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MINISTÈRE DE LA DÉFENSE

Low cost heat flux and flame temperature characterization of NATO standard kerosene pool fires

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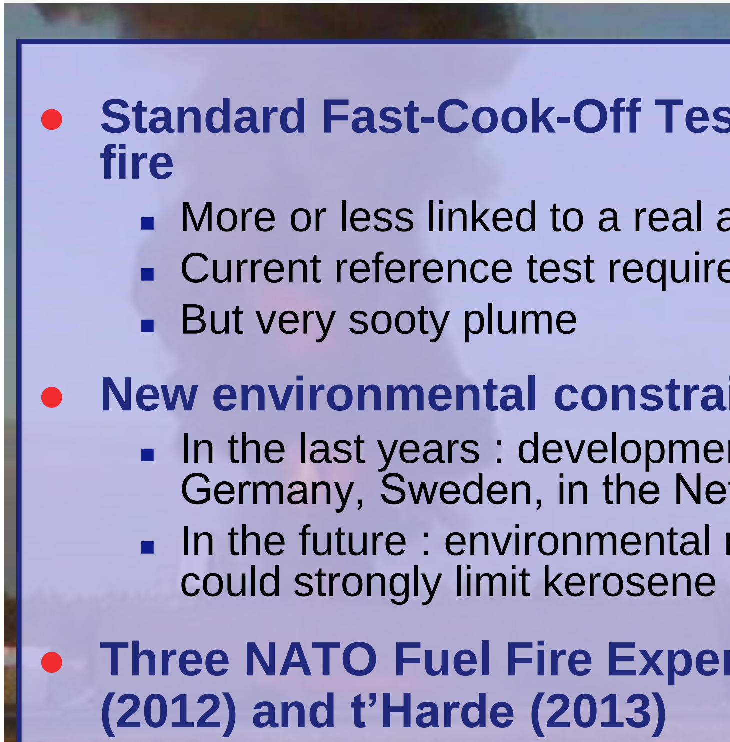
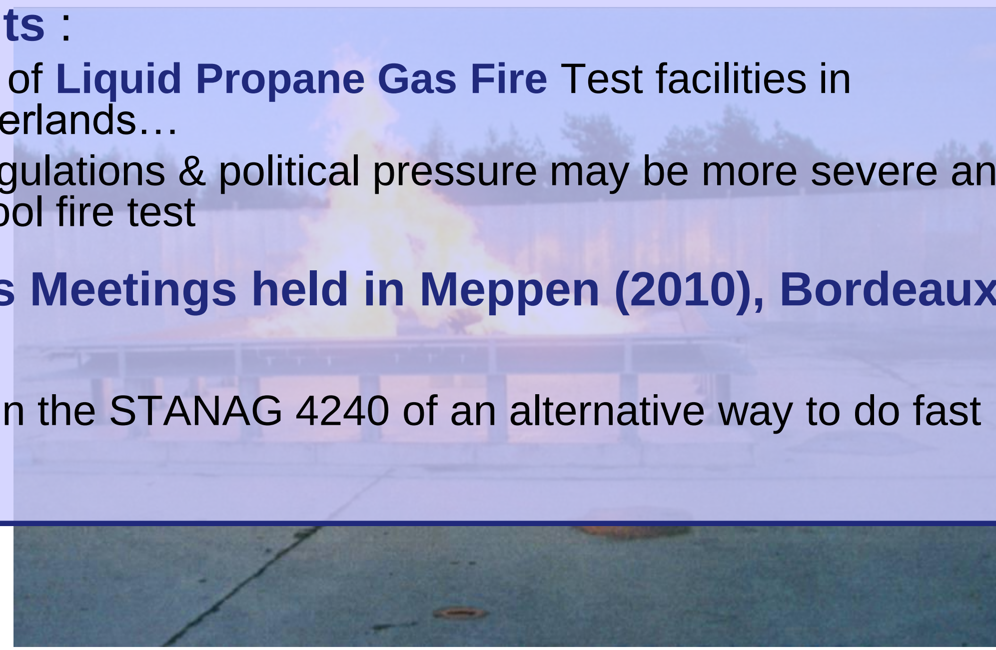
DGA

DIRECTION GÉNÉRALE DE L'ARMEMENT

Background (1/2)





