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1 **Repeatability assessment of large scale fire experiment involving wa-**
2 **ter spray system in a forced ventilated compartment**

3
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8 **ABSTRACT**

9 Repeatability of large scale fire test remains a key issue for code validation process. Most of the
10 large scale experimental studies are based on single experiment and the influence of repeatabil-
11 ity is barely considered in the test analysis process. Due to the substantial cost, reproducing sev-
12 eral trials of a given large scale fire scenario is not often performed. In the framework of the
13 OECD PRISME 2 project, this topic has been identified and a specific large scale fire test has been
14 reproduced twice in the final goal of assessing the level of repeatability. The scenario is an oil
15 pool fire in a enclosure mechanically ventilated and during which a water spray system is acti-
16 vated. The analysis consists in identifying a set of variables on which metrics is applied in order
17 to quantify the levels of discrepancy between the two tests. A set of 27 variables are selected
18 such as they characterize the whole fire scenario (the fire source, the gas phase, walls, the venti-
19 lation network and the water spray system). The analysis points out that the repeatability levels
20 are different depending on the type of variable. The gas temperature or species concentrations
21 are more repeatable than gas pressure or air flow rate. In addition, a new methodology is pro-
22 posed in comparing, for each physical variable, the variations due to repeatability (i.e. the preci-
23 sion) and the uncertainty. A new metric is proposed helping modelers in code validation pro-
24 cess.

25 **KEYWORDS:** repeatability, uncertainty, large scale fire test, sprinkler, pool fire, ventilation,
26 compartment

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INTRODUCTION

The data accuracy, i.e. the closeness of agreement between a measured value and the true value, and the data repeatability of large scale fire tests remains a key issue for code validation process as well as for the understanding of the physics. Due to the complexity of the fire source (pool, electrical cables), of the fire development (ignition, propagation, flashover, extinction) and of the fire consequences (smoke propagation, doorway flows), the repeatability of large scale fire test is often an answer for explaining discrepancies between data and numerical simulations. It is therefore an important issue to propose an assessment of fire test repeatability.

The repeatability is defined by the International Standardization Organization as the precision, ie. the closeness of agreement between independent measurements or trials, of the same experiment performed at the same place, with the same facility and measurements techniques, the same operators and within a short period of time [1]. It differs from reproducibility that specified the difference between trials of the same experiment but performed at different place, with different teams and facility. The repeatability studies are mostly associated to a given apparatus or facility, whereas reproducibility studies are associated to comparisons or round robins between laboratories or tests apparatus.

Repeatability (or reproducibility) can be related to uncertainty. Following the ISO definitions, uncertainty is a range associated to the measured value in which the true value should be in (see illustration in Fig. 1). Error, that can be random (noise, equipment sensitivity or acquisition resolution) or systematic (bias due to calibration), is the difference between one measured value and the true value. In case of identical physical phenomenon (i.e. identical true value for each measurement or trial) and considering only random errors, the uncertainty corresponds to the precision of the measurement and thus to its repeatability. However, there are domains of physic, and it is the case for fire phenomena, where reproducing the same experiment, i.e. the same true value, is barely achievable. For those situations, uncertainties and repeatability may be significantly different. In addition to uncertainty assessment, repeatability studies are then necessary stages for fire experimentalists in the final goal of quantifying the measurements variability that can be use then by the modelers for validating numerical simulations.

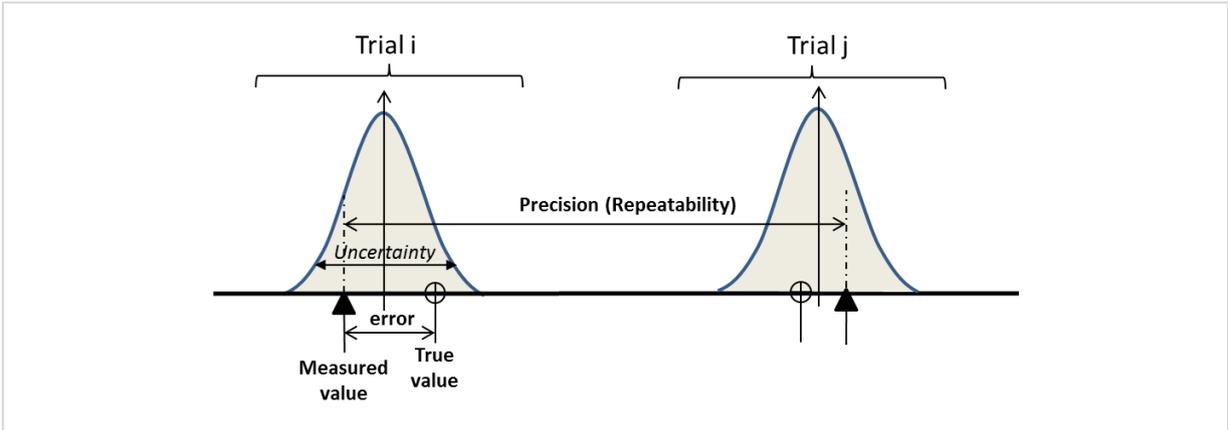


Fig. 1: Illustration of the ISO definitions related to repeatability and uncertainty.

In the field of fire phenomena, several experimental teams have undergone repeatability studies focusing on physical phenomenon as ignition [2] burning rate of furniture [3], or on specific apparatus as the tube furnace [4] or the cone calorimeter [5]. These studies gave the level of confidence of the experimental characterizations.

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Table 1: Characteristics of previous studies.

| Reference | Fang & al. [6] | Johansson & al. [7] | Melcher & al. [8] |
|---------------------------|---|--|---|
| Nb. of scenario | 1 | 4 | 3 |
| Nb. of trial per scenario | 4 | 10 - 8 - 15 - 12 | 25 - 20 - 20 |
| Type of scenario | Furniture fire | Heptane pool fire | Hexane pool fire / Wood cribs |
| Facility dimension | One room 11 m ² | 3 rooms ~40 m ² | 2 rooms ~28 m ² |
| Fire power | Flashover | ~1000 kW | 60kW - 110kW |
| Statistical variables | Mean/Std Dev/CV | ERD/EPC/SC | Mean/Std Dev/CV |
| Variables studied | Times Gas temperature Heat fluxes | Times Mass loss rate Gas temperature | Times Mass loss rate Gas temperature Gas concentrations Smoke obscuration |

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3 These former studies deal with laboratory scale tests. The repeatability studies for large scale
4 tests are less numerous, due to the high financial costs or technical organization difficulties in
5 performing several trials of the same experiment. Three contributions have been identified and
6 summarized in Table 1. In the eighties, Fang *et al* [6], proposed a repeatability study based on
7 four trials of a furnishing fire scenario in a 11 m² room equipped with identical interior furnish-
8 ings and finish materials and leading to flashover temperature. The repeatability is assessing
9 from mean, standard deviation and coefficients of variation for several quantities, critical times
10 (propagation, steady regime and extinction times), gas temperature and heat fluxes. The results
11 show differences for critical times between 5 to 13% and for gas temperature in the order or
12 6%. More recently two studies have also presented repeatability assessment of large scale fire
13 tests. A first one analyzed a database produced by students in the framework of academic cours-
14 es over 6-year period [7]. They analyzed test repeatability on four scenarios with 10 to 15 trials
15 per scenario. The scenarios consisted in a 1 MW heptane pool fire located in a three-room
16 apartment of 40 m². They based their analysis on mean and standard deviation as well as with
17 more advance metrics as Euclidian relative distance, Euclidian projection coefficient and Secant
18 cosine. The results show that the 95% confidence interval of the measured temperature covered
19 +-7 to 35% around the mean for each scenario. A second study proposed a repeatability analysis
20 with a larger number of trials, from 20 to 25, for three simple scenarios. The scenario consisted
21 in two rooms (one fire room and a corridor) of 28 m² with less powerful fires, 60 kW n-hexane
22 pool fire and 100 kW wooden cribs fires. The analysis discussed the repeatability on critical
23 times, fuel mass loss rate, gas temperature, gas concentration and smoke obscuration. They
24 showed that gas temperature and smoke density provide reliable value, whereas, mass loss rate
25 and gas concentrations may show higher level of variation.

