CONSTRUISONS ENSEMBLE
LA DÉFENSE DE DEMAIN

CONSIDERATIONS ON THE WAY TO DUPLICATE THE NATO STANDARD LIQUID FUEL FIRE FOR THE FCO TEST

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Summary

- **Background : from Meppen to Rome…**
- **What is the Standard kerosene pool fire ?**
- **What are the Alternative fuel fires ?**
- **Numerical Approach : Simulations of the standard and alternative fuel fires**
    - Computed thermal environment around the munitions
    - Effect of munitions emissivity on radiative transfer and munitions surface temperature
    - Effect of setup parameters on thermal environment around the munitions
- **Discussion / Conclusion**

Background

- **Fast Cook Off Test :**
    - NATO standard IM test to evaluate the reaction level of the munitions when engulfed in a liquid kerosene fuel fire
    - One of the UN standard tests to determine the hazard classification of the munitions

- **How to mimic the Standard Kerosene Pool Fire ?**
    - NATO Fuel Fire Experts Meetings from 2010 to 2015
    - Discussion about the introduction of an alternative way to do fast heating


Standard Kerosene pool fire

What is the Standard Kerosene Pool Fire ?

Large-scale pool fire

- Pool diameter ~ 4-6 meters
- L/d ~ 2-2.5
- Turbulent flow regime

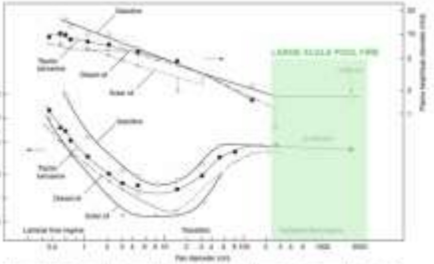
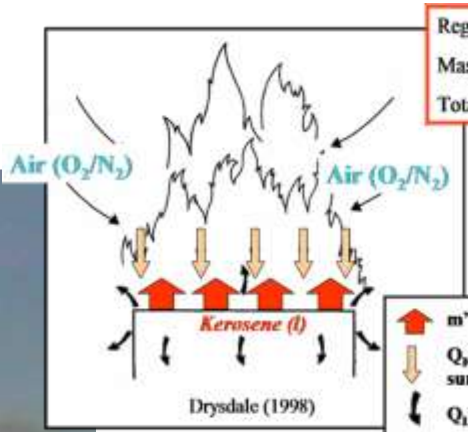


Figure 2-10.16 Regression rate and flame height data for liquid pools from Blinov and Khudiakov.

But convective heat transfer not predominant



Drysdale (1998)

Regression rate R ~ 5 mm/min

Mass flow rate m'' ~ 0.068 kg/m²/s

Total heat release rate Q_c ~ 37 MW

$$Q_c = \chi \cdot m'' \cdot \Delta H_c \cdot A_c$$

A_c : liquid fuel surface (~ 36 m²)

ΔH_c : heat of combustion (kJ/kg)

χ : efficiency factor

- ⬆ m'' : mass flow rate (kg/m²/s)
- ⇩ Q_F'' : heat flux from flame to pool surface (kW/m²)
- ↓ Q_L'' : heat losses (kW/m²)

Flame temperature ~ 800-1100°C

Gas (CO_2, H_2O, CO,…) + Particles (Soot)

Very sooty flame plume

Figure 2-13.1 Transmission electron micrograph of a soot particle. The overall size of the agglomerate is about 6 µm, and the diameter of the individual spherules is about 0.03 µm.

Mulholland (1998)

Heat Transfer to the surroundings and into the flames is mainly due to RADIATION from :

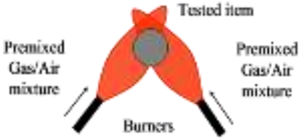
- Luminous flame
- Hot gases (CO_2, H_2O, CO)
- Soot particles (Rayleigh diffusion)

What are the Alternative Fuel Fires ?