- **Standard Fast-Cook-Off Test** : munitions engulfed in a liquid **kerosene pool fire**
  - More or less linked to a real accidental scenario
  - Current reference test required by the **4240 STANAG ed.2**
  - But very sooty plume
- **New environmental constraints** :
  - In the last years : development of **Liquid Propane Gas Fire** Test facilities in Germany, Sweden, in the Netherlands…
  - In the future : environmental regulations & political pressure may be more severe and could strongly limit kerosene pool fire test
- **Three NATO Fuel Fire Experts Meetings held in Meppen (2010), Bordeaux (2012) and t'Harde (2013)**
  - To discuss on the introduction in the STANAG 4240 of an alternative way to do fast heating

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Background (2/2)

- First conclusions :
  1. **Necessary to better characterize thermal loading around the tested item**
  2. **Fire Temperature : not the only parameter that could define thermal loading**
  3. **Need for more data (experimental and numerical)**
- How to know more accurately both LPG and kerosene fires ?
  - **By new experimental tests**
  - **By theoretical studies**
  - **By testing new in situ measurements**

LPG Fire in Meppen (WTD-91)

Kerosene Pool Fire in Bordeaux (DGA)

Current STANAG 4240 ed.2

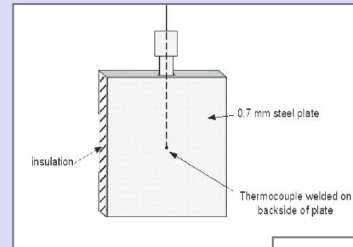
- Objective of the selected fuel fire test : determination of the reaction and time to reaction. of the munitions

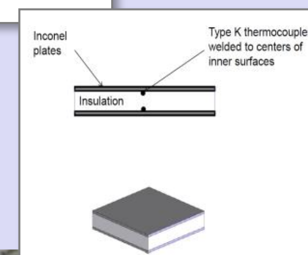
What about the heat flux received by the munitions ?

- Test (Environment) Requirements :
  - Wind velocity : less than 10km/h
- Test (Flame) Requirements:
  - Average flame temperature : at least 800°C
  - Flame temperature shall reach 550°C in the order of 30s
- Instrumentation Requirements :
  - Minimum of 4 thermocouples to provide a consistent, remote indication of the full development of the fire
    - Mounted 40-60 mm from the surface of the test item at positions fore. aft. starboard and port
    - Additional thermocouples may be positioned at the discretion of the Trial Authority
  - Type K thermocouples

How to measure heat flux in the flames ?

- Main usual heat flux measurements in fire tests :
  - Plate Thermometer (PT)
  - Directional Flame Thermometer (DFT)
  - Calorimeters
  - Others : Sandia Hemispherical Flame Gage (HFG),…
- Advantages :
  - In situ measurements
  - Simple to use : **based on temperature difference measurements in a solid**
  - Not too expansive
- Drawbacks :
  - Intrusive : reactive gas flow is modified / screen effect
  - Time response may be higher than time to reaction of the munitions



