The fire growth curve revisited

1 Introduction

Every firefighter knows the fire growth curve which is taught in basic firefighting training. Where in the past, there used to be just one fire growth curve, now there are two. One is the old curve, defined with the term "*ventilated fire"* (see figure 1). This article discusses this curve. It represents a fire in in a room with the following conditions:

- Sufficient fire load that is situated at just the right place in the room
- Sufficient ventilation

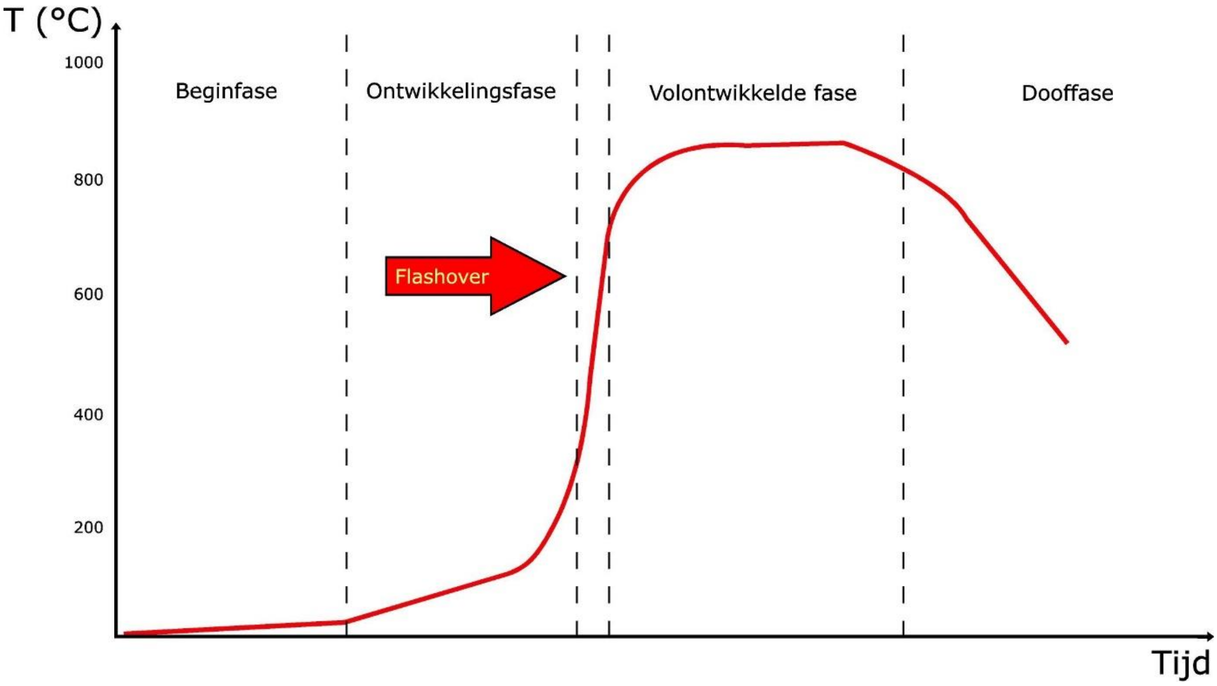

figure 1 The ventilated fire growth curve *(figure: Karel Lambert)*

It often occurs that a fire goes out by itself because the initial object to catch fire is unable to produce a high enough Heat Release Rate to ignite another flammable object nearby. In these cases there is often a lot of smoke, but hardly any heat. So there is enough fuel load available to allow the fire to progress into flashover, but the arrangement of the fuel package prevents this from happening. The fire dies down in the incipient stage.

Just recently, the fire service of Oostkamp found themselves at such a fire. They were dispatched to a fire in a house which had trapped an entire family on the first floor of the building. Upon arrival, the entire ground floor turned out to be filled with smoke. The smoke was blocking the escape route of the occupants, which were on the first floor. On top of that, the windows on the first floor were all single glazed. The fire seemed to be under ventilated and fire crews acknowledged that breaking the windows could lead to ventilation induced flashover. An interior attack was started using 45 mm attack lines. During the advance of the attack line, it turned out that smoke in the living room was not at all warm.

