Fire behavior in multiple rooms

1 Introduction

Every firefighter knows the fire development curve in figure 1. That curve depicts a possible manner in which a fire could behave inside a building. In order for this curve to manifest itself, several conditions have to be met:

- There has to be enough fuel inside the room.
- The fuel load has to be positioned in such a way that a fire can grow of which the heat release rate exceeds the limit needed for flashover to occur in the room.
- Sufficient air (ventilation) has to be available to allow the fire to reach that heat release rate.

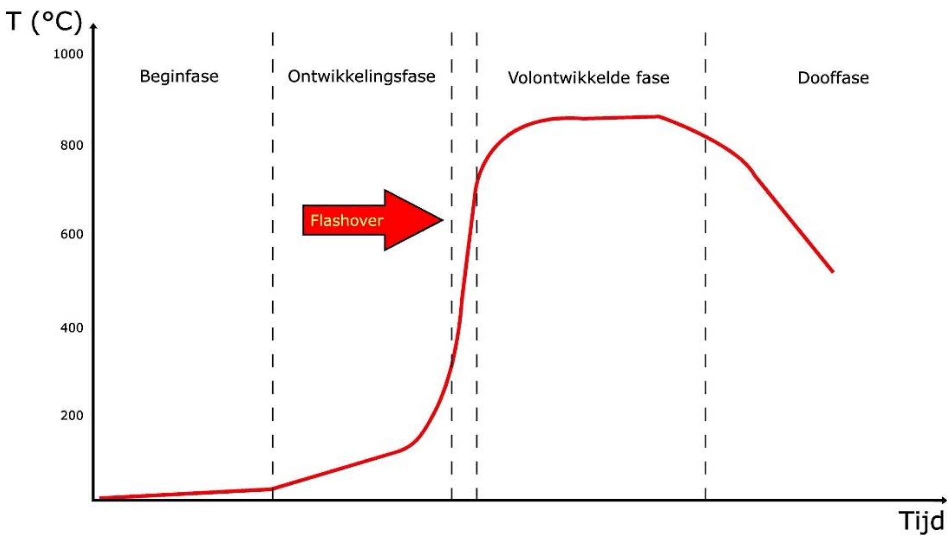

figure 1 The ventilated fire growth curve *(Figure: Karel Lambert)*

Not every firefighter understands that this curve illustrates an evolution of temperature as a function of time, while actually heat release rate is referred to in the conditions described above. The article *The fire growth curve revisited* presents the fire in a 'time-HRR' graph [2]. The article looked at the impact of different variations (ventilation, fuel load) on the HRR.

This curve only relates to a fire in a single compartment. *Then how does a fire behave and grow when there are multiple compartments involved?*

In this article, we take a closer look at fire behavior in multiple rooms. The article will not be exhaustive, nor does it intend to be. The focus is put on a fire that starts in one room and spreads through a doorway into a second room.

2 Smoke is what it is all about

Every fire produces smoke. Smoke is crucial to the spread of the fire because smoke itself spreads three things that are important to firefighting crews:

1. Spread of energy
2. Spread of fuel
3. Spread of toxicity

The section below covers the spread of smoke and its consequences in more detail.

2.1 Smoke spread

A fire produces smoke. Smoke consists of soot particles, aerosols and gases. However, for the largest part, smoke consists of air. *How is that actually?*

Smoke is produced at the seat of the fire. A large part of the energy (the heat) released by the fire, is used to heat up the smoke. So the HRR of the fire plays an important role in smoke spread: the higher the HRR, the more "force" the fire has to push the smoke far away from itself so to speak. The initial temperature of the smoke depends on the amount of air that can flow onto the seat of the fire. The size of the outline of the fire is important here. The bigger the outline, the more air can flow in. If the HRR remains constant, the temperature of the smoke rising from a larger outlined fire, will be lower.

Because smoke is hotter than the surrounding air, it will rise upward. The effect causing this is the same one that causes a hot air balloon to rise: hot air rises. However, in a hot air balloon, the air is trapped inside the balloon. It cannot mix with the colder outside air.

Smoke differs somewhat in that regard. Smoke rises and as it gets higher, air is mixed more and more into the smoke plume. This causes several things to occur:

- The temperature of the smoke decreases. The hot smoke that started down at the fire mixes with the colder surrounding air.
- This causes the temperature difference with the surrounding air to decrease as well, and the smoke will rise less swiftly than before.
- The mass of the smoke increases as well. After all, a large part of air has been mixed into the smoke.