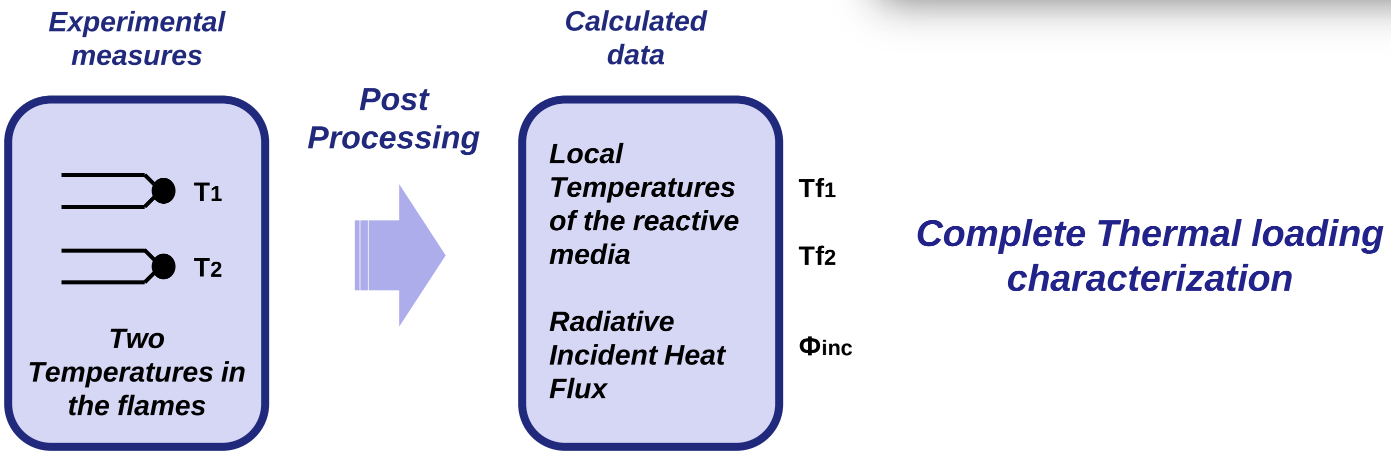


Proposal of testing a new and low-cost experimental method <u>based on flame temperature measurements</u>

Two-paired thermocouples experimental method (1/2)

Principle

- Use of two K-type thermocouples:
  - located close to each other (at around 10 mm)
  - in the flames
  - whose diameters (and so response times) are not equal : 1mm and 0,5mm diameters for example
- **Low cost** and almost non intrusive technique
- **Easy to implement when testing live munitions**



Two paired thermocouples experimental method (2/2)

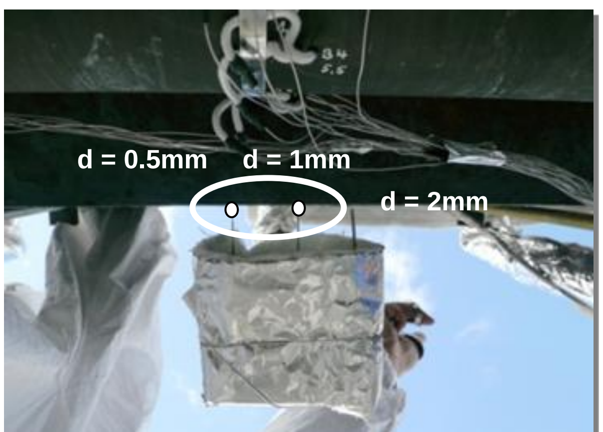
Post-Processing

- Energy balance applied to each thermocouple (radiative + convective heat transfer between flame and thermocouple)

$$\frac{m_i C_p}{S_i}\frac{dT_i}{dt} = \underbrace{h(Tf_i - T_i)}_{\text{Convective net heat flux}} + \underbrace{\int_0^\infty \left[\varepsilon_f(\lambda)\cdot\phi_{incident}(\lambda) - \varepsilon_i(\lambda)\cdot L^0_\lambda(T_i)\right]d\lambda}_{\text{Radiative net heat flux}}$$

Convective net heat flux **Radiative net heat flux**

- Error minimization technique to calculate local temperature of the reactive media (Tf) **and** Radiative incident heat flux (Φinc)



$T_1(t)$ = Temperature measured by the 0.5mm thermocouple

$T_2(t)$ = Temperature measured by the 1mm thermocouple

$T_\infty(t)$ = Blackbody temperature that produces radiative incident heat flux on the thermocouple surface

τ_1 and τ_2 : time constants

Grey body assumption

$$Tf_1 = T_1 + \tau_1\left[\frac{dT_1}{dt} + \frac{\beta}{d_1}\left(T_1{}^4 - T_\infty{}^4\right)\right]$$

$$Tf_2 = T_2 + \tau_2\left[\frac{dT_2}{dt} + \frac{\beta}{d_2}\left(T_2{}^4 - T_\infty{}^4\right)\right]$$

