INNOVATIVE MEASURES FOR ENVIRONMENTAL TECHNOLOGIES AT TUNNEL FIRES

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Abstract
Many tunnels are built below the ground water level. In case of a fire or oil spill there is a risk of environmental contamination of ground water supplies or sensitive recipients. Successful treatment of extinguishing water or spills needs rapid attention in such cases. This paper discusses the environmental consequences of a tunnel fire or an oil spill inside the tunnel. It is suggested from the present study of existing technologies, that the work of development within this field be divided into three different areas where two are pro-active while the last requires the development of new technologies for on-site collection and treatment of water. In sensitive areas, this treatment could be combined with in-situ surveys and treatments both prior to and after an incident.

The two pro-active steps are characterization and categorization of tunnels along with the development of a digital system where site specific properties can be modeled. Additionally, at the fire scene, new mobile technologies are needed for effective treatment.

Finally the paper discusses the environmental challenges the fire officer has to with deal during an incident and the need for further education of first responders on how to deal with these issues both in terms of short term and long term incident management priorities.

Key words: tunnel fire, oil spill, water treatment, soil treatment, contamination transport

Background
Urbanisation is continually increasing, worldwide. New societal demands in the face of this urbanization include fast transportation, effective and uncompromised access to Internet, heating, water and electricity. Tunnels are built to free valuable land for other uses and to shorten transport distances between important city centers. As the number of tunnels and their siting increasing, many tunnels are built below the ground water level. Both during construction and later during the full life cycle of the tunnel, the surrounding environment is sensitive to undesired effects in case of an accident or a fire. Road tunnels can be used by many hundred thousand vehicles per day in busy areas. In case of a fire, extinguishing water can contaminate not only the near environment, but also leak into the ground water or be transported to the waste water treatment plant by the sewage disposal systems. In the case of accidents which involve dangerous goods, the risk of considerable damage is substantially higher. In vehicle fires, petrol or diesel fuel can easily leak to the surface, to the soil or through the ground water to the source of municipal water supplies.
In modern road tunnels separate sewage and drainage systems are installed, where extinguishment water and oil spills can be detected, collected and treated. In older tunnels the effects on the environment in the case of an accident are higher and the need for immediate action is more urgent. In rail tunnels the tracks are placed on macadam and gravel beds. Usually a drainage system is installed in order to restore the ground water level or convey water out of the tunnel. The water leaking from a bored tunnel could be re-infiltrated back to the ground water or in some cases to sensitive recipients close to the tunnel. In rail tunnels the opportunity to collect the extinguishing water or spill is far less than in modern road tunnels.

Clearly, one needs to consider the environmental impact of an incident in advance of its occurrence. Optimally environmental planning should take place at the design phase so that systems for the treatment of spills or run-off water from fire fighting can be installed during the building. Presently planning does not always involve environmental management unless potential recipients have been identified as particularly sensitive or worthy of preservation.

This article outlines some of the methodology that is presently available for the identification of sensitive recipients and available preventative methods to minimize environmental impact to these environments in the event of an incident.

**Fire emissions and transfer mechanisms**

The interaction between a fire and its surroundings or environment is best illustrated in Figure 1. This figure shows how fires effect the environment through:

- direct gaseous and particulate emissions to the atmosphere (fire plume)
- spread of atmospheric emissions
- deposition of atmospheric emissions
- soil contamination
- aquifer contamination

![Figure 1: Emission pathways from fires (reproduced with minor modification from reference 18).](image-url)
This paper will concentrate on aquifer contamination due to run-off water from a fire or oil spills.

The effect of these emissions depends mainly on: the transfer mechanism (i.e., atmospheric emission of gaseous species or soil and aquifer contamination) and the specific species (i.e., small gaseous compounds, large particles and the range of species in between). Risk assessments may not be possible for all potential impacts but contingency planning should take into account “worst-case” scenarios.

**Environmental risk assessment in urban planning**
When planning new infrastructure, protection of the environment is one of many important issues to deal with. In Sweden a thorough investigation of environmental effects of a new road or rail route is benchmarked against the “zero-case”, i.e., the case where nothing is built. As a result of this type of environmental-impact assessment, sensitive surroundings are mapped and preventive measures can be taken. In Sweden the risk management for rail routes have a probabilistic approach and for low probabilities the cost for preventive measures are not taken. In tunnels with environmentally sensitive surroundings or where dangerous goods are transported, deeper studies are performed.