Swedish/Dutch-type setup : premix Gas/Air injection

Toreheim et al. (2010)

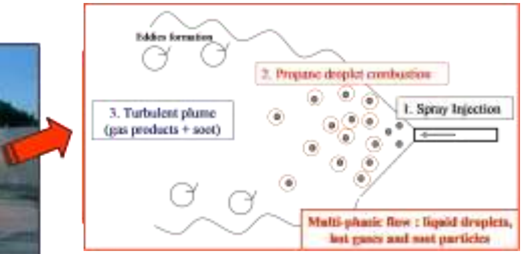
Scholtes et al. (2013)



German-type setup : Liquified Propane Gas Injection

Weigand et al. (2010)

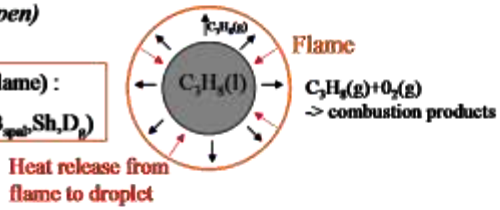
German setup (WTD91, Meppen)



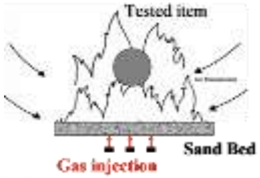
Fuel Droplet combustion

Combustion law (diffusion flame) :

$d^2(t) = d_0^2 - k.t$ with $k(\rho_d, B_{spal}, Sh, D_g)$

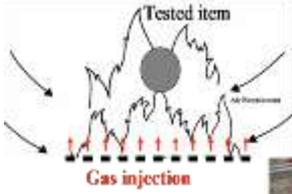


New Swedish-type setup : LPG injection within a sand bed



Toreheim et al. (2013)

US-type setup : Propane gas injection



Hubble et al. (2014)

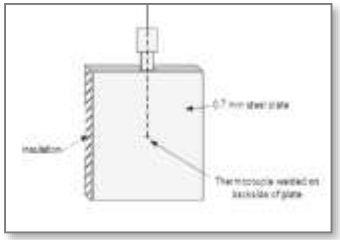
Standard Kerosene Pool fire vs Alternative Fuel Fires

Test facility	Standard Kerosene Pool	German-type	Dutch-type	New Swedish-type	US-type
Fire	Pool fire	LPG droplet spray	Premixed Gas/Air Mixture	LPG within a sand bed	LPG
Combustion	Liquid fuel combustion	Propane liquid droplet combustion	Premixed Gas/Air flame combustion	Liquid fuel combustion	Liquid fuel combustion
Flow regime	Turbulent (vertical)	Turbulent (horizontal jet)	Laminar or turbulent (mass flow rate dependent)	Turbulent (vertical)	Turbulent (vertical)
Burnt gases	CO2,CO,H2O,…	CO2,CO,H2O,…	CO2,CO,H2O,…	CO2,CO,H2O,…	CO2,CO,H2O,…
Soot production	Black smoky plume Unobservable munitions	Yellow/orange flame Munitions can be seen	Blue/orange flame Munitions can be seen	Yellow/orange flame Munitions can be seen	Orange flame Munitions can be seen

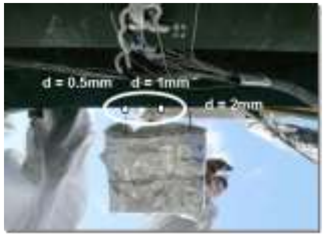
What about the thermal load ?

- Fuel Fire Experts Meetings : from Meppen to Rome, a significant work to EXPERIMENTALLY characterize the thermal load induced by :
  - The Standard Kerosene pool fire
  - The Alternative Fuel Fires (German, Dutch, Swedish and American – types)
- Heat flux and temperature measurements within the standard and alternative fires by the US basket and other methods

Yagla et al. (2013)



Wickstrom et al. (2012)



Chassagne et al. (2013)

But few NUMERICAL investigations

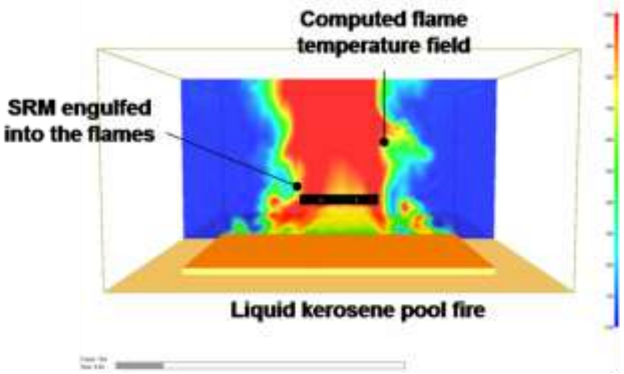
French Numerical Approach

OBJECTIVES :