$$E^2 = \frac{1}{N}\sum_{t_a}^{t_b}\left[Tf_2 - Tf_1\right]^2$$

Equation system to calculate τ_1 τ_2 and T_∞

$T_{fi}(t)$

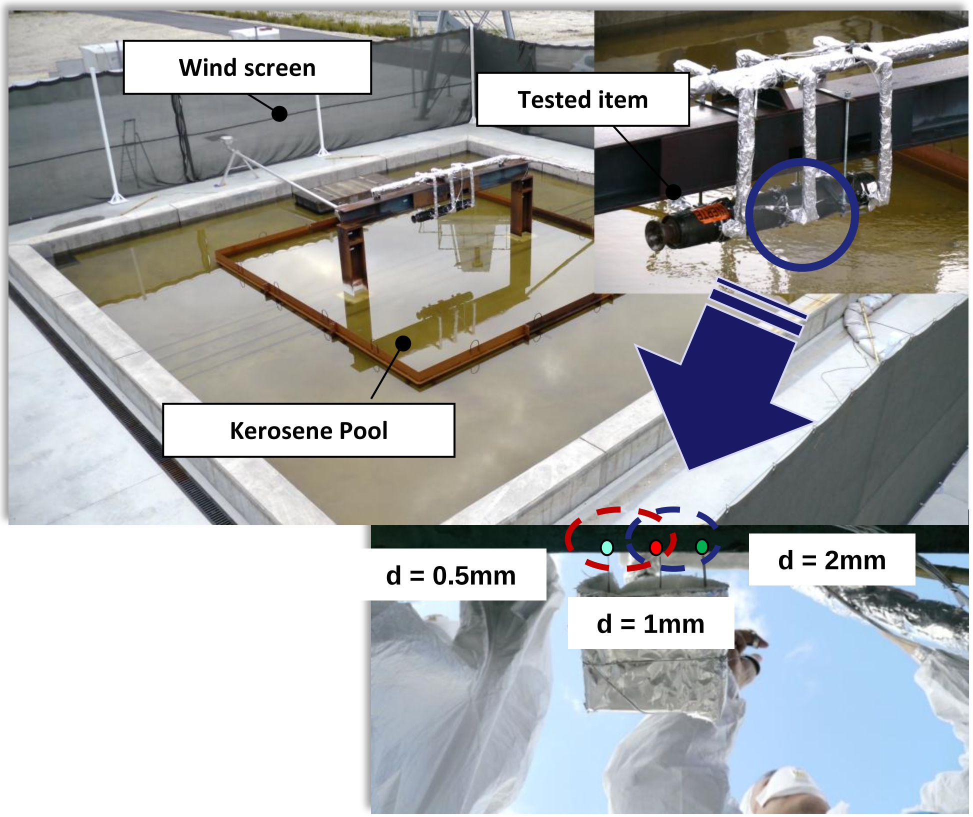
$\Phi_{inc}(t)$

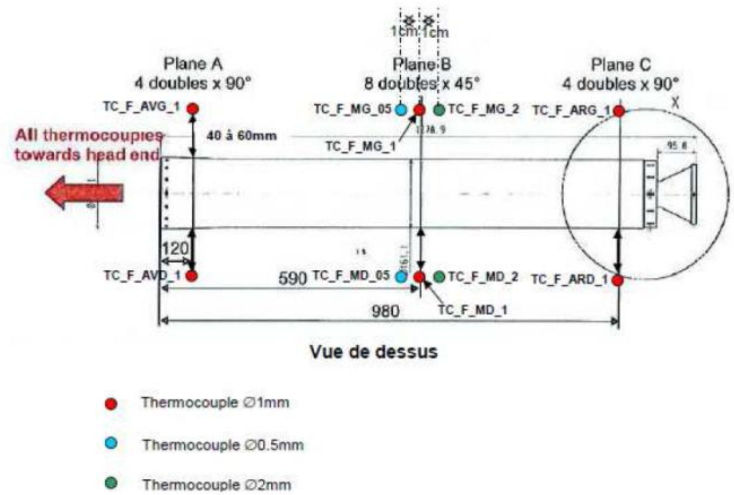
E = error to be minimized

N : number of measurement points between [t_a;t_b]

Application to the Standard Liquid Kerosene Pool Fire

- Two FCO Tests made in 2013 at DGA Missiles Testing (Bordeaux, France)
- Linked to the technical agreement signed between DGA (France) and BwB/WTD-91 (Germany)