**Tunnel specific environment**
In road tunnels, the sewage system is usually equipped with oil deflectors. The water is pumped to collection vessels where contaminated extinguishing water or oil spills can be stopped before they reaches the waste water treatment plant and can thereby put the biological cleaning at risk. Further, the drainage systems in new tunnels are built so that the first responders in case of an incident can stop pumps and prevent contaminated fluids from reaching sensitive recipients.

Rail tunnels on the other hand, have a foundation of gravel or macadam placed on the solid rock on the bottom of the bored or blast rock tunnel. To prevent uncontrolled leakage to the environment underlying rubber sheets can be placed to collect and direct the water to collection ditches or other collection points, separated from the protected area. Depending on the tunnel geometry and the inclination of the tunnel the drainage water is pumped or simply directed out of the tunnel.

**Transport of extinguish water**
Much is known about the transport and mobility of contaminants once entered the subsurface zone and/or the ground water, in general. In general one can identify two basic elements of major importance, i.e.: the subsurface properties and the physiochemical and biological properties of the contaminants. Once contaminants are released to the environment some of the material will potentially dissolve into the aqueous phase and be transported with the groundwater. The released contaminants are reduced by natural attenuation (NA), i.e. the natural reduction of mass, toxicity, mobility and volume after a spill, to some extent. Natural attenuation contributing processes are, e.g.: dissolution, mass transfer to flowing ground water, dispersion and diffusion, sorption and chemical and biological transformations. Key issues influencing the NA are, e.g.: subsurface electron receptor processors, pH, temperature, site geochemistry and hydrology.
GIS based mapping of sensitive areas

At a tunnel fire site, it is important specifically to characterize geochemistry and hydrology rapidly in the case of an incident. Information is often required only at specific boundaries, not everywhere in the domain. These boundaries may be regulatory interfaces (e.g. property boundaries, receptors of concern) or hydrologic interfaces (streams, lakes, wetlands, springs or aquifers). Spatial data requirements are enormous and often the limiting factor. One solution to these problems could be to use digital maps for planning the fire fighting and contaminant control. By integrating these methods with a geographical information system (GIS), advantage can be taken of the digital hydrography that has become widely available. GIS has been suggested to represent hydrological “fields” as database “objects”. Vector data are then imported to the GIS to construct a ground-water flow model. Fluid dynamics modeling of ground water transport, e.g. by using Dymola, can then be used to predict mobility of dissolved contaminants from the fire site, via the groundwater to the surrounding environment.

A well prepared contingency planning is one of the key factors for successful rescue operations. In Sweden the new Civil Protection Act requires that written documentation is sent to the Rescue Services for complex buildings, buildings with many people or traffic tunnels longer than 500 m. Such written documentations can later be used in the rescue services contingency planning and be supplemented by necessary environmental information. A GIS based environmental sensitivity map can then be constructed where risk and protection objects are shown, together with additional information. This has been tested successfully in the Umeå area, where the rescue services have had access to GIS based environmental sensitivity maps since 1999.

Contaminants at a fire or incident scene

The contaminants released at a fire scene depend greatly on the materials present in the fire and the ventilation conditions during the fire. In a road tunnel fire, emissions from vehicles will be assumed to dominate the potential contamination of the surrounding water resources, whether ground water or surface water. The emissions to water in an automobile fire were measured in a full scale experiment in Sweden, where approximately 105 l of water was collected out of 200 l used to extinguish the fire. The parameters chosen were: pH and conductivity, nutrients, TOC (total organic carbon), total aliphatic organic compounds, total aromatic organic compounds, non-polar aromatics and aliphatics, AOX (adsorbable organic halogens), EOX (extractable organic halogens), nitrotox (measure of reduction potential on denitrifying bacteria) and PAH (polycyclic aromatic hydrocarbons, e.g., fluoranthene, benzo(b+k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, benzo(g,h,i)perylene) as well as the sum of PAH.