26 These three studies demonstrated that some variables may give non negligible variation and
27 therefore performing repeatability analyses are a necessary task. The results also show different
28 levels of repeatability according to the complexity of the scenario, the dimension of the facility,
29 the type and the power of the fire, the type of variables investigated and the mastering of the
30 input conditions. These three studies also point out the difficulties in performing within the
31 same study, a large number of trials in a large scale facility and with a representative number of
32 measured variables.

33 The present contribution proposes a new example of repeatability assessment for large scale fire
34 test. The scenario consists in hydrocarbon pool fire of about 400 kW in one room of 42 m²,
35 closed and forced ventilated and including the activation of a water spray system. The particular
36 feature of this scenario concerns the forced ventilated compartment with water spray system
37 leading to complex flow for which numerical simulations involved complex modeling. This study
38 has been performed in the framework of the OECD PRISME 2 project and only two trials could
39 have been performed. The novelty of this study concerns the fire scenario including water spray
40 system and mechanical ventilation at large scale (400 kW fire in a 42 m² enclosure). It permits to

1 focus on the repeatability in measuring variables associated to mechanical ventilation and water
 2 flow rate. In addition, assessing the level of repeatability of such scenario is of importance for
 3 modelers when performing code validation process. Therefore, the analysis focuses on the com-
 4 parison between the repeatability of a variables and its uncertainty. A new metric is proposed to
 5 enhance the possible difference between uncertainty and repeatability in case of large scale fire
 6 tests and to indicate to modelers which variation interval should be considered, the measure-
 7 ment uncertainty or its repeatability.

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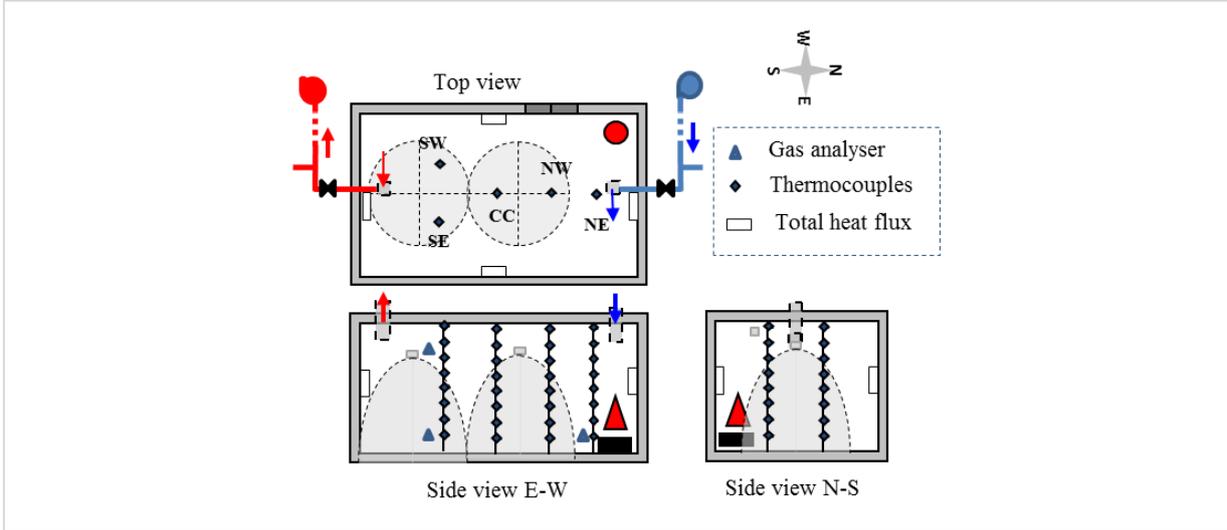


Fig. 2: Sketch of the facility with the location of the measurement points, the fire place and the spray pattern.

9 **THE FIRE EXPERIMENT**

10 **Test facility**

11 The fire scenario, also presented in [9] and [10], consists in a fire in a closed and mechanically
 12 ventilated compartment. The compartment is a room of the DIVA facility of IRSN, rectangular
 13 (4.88 m × 8.67 m = 42.3 m²) with a height of 3.90 m (Fig. 2). The walls, the floor and the ceiling
 14 are made of concrete and the ceiling is covered with silicate of calcium panels avoiding its ther-
 15 mal degradation. The ventilation system consists in an admission and exhaust lines connected in
 16 the upper part of the room at about 0.80 m from the ceiling. The ventilation lines are connected
 17 to an industrial network equipped with blowing and exhaust fans. The targeted flow rate of ven-
 18 tilation was 2550 m³/h. This value is designed prior to the test from numerical calculations in
 19 order to avoid extinction by lack of fuel and thus to ensure combustion of the total mass of fuel.

20 **Fire source**

21 The fire source was a liquid fuel pool located on the North-West corner of the room in order to
 22 avoid extinction when the water spray is activated. The objective of this fire scenario is to study
 23 the interaction between water droplets and smoke layer without extinguishing the fire. The fuel
 24 is lubricant oil, DTE Medium from Mobil, preheated to 120°C before ignition. The pool is a cir-
 25 cular 0.7m² pan, made of carbon steel with a depth of 130mm and placed on a weighting device.
 26 The mass of fuel is about 25kg before ignition. The pool combustion was ignited by a 20 kW pro-
 27 pane gas burner.

28 **Water spray system**

29 The water spray system is the one presented in detail in [10]. It is made of two nozzles located
 30 2.97 m from the ground and about 0.85 m from the ceiling and centered in the room as indicated
 31 in Fig. 2). The nozzles are connected to a system of pipes equipped with valves, pressure trans-

1 ducer and water flow meter. The water spray is activated and shut off manually with a valve. The
2 two nozzles are Deluge type, Protectospray® D3-HV unit with k nozzle coefficient of
3 26 l/min/bar^{0.5} [15]. The targeted total water flow rate is 110.3 l/min. The nozzle has been char-
4 acterized using the Phase Doppler Anemometer technique giving the droplet diameter and ve-
5 locity as well as the spray envelope. Each nozzle produces water droplet flow with a maximum
6 45° angle in relation to the nozzle axis at 55 l/min. The droplet velocity measured 200mm from
7 the nozzle is in the range [5;12] m/s. The droplet size distribution fits a log-normal distribution
8 with a mean mass median diameter (MMD) of about 450 µm at 568 kPa.

9 **Measurements**

10 The fuel mass was measured with a SARTORIUS weighting balance. The fuel mass loss rate was
11 then determined from the time derivative of the mass.

12 The ventilation flow rates were computed from the pressure difference measurements per-
13 formed at the ports of averaging Pitot tubes located at inlet and exhaust ventilation lines. The
14 gas pressures in the room and in the ventilation network were also measured with pressure
15 transducers.

16 The gas temperatures were measured with set of eight 1.5 mm K-type thermocouples positioned
17 on five vertical trees (Fig. 2) named SW, SE, CC, NE and NW. The thermocouples were equipped
18 with metal protective caps to prevent droplets coming into contact with their tips. Temperatures
19 were also measured in the liquid fuel and on the walls of the facility.

20 Oxygen, carbon dioxide and carbon monoxide concentrations were measured at three positions
21 within the room: two on the SE tree, in the lower and upper part and one close to the fire. Con-
22 centrations are also measured in the ventilation ducts. Each sample point was connected to
23 sampling system and gas analyzers. Molar fractions are measured with SERVOMEX® XANTRA
24 4100 apparatus for oxygen and SIEMENS® ULTRAMAT-23 apparatus for carbon dioxide and
25 monoxide. The time delay due to the sampling process was corrected. The vapor content was
26 also measured in the exhaust ventilation duct with the ProCeaS® H₂O analyzer.