Cold smoke can be a consequence of an under ventilated fire. Due to a lack of air, the Heat Release Rate of the fire is very low (see figure 2). This means that very little heat is built up. Using the Thermal Imaging Camera, the crews were able to find the seat of the fire. The source was a hoverboard that had been left charging. The object was located next to a solid oak cabinet. The cabinet was of course blackened and scorched, but the HRR of the burning hoverboard was insufficient to fully ignite the wooden cabinet. The hoverboard had burned up completely and entered its decay stage. The fire had produced a large amount of smoke, but very little heat. With the use of a fan, the smoke was vented from the building and the family were saved from their predicament. Even though the smoke was not warm, levels of toxicity were high enough that fleeing through the smoke without a breathing apparatus was not viable.

This scenario could have turned out completely different however. On the other side of the living room stood the cardboard box in which the hoverboard was usually stored. This cardboard box was standing next to a large three seat sofa. Suppose for a minute that the hoverboard had been placed inside or on top of the box and then it had caught fire. In all likelihood, the sofa would have been ignited as well. The sofa would have generated enough HRR to cause a flashover in the living room. Upon arriving, the fire service would have been faced with large, fully developed fire on the ground floor. The temperature of the smoke coming from such a fire and flowing into the first floor, would be 10 times higher. We can only guess whether the bedroom doors would have protected the family long enough for help to arrive.

The only variable that is different in these two cases, is the placement of the hoverboard (the initial burning object) at the time of ignition. Everything else about the living room contents remains the same. One scenario results in a large amount of smoke damages, the other leads to a burnt down home and possibly several victims dead. For a ventilated fire to reach flashover, sufficient fuel needs to be present <u>in the proper arrangement</u>.

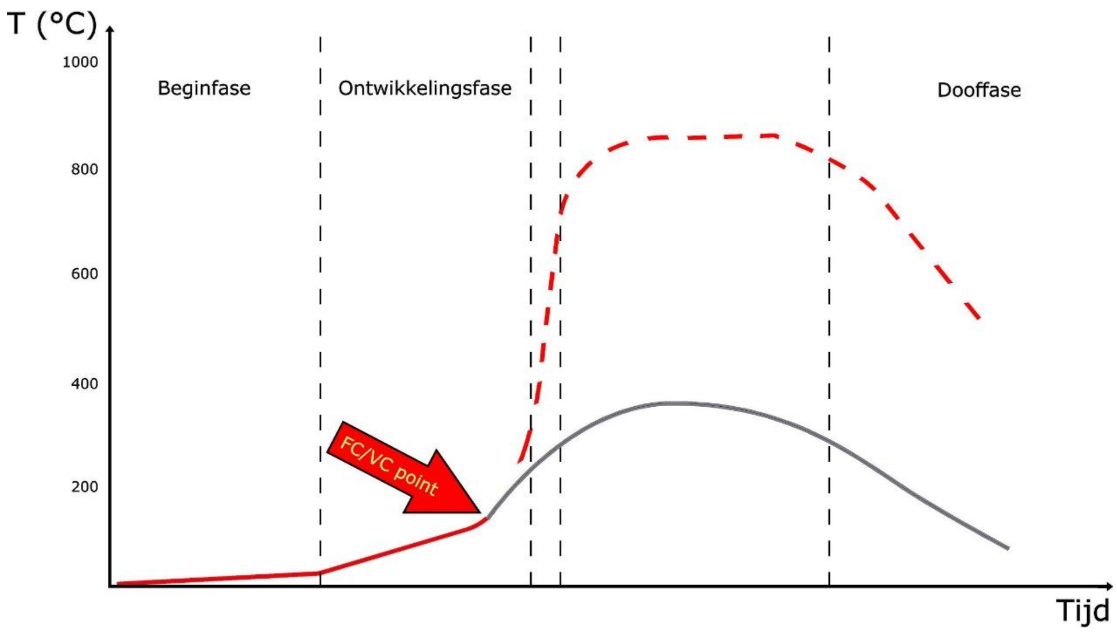

figure 2 When there is insufficient air, the fire passes from the red to the gray line. This is called an under ventilated fire. *(Figure: Karel Lambert)*

When there is insufficient ventilation that leads to flashover being unable to occur, then we are dealing with an *under ventilated fire*. The fire will remain small until it goes out by itself or until extra ventilation openings are created. This fire will have a different curve, depicted in figure 2.