- To assess the thermal load of the standard and alternative fires
- To compute the effect :
    - of munitions emissivity on radiative transfer and munitions surface temperature
    - of adjustable setup parameters on thermal load around the munitions

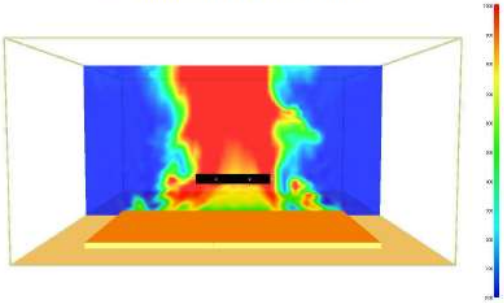
MEANS :

- CFD Code : Fire Dynamics Simulator v5 – developed by the NIST (USA) – typically used for fire safety issues (Mc Grattan et al. 2009)
- Low Mach number flows – Large Eddy Simulation (LES) – Mixture Fraction model
- Used to simulate large scale liquid fuel fires (FCO Test)

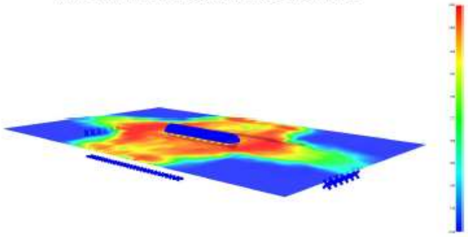


Simulation of the thermal load around the munitions

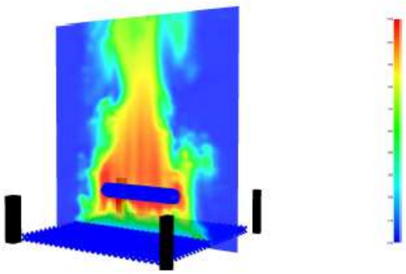
(a) Standard Liquid Fuel Fire Simulation



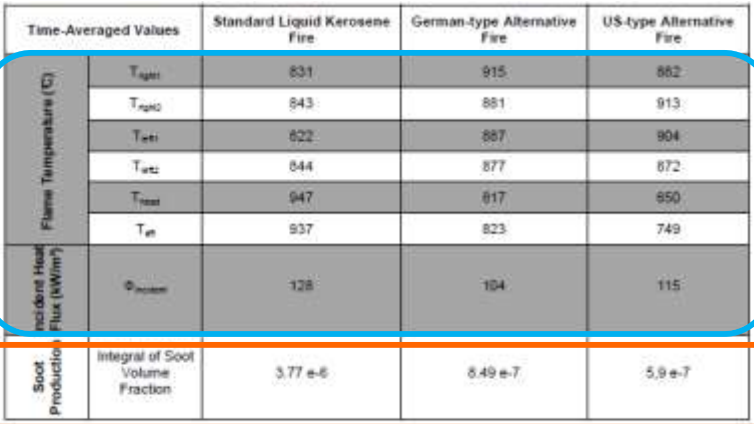
(b) German-type Alternative FireSimulation



(c) US-type Alternative FireSimulation



Thermal loads globally in the same order



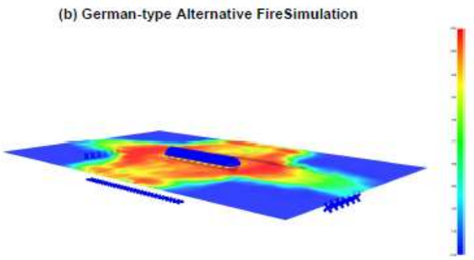
Time-Averaged Values		Standard Liquid Kerosene Fire	German-type Alternative Fire	US-type Alternative Fire
Flame Temperature (C)	T_{right1}	831	915	882
	T_{right2}	843	881	913
	T_{left1}	822	887	904
	T_{left2}	844	877	872
	T_{head}	947	817	850
	T_{aft}	937	823	749
ncident Heat Flux (kW/m²)	$\Phi_{incident}$	128	104	115
Soot Productio	Integral of Soot Volume Fraction	3.77 e-6	8.49 e-7	5,9 e-7

Soot volume fraction has strongly decreased within the alternative fires

LPG Time-averaged Temperature > 800°C but… …is it still realistic to assume $\varepsilon_{munitions}$ = 0.9 during the whole test ?

