Final recommendations – GRUVAN project

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Summary

This report is the final part of the research project "Concept for fire and smoke spread prevention in mines", conducted by a research group at Mälardalen University.

The project is aimed at improving fire safety in mines in order to obtain a safer working environment for the people working for the mining companies in Sweden or for visitors in mines open to the public.

This report comprises the recommendations given in the earlier parts of the project.

The main purpose of the report is to give final recommendations of the project in order to facilitate the continuing work within the subject.

Special recommendations for visitors in mines open to public will be presented in Swedish but some of the recommendations are also given here.

Based upon the findings, conclusions and recommendations of the individual parts of the GRUVAN project, the following recommendations were picked out as the most significant and important of them all:

- Full scale fire experiments with respect to vehicle fires should be performed, resulting in heat release rate curves.
- Further studies and experiments should take place that vary additional parameters besides the distance between the individual fuel objects. This in order to further develop a methodology to predict the total heat release rates of complex objects, such as for example a vehicle.
- The heat release rate curves of design fires involving all common vehicles should possibly be reconstructed using the potential theoretical methodology. The results of the theoretical model should be validated using the results from performed full-scale tests.
- The results from the full scale fire experiments should be compared with the corresponding results from one- or two-dimensional calculation models as well as three-dimensional CFD calculation models.
- The use of a CFD model together with a ventilation network simulation program should be further investigated. The results should be compared with corresponding fire experiments.
- Further and deeper studies of the applied mine ventilation network simulation program should be performed, investigating for example the assumptions and calculation models behind the specific software.
- As spray fires are a common type of fire underground and leads to a rapid fire growth with considerable smoke spread, non-flammable hydraulic fluids are strongly recommended for use in underground mines.

- In order to improve the fire safety in production areas, the lack of fire barriers (due to the blasting operations taking place every day which would destroy any existing fire barriers) should be investigated further and alternative methods should be looked into.
- During the work in the project it has been shown that the fire behaviour in loader cabs can be very rapid and have a large impact. Thus it is recommended that automatic extinguishing systems are installed in loader cabs that are manned.
- The research has shown that the time space for smoke spread during a large fire in an underground mine is larger than the minimum demand on the air supply in refuge chambers (4 hours). Thus it is recommended that the minimum demand is revised and increased.

Preface

This report is part of the research project "Concept for fire and smoke spread prevention in mines", conducted by a research group at Mälardalen University.

The project is aimed at improving fire safety in mines in order to obtain a safer working environment for the people working for the mining companies in Sweden or for visitors in mines open to the public.

The following organisations are participating in the project: Mälardalen University, LKAB, Sala Silvergruva, Stora Kopparberget, Brandskyddslaget and Swepro Project Management.

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Contents

1. Introduction

Research regarding fire safety in mines has so far mainly been directed towards coal mines. Thus the need for recommendations, models, engineering tools etc for non-coal underground mines are in great need.

The aim of the current research project "Concept for fire and smoke spread prevention in mines" is to improve fire safety in mines in order to obtain a safer working environment for the people working for the mining companies in Sweden or for visitors in mines open to the public. The fire safety record in mines in Sweden is in general good with very few fire accidents that have occurred. The main reason is that there is a great awareness of the fire safety problems in mines. The awareness comes from the fact that escape routes from mines are generally limited. The reason why there is a limited amount of escape routes is that it is expensive to construct extra escape routes which are not a part of the tunnel mining system. The costs to build extra escape tunnels may be better spent on different safety equipment or systems for fire prevention or evacuation. Such systems can be ventilation systems, fire fighting equipment or rescue chambers located at different places in the mines.

The project consists of different steps, where each step is based on results and knowledge from the earlier steps. The steps are: literature survey, inventory of technical and geometrical conditions, calculation of smoke spread, model scale tests and reports and recommendations. All results will be compared and evaluated against earlier experiences.

This report deals with the last step final recommendations from the project.

The main purpose of the report is to give final recommendations of the project in order to facilitate the continuing work within the subject.

Special recommendations for visitors in mines open to public will be presented in Swedish but some of the recommendations are also given here.

2. Background

The fire safety problems in mines are in many ways very similar to the problems discussed in road, rail and metro tunnels being under construction. There is usually a limited amount of escape routes and the only safe havens are the safety chambers consisting of steel containers with air supply within and rescue rooms which have a separate ventilation system and will withstand a fire for at least 60 minutes.