This article however is about the ventilated fire as shown in figure 1. This curve is known by most firefighters as a temperature curve. This type of curve illustrates the development of temperature as a function of time. Several questions can be asked about this statement: *Which temperature exactly is illustrated by the curve?* Or in other words: *At which spot do we have to place a thermometer so that the measured temperatures are those shown by the aforementioned graph?* A lot of firefighters cannot answer that question.

Do you know the correct answer? This article will address the reader directly from time to time. Try thinking through the question before reading the next section. Does the text confirm your answer? Good! If not, think about why your answer was incorrect. In either case, you will have learned something.

2 Heat release rate of a fire

Every fire produces a certain heat release rate. This can be described as follows: Picture a three seat sofa. Suppose that the sofa ignites due to a forgotten cigarette. On the seat of the sofa, an area of one quarter square meter is burning. The flames are rising up about 50 cm from the sofa. *Can you see the image in your mind?*

The heat of the flames will largely flow upwards. There, it will heat up the smoke layer. Part of the heat is radiated back towards the sofa. This causes the sofa to heat up. The high temperature of the sofa (fuel load) will cause part of the sofa to start pyrolyzing. This means that the sofa is losing part of its mass. If the sofa was standing on a scale, we would see the weight going down slowly. The scientific term for this is *Mass Loss Rate* (in kg/s). The hotter the fuel, the quicker pyrolysis gases will be formed (and the quicker the weight on the scale will go down). Pyrolysis gases are nothing more than gaseous fuel. The flames are being fed by these pyrolysis gases. The flames are burning the pyrolysis gases using oxygen from the surrounding air.

A gas stove is operated by opening a tap. Next the exiting gas is ignited by a spark. By manipulating the tap, a larger or smaller flame is formed. In a real fire, the function of the tap is taken over by the heat falling onto the fuel load. The hotter the fuel, the more pyrolysis gases per second are released. The more pyrolysis gases per second, the higher the heat release rate of the fire.

The section above only applies to fuel controlled fires. At such fires, there is air (oxygen) in abundance. The heat release rate of the fire will depend on the amount of pyrolysis gases (the mass loss rate). When a fire becomes ventilation controlled, this means that there is insufficient air to burn off all of the pyrolysis gases. Part of these gases will be added to the smoke layer. This means unburnt particles are gathering in the smoke layer. The heat release rate of the fire is being limited by the available air. This is shown in figure 2 where the fire switches from the red to the grey line. However it also occurs in figure 1. Just before the curve tops out horizontally, the fire has become ventilation controlled. Both fire curves have a section that is ventilation controlled.

The graph in figure 1 could also be described as a *heat release rate – time graph*. This graph shows how the heat release rate progresses as function of time. Figure 1 shows the incipient stage. The incipient stage is fuel controlled and is characterized by a very limited HRR. The fire remains fuel controlled through the growth stage but becomes ventilation controlled during flashover. The fully developed fire is ventilation controlled. The horizontal section of the graph during the fully developed stage is a direct consequence of the fact that only a limited amount of air can get into the room through the ventilation opening(s).

3 Which information can be unpacked from the fire curve?

Take a look at the fire shown by figure 3. It is clearly a fully developed fire. The fire has vented through two windows that are next to each other. Both windows are of the same height and surface area.

Suppose these windows connect to a living room and suppose the living room door is closed. The two windows would then be the only ventilation openings for the fire in the picture. The living room contains a large amount of fuel: sofas, a coffee table, cabinets filled with books, a TV, … It is clear that the entire room is on fire. The HRR of the fire is limited by the amount of air entering the room. It is a typical example of a ventilation controlled fire.