The temperature of the smoke, the velocity at which it rises and the mass of the smoke all change as it gets higher (see figure 2).

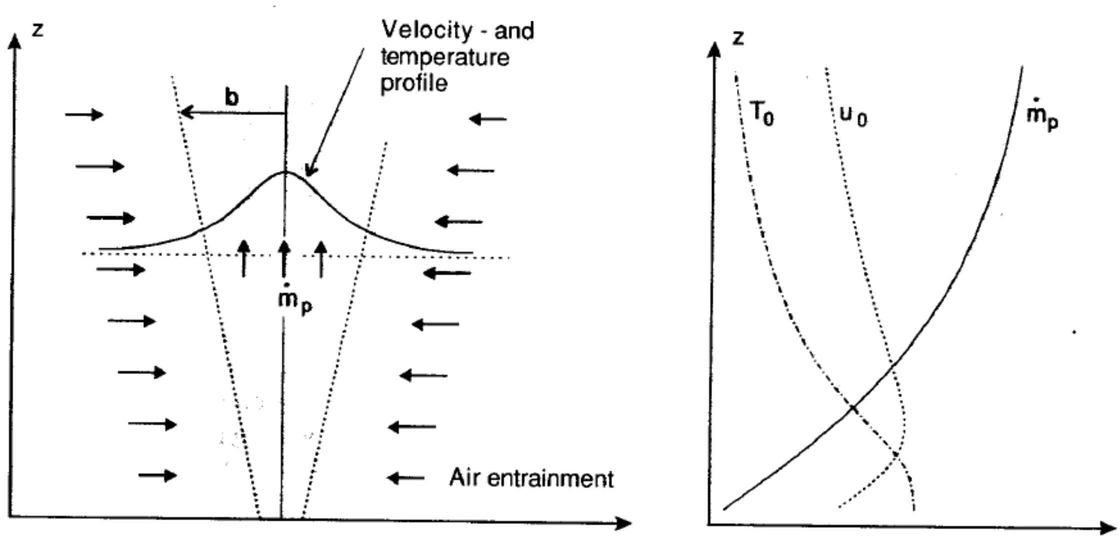

figure 2 A schematic depicting a smoke plume. As the smoke plume rises higher, it widens. The temperature and velocity are highest in the middle and decrease towards the outsides of the plume. The temperature (T) and the velocity (u) decrease as the smoke rises. The mass (m) increases. (Figure: [7])

Every firefighter knows that a fire in a room, first produces a smoke plume and then a smoke layer. The smoke plume hits the ceiling after which it will spread horizontally. The smoke will continue to spread until it hits a wall. The walls and ceiling of the room limit the smoke layer. The smoke layer will then become thicker (= expand and drop down).

This then causes the vertical distance that the smoke plume travels, from the seat of the fire to the smoke layer, to decrease. That means that less air is allowed to be mixed into the rising smoke plume. This in turn means that the smoke plume will cool down less than before and smoke with a higher temperature is flowing into the smoke layer.

The ceiling height of the room therefor plays an important role in all this. In a warehouse that is 8 meters high, the smoke plume will cool down over that distance before it enters the smoke layer. Then again the thickness of the smoke layer is determined by the surface area of the compartment. The surface area partly dictates how much smoke can be stored in the smoke layer. A larger room will take longer to form a smoke layer that is one meter thick. A large and high compartment forms a sort of buffer for smoke so to speak.

What is also important here are openings in walls. If there is an open window, the smoke will start to flow out as soon as the smoke layer reaches the top of the window. From that point, smoke will both flow into the smoke layer (from the plume) and it will flow out of the room (through the window). When that happens, there are – theoretically – three possibilities:

1. More smoke is flowing into the smoke layer than out. The smoke layer will continue to drop.
2. Smoke is flowing out at exactly the same rate as it is flowing in. The height of the smoke layer will remain the same.

3. Less smoke is flowing in than out. The size of the smoke layer will decrease. This could occur for example when smoke vents in the ceiling are opened at a fuel controlled fire.