Background | Liquid Fuel Fire | Alternate Fuel Fire | Modeling | Results | Conclusion

Effect of munitions emissivity

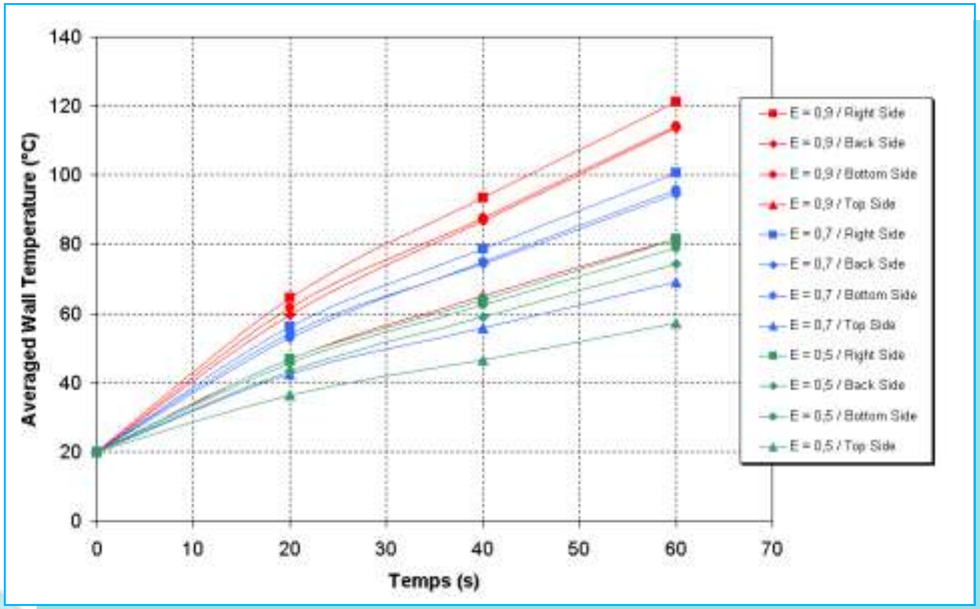


Droplet Flow Rate = 30 L/min – Nozzle-munition distance = 2.5 m – Munitions length : 2m

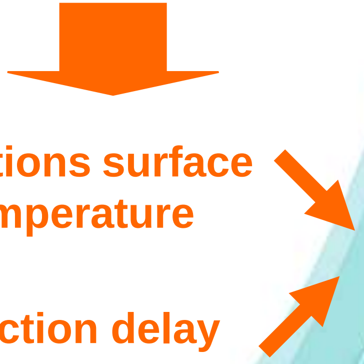
Lower soot production within alternative fires

$\varepsilon_{\text{munitions}}$ may be not close to 1

Numerical simulations : German-type setup with $\varepsilon_{\text{munitions}}$ = 0.5 to 0.9