Fuel spills and fuel contaminated extinguishing water also contain other substances that are added to the original fuel. For example, the chemical substance methyl tertiary butyl ether (MTBE) is used as a petrol additive in order to raise the octane number, to prevent engine-knocking and to fulfill oxygenate requirements. Even if an alternatives to MTBE, such as for example ethanol, is introduced MTBE is commonly used in Europe. The world consumption of MTBE 2004 was approximately 17.5 billion metric tons. Even very small amounts of MTBE or diesel fuel can contaminate large quantities of drinking water. As MTBE is highly soluble it moves faster and further in soil and water than many other petrol components. MTBE itself, at low exposure levels in drinking water, is not considered a human carcinogen,
but concentrations as low as 5 µg/l of MTBE can be tasted in water thereby reducing the water quality.\textsuperscript{11-12}

\textbf{Site specific risks}
In the case of a tunnel fire, the damage to humans and the surrounding eco-system depends on a series of different site specific factors. Obviously, there is a need for very rapid actions in case of fire close to a water protection area. Even sensitive eco-systems and recreation areas are examples where rapid intervention is necessary. Several site specific risks are dealt with separately below.

\textit{Contamination of ground water}
If the area around the tunnel is protected for fresh water extraction, leaching of contaminated extinguishing water from a fire scene can become a threat to human health. Firstly, the contaminants, if consumed by humans, can be acutely toxic or have more long term effects such as carcinogenic effects. Secondly, if the water source is taken out of use for a period due to contamination, lack of fresh water will become a problem. Slow release of contaminants via natural attenuation can also affect the ground water years after the contamination.

\textit{Threat to surrounding eco-system}
Given that the extinguishing water released moves from the site to the surrounding environment, the chemical threat can vary depending upon the specific eco-system. To work with this, as an example reference\textsuperscript{13} divides a fresh water system into several sub-systems where different key organisms prevail, thereby increasing the robustness of the treatment system as a whole.

\textit{Urban environments/refreshment areas}
Contamination of groundwater and land in exploited areas can have long term effects. Humans can be exposed to contaminants not only via drinking water but also from swimming in lakes, eating meat from affected animals or crops polluted by the contaminants.

\textbf{Existing technologies}
In general, treatment of soil and ground water can be divided into \textit{in situ} (treatment is conducted directly on-site, in the ground), \textit{ex situ} (the material is transported off-site for treatment) and \textit{on-site} (the material is treated in a plant, reactor or facility and put back afterwards).

Remediation of sites contaminated by a fire incident involves mainly the remediation of the zone contaminated by NAPLs (non-aqueous phase liquids). Devising suitable techniques for remediation of NAPL-contaminated sites is a challenge because it involves modeling and analysis of multiphase flow. Existing technologies include: pump-and-treat methods, \textit{in situ} biodegradation, \textit{in situ} soil washing and steam-enhanced extraction. The pump-and-treat technology attempts to keep the aquifer plume from spreading and to remove the contaminants from the aquifer using physical processes\textsuperscript{14}. Pumps are commonly used to bring contaminants to the surface where they can be treated more effectively. \textit{In situ} biodegradation involves the partial or complete degradation of aqueous phase compounds by microorganisms in the subsurface. \textit{In-situ} soil washing is also termed flooding of flooding and involves the use of alkali agents, hydrophilic co-solvents, viscosifiers, and surfactants to enhance the removal of NAPLs and their dissolved constituents. Stem-enhanced extraction, or soil heating,
involves thermal heating by stem injection, hot water injection and electrical heating. A major risk with this method is that the contaminant may be displaced by the injected fluid to areas other than the recovery points.

Recently, the on-site bioreactor approach was evaluated for the treatment of explosives contaminated soil with promising results. In the process, soil and water are mixed into a slurry, where denitrifying bacteria can degrade the molecules. The technique can be adjusted to take either an anaerobic or aerobic approach. For example MTBE is biodegradable to CO₂ and water under aerobic conditions. Most of the bacteria needed to degrade the ether bonds in MTBE are slow growing and needed to be prepared and “trained” beforehand in a laboratory environment so the bioreactor placed at the fire or incident scene are efficient under active-service conditions.

Needless to say all treatment methods currently available are expensive and full remediation of sites is only feasible in a limited number of applications.

