For recent details please consult:
www.suveren-nec.info

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