This fire started small of course. For the sake of simplicity, we assume in this reasoning that both windows were open at the start. Suppose the fire started on a three seat sofa. In the beginning there is only a limited HRR. As the fire grows, the HRR will increase.

figure 3 A view of a fully developed fire venting out of two windows. *(Photo: www.nufoto.nl)*

Figure 4 shows how the HRR progresses as time goes on. The fire starts out small, grows, reaches flashover and becomes fully developed (the horizontal line). After some time, the amount of fuel will have been severely reduced. A lot of fuel will have burned. This means that because of the mass loss rate, very little fuel will be left over. A large amount of fuel will have been transformed into pyrolysis gases. It is reasonable to assume that the decay stage will start when 70% of the fuel load has been burnt. The amount of pyrolysis gases (per second) decreases because there is barely any fuel left. At some point there will again be sufficient air flowing in through the openings to burn all of the pyrolysis gases. The fire will have become fuel controlled once again. As pyrolysis decreases further, so will the HRR. After some time the fire will self-extinguish. The production of pyrolysis gases will have become so small that a flaming combustion can no longer be supported. The remaining fuel will continue to smolder, but as time goes on everything will cool down and the fire will go out completely.

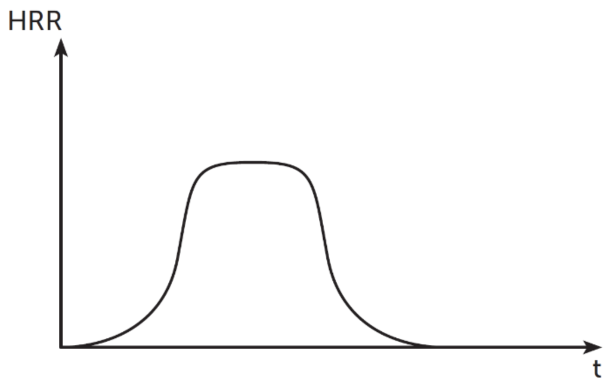

figure 4 Heat release rate as a function of time in a ventilated fire. *(Drawing: Karel Lambert)*

Suppose the fire had started in another living room, in a house constructed exactly the same with the same size as the first living room. Suppose the fuel load is identical and of the pieces (sofa, table, …) are at the exact same place. The fire also starts exactly the same, a cigarette in the sofa. Everything is identical to the first scenario except from one thing: there is only one window instead of two. The surface area of the windows is half that of the one in the previous fire. What is the effect of this on the HRR? Will the fire grow more slowly than when there were two windows? Or will it progress faster somehow?

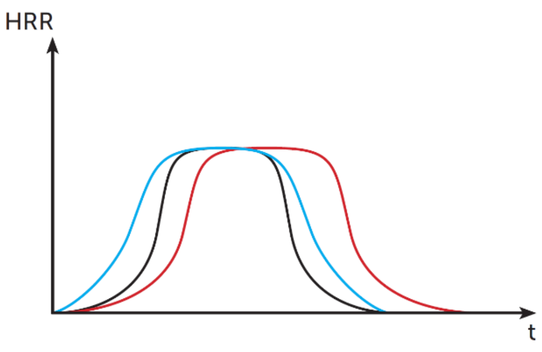

figure 5 Two possible variations of a HRR graph for a fire with one instead of two windows. *(Figure: Karel Lambert)*

Figure 5 has a black line showing how the fire progressed when there were two open windows.

The blue graph indicates a fire that is progressing faster.

The red graph is a fire that is progressing more slowly. Which of the two is the correct one? Or are both of them wrong perhaps?

Try thinking of arguments to support your position.