27 Total heat fluxes were measured with four CAPTEC® sensors positioned at the centre of the four
28 side walls. Radiative heat fluxes was measured with four Schmidt-Boelter MEDTHERM® sensors
29 located on the vertical tree positioned in the NE corner of the room.

30 The water flow rate delivered by the water spray system was measured with a ROSEMOUNT®
31 magnetic flowmeter. In addition, the spatial distribution of the water density received at the
32 ground during a fire test was measured with set of collectors distributed over the room floor and
33 equipped with pressure transducers measuring water height [9].

34 The measurement uncertainties of each physical variable are shown in Table 2. They are evalu-
35 ated either from the sensor characteristics given by the manufacturer or determined experimen-
36 tally from calibration tests in comparing the responses of the sensor and a reference. These un-
37 certainties correspond to standard uncertainties and are obtained only at ambient temperature
38 without the effect of the fire. They are comparable to uncertainties proposed for fire test by the
39 NIST [11]. For each sensor, it is assumed that the uncertainty is characterized by a Gaussian dis-
40 tribution and its value can be assessed as the standard deviation σ_e . The standard deviation is
41 obtained from the characteristic of each sensor given in Table 2. Two situations are encountered
42 whether the standard deviation is constant whatever the signal amplitude or proportional to the
43 signal amplitude.

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Table 2 – Uncertainty assessment of the measured physical quantities

| Physical variable | Sensor type | Range | Unit | Standard uncertainty σ_e (absolute or relative) |
|--------------------------------|---------------------------|---------------|----------------------|---|
| Mass | IS 300IGGS- Sartorius© | [0-300] | kg | 0.005 |
| O ₂ concentration | Paramagnetic- Servomex | [0; 25] | %-vol | 0.2 %-FS (0.05 %-vol @ Full scale) |
| CO ₂ concentration | Ultramat-23 Siemens© | [0; 20] | %-vol | 2 %-FS (0.4 %-vol @ Full scale) |
| CO concentration | Ultramat-23 Siemens© | [0; 10000] | ppm | 2 %-FS (200 ppm @ Full scale) |
| H ₂ O concentration | AP2E-Proceas© | [0; 10] | %-vol | 2 %-FS (0.2 %-vol @ Full scale) |
| Pressure | Press. transducers | [-2500;+2500] | Pa | 0.50 % (12.5 Pa @ Full scale) |
| Air flow rate | Press. transducers | [0;+5000] | m ³ /h | 2 % (100 m ³ /h @ Full scale) |
| Temperature | K type thermocouple | [0;1300] | K | <2.5K @ 293K |
| Radiative heat flux | Schmidt-Boelter/Medtherm© | [0;25000] | W/m ² | 1 %-FS (250 W/m ² @ Full scale) |
| Convective heat flux | Thermopile CAPTEC© | [0;100000] | W/m ² | 1 %-FS (100 W/m ² @ Full scale) |
| Water flow rate | Magnetic flowmeter | [0;400] | l/min | 1 % (4 l/min @ Full scale) |
| Water density | Press. transducers | [0;20] | l/min/m ² | 5 % (1 l/min/m ² @ Full scale) |

FS : full scale

3

4 Test scenario and experimental procedure

5 The test scenario is designed such as it permits in a first stage to characterize the behavior of the
6 fire source in confined and ventilated environment without water spraying and then in a second
7 stage to study the effect of water spray application. Therefore, the test procedure was as follows.
8 First the targeted ventilation flow rate, 2550 m³/h, was stabilized by operating the ventilation
9 network. Then the preheated fuel was poured in the pan and ignited. A steady period of burning
10 is waited in order to reach a stabilized hot layer of smoke (transient period of about 15
11 minutes). Then the water spraying system was turned (here at t=948 s) during a constant period
12 of 600 s. The test ends with the combustion of the remaining amount of fuel in the pan.

13 Two trials, named PR2_FES_1 and PR2_FES_1A in the context of the OECD PRISME 2 project and
14 renamed here TEST1 and TEST2, were performed in about one month interval, with the same
15 experimental set-up.

16 METRICS FOR DATA ANALYSIS

17 To quantify the differences between tests, a set of variables considered as representative physi-
18 cal quantities was selected. Each variable was measured during the two trials with the same
19 measurement technique and acquisition chain. The analysis is based on the comparison of the
20 time variation of all variables. For both trials, the time t = 0 s corresponds to the instant of igni-
21 tion. In the following, the two signals of each variable are named $x^1(t) = x_i^1$ and $x^2(t) = x_i^2$ for
22 the tests TEST1 and TEST2 respectively. They are discrete time-dependent signal considered as
23 vectors with i, the time index.

24 Repeatability assessment is based on the analysis of metrics quantifying the difference between
25 signals. Various metrics can be used according to the specificity of the tests [12]. In the present
26 study, two metrics are considered.

27 The first one is defined for comparison between two time-dependant signals, here, the signal x_i^k
28 of one trial k and the average signal, \bar{x}_i , which is the mean time-dependent signal over the n tri-
29 als. This first metric, named NED, expresses the normalized Euclidean distance between this two
30 signals as :

$$1 \quad NED_{[t_1; t_2]}^k = \frac{\sqrt{\sum_{i=t_1}^{t_2} (x_i^k - \bar{x}_i)^2}}{\sqrt{\sum_{i=t_1}^{t_2} (\bar{x}_i)^2}} \quad (1)$$

2 with \bar{x}_i the average time-dependant signal (index i) over the n trials computed as: $\bar{x}_i =$
3 $\frac{1}{n} \sum_{k=1}^n x_i^k$. $NED_{[t_1; t_2]}^k$ is computed for each trial k and over a given period of time $[t_1; t_2]$. It repre-
4 sents the mean discrepancy between one trial and the mean behaviour or the precision, follow-
5 ing the ISO definitions [1]. In the present study, with only two trials ($n=2$), the two normalized
6 differences, $NED_{[t_1; t_2]}^1$ and $NED_{[t_1; t_2]}^2$ are equal and will be named NED in the following. This
7 variable is identical to the Euclidian relative distance ERD defined in [7].

8 The second metric, proposes here by the authors, is the ratio between the range due to repeat-
9 ability (the difference between the signal of one trial k and the mean signal over the n trial,
10 $x_i^k - \bar{x}_i$), and the range characterized by the uncertainty of the sensor $\sigma_e(\bar{x}_i)$ also written $\sigma_{e,i}(\bar{x})$
11 (see Fig. 3). This ratio, named R_i^k is expressed as:

$$12 \quad R_i^k = \frac{x_i^k - \bar{x}_i}{\sigma_e(\bar{x}_i)} \quad \text{with} \quad \bar{R}_i = \frac{1}{n} \sum_{k=1}^n R_i^k, \quad \sigma_{R,i} = \frac{1}{n} \sqrt{\sum_{i=t_1}^{t_2} (R_i^k - \bar{R}_i)^2} \quad (2)$$

13 \bar{R}_i is the mean value of R_i^k at the time i over the n trials. $\sigma_{R,i}$ is the standard deviation of R_i^k at
14 time i .