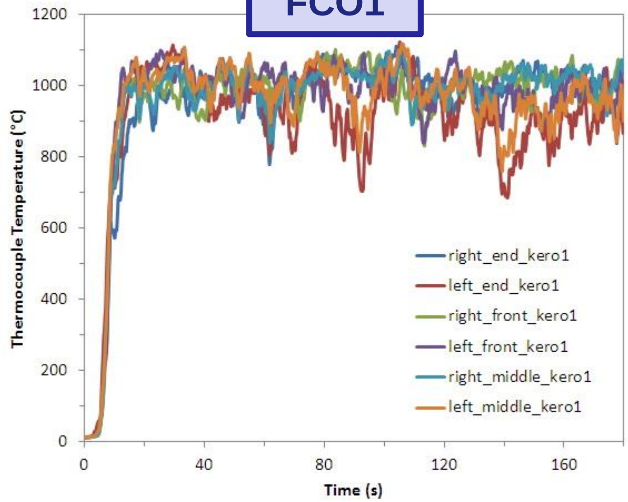




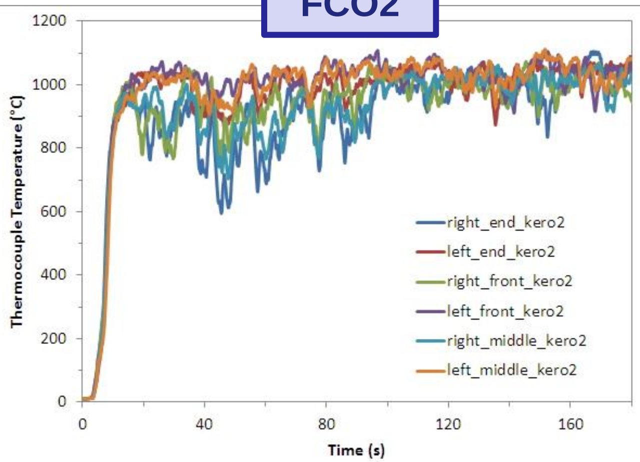
- STANAG measured temperatures (x6) (red dots)
- Corrected temperatures $T_{fi}(t)$
- **Radiative Incident Heat Flux $\Phi_{inc}(t)$**

Results : *STANAG temperatures*

FCO1



FCO2

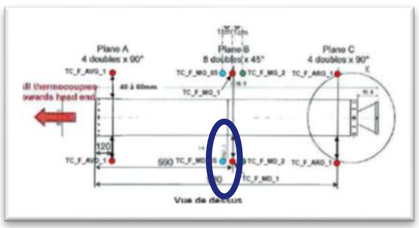


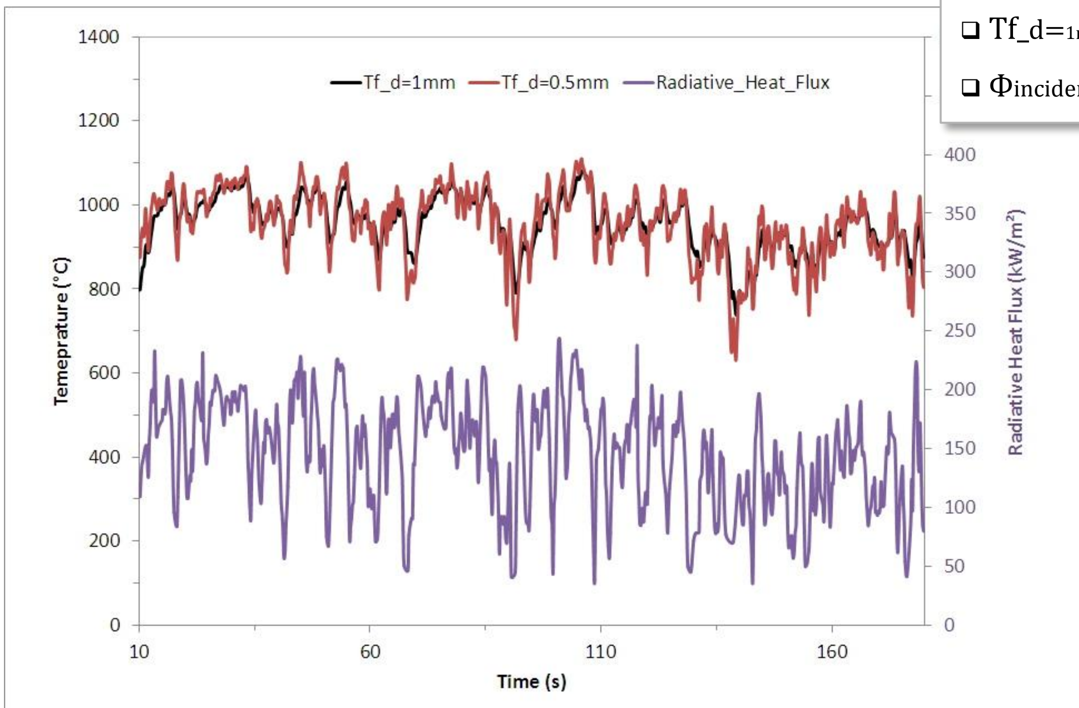
- STANAG requirements on temperature rise and average are respected both for FCO1 and FCO2
  - STANAG initial time = 8s
  - Mean temperature > 800°C
- Good repeatability of the kerosene fire
- No windy conditions (v << 10km/h) thanks to wind screen