Rescue operation is hard to perform when the attack routes often are equal with the possible path for smoke to reach the outside. The possibilities for a safe evacuation and a successful fire and rescue operation are strongly linked to the fire development and the smoke spread in these kinds of constructions.

For mining companies the problems with evacuation and rescue operations in case of fire are closely linked to policies, work environment protection and their systematic fire safety work. An accident not only can cause injuries, or in the worst case deaths, but also large costs due to production losses, reparations and loss in good-will.

The main problem with mines today is that they have become more and more complicated, with endless amount of shafts, ramps and drifts, and it is difficult to control the way the smoke and heat spread in case of a fire. The ventilation strategy is of the greatest importance in such cases in combination with the fire and rescue strategies. Since there are very few fires that occur, the experience of attacking such fires in real life is little. New knowledge about fire and smoke spread in complicated mines consisting of ramps is therefore of importance in order to make reasonable strategies for the personnel of the mining company and the fire and rescue services. The main experience from fighting mine fires comes from old coal mines, which are usually quite different in structure compared to mines in Sweden which mainly work with metalliferous rock products. In Sweden the mines consist of either active working mines with road vehicle traffic and elevator shafts for transportation of people and products or old mines allowing visitors. In some cases it is a combination of both types.

As the mine industry is changing and the challenging techniques are developed, the measures to guarantee the safety of personnel need to be adjusted. The new technology means new types of fire hazards, which in turn requires new measures to cope with the risks. New equipment means new types of fire development. The knowledge about fire developments in modern mines is relatively limited. The fire development of vehicles transporting material inside the mines is usually assumed to be from ordinary vehicles, although the vehicles may be considerably different in construction and hazard. The difference may mainly be in the amount of liquid (e.g. hydraulic oil) and the size of the rubber tyres.

The final recommendations will be a valuable asset in the continuing work with respect to improving the fire safety in underground mines.

3. Literature survey

The main purposes of the literature survey were:

- To investigate and present what has been done in the non-coal underground mine fire field in the past.
- To give recommendations on the continued work with regard to fire safety in underground non-coal mines.

The following conclusions were made based upon the findings of the literature survey [1]:

Starting with the statistical material, the most common fire cause in underground mines was flammable liquid sprayed onto hot surface, followed by electrical shorting/arcing and hot works. So based upon the statistics, a conclusion would thus be to focus on spray fires, fire caused by flammable liquid ignited by hot surface, vehicles fires (including rubber tires) and cable fires.

Continuing on with the interesting locations in underground mines, mobile equipment working areas would be first priority due to the high risk of fires in mobile equipment.
Furthermore the types of mobile equipment to focus on should be: service vehicles, drilling rigs and loaders.

A major concern was the lack of documented fire experiments in vehicles/mobile equipment. This is essential knowledge when designing new mine sections and overlooking existing sections. Thus there is a great need for heat release rate curves, also due to for example the fact that a majority of the fires in underground mines involve vehicles/mobile equipment.

Taking into account the enormous volume of cables present in an underground mine and the fact that the statistics put cable fires high on the list, some efforts should be made with respect to this type of fire.

Generally there is a demand for investigation of the friction losses of fire gases in a mine drift (as not all CFD models will be able to take this into account). Further work is needed within this discipline.

When performing full scale experiments in an underground mine, models and equations describing the heat exchange between fire/fire gases and rock should be validated at the same time.

Regarding the movement of fire gases in a mine ventilation network, the earlier work will have to be supplemented with fire experiments with more complicated and varying geometry (opening area, inclination, aspect ratio), larger test area, reversing/increasing the ventilation, and larger, non-steady state fires are needed. Besides performing the fire experiments the results should also be examined against the results of corresponding CFD/ventilation network simulation program.

A practical issue that would greatly affect the fire safety in production areas is the difficulty in preventing smoke spreading from a fire affected production area, as no fire barriers are possible (the blasting taking place every day would destroy the fire barriers), other methods will have to be looked into.

The use of a CFD model together with a ventilation network simulation program would be highly interesting to investigate. The results should be compared with corresponding fire experiments. Ventilation network simulation programs could at the same time be validated for a non-coal mine.