So there quite a few parameters that determine how the smoke plume and smoke layer will behave:

- The HRR of the fire
- The circumference (outline size) of the fire
- The height of the room
- The surface area of the room
- Presence of openings

Fire makes for a very complex system in which everything is constantly changing.

The smoke plume forms a bridge between the seat of the fire and the smoke layer. Through the smoke plume, fuel, energy and toxic particles flow into the smoke layer.

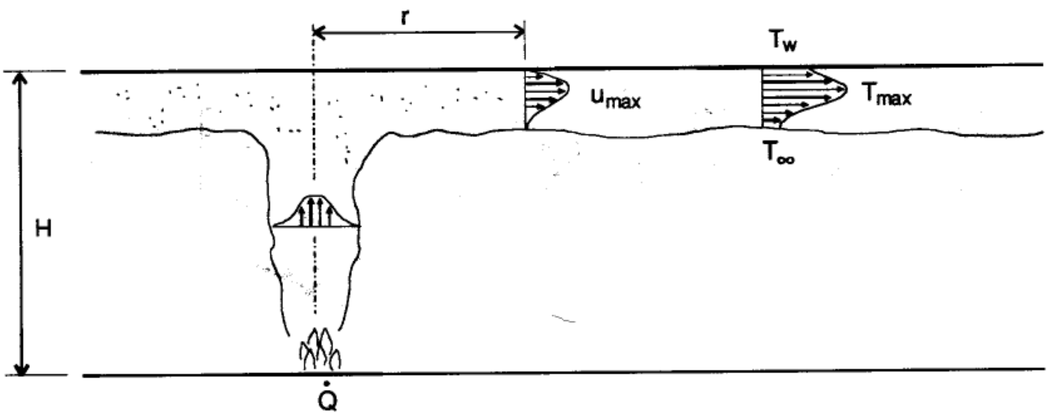

FIGURE 4.17 An idealization of the ceiling jet flow beneath a ceiling.

figure 3 Illustration of a smoke plume flowing into the smoke layer. A ceiling jet is formed in the smoke layer. The jet is divided into sections with different flow velocities (u) and different temperatures (T). Both will rise when the HRR of the fire increases. Both will decrease when the room is higher. *(Figure: [7])*

The smoke layer is connected to the walls and ceiling. At the start of the fire, the insides of the wall roughly have the same temperature as the interior environment. As soon as the walls come into contact with hot smoke, they will of course start to heat up themselves. Part of the energy contained in the smoke layer, is transferred unto the walls.

As soon as the smoke layer drops below the top end of a door opening connecting a neighboring compartment, smoke will start to flow into that second room. That flow will cause a displacement of energy, fuel and toxicity.

2.2 Energy spread

The smoke flowing through the connecting doorway, will rise back up to the ceiling. All of the comments made concerning the buildup of the smoke layer (thickness, temperature) in the first room, apply once more for the second room.

That smoke layer however, forms a significant threat to everyone and everything in that second room. The smoke layer will transfer energy onto all objects and occupants that have a lower temperature than the smoke layer.

Just as in the initial room, the smoke layer will radiate heat onto everything below it. That radiant heat could be quite high when the temperature of the smoke is layer is high as well. If there is a high enough amount of radiation, the objects underneath the smoke layer at some point will start to pyrolyze. This means that the smoke layer is causing flammable gases to form in the second room.

Special consideration must be made to flammable wall and ceiling cladding. The ceiling is directly in contact with the hot smoke layer. The smoke will heat up the ceiling through convection. That is a different method of heat transfer as opposed to radiation. Convection requires direct contact between the smoke and the colder object. So if the smoke is touching the flammable ceiling (wood or flammable insulation), then flammable gases can form there as well. The pyrolyzing of furniture beneath a smoke layer might possibly still be visible to fire crews inside the room, the production of flammable gases high inside the smoke layer however, is not. Therefor is much more treacherous.

Eventually, the heat of the smoke layer could cause ignition to occur in the second room. From that point, a second flashover will soon follow. The second flashover however, will be in the second room and not in the first one. The fire is considered to have spread and further spread could still happen.

2.3 Fuel spread

Fuel in gaseous form is flowing into the second room through the door opening. Up to that point the room had been filled with 100% air. Now, fuel particles (pyrolysis gases and also partially combusted gases such as CO) are flowing into the room. A smoke layer forms at the ceiling. This should be viewed as a reservoir of gaseous fuel. If objects start to pyrolyze in the second room, the gases formed will also end up in that smoke layer.