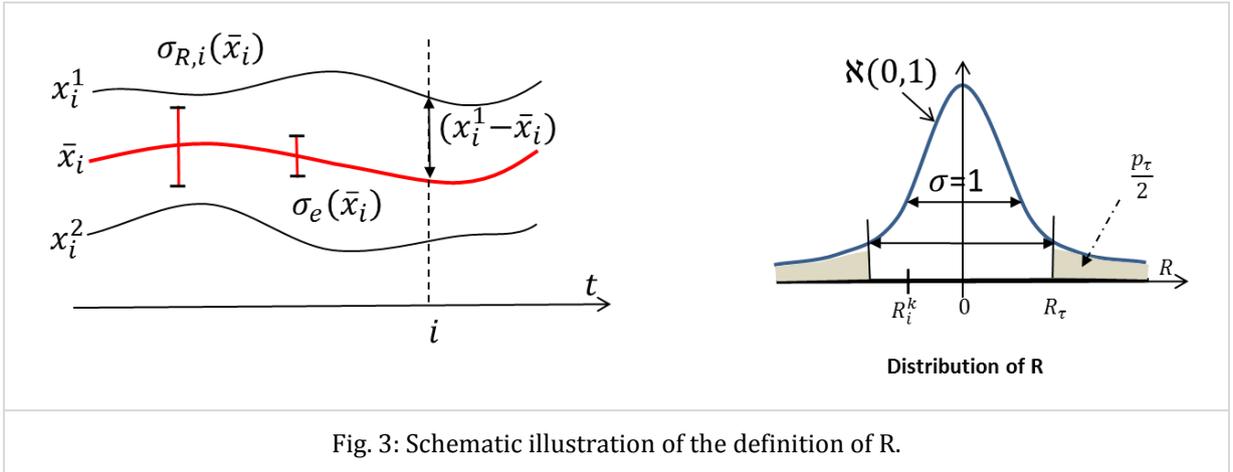


Fig. 3: Schematic illustration of the definition of R .

15 The aim of this metric is to identify which standard deviation has to be considered when compar-
16 ing an experimental data and a numerical simulation, either $\sigma_{e,i}$ the uncertainty of the sensor
17 indicated in Table 2 or $\sigma_{R,i}$, the standard deviation obtained from n repeatable tests.

18 The properties of this metric \bar{R}_i are demonstrated in the following. Let's considered the hypoth-
19 esis, H , that the physical phenomenon is identical for all repeatable tests and that these tests
20 have a measurement noise following a normal law, the difference $x_i^k - \bar{x}_i$ follows a normal law
21 with a null mean value equal to zero ($\bar{x}_i = \bar{x}_i^k$). The standard deviation of a repeatable k test x^k
22 at time i , is defined as $\sigma_{R,i}(x^k)$ and is equal to $\sigma_{e,i}$, the uncertainty of the sensor.

23 From these two statements, the metric R_i^k , for a repeatable k test and for a given time i , follows a
24 normal law with a mean value equal to zero and a standard deviation equal to 1, i.e. $R^k \rightsquigarrow$
25 $N(0,1)$ (illustration in Fig. 3). For a given R_i^k , we can compute the probability p , that $|R| > R_i^k$
26 using $N(0,1)$. If this probability p is lower than a fixed probability p_τ , the hypothesis H is consid-
27 ered false and $\sigma_R \neq \sigma_e$. The probability p is here computed as:

$$28 \quad p = \int_{-\infty}^{-R_i^k} \exp(-R^2) dr + \int_{R_i^k}^{\infty} \exp(-R^2) dr \quad (3)$$

1 Table 3 – Equivalence between the probability p_τ , and the metric R_τ use in the definition of R

| | | | | | | | | |
|------------|------|------|------|------|------|-------|--------------|-------|
| p_τ , | 0.2 | 0.1 | 0.05 | 0.02 | 0.01 | 0.005 | 0.002 | 0.001 |
| R_τ , | 1.28 | 1.64 | 1.96 | 2.24 | 2.58 | 2.80 | 3.09 | 3.29 |

2 This condition permits to characterize sensors. For sensors for which R_i^k are lower than R_τ , the
3 hypothesis H is considered as true, the physical phenomenon is identical for all repeatable test,
4 thus $\sigma_R = \sigma_e$. The uncertainty of the sensor can be considered as the standard deviation when
5 comparing with numerical simulation. For sensors for which R_i^k are larger than R_τ , the hypothe-
6 sis H is considered as false, the physical phenomenon is not identical for all repeatable test and
7 thus $\sigma_R \neq \sigma_e$. The standard deviation used for comparison with simulations should be the one
8 obtained from the set of repeatable tests $\sigma_{R,i}$. Here, this ratio R_i^k is computed at each time step
9 (index i). Again, here with only two trials, the two ratios R_i^1 and R_i^2 are equal and named R_i .

10 The purpose of this new metric is to highlight possible difference between uncertainty assessed
11 on controlled conditions (calibrator and reference apparatus) and precision assessed from trials
12 of fire tests. If the ratio is lower or equal to a given criterion R_τ (here R_τ is set to 3 so that
13 $\text{prob}(|R_i^k| > R_\tau)$ is lower than 2.10^{-3} as indicated in Table 3), precision is identical to uncertainty
14 and the uncertainty is appropriate to characterize the range in which the true value is asserted
15 to be. If the ratio R is greater than the criterion, precision is larger than uncertainty. In this case,
16 true values are probably different between trials and precision have to be considered to expand
17 the range of uncertainty.

18 In practice, it would have been preferable to work with a larger number or trials. Unfortunately,
19 in the context of the OECD PRISME 2 project, only two trials could have been performed. In the
20 present study, the variable R gives only the behavior of one trial. A larger number of trials
21 should be considered to propose global conclusion. The present study proposes an illustration of
22 application with two trials.

23 A set of 27 variables are selected such as they are representative of the whole fire scenario.

24 For the fire source, the variables are the fuel mass burnt (MASS, i.e. the difference between the
25 mass of fuel before ignition and the mass of fuel during the experiment) and the mass loss rate
26 (MLR), two temperatures, one in the liquid fuel (TCOMB_L4_2) and one in the gas just above the
27 fuel surface (TCOMB_L4_5) and the fire heat release rate (HRR) computed by the three methods
28 (oxygen consumption (HRROC), carbon dioxide generation (HRRCDG) and mechanical from the
29 MLR measurement and the effective combustion enthalpy set to 37.3 MJ/kg for DTE MEDIUM oil
30 (HRRM)). For the ventilation, the variables are the pressure in the room (P_L4) and in the venti-
31 lation exhaust nod (PEXT_NOD_L3), the admission and exhaust flow rates (DADM_L4, DEXT_L4)
32 and the gas temperature in the admission and exhaust lines (TGADM_L4, TGEXT_L4). For the gas
33 phase, the variables are a mean temperature at the height 3.8 m averaged over the four trees
34 (TZMOY8) and the upper layer temperature (TSUP_2ZG) computed with a regression method
35 from vertical temperature profile [13]. For the wall's behaviour, the variables are a radiative
36 heat flux (FLR_L4_NE260), a total heat flux (FLT_L4_NC265) and a wall temperatures
37 (TP_L4_NC_255). For the gaseous species concentrations, the variables are concentrations of
38 oxygen (O2_L4_BAS, O2_L4_HAUT), of carbon dioxide (CO2_L4_BAS, CO2_L4_HAUT) and of car-
39 bon monoxide (CO_L4_BAS, CO_L4_HAUT) measured in the room and the concentration of water
40 vapour measured in the exhaust line (H2OEXT_L4). For the water spray system, the variables are
41 the water flow rate (D_WATER_SPRAY) and two local density measurements (QWS_7, QWS_18).

42 Examples of comparison between these variables are presented in Fig. 4 and Fig. 5 and the anal-
43 ysis are presented in the next section. In the two figures, for each variable, the upper plot shows
44 the time variation of the given variable for the two trials and the lower plot the difference be-
45 tween the two variables.