The work on CFD modelling in underground mines has so far been fragmentary; a more extensive work is needed, where:

- The geometry is varied (opening area, inclination, aspect ratio etc.) and made more complicated in the vicinity of the fire.
- Non-steady state fires and larger fires.
- Friction losses/obstacles.
- Heat losses to surrounding rock.
- Changes in ventilation (non-steady state ventilation).

Besides the investigation of the above factors the investigation should also include the implementation of CFD models and suggestions on improvements should be made.

With respect to the risk of spray fires: the type of hydraulic fluid being used in the Swedish mines should be investigated and fire-resistant hydraulic fluid should be recommended being used whenever possible.

The use of fire suppression systems and rapid fire detection systems should be considered for manned cabs in Swedish mines. The reason for this is the rapid fire behaviour of spray fires.

The duration of the air supply in refuge chambers must be investigated further in order to validate it against the duration of large vehicle fires and lingering smoke.

During the search no material related to tourist mines was found.

3.1 Recommendations based on the literature survey

The six activities most prioritized to go ahead with, with respect to the findings of the literature survey are:

- Conducting fire experiments with respect to cab/vehicle fires, resulting in heat release rate curves.
- Conducting an extensive work on CFD modelling (validating the results with corresponding fire experiments), where:
    - The geometry is varied (opening area, inclination, aspect ratio etc.) and made more complicated in the vicinity of the fire.
    - Non-steady state fires and larger fires.
    - Friction losses/obstacles.
    - Heat losses to surrounding rock.
    - Changes in ventilation (non-steady state ventilation).
- Investigating the use of a CFD model together with a ventilation network simulation program. The results should be compared with corresponding fire experiments.
  With respect to the risk of spray fires: the type of hydraulic fluid being used in the Swedish mines should be investigated and fire-resistant hydraulic fluid should be recommended being used whenever possible.
- The use of fire suppression systems and rapid fire detection systems should be considered for manned cabs in Swedish mines. The reason for this is the rapid fire behaviour of spray fires.
- The duration of the air supply in refuge chambers must be investigated further in order to validate it against the duration of large vehicle fires and lingering smoke.

4. Site inventories

The main purposes of the site inventories were:

- To get a clear picture of the risks in the different mines.
- To get a clear picture of the protective measures of each mine.
- Optimize the choice of design fires for each mine.

To find out what the present situation was at the operational mines, a site inventory was conducted at the two LKAB mines in northern Sweden: the Kiruna mine and the Malmberget mine.

The site inventories were conducted through actual visits to the specific sites and through e-mail correspondence with LKAB personnel responsible for the different sections and areas. During the inventories, predefined forms for each type of item were used in order to facilitate the work. The following items were examined:

- Combustible materials in general, for example large amounts of wood.
- Vehicles
- Cables
- Fire barriers
- Ventilation systems
- Extinguishing systems

Besides the above items, earlier fires and fire incidents were also examined.

As the two LKAB mines are tremendously large with a large amount of equipment etc, only the most common vehicles were listed and examined further. Also, only the sites with the largest amount of cables and other combustible materials were listed.

The following conclusions were made based upon the findings of the inventory [2]:

- With respect to earlier fires and fire incidents for the two LKAB mines, the most common causes and the causes to focus on are: electrical cause, flammable liquid or material on hot surface, hot works and equipment running hot.
- Both the production area and the infrastructure part should be regarded in the future studies as fires are almost identically frequent in both areas.
- When it comes to combustible material in general, the amount of combustibles seems to be more frequent in the Malmberget mine. In the Kiruna mine, the places with wood and conveyor belts seems to be interesting enough for further investigation. Even though self extinguishing conveyor belts means a limited fire in size, the amount of smoke emitted can be quite extensive. Also the storage of tyres at the contractor's depots could be worthwhile investigating due to the sensitive surroundings.

