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Logic missing in the new NFPA 502-2020 version and its requirements for ventilation (critical velocity) for road tunnels when aiming to implement compensation effects from a Fixed Fire Fighting system?

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We as a company, along with other Fixed Fire Fighting System manufacturers have experienced an increase in demand for our road tunnel FFFS solutions.
However, when talking to consultants, tunnel owners and other stakeholders we find that the full effect of an installed Fixed Fire Fighting System is often not exploited.
The NFPA 502-2020[1)] edition's minimum critical velocity calculation methods and velocity requirements also do not support the logic around, or understanding of, the compensatory effect of a Fixed Fire Fighting System.

Fixed Fire Fighting Systems have, over the last decade, been subject to a significant number of full-scale tunnel fire tests and research projects, including tests with longitudinal ventilation systems. These tests have provided a lot of evidence regarding the effect of a Fixed Fire Fighting System in combination with a ventilation system.

This article will provide our point of view and share some of our findings regarding the effects of our Low Pressure Watermist System in relation to the full scale tunnel fire tests we performed, and not least how the mitigation effect from a Fixed Fire Fighting System could be acknowledged in the design of the ventilation system.

1. Introduction to FIXED FIRE FIGHTING SYSTEMS (FFFS)

A Fixed Fire Fighting System (FFFS) is a system that in an active way fights a fire. Such systems are typically also called water-based firefighting systems or suppression systems. The most common FFFS for tunnels are either deluge (low pressure) or watermist (in high, intermediate, or low pressure).
All the above technologies work in zoned operation, dividing the tunnel into fire zones with typically 20-30 m of open nozzles activated by opening a section valve.

2. Tunnel fires

Controlling the fire size not only reduces or prevents tunnel damage, but also assists the control of smoke back layering, as the propensity for smoke to move upstream increases with the increasing size of a fire.
A tunnel (longitudinal) ventilation system is designed to control back layering, based on an assumed peak fire size. If a ventilation system is correctly dimensioned to handle a large fire with a major HRR peak when all other parameters are unfavorable (location, grade, traffic queue etc.), then the ventilation velocity will be high enough to also have a great impact on fire growth rates. Higher velocities will increase the speed at which the HRR will rise. The production of CO_2 and toxic substances inclusive CO rises along with the increase of the HRR.

3. Compensating effects or potentials by installing a FIXED FIRE FIGHTING SYSTEM

It is a known fact that a Fixed Fire Fighting System or suppression system can substantially reduce fire heat release rates (HRR) and temperatures in a tunnel fire, but the compensatory effects of a FFFS are less known, and are, in fact, not acknowledged.

4. Risk analysis and ventilation design

In a typical road tunnel project without a FFFS, we often see a ventilation design that supports potential fire size (vehicle fires) between 100 and 200 MW. Let us in the below example assume that the fire size is 100 MW, and a more conservative design approach is adopted for safety reasons. Then it is not unusual to see ventilation design dimensioned for e.g. a 200 MW fire size. The risk analysis and safety factor in an actual road tunnel project can off course be both lower and higher.

So, one of the compensating effects of installing a FFFS is that it lowers the (Q_{max}. HRR) of a vehicle fire. Let us use the example as described above, with a potential vehicle's fire size of 100 MW. By choosing a FFFS manufacturer who has performed full-scale tunnel fire tests where the tests proved the ability to suppress e.g. a potential 100 MW vehicle fire to e.g. (Q_{max} HRR) 50 MW, it would be logical to include a conservative safety factor of 2 for the ventilation system, and then design it for a fire size of 100 MW.

5. NFPA 502-2020 edition vs. the 502-2014 edition

There seems to be some systematic problem with the recent approaches. The equations in NFPA 502-2014 and 2017 are based on the convective heat release rate, while the new approach in NFPA 502-2020 reverts to the total heat release rate.