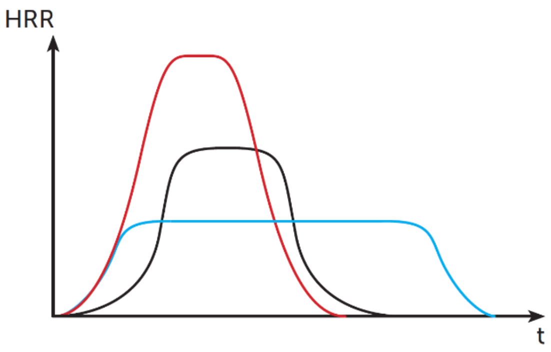

figure 6 Two other possible outcomes for the HRR of the fire when there is only one window instead of two. *(Figure: Karel Lambert)*

It is also possible to come up with two graphs that both progress faster, but have either a higher or lower HRR. Figure 6 shows these two graphs. The black line still represents the fire in the living room with two windows open. The blue line illustrates a fire that is developing faster, but also quickly stops growing and keeps burning at a lower HRR. The fire sustains this stage for a longer period of time.

The red line illustrates a fire that develops faster and on top of that, reaches a higher HRR. This causes it to burn less long in time. Is one of these two graphs the correct representation of a fire in a living room with one open window?

Again, think of arguments to support your reasoning.

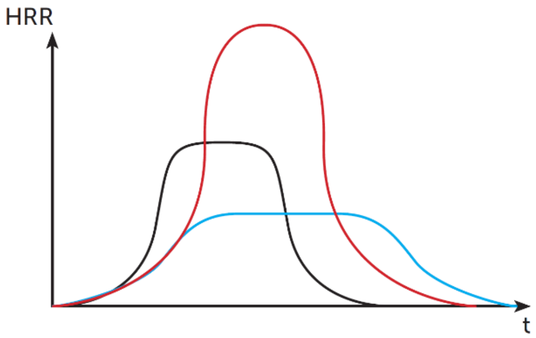

figure 7 Two new possible variations for the same fire. *(Figure: Karel Lambert)*

figure 7 shows a variation of figure 6. This time the red and blue line represent fires that develop more slowly than the fire in the living room with two open windows (the black line). Just as in figure 6, the blue line tops out at a lower HRR than the black line. The red line reaches a higher HRR than the black line. Is one of these lines perhaps the correct one?

It is up to you to think about this critically and formulate an answer.

Figures 5, 6 and 7 all represent fires that develop faster or slower than the fire depicted by the black line. However, it could easily be the case that the growth of the fire is unaffected by the lack of a second open window. Figure 8 shows two of these possibilities. The blue line is exactly the same as the black line in the initial stages. This means that the fire is growing in the exact same way. However, the fire becomes less intense (lower peak HRR) at a later stage. The red line also has the same growth as the black line, but ends up with a higher peak HRR than the fire with two open windows. Maybe the correct graph is in here? Or perhaps

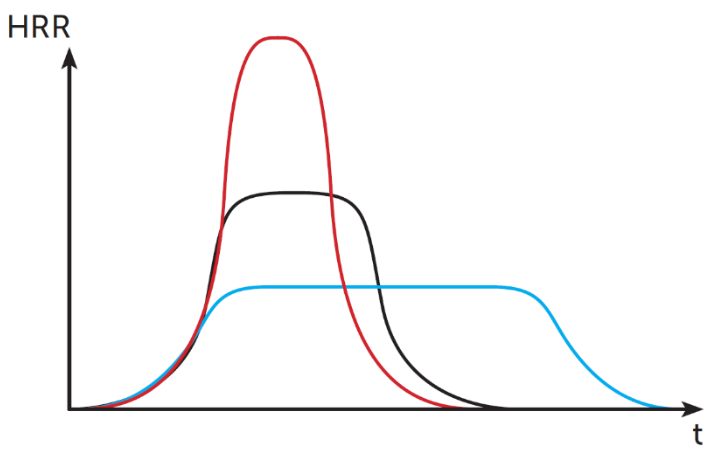

figure 8 Again two possible representations of the HRR of a fire with one open window instead of two. *(Figure: Karel Lambert)*

there is another possibility that has not come up yet.

Think about your answer and why you think it is correct.