Results : *Corrected Temperatures AND Radiative Incident Heat Flux*

FCO1 : On the left side of the mock-up / In the middle cross section

- $(d_1 = 0.5mm ; d_2 = 1mm)$
- $[t_a = 10s ; t_b = 180s]$





Average values over time :

- $Tf\_d=_{0,5mm} = 954.7°C$
- $Tf\_d=_{1mm} = 954.9°C$
- $\Phi_{incident} = 147.3\ kW/m^2$

Local radiative incident heat flux produced by the reactive media
vs
Time

Results : synthesis

Thermal loading characterization

Temperature

- Corrected temperature Tfi = “real” local temperature when taking into account heat transfer between the K-type thermocouple and gas flow
- Error between Tfi and Ti < 3.3%
- Sufficiently low to be neglected for the IM test requirements

≠ measured Temperature Ti

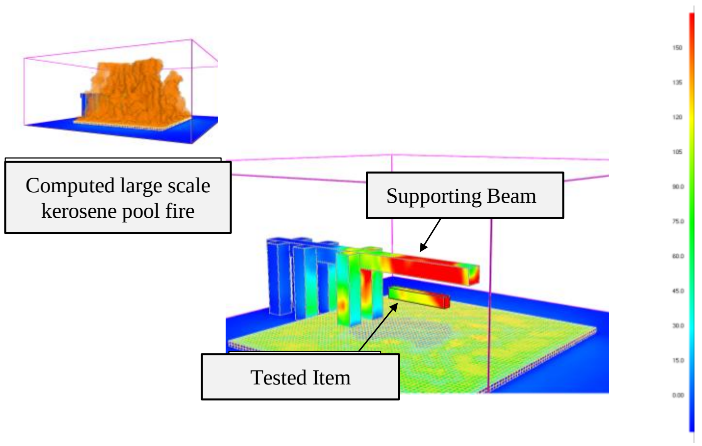
Incident Heat Flux

Mean values over [10s-180s] time range

Two-paired thermocouple (d1 ; d2)	Left (0.5mm ; 1mm)	Left (1mm ; 2mm)	Right (0.5mm ; 1mm)	Right (1mm ; 2mm)
Radiative incident Heat Flux (kW/m²) *FCO Test n°1*	147.3	146.7	157.4	153.9
Radiative incident Heat Flux (kW/m²) *FCO Test n°2*	168.6	160.1	146.1	140.2

Conclusion & Discussion

- Characterization of the NATO standard kerosene pool fires **by temperature and radiative incident heat flux measurements**
- By using **a low cost experimental method** based on flame temperature measurement by two-paired K-Type Thermocouples
- Within kerosene pool fire : mean **radiative incident heat flux** in the **140-170 kW/m²** range
- In good agreement with heat flux measured by others experimental methods (PT, DFT,…) in kerosene pool fires *(US Teams : Yagla et al. / Blanchat et al.) :* ***130-170 kW/m²***
- Consistent with the incident radiative heat flux computed by Fire Dynamics Simulator (NIST) code : ***80-150 kW/m²***



Further work

- To evaluate and **directly compare to usual heat flux measurements** like PT and DFT in kerosene pool fire
- To test the present low-cost experimental method **within LPG fire test facility** (in Meppen for example)

- **To improve the post-processing**, particularly the identification and error minimization technique

THANK YOU FOR YOUR ATTENTION

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