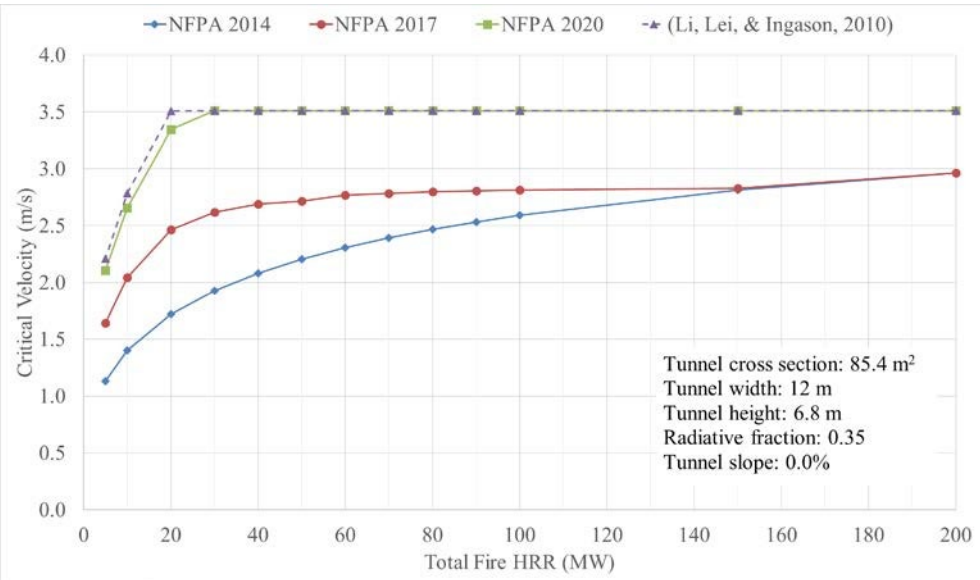


Fig. 1 – Graphs NFPA 2014-2017 and 2020[3]

According to NFPA 502[1)] with reference to longitudinal tunnel ventilation systems, the critical velocity required to prevent back-layering of smoke was in the 2014 edition including parameters on "the heat the fire is adding directly to the air at the fire site". This heat may also be called "convective heat release rate"($_{convective}$HRR) <u>and is always smaller than the total heat release rate</u> (Q_{max} HRR) determined with oxygen depletion, because of heat radiated to the tunnel walls and evaporative cooling by the FFFS and watermist.

If fire size control is only necessary to prevent back-layering of smoke, i.e. to maintain tenability upstream the fire, it seems more appropriate to compare the measured ($_{convective}$HRR) with the specified critical fire size than the measured total HRR Q_{max}.

See NPFA502-2014 Annex C:

Annex C Critical Velocity Calculations

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

C.1 General. The simultaneous solution of equations C.1 and C.2, by iteration, determines the critical velocity. The critical velocity, V_c, is the minimum steady-state velocity of the ventilation air moving toward a fire that is necessary to prevent back-layering.

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{1/3} \quad \text{(C.1)}$$

$$T_f = \left(\frac{Q}{\rho C_p A V_c} \right) + T \quad \text{(C.2)}$$

where:

A = Area perpendicular to the flow [m² (ft²)]
C_p = Specific heat of air [kJ/kg K (Btu/lb°r)]
g = Acceleration caused by gravity [m/sec² (ft/sec-sec)]
H = Height of duct or tunnel at the fire site [m (ft)]
K_1 = 0.606
K_g = Grade factor *(see Figure C.1)*
$\dot{Q}$ = Heat fire is adding directly to air at the fire site [MW (Btu/sec)]
T = Temperature of the approach air [K (°r)]
T_f = Average temperature of the fire site gases [K (°r)]
V_c = Critical velocity [m/sec (ft/min)]
ρ = Average density of the approach (upstream) air [kg/m³ (lb/ft³)]

$\dot{Q}$ = Heat fire is adding directly to air at the fire site [MW (Btu/sec)]

Fig. 2 – Annex C

See NPFA502-2020 Annex C now called D:

Annex D Critical Velocity Calculations

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

Δ **D.1 General.** The critical velocity can be calculated according to Equation D.1:

Δ [D.1]

$$\frac{u}{\sqrt{gH}} = \begin{cases} 0.81 \left(\dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}} \right)^{1/3} \left(\dfrac{H}{W} \right)^{1/12} e^{\left(-\frac{L_b}{18.5H}\right)}, & \dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}} \leq 0.15 \left(\dfrac{H}{W} \right)^{-1/4} \\ 0.43 e^{\left(-\frac{L_b}{18.5H}\right)}, & \dfrac{\dot{Q}}{\rho_a C_p T_a g^{1/2} H^{5/2}} > 0.15 \left(\dfrac{H}{W} \right)^{-1/4} \end{cases}$$

where:

ρ_a = ambient density (kg/m³)
C_p = heat capacity (kJ/kg K)
g = gravitational acceleration (m/sec²)
H = tunnel height (m)
L_b = backlayering length (m), where $L_t = 0$ defines critical velocity (no backlayering of smoke), and $L_t \neq 0$ defines confinement velocity (velocity corresponding to the controlled backlayering length)
T_a = ambient gas temperature (K)
u = longitudinal velocity (m/sec)
$\dot{Q}$ = total heat release rate (HRR) (kW)
W = tunnel width (m)

The effect of the tunnel grading is obtained by multiplying the calculated critical velocity, u_c, by the grade factor, K_g, given in Figure D.1.