- 1 For the two tests and all variables, the mean values $\bar{x}^1 = \frac{1}{t_2-t_1} \sum_{i=t_1}^{t_2} x_i^1$, $\bar{x}^2 = \frac{1}{t_2-t_1} \sum_{i=t_1}^{t_2} x_i^2$ and
- 2 the metric NED are computed over several periods of time $[t_1; t_2]$: prior to ignition, during a
- 3 phase of combustion without a water spraying, during a phase of combustion and water spraying
- 4 and during the whole test duration. Results are displayed in Table 4 and discussed in the
- 5 next sections.
- 6

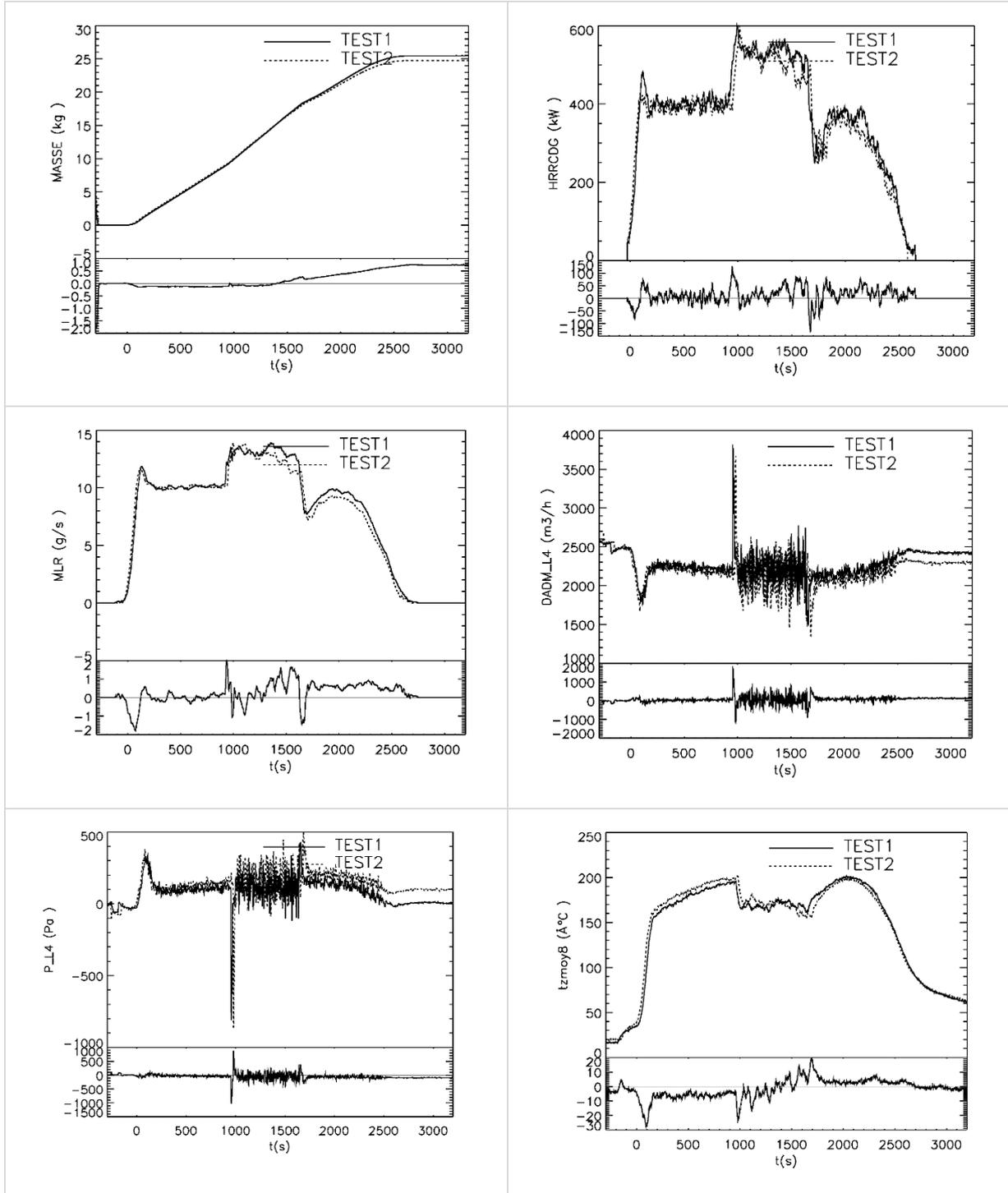


Fig. 4: Comparison of time variations of the mass of fuel (MASS), the fire HRR (HRRCDG), the fuel MLR (MLR), the pressure in the room (P_L4), the ventilation flow rate (DADM_L4), the gas temperature (TZMOY8), (the upper plot gives the signals of the two sensors and the lower plot the difference between the two sensors with the same unit; solid line is for TEST1 and dotted line for TEST2, solid line of the

lower plot the sensor difference)

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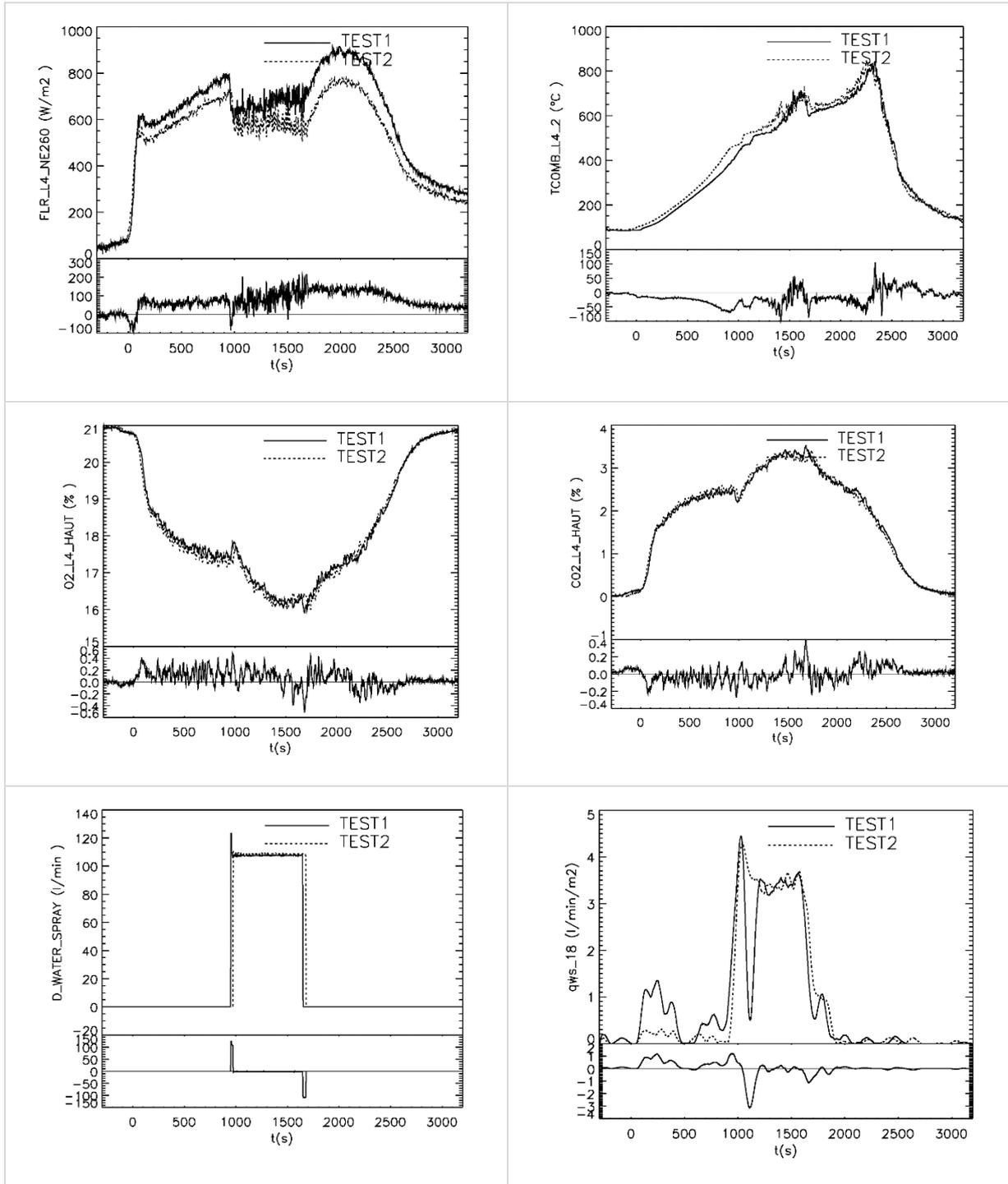