- Regarding the Malmberget mine, the sites with wood combustibles, tyres and conveyor belts are all interesting for further investigation due to the large amount of combustibles and the surroundings.
- With respect to flammable liquids:
    - The tank stations in both mines should be looked into with respect to potential pool fires.
    - The larger workshops and warehouses in both mines should also be investigated with respect to pool fires.
    - The crusher levels and draw points in the two mines should be investigated with respect to spray fires.
    - The diesel tanks in the main ramps and the production areas of both mines should be investigated with respect to pool fires.
    - The media drifts, distribution levels, shaft hoisting levels and pumping stations should be investigated with respect to pool fires.
- With respect to fire barriers: as the main ramps of each mine does not contain any fire barriers the impact of a vehicle fire in the main ramp would be interesting to investigate. It would also be interesting to validate the ventilation strategy in the Malmberget mine regarding preventing smoke spread to adjacent compartments.
- With respect to vehicles, all the common heavy vehicles listed in this report would be worthwhile to try to reconstruct a possible fire scenario for each type of vehicle. The reason for this is to have better tools when working on possible scenarios of each mine.
- Regarding cables, all listed sites with a high load of electrical cables would be interesting to investigate. Even though the immediate surroundings are not sensitive, an extensive smoke spread would make a large impact on a large portion of the mine.
- When looking into the ventilation system of the Kiruna mine, both the mine production area and the infrastructure part should be investigated due to the differences in each system and their surroundings. Also, the difference in systems whether you are below or above level 775 should be considered. The function and impact of oversteering should also be included in the investigations.
- The impact of a ventiflex PVC-tube being burned up on the fire behaviour in a production area should be investigated. The different fire scenarios in a production area depending on the position of the fire with respect to the ventilation should also be investigated.
- One scenario should put the fire right at the end of the intake air tube, other scenarios should be at a certain length interval from the end of the intake air tube. The likelihood of the power cables to the intake and exhaust air fans being burned off should be looked into. The impact on the surroundings should also be investigated. The return air fan capacity should be examined with respect to fires, such as vehicle fires.
- In order to improve the fire safety in production areas, the lack of fire barriers (due to the blasting operations taking place every day which would destroy any existing fire barriers) should be investigated further and alternative methods should be looked into.

4.1 Recommendations based on site inventories

Based upon the site inventories the following recommendations are the most prioritized to go ahead with:

- The focus in future studies – with respect to fire causes - should be on: electrical cause, flammable liquid or material on hot surface, hot works and equipment running hot. Both the production area and the infrastructure part should be regarded as fires are almost identically frequent in both areas. The fire object to focus on should be vehicles and the heat release rate curves of design fires involving all common vehicles should possibly be reconstructed.
- A vehicle fire or a pool fire in a main ramp should be considered in the future studies as the main ramps do not contain any fire barriers.
- With respect to the ventilation system of the Kiruna mine, both the mine production area and the infrastructure part should be investigated due to the differences in each system and their surroundings. Also, the difference in systems whether you are below or above level 775 should be considered.
- The possible design fire scenarios in a production area depending on the position of the fire versus the ventilation should be further investigated and the impact of a ventiflex PVC-tube being burned up on the fire behaviour in a production area should also be further investigated.
- In order to improve the fire safety in production areas, the lack of fire barriers (due to the blasting operations taking place every day which would destroy any existing fire barriers) should be investigated further and alternative methods should be looked into.

5. Design fires

The main purposes of the work on the design fires were to:

- Describe different approaches to describe design fires.
- Develop suitable design fires for different systems, mines, warehouses, workshops etc.
- Discuss the position of the design fires with respect to adjacent installations, egress, interruptions in the production etc.
- Discuss the influence of ventilation on the fire growth and its influence when working out the design fires.
- Discuss the influence of fire fighting on the choice of design fires.

The following conclusions were made based upon the findings of the report [3]:
The five selected and presented design fire curves of the report were:

- A pool fire in the main ramp (involving a diesel tank).
- A vehicle fire (heavy vehicle) in a parking drift which is protected by a sprinkler system.
- A vehicle fire (loader/drilling rig) in the production area.
- A cable fire at the visitor museum, with no automatic fire alarm at the site of the fire.
- A bus fire at the visitor museum, with no automatic fire alarm at the site of the fire.

The design fire curves that were developed represented various aspects and variables connected to an underground mine, such as active fire protection, ventilation, sensitive surroundings etc.