At some point in time, the smoke layer, or certain parts of it, will reach the lower flammability limit. Depending on the temperature of the smoke layer, the smoke will ignite at some point. This could happen in several ways:

- Flames exiting the first room through the door opening
- Dancing angels in the smoke layer
- Rollover in the second compartment

Each one of these phenomena needs fuel to occur. That is why the spreading of fuel from the first to the second compartment (and the "production" of fuel in the second room) is so important.

Each of these phenomena produces energy locally. Wherever there are flames, heat is released. The smoke layer will be heated (temporarily) in certain parts. This will cause the heat transfer (through radiation and convection) to increase as well. A self-reinforcing cycle is formed of spreading energy and spreading fuel. Higher temperatures will lead to more pyrolysis (= more fuel). When there is sufficient fuel, ignition could occur which in turns leads to more energy.

The article "How do people die in fires?" [9] explained that radiation is proportionate to absolute temperature to the fourth power. This principle dictates that flames (in certain parts of the smoke layer) give off 16 times more radiant heat than smoke with a temperature of 200 °C. So when parts of the smoke layer ignite, radiation suddenly increases 16 fold.

2.4 Spread of toxicity.

The third problem related to the spreading of smoke, is the spread of toxic particles. For fire crews, this does not directly pose a problem as they are usually wearing SCBA. Even though the concentration of toxic gas reaches significant levels, as long as they have air in the cylinder, they can breathe just fine. But this does not apply to victims in the room. Occupants in the building could be located in another room, but when the door is open, smoke will transfer a large amount of toxic substances into the room. Studies by UL have shown that this very quickly leads to lethal levels of toxicity. In a standard dwelling, the expectation is that occupants trapped in the fire room only have 5 minutes.

However, when those victims are trapped in another room with the door closed, the time it takes before conditions become unviable is up to thirty minutes. This also has tactical implications for crews doing search & rescue in a house fire: when a crew is in a room filled with heavy smoke (e.g. kitchen or living room), they have to be careful when opening doors. It is quite possible that they could open a door from the smoke filled living room, to a bedroom that was until then clear of smoke. As soon as the door is open, smoke will flow into the bedroom where there could be a potential victim still alive and well. After all, inside the bedroom there is still air of sufficient quality left. That will quickly change once the door opens and there is no longer a barrier holding the smoke back. It could possibly be the case that the actions of the fire crew endangers the safety of the victim. That would be the opposite of what search & rescue tries to achieve.

When a search crew finds itself opening a door to a room that was free of smoke up to then, it could be a good idea to immediately close that door again. Any occupants inside that room are not in immediate danger. Leaving the victims in that room, maybe with a firefighter to inform and reassure them, could be an option. At the same time, the fire could be knocked down and most of the smoke could be cleared using PPV fans. That way, the victims could be evacuated through rooms in which most of the smoke has been cleared. It is imperative that search & rescue crews communicate clearly with their commanding officers when implementing this tactic.

Keep in mind that it will not always be possible to keep victims in a compartment for a longer period of time. Sometimes it takes a while before the fire can be brought under control. In that case, more smoke would be allowed to spread into the neighboring rooms. Even when there is a fire resistant door separating the rooms, there would still be some smoke that would seep through. Most fire resistant doors are not completely smoke tight.

The Brussels fire department once had the following happen at a fire on the 12th floor in a high rise building. One apartment unit was almost entirely fully involved. Fire crews faced a variety of different problems (faulty water supply, very large fuel load in the unit with objects partly blocking the door, …). Because of these issues, it took a long time before the fire service was able to knock down the fire. Across the hallway on the 12th floor, a mother was trapped in her apartment along with four young children. The hallway was filled up completely with thick, black smoke. The initial idea was to keep them in their apartment and have them "ride out" the fire. After 45 minutes however, smoke had seeped in to such levels that they had to be evacuated. This was done using rescue masks (see figure 4).