Fig. 3 – Annex D

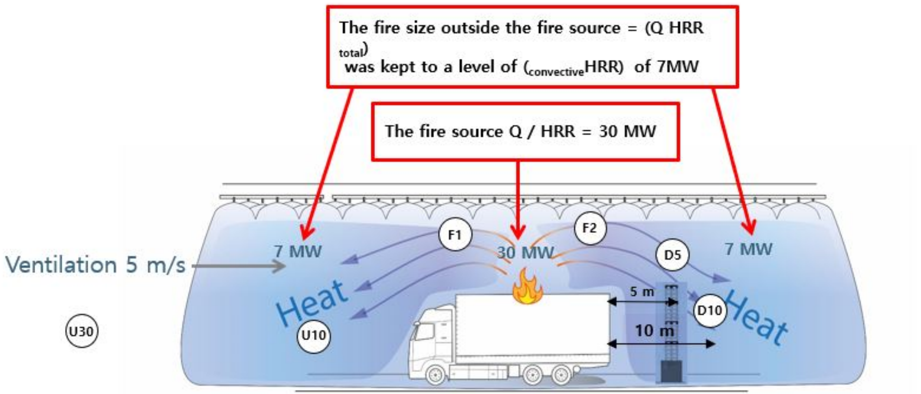
The NFPA 502[1)] equation D1 prevents exploitation of the full effect of the ($_{convective}$HRR), which is <u>without logic, and ought to be reflected in the next NFPA 502 edition.</u>

6. Validation from full scale tunnel fire testing

As mentioned above, a substantial number of full scale tunnel fire tests with various Fixed Fire Fighting Systems has, over the last decade, led to a significant number of third party verified test reports presenting test and validation data of the full scale tunnel fire tests. A lot of evidence has been documented regarding the effects of FFFS. Some of our published test results from our latest full-scale tunnel fire test (Spain 2018[2])) are shown below.

7. Full scale tunnel fire test for a large HGV fire (250 MW)

From May – October 2018[2]), we ran a series of full-scale tunnel fire tests in Spain where we simulated large HGV fires to validate our Low Pressure Watermist System against several criteria. We looked at NFPA 502[1]) tenability criteria including structural protection and back-layering for a potential large fire load (simulated HGV) of 250 MW exposed to a high ventilation velocity of 5 m/s.



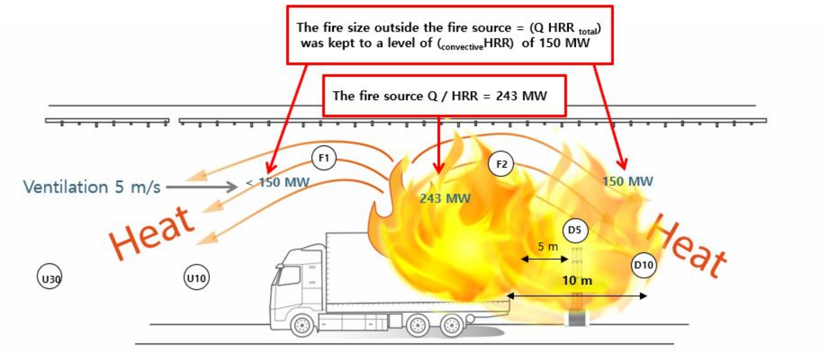
Higest Gas temperatures measured					
D10	D5	F2	F1	U10	U30
120 °c	200 °c	380 °c	42 °c	20 °c	20 °c

Fig. 4 – Full scale tunnel fire test with FFFS – Spain 2018[2])

8. Results

With reference to the results of the above mentioned Spain tests, we obtained, in the 250MW potential vehicle fire with our system activated, a total HRR ($Q_{max.}$HRR) an average of ~ 30MW, and for the ($_{convective}$HRR) was measured to 7MW.

In the test series we also tested and validated results for a "free burn" fire scenario to simulate similar tunnel fire scenario as per above described, but without a FFFS installed. When comparing the two fire scenarios, it's obvious what positive effects a FFFS can have on a ventilation design, but also with reference to other safety aspects, such as structural protection, supporting quick fire brigade intervention etc., especially for large vehicle fires.



Higest Gas temperatures measured					
D10	D5	F2	F1	U10	U30
1300 °c	1200 °c	1200 °c	700 °c	180 °c	25 °c

Fig. 5 – Full scale tunnel fire test (Free burn) – Spain 2018[2)]

9. Conclusion

In the example given in Chapter 4 with a 100 MW fire risk and by assuming a conservative risk assessment and safety factor, this could, as seen in several tunnel projects, result in an adopted 200 MW fire size when designing the ventilation system, for a tunnel without a FFFS.

If we include the results we obtained in our latest Spain 2018 test series for our Low Pressure Watermist Suppression System, and the ($_{convective}$HRR) is utilized, then the proper adopted design fire would then be 2x7 =14 MW, so even if this seems "too optimistic" and additional safety is required, then there should be plenty of room for designing a lower critical velocity and a less expensive ventilation system without compromising safety.

A calculation method for the "compensation effect" ($_{convective}$HRR) when installing a Fixed Fire Fighting System should logically be reflected and incorporated in the new release of NFPA502 Annex D.

Refences.:

1) NFPA 502-2020
2) Efectis – R002191 (Rev.) full scale test report
3) CRITICAL OF CRITICAL VELOCITY (Conrad Stacey, Michael Beyer)