5.1 Recommendations based on design fire study

In future work the main effort should be aimed at developing other representative design fires for underground mines than the five developed design fire scenarios; this would serve as a powerful tool during the design process when working on an underground mine.
In future work design fire scenarios involving vehicles should be obtained by using physical models. One way of doing this is by summing up the individual combustible components taking into consideration when ignition will occur.
The five presented design fire curves should be included in a continued study where for example the smoke spread is calculated and simulated using fire modelling software, presenting the effects on the surroundings that the selected design fires will have.

6. Smoke spread calculations

The main purposes of the smoke spread calculations were to:

- Use both one- or two-dimensional calculation models as well as three-dimensional CFD calculation models.
- Position the design fires (a pool fire, a fire in a loader, a fire in a loader in a sprinklered drift, a cable fire and a bus fire) at various sites with respect to for example the ventilation system.
- Investigate the complexities of the various models, their limitations and deficiencies etc.
- Compare the results from the calculation models with each other and with experimental data where applicable and available.

The work started with describing smoke spread in underground mines in general and then continuing with describing three types of calculation models used in this report. After that calculations and simulations were conducted – using the three models – for the five designated design fire scenarios and the results were presented for strategic sites with respect to egress safety and the intervention of the fire and rescue services. The results from the CFD simulations were thereafter validated with respect to flame temperature and grid size convergence.

When comparing the results of the three calculation models the following conclusions could be drawn:

- The mine ventilation network simulation program generally showed higher temperatures at the measuring points compared with the outputs of the other two models. One probable reason for this is that the heat release rate could not be represented as adequately as for the other two models; in all cases the heat release rate levels were higher for the mine ventilation network simulation program.
- Generally the hand calculations showed much lower visibility figures than the CFD model. One reason for this – besides the fact that we are dealing with two models with vastly different approaches - is most likely in the difference in the types of smoke characteristic factors used in the two types of models.
- The FDS simulations generally showed small changes in temperature when comparing with the other two models. This could be attributed to the fact that the measuring points are positioned at fairly large distances from the fire and thus the fire gases will cool considerably. Also the maximum heat release rate of some of the fires was small - ~1 MW – and thus the impact on the nearby environment will be limited.
- The results of the hand calculations with respect to the visibility was a good approximation for the design fires with fairly low maximum heat release rate as the stratification in this case would be almost nonexistent and thus the smoke spread could be assumed to be equal to the ventilation velocity in a drift (one dimensional smoke spread).

- With respect to the egress safety the visibility will be the critical factor. In the case of the pool fire (design fire) the visibility would start to decrease at an early stage of the fire both according to the hand calculations and the FDS simulation. After approximately a few minutes the visibility in a large section of the connecting main ramp would be affected due to the open nature of the area. Thus the egress will have to take place at an early stage in order to ensure safety. Regarding the fire in the loader, the fire in the parking drift and the cable fire the hand calculations indicated a sharp decline in visibility after a few minutes, but the facts that the FDS simulation showed no differences in visibility and that the heat release rate was relatively small in all three cases (<1 MW) would indicate that the visibility would be affected but in a limited manner and thus the egress safety would not be largely affected during the first 10-20 minutes due to for example the large spaces in the mine drifts. With respect to the bus fire the same conclusions were drawn as in the case of the pool fire except that the FDS simulation predicted a much slower smoke spread than the results from the hand calculations.
- With respect to the intervention from the fire and rescue services the visibility would also be the critical factor as for the egress safety. The loader fire in the sprinklered drift and the cable fire should generally not pose any large problem to the intervention of the fire and rescue service, as the maximum heat release was small and the smoke spread largely limited. But the pool fire, the loader fire and the bus fire would be problematic to the intervention of the fire and rescue service as the maximum heat release was large and the smoke spread was extensive affecting a large area before the arrival of the fire and rescue service (>30 minutes). Thus the fire and rescue service would have to start the intervention at a large distance from the site of the fire and work its way towards the fire. This would take a long time and would decrease the chance of rescuing any personnel left in the area.

6.1 Recommendations based on smoke spread calculations

As no data from conducted full-scale fire experiments were found that were applicable to any of the five design fire scenarios, future work should deal with validating the results of the three models with experimental results from conducted full scale fire tests corresponding to any of the five design fire scenarios. In this case more profound comparisons and conclusions could be drawn.

Measuring points should be placed in the near vicinity to the fire as well as sites further away from the fire (> 50 m), this in order to effectively investigate and compare the results of one- and two-dimensional models versus a three dimensional model.