There are different sorts of masks available. Some operate using filters, others use an air tank. When using filter based masks, there has to be enough oxygen left in the smoke in order to evacuate people safely. That is not required when using a BA with an air tank. If the temperature of the smoke is low enough, people could evacuated through even very thick smoke using these rescue masks.

figure 4 A rescue mask which can be put on the victim's head. A regulator or lung demand valve has to be attached, preferably with an extra-long hose so that both victim and firefighter can move easily alongside each other. *(Photo: Pieter Maes)*

It is possible that a search crew opens a door into a room with less smoke than where they were originally in, but still enough to cause safety issues for any possible victims inside. Things are seldom clear cut, black or white issues in firefighting. Search crews will have to assess to the best of their abilities which tactic they will employ.

3 Second compartment on fire: some possible curves

Firefighters know the temperature curve of a ventilated compartment fire very well. That is the graph shown in figure 1. *How does that graph change when the fire spreads into a second room?*

Figure 5 again illustrates the fire from figure 1 with a red line. This red line depicts the fire behavior in a bedroom for instance. Because the bedroom door is open, smoke will flow from the bedroom into the neighboring room (e.g. a living room). As soon as the smoke layer drops below the top of the door opening, a flow will form. As described above, the hot smoke will radiate heat onto every object underneath it. The couch in the living room will be heated up that way.

After flashover in the first room, flames from the bedroom will exit through the door into the living room. Temperatures in the living room will start to rise significantly. This will cause radiation to rise drastically as well (proportionate to the fourth power of the absolute temperature). This will cause a fire to start in the living room. That second fire is illustrated by the blue line. This line also has a growth stage and also goes into flashover. It is very important for firefighters to realize that two fires in different rooms, can be in different stages. The bedroom fire can be fully developed (post flashover) while the living room fire can still be in the growth stage (pre flashover). A fully developed fire in one room does not mean that flashover cannot occur in another room. In other words, while advancing towards a fully developed fire, flashover could happen in the room through which the attack crew is advancing.

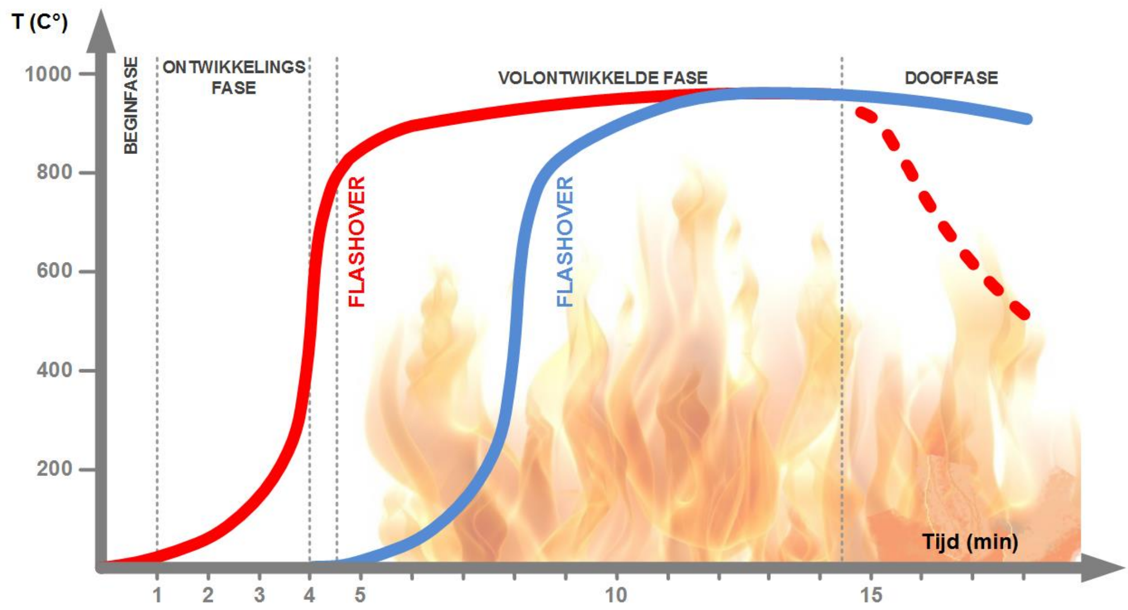

figure 5 Fire development in multiple rooms. The red line depicts the fire development in the room where the fire originates. During the fully developed stage, flames exit the room through a door opening. The flames enter a second room. The radiant heat of these flames will create a secondary fire (blue line). After a few minutes, that secondary fire will progress into flashover. *(Drawing: Bart Noyens & Karel Lambert)*

After a certain period of time, the fuel load in the first room will run out. The intensity of the fire will decrease. The fire will enter the decay stage. The fire in the living room however, is still burning fiercely. That fire is in the fully developed stage. Again, the two fires are behaving in different ways (and will look different as well).