Fig. 5: Comparison of time variations of the radiative heat fluxes (FLR_L4_NE355), the fuel temperature (TCOMB_L4_2), the concentrations of O_2 (O2_L4_HAUT), of CO_2 (CO2_L4_HAUT), the total water flow rate (D_WATER_SPRAY) and the water density collected at the ground (QWS_18), (the upper plot gives the signals of the two sensors and the lower plot the difference between the two sensors with the same unit; solid line is for TEST1 and dotted line for TEST2, solid line of the lower plot the sensor difference)

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| Variables | Prior to ignition t=[-200;-180] s | | | Combustion phase only t=[60;500] s | | | Water spraying phase only t=[1100;-1500] s | | | Whole test t=[60;2400] s | | | |
|-----------------------|--------------------------------------|-------------|-------------|---------------------------------------|-------------|-------------|---|-------------|-------------|-----------------------------|-------------|-------------|-------------------------------------|
| | \bar{x}^1 | \bar{x}^2 | NED | \bar{x}^1 | \bar{x}^2 | NED | \bar{x}^1 | \bar{x}^2 | NED | \bar{x}^1 | \bar{x}^2 | NED | #R _i >R _r (*) |
| MASS (kg) | - | - | - | 3,0 | 3,1 | 0,02 | 13,9 | 13,9 | 0,00 | 13,6 | 13,5 | 0,01 | 2109 |
| HRROC (°) (kW) | - | - | - | 405 | 414 | 0,05 | 458 | 443 | 0,05 | 363 | 358 | 0,08 | 146 |
| HRRCDG (°) (kW) | - | - | - | 401 | 393 | 0,03 | 537 | 517 | 0,03 | 406 | 391 | 0,04 | 9 |
| MLR (°) (g/s) | - | - | - | 10 | 10 | 0,02 | 13 | 13 | 0,03 | 10 | 10 | 0,03 | 0 |
| P_L4 (Pa) | -33 | -73 | 0,45 | 125 | 134 | 0,12 | 114 | 165 | 0,45 | 113 | 158 | 0,39 | 1912 |
| PEXT_NOD_L3 (Pa) | -1030 | -1067 | 0,02 | -1031 | -1023 | 0,01 | -1010 | -899 | 0,06 | -1009 | -915 | 0,06 | 1006 |
| DADM_L4 (m³/h) | 2496 | 2563 | 0,02 | 2187 | 2180 | 0,02 | 2198 | 2133 | 0,07 | 2204 | 2147 | 0,05 | 159 |
| DEXT_L4 (m³/h) | 2603 | 2572 | 0,01 | 3267 | 3236 | 0,01 | 3287 | 3151 | 0,03 | 3290 | 3165 | 0,03 | 27 |
| TGADM_L4 (°C) | 15,0 | 20,1 | 0,14 | 15 | 20 | 0,14 | 16 | 21 | 0,13 | 16 | 21 | 0,13 | 0 |
| TGEXT_L4 (°C) | 16,2 | 19,8 | 0,10 | 117 | 124 | 0,03 | 141 | 144 | 0,02 | 141 | 143 | 0,02 | 8 |
| TZMOY8 (°C) | 16,7 | 20,1 | 0,09 | 161 | 169 | 0,03 | 169 | 172 | 0,02 | 175 | 177 | 0,02 | 0 |
| TSUP_2ZG (°) (°C) | - | - | - | 111 | 116 | 0,03 | 115 | 116 | 0,02 | 123 | 124 | 0,02 | 0 |
| TCOMB_L4_2 (°C) | 85,9 | 89,9 | 0,02 | 163 | 183 | 0,05 | 535 | 570 | 0,04 | 473 | 497 | 0,03 | 1754 |
| TCOMB_L4_5 (°C) | 25,0 | 26,2 | 0,04 | 625 | 625 | 0,01 | 697 | 681 | 0,02 | 672 | 672 | 0,02 | 781 |
| TP_L4_NC255 (°C) | 17,7 | 20,9 | 0,08 | 30 | 34 | 0,06 | 38 | 41 | 0,04 | 41 | 43 | 0,04 | 0 |
| FLR_L4_NE260 (W/m²) | 47,6 | 54,8 | - | 613 | 557 | 0,05 | 670 | 585 | 0,08 | 713 | 622 | 0,07 | 2049 |
| FLT_L4_NC265 (W/m²) | 7,2 | 0,8 | - | 1076 | 1088 | 0,03 | 859 | 815 | 0,05 | 1109 | 1069 | 0,05 | 1023 |
| O2_L4_BAS (%-vol) | 20,9 | 20,9 | 0,00 | 19,7 | 19,7 | 0,00 | 16,6 | 16,5 | 0,00 | 18,4 | 18,3 | 0,00 | 166 |
| O2_L4_HAUT (%-vol) | 20,9 | 20,9 | 0,00 | 18,4 | 18,2 | 0,00 | 16,5 | 16,4 | 0,01 | 17,4 | 17,3 | 0,01 | 549 |
| CO2_L4_BAS (%-vol) | - | - | - | 0,9 | 0,7 | 0,12 | 3,0 | 2,6 | 0,06 | 1,8 | 1,5 | 0,07 | 1298 |
| CO2_L4_HAUT (%-vol) | - | - | - | 1,8 | 1,9 | 0,02 | 3,1 | 3,1 | 0,01 | 2,5 | 2,5 | 0,02 | 43 |
| H2OEXT_L4 (%-vol) | 1,0 | 1,1 | 0,04 | 3,3 | 3,5 | 0,03 | 7,4 | 7,8 | 0,03 | 5,4 | 5,5 | 0,03 | 90 |
| CO_L4_BAS (ppm) | - | - | - | 165 | 149 | 0,05 | 607 | 586 | 0,02 | 354 | 332 | 0,04 | 347 |
| CO_L4_HAUT (ppm) | - | - | - | 364 | 368 | 0,02 | 628 | 610 | 0,02 | 515 | 500 | 0,03 | 202 |
| D_WATER_SPRAY (l/min) | - | - | - | - | - | - | 107,6 | 108,8 | 0,01 | 30,5 | 31,2 | 0,14 | 1368 |
| QWS_7 (l/min/m²) | - | - | - | - | - | - | 3,7 | 3,7 | 0,14 | 1,2 | 1,2 | 0,19 | 1397 |
| QWS_18 (l/min/m²) | - | - | - | - | - | - | 3,0 | 3,4 | 0,16 | 1,2 | 1,1 | 0,18 | 1519 |

2 Table 4: Metrics for the variables and for the two tests (the variable x^1 corresponds to TEST1 test and x^2 to TEST2 test) (*) number of points for which R_i is greater
3 than R_r during the whole period of test which corresponds to 2186 instants.

1 RESULTS AND DISCUSSION

2 Global behavior of the fire test

3 The fire shows a typical behavior of a pool fire in an enclosure. The fuel MLR and the fire HRR
4 increase during the fire growth and then reach a steady state at about 400 kW (Fig. 4). This
5 steady regime results from equilibrium between the fuel burning rate, lower than in open at-
6 mosphere, and the oxygen feed by the ventilation. The consequence on the gas phase is an in-
7 crease of the gas temperature (to about 200 °C in the upper part, variable TZMOY8 in Fig. 4) and
8 a decrease of the oxygen concentration (cf. variable O2_L4_HAUT in Fig. 5). As expected for con-
9 fined and mechanically ventilated fire room scenario, the ventilation flow rate and the pressure
10 in the room are very sensitive to the fire growth and to the increase of gas temperature leading
11 to an increase of the exhaust flow rate and a decrease of the admission flow rate as observed in
12 Fig. 4 (cf. variables P_L4, DADM_L4 and DEXT_L4). After about 950 s of combustion, the water
13 spray system is activated during 600 s (cf. variable D_WATER_SPRAY in Fig. 5) without extin-
14 guishing the fire. It leads to a decrease of the gas temperature, to a homogenization of the spe-
15 cies concentration but also to an enhancement of the burning rate. This unexpected behaviour is
16 interpreted as an increase of the turbulence level within the compartment, illustrated by large
17 fluctuations of the pressure and ventilation flowrate measurements (variables P_L4, DADM_L4
18 and DEXT_L4 in Fig. 4). The activation and shut-off of the water spray system lead also to sudden
19 variations of pressure in the room (variable P_L4 in Fig. 4).