To reduce $\varepsilon_{\text{munitions}}$ from 0.9 to 0.5



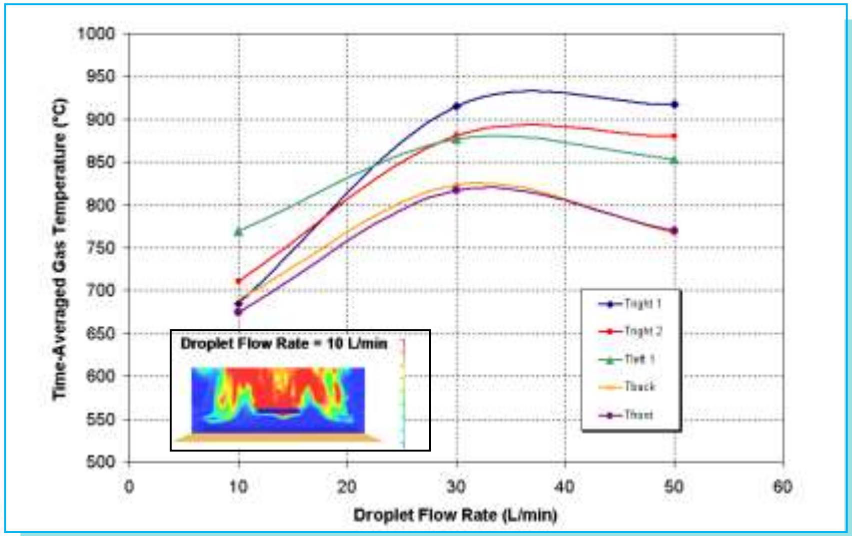
Munitions surface temperature

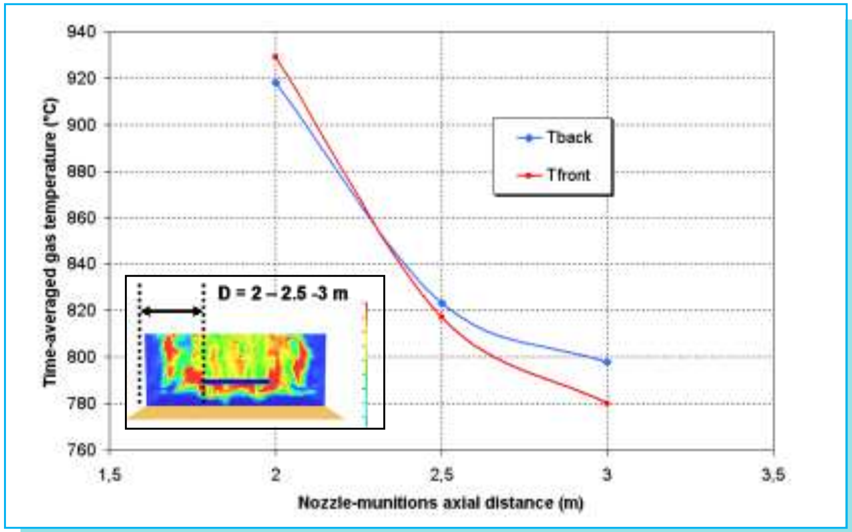
Reaction delay

Effect of LPG setup parameters

Droplet Flow Rate is reduced from 50 to 10 L/min

Nozzle-munitions distance = 2 – 2.5 – 3 meters





Gas temperature field (and so heat transfer) around the munitions strongly depends on the droplet flow rate and the nozzle-munitions distance

Experience and experimental tests are needed to determine the optimal value

Discussion about numerical results

Numerical analysis showed that :

- 800°C gas temperature and 100 kW/m² heat flux can be achieved by Standard and Alternative fires but thermal load is not uniform along the munitions
- Standard Kerosene Fire produces pretty much soot particles
- To assume $\varepsilon_{munitions} = 0.9$ could be false in the Alternative cases because of a weaker soot production
- To assume $\varepsilon_{munitions} < 0.9$ may be more realistic but may induce weaker munitions surface temperature and higher reaction delay
- Thermal environment around the munitions depends on the LPG design and some adjustable key parameters (fuel flow rate, nozzle-munitions distance)

Conclusion

Standard Kerosene pool fire

Alternative fuel fires

Kerosene pool fire is still the Standard fire because :

It is more linked with a real accidental scenario

It is not adjustable

It is well-adapted to the whole types of munitions (from large solid rocket motor to ammunition)

Strong feedback is still missing to assert equivalency in terms of reaction between Standard and Alternative fires

Calibration of the Alternative fire test facilities is needed

Calibration tests shall be in accordance with the tested munitions (dimension, time to reaction,…)

Both temperature and heat flux around the tested item shall be measured

Whatever the adjustments the alternative test facilities must be compliant with the future AOP 4240 requirements in terms of thermal load around the munitions

THANK YOU FOR YOUR ATTENTION

ANY QUESTIONS ?