We can also look at the HRR curve, which illustrates the power or HRR that is built up during the fire. These curves are totally different from that in figure 5. The important thing to note is this: two temperatures cannot be added together, two HRR can!

The orange line figure 6 illustrates the HRR of the fire in the bedroom (red line in figure 5), developing from incipient to growth stage and then into fully developed stage. The decay stage is not depicted. The progression of the HRR is depicted in a simplified way. Once the fire reaches the fully developed stage, the HRR remains the same. The fire has become ventilation controlled and the HRR is determined by the amount of air that is allowed to flow into the room.

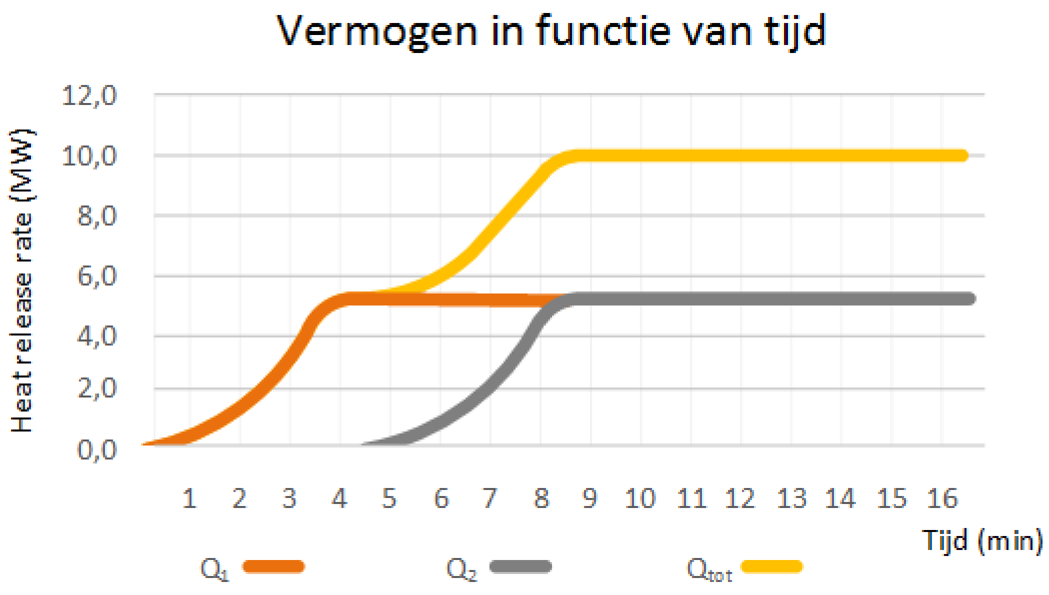

figure 6 A simplified representation of the buildup of HRR in a fire that extends into a second room. Two different HRR may be added together. *(Figure: Bart Noyens & Karel Lambert)*

The grey line illustrates the HRR in the second room (the blue line in figure 5). Here as well, the HRR remains the same after flashover. The graph is not entirely accurate. In reality, it will probably be that the flashover in the living room will have an effect on the fire in the bedroom. A (large) portion of the oxygen needed for the fire in the bedroom, will be used up by the fire in the living room. For simplicity's sake, this is ignored in the current representation.

The yellow line depicts the total HRR that is being built up. The yellow line is the sum of the two other lines. When both fires each produce a 5 MW HRR, then in total a HRR of 10 MW is reached.

Even though temperature is a physical quantity that familiar to firefighters, the amount of extinguishing power we have in our hose lines is presented as a HRR or power. It is important for our own safety that we always have more extinguishing power than the HRR of the fire. The goal is not to be complete

4 Closing remarks

Fire behavior in a single room is very well known to firefighters. The rules that apply to a fire in multiple rooms, are much more complicated. This article attempts to present the most important rules in a simplified manner. The goal is not to fully cover the subject matter. The reader therefore has to keep in mind that certain simplifications were made and that reality is even more complex than presented here.

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