20 Repeatability on the input conditions

21 First, the differences, prior to ignition are quantified. For 15 variables, for which the mean value
22 is non zero, the mean relative differences NED, i.e. the precision between one trials and the mean
23 signal, are displayed in Table 4 and are illustrated in Fig. 6-a. NED values span from 0.001 for the
24 oxygen concentration to 0.45 for the pressure in the room P_L4. Concerning the fire source, the
25 fuel temperature (TCOMB_L4_2) shows a difference of 4 °C (NED=0.02 in Fig. 6) for a fuel tem-
26 perature of about 85 °C (the fuel being preheated before ignition). The pan was ignited with the
27 same burner during similar time duration. The settings for the operating conditions of the venti-
28 lation prior to ignition are well reproduced. The difference of air flowrates was of 50 m³/h for a
29 total flow rate of about 2550 m³/h (NED=0.02 in Fig. 6). Only, the initial pressure in the room
30 was not set to the same value -33 Pa and -73 Pa (NED=0.45 in Fig. 6). Regarding the ambient
31 temperature, a difference of a maximum of 5 °C is noticed due to the change of the environment
32 conditions.

33 The differences in the mass of fuel and ventilation conditions are linked to slight changes in the
34 experimental protocol (ignition process, mass of fuel) and the way the ventilation network was
35 set. The variations in temperature depend in the changes in the environmental conditions. For
36 the other variables, the differences between the two tests are within the measurements uncer-
37 tainty.

38 Repeatability during the combustion phase

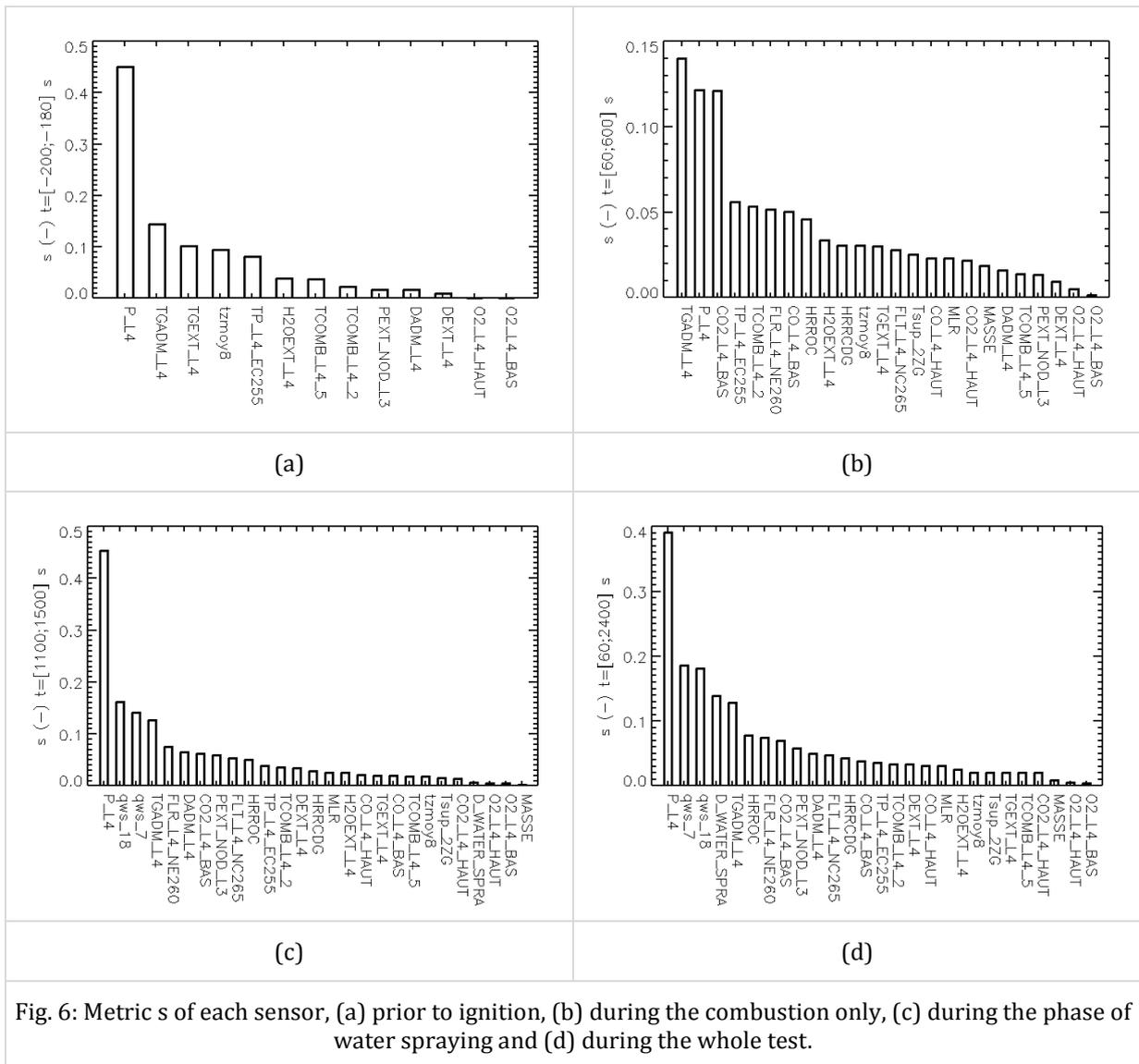
39 A first observation of Fig. 4 and Fig. 5 shows good qualitative agreement between the two tests.
40 The amplitudes as well as changes of variation are very similar. For example, the peaks of pres-
41 sure are similar (in time and in amplitude) and the time variations of the fuel MLR and the fire
42 HRR follow identical trends. The activation and the shut-off of the water spray system are ob-
43 served with the same qualitative behaviour for the two trials.

44 A quantitative analysis based on the metric NED shows that the repeatability or precision may
45 be different according to the type of physical variables (temperature, concentration, flowrate,..)
46 and according to the items concerned (fire, gas phase, walls or ventilation). The values of NED
47 during the combustion phase are presented in Fig. 6-d. The variable showing the best repeatabil-
48 ity are the oxygen concentration ($\bar{x}^1 = 16.6\%$ and $\bar{x}^2 = 16.5\%$), the fuel mass burnt
49 ($\bar{x}^1 = 13.9 \text{ kg}$ and $\bar{x}^2 = 13.9 \text{ kg}$), and some gas temperature (for TZMOY8 $\bar{x}^1 = 169^\circ\text{C}$ and
50 $\bar{x}^2 = 172^\circ\text{C}$), with NED values below 0.05. Physical variables such as heat fluxes, flow rates and

1 carbon dioxide concentrations show larger discrepancy with NED values in the interval
2 [0.05;0.1]. These measurements correspond to quantities that can be difficult to measure. The
3 levels obtained for gas temperature are very similar to the levels obtained by Johansson [7].
4 Then the pressure in the room, the ambient temperature and the quantities related to water
5 spray give much larger value with a maximum of 0.45 for the pressure in the room ($\bar{x}^1 = 114 Pa$
6 and $\bar{x}^2 = 145 Pa$). For the pressure, this large value is explained by the fact that this quantity is
7 very sensitive to few change of temperature within the room and therefore is much more diffi-
8 cult to reproduce.