Also further and deeper studies of the applied mine ventilation network simulation program should be performed, investigating for example the assumptions and calculation models behind the specific software.

7. Model scale tunnel fire tests

The model scale tests comprise a number of model scale fire experiments conducted in a model tunnel at SP facilities in Borås, Sweden.

The main purposes of the tests were:

- To obtain data which can validate models to calculate the total heat release rate of multiple objects
- To investigate the influence on the heat release rate curve that a varying distance between the fuel objects will have.
- To investigate the influence on the heat release rate, fire growth rate and time to ignition for adjacent fuel objects that increasing ventilation will have.

The work started with describing the theoretical basis of scaling theory and the determination of heat release rate at fire experiments, continuing with describing the experimental setup with the fuel load and instrumentation used. After that the experimental procedure and the experimental results were described. The results from the experiments were thereafter examined and discussed and finally conclusions were drawn.

The findings and conclusions of the study were the following [5]:
It was found that an increasing ventilation rate also increases the maximum heat release rate. Also the ventilation rate will have an influence on the fire growth rate, in the tests the case with the highest ventilation rate displayed a slower fire growth rate than the other two cases, this could possibly be explained by the fact that the height of the pile of wooden pallets (205 mm) was practically equal to the short side of the pile (200 mm) and the fire was started on the long side, thus as the longitudinal ventilation is increased less fuel area is exposed to the tilted flames and thus the fire growth rate decreases.
When studying the graphs of the various heat release rates it was found that when the distance between the ignited pile and the second pile behind it increased to a certain level the ignition of the pile behind it will be delayed resulting in that not all piles are burned with their maximum heat release rate at the same time. The delay in ignition can be distinguished by a "hump" before the peak value in the heat release rate curves. In cases with short distances between the piles the ignition of adjacent piles took place almost simultaneously and resulting in a total heat release curve where the pallet piles burn at their maximum at practically the same time
It was also found that the peak value of the heat release rate decreases as the distances between the piles are increased – from ~500 kW down to ~450 kW – as the curve is stretched out in time. The ignition data indicated that the time to ignition of adjacent piles would decrease as the longitudinal ventilation was increased.

7.1 Recommendations based on model scale tests

Further validation work should take place with respect to validating the experimental data with output data from theoretical models.
Further studies and experiments should take place that vary additional parameters besides the distance between the individual fuel objects. This in order to further develop a methodology to predict the total heat release rates of complex objects, such as for example a vehicle.

8. Final recommendations based on the project work

Based upon the findings, conclusions and recommendations of the individual parts of the GRUVAN project, the following recommendations were picked out as the most significant and important of them all:

- Full scale fire experiments with respect to vehicle fires should be performed, resulting in heat release rate curves.
- Further studies and experiments should take place that vary additional parameters besides the distance between the individual fuel objects. This in order to further develop a methodology to predict the total heat release rates of complex objects, such as for example a vehicle.
- The heat release rate curves of design fires involving all common vehicles should possibly be reconstructed using the potential theoretical methodology. The results of the theoretical model should be validated using the results from performed full-scale tests.
- The results from the full scale fire experiments should be compared with the corresponding results from one- or two-dimensional calculation models as well as three-dimensional CFD calculation models.
- The use of a CFD model together with a ventilation network simulation program should be further investigated. The results should be compared with corresponding fire experiments.
- Further and deeper studies of the applied mine ventilation network simulation program should be performed, investigating for example the assumptions and calculation models behind the specific software.
- As spray fires are a common type of fire underground and leads to a rapid fire growth with considerable smoke spread, non-flammable hydraulic fluids are strongly recommended for use in underground mines.
- In order to improve the fire safety in production areas, the lack of fire barriers (due to the blasting operations taking place every day which would destroy any existing fire barriers) should be investigated further and alternative methods should be looked into.
- During the work in the project it has been shown that the fire behaviour in loader cabs can be very rapid and have a large impact. Thus it is recommended that automatic extinguishing systems are installed in loader cabs that are manned.
- The research has shown that the time space for smoke spread during a large fire in an underground mine is larger than the minimum demand on the air supply in refuge chambers (4 hours). Thus it is recommended that the minimum demand is revised and increased.

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