**Tactical environmental approach at tunnel fires**

In case of a fire or an accident in a tunnel the main objectives are to: 1) save people in danger, 2) save the tunnel and 3) as far possible reduce the effects on the environment. In the open air the best tactical decision in the case of a dangerous goods HGV fire involving large quantities of, for example, diesel fuel can be to let the fuel burn as efficiently as possible provided spread of the fire can be eliminated. This method is suitable if the surrounding environment is sensitive to soil or water contamination. In a tunnel this choice is not realistic. To facilitate the evacuation of people, the best method is of course to extinguish the fire if it is possible. If the fire can be put out the temperature load to the tunnel walls lowers considerably and the smoke generation stops. In other words, the strategy and the tactics that are most suitable in any given situation are highly dependant on the actual fire or accident, the conditions at the specific tunnel and the available resources from the fire brigade.

In a tunnel fire the fire fighters may need to move long distances in a smoke filled environment to reach the seat of the fire. To be able to reach the fire the fire fighters may need to ventilate the tunnel and thereby lower the influence of the heat flux from the smoke layer and reduce the distance they must walk in a smoke filled environment. Usually the flow direction in the tunnel is chosen with respect to the natural direction, distance to the fire, the fire fighting resources and access, and the location of people trapped in the smoke; but environmental aspects can also be included in this decision making process, in particular concerning the ventilation and flow direction. The rescue of persons in the tunnel or the use of ventilation as a tactical resource for the fire fighters is naturally given priority over the protection of the environment, but in those cases it is possible basic environmental information must be available in advance of the incident to facilitate environmental friendly decisions.

**Education requirements for first responders**

To be able to make correct decisions the first responders and the officer in command need to have a sound knowledge of environmental protection and the basics in contamination transport. Environmental education therefore needs to be implemented as a natural part of the further education and training of fire fighters and officers. In the case of an accident in a sensitive areas, environmental protection can easily become a complex task that needs special
expertise. To support the rescue services a national environmental emergency program has been proven successful in Canada\textsuperscript{16}. As the environmental protection at large can be divided into four sub-areas: prevention, preparedness, response and restoration, the field of responsibility reaches further than the Rescue Services. A national resource can support organizations at all levels. The Swedish Rescue Services Agency has developed a decision support tool, RIB, which includes for example information about hazardous materials, expert networks, equipment resources and computational calculation programmes\textsuperscript{17}. RIB also includes education programmes for fire fighters. The use of RIB is well implemented among Swedish rescue services and provides a good information path for new knowledge.

**Discussion and conclusions**

The tunnel environment is unique compared to other sites in terms of water transport and the mobility of contaminants. In order to rapidly prevent environmental damage in tunnel fires, solutions must be pro active. Preventative studies and techniques must be designed for each tunnel or tunnel specific site, e.g. marine tunnel environments, tunnels in sensitive eco-system areas, tunnels in water protection areas or tunnels in urban environments. The work should be conducted in steps where the first step should contain the following:

- Categorization of tunnels,
- Priority of tunnels in sensitive areas,
- Assessment of risk of fire or oil spill.

Starting with the highest priority tunnel and working through the tunnels of Sweden, we suggest the development of a digital system based on the following:

- Investigation of site specific properties, i.e. water transport and mobility of contaminants,
- Investigation of traffic and thereby assessed contaminant load in the case of a fire or spill,
- Development of tunnel specific mathematical models.

In the case of a fire, the digital models should be kept available for rapid action to prevent environmental damage. Depending on the tunnel specific properties, given by the models described above, the most effective actions can be chosen. Some methods for environmental damage control, especially in sensitive areas, can be preventative, e.g. treatment ponds and barriers.

The research outlined above is necessary but not sufficient for the prevention of on-site environmental damage. Apart from this preventative work, new technologies should be developed, specifically for the treatment of extinguish water \textit{on-site}. We suggest mobile systems, brought to the fire scene as fast as possible during a fire, should be developed. Presently research literature lacks information concerning such systems and it is therefore crucial to enhance the technology of environmental protection within this field. We suggest development of, e.g.:

- Rapid water collection systems
- Mobile water treatment systems
- Mobile soil treatment systems for treatment of the ground/soil beneath the fire
- A survey and treatment plan for *in-situ* treatment of the surrounding environment where necessary.

To conclude, we suggest an innovative package of new technical solutions, ranging from action plans to tunnel models and mobile bioreactor techniques.

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