9 The variables related to the water spray system (water flow rate and water density) are also
10 difficult to reproduce (for sensor QWS_18 $\bar{x}^1 = 3.0 l/min/m^2$ and $\bar{x}^2 = 3.4 l/min/m^2$). This re-
11 sult is attributed to the complex physic associated to process of droplet generation by the nozzle
12 and the spraying pattern in the room. For the measurement of the water density, the results are
13 also explained by a larger uncertainty attributed to the water collector technique.

14



15

16 The elaborated variables, as the heat release rate, not directly measured but computed from
17 analytical models with calorimetry methods or the upper and lower temperatures with regres-
18 sion methods, show also different results. The mechanical method for the computation of the

1 HRR is the most repeatable method. In between the two calorimetric methods (Oxygen Con-
2 sumption, OC and Carbon Dioxide Generation, CDG), the CDG method is the most repeatable one
3 ($\bar{x}^1 = 537 kW$ and $\bar{x}^2 = 517 kW$). This result is in agreement with previous studies mentioning
4 OC methods as less accurate in case of mechanically ventilated compartment.

5 The effect of the water spraying on the precision is discussed in comparing the NED values on
6 the first period of combustion $t=[60;600]$ s without water spraying and on the period
7 $t=[1100;1500]$ s with the effect of the water spraying. Results are presented in Fig. 6-b and Fig.
8 6-c and in Table 4. Water spraying affects mainly the repeatability on the pressure in the room
9 (sensor P_L4) and on the ventilation flowrate. The sudden pressure peaks induced by the activa-
10 tion of the water spray is difficult to repeat. Concerning the other variables (temperature, spe-
11 cies concentration), similar levels of precision are obtained.

12 **Discussion about repeatability and uncertainty**

13 The second metric, R (relation (3)), normalizes the discrepancy due to repeatability with the
14 discrepancy due to sensor uncertainty. Examples of results are given in Fig. 7 showing time
15 variation of the ratio R_i^k , versus time for twelve representative sensors. For the six first sensors,
16 the ratio is mainly greater than 3 and lower than 3 for the six followers. The choice of three is
17 here set as a criterion fixed for this analysis.

18 In Fig. 8, the sensors are sorted with the percentage of point having a value of R_i^k greater than
19 the chosen R_τ . The fuel mass loss rate (MLR), some temperature (TGADM_L4, TGZMOY8,
20 TSUP_SZG) and the fire HRR with the CDG methods give very small (nearly zero) percentage
21 which indicated that the ratio R_i^k is always lower than R_τ . For those variables, the difference due
22 to repeatability is lower than the sensor uncertainty. If this former is considered as acceptable
23 then difference due repeatability is included to the sensor uncertainty. Repeatability tests will
24 not give additional information to the uncertainty.

25 On the opposite there are variables, here the fuel mass (MASS), the pressure in the room (P_L4)
26 for instance, for which the value of R_i^k is mostly greater than R_τ . For these physical quantities,
27 the difference due to repeatability is much larger than the sensor uncertainty and therefore re-
28 peatability tests are required to give a better estimate of the range of variation compared to un-
29 certainty.

30 In the perspective of comparing a numerical simulation with a fire experiment, these results
31 demonstrate that two types of situations can be encountered. The first one concerns variables
32 for which variations due to repeatability are lower than those due to sensor uncertainty ($R^k < R_\tau$).
33 For those measurements, comparison can be performed on one test, using the sensor uncertain-
34 ty as the critical distance ensuring that the simulation is validated. Having additional trials will
35 not give more information, since the variation due to repeatability is within the sensor uncer-
36 tainty. The second situation concerns variables for which variations due to repeatability are
37 greater than those due to sensor uncertainty ($R^k > R_\tau$). In this case, comparison between the nu-
38 merical simulation and the measured signal of one test cannot be based on the sensor uncertain-
39 ty but on a larger critical distance that takes into account the variation due to repeatability. In
40 this case, several trials of the fire scenario should be available to validate the simulation.

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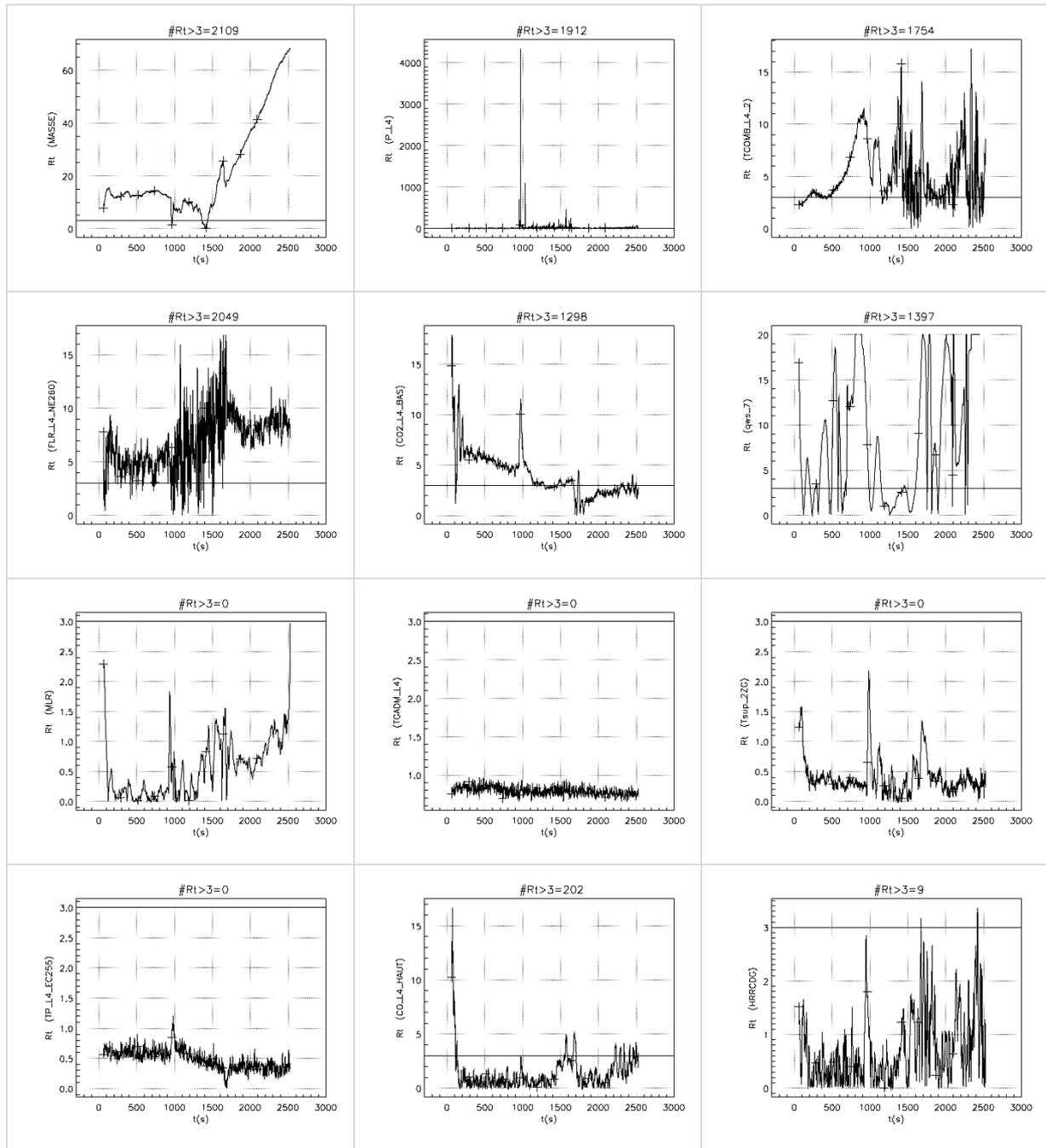