4 The effect of one window instead of two.

The black line illustrates how the HRR of a fire progresses in relation to time, for a fire in a living room with two open windows. The first part of the line represents the incipient and growth stage of the fire. The fire is fuel controlled at that time. This means that there is enough air to burn the pyrolysis gases that are being produced. If the size of the ventilation openings was to be increased, this would not affect growth of the fire. After all, there is already sufficient air. Reducing the size of the ventilation opening will not have an effect either in the beginning stages of the fire. As long as there is sufficient air flowing in through the opening to burn the pyrolysis gases that are being formed, the fire will be fuel controlled and this means there is no effect of increased ventilation.

A fuel controlled fire will not burn faster or slower in the beginning stage by having one open window instead of two. The lines of the two fire (two windows and one window) are congruent.

The fire in the living room with one open window will also progress to flashover. Enough air is entering the room through the open window, to allow the fire to grow. Keep in mind that the surface area of the open window must remain larger than a certain minimum size. The fire in the living room must be able to grow to a certain HRR to achieve flashover in the room. Suppose that the two windows in figure 3 are replaced by one window of $1/4^{th}$ surface area of the original window, then the fire would probably become ventilation controlled before flashover can occur. Then were are dealing with an under ventilated fire. Figure 2 could be a possible illustration of this scenario.

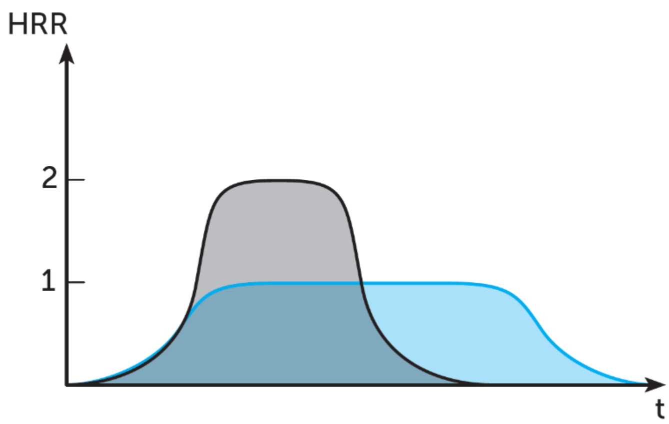

figure 9 The blue graph produces only half of the maximum HRR of the black graph. Because of this the fuel is consumed more slowly and the graph is about twice as long. *(Figure: Karel Lambert)*

When the surface area of the windows in the second scenario living room is half that of the first, then only half the amount of air will be able to flow in. This means that the HRR produced by the second fire will be half that of the first fire. The blue line in figure 8 illustrates the correct answer. The height of the of the horizontal lines (peak HRR) is determined by the total surface area of the open windows. They determine how much air can flow in at any given time, and thus they determine what the maximum HRR will be. The height of the horizontal part of the blue line has to be exactly half of that of the black line. If four windows were to be opened instead of two, then the red line in figure 8 would be the correct one. A HRR of exactly twice the size of the black fire would have to be reached.

Finally, it is important to realize that the surface below the lines represents the fuel load. This is why the blue line in figure 8 is longer than the black line (and the red one is more narrow). When the HRR is only half that of the black line, then only half the fuel will be burned at any given time. This means that the fuel load will last twice as long. A perfect example to illustrate this is a wood stove. Any number of wooden logs can be put in the stove to feed the fire. But when the air inlet is halved, the heat the stove is producing will decrease (because the HRR has been halved). The amount of wood in the stove will last twice as long.

This can be clearly seen in figure 9. The surface area marked in grey has to be equal to the one marked in blue. After all they represent the exact same fuel load. In the "black" fire there is twice the amount of air available and so the fuel load is consumed twice as fast. This leads to a fire that lasts only half the amount in time (but is twice as intense).

5 Bibliography

[1] *Lambert Karel, Baaij Siemco (2018) brandverloop: technisch bekeken, tactisch toegepast, 2nd edition, Sdu*
[2] *Lambert Karel (2009-2019) CFBT-instructor course for the Attack cell, CFBT-BE*
[3] *McDonough John (2009-2019) personal talks*
[4] *Grimwood Paul (2008-2019) personal talks*

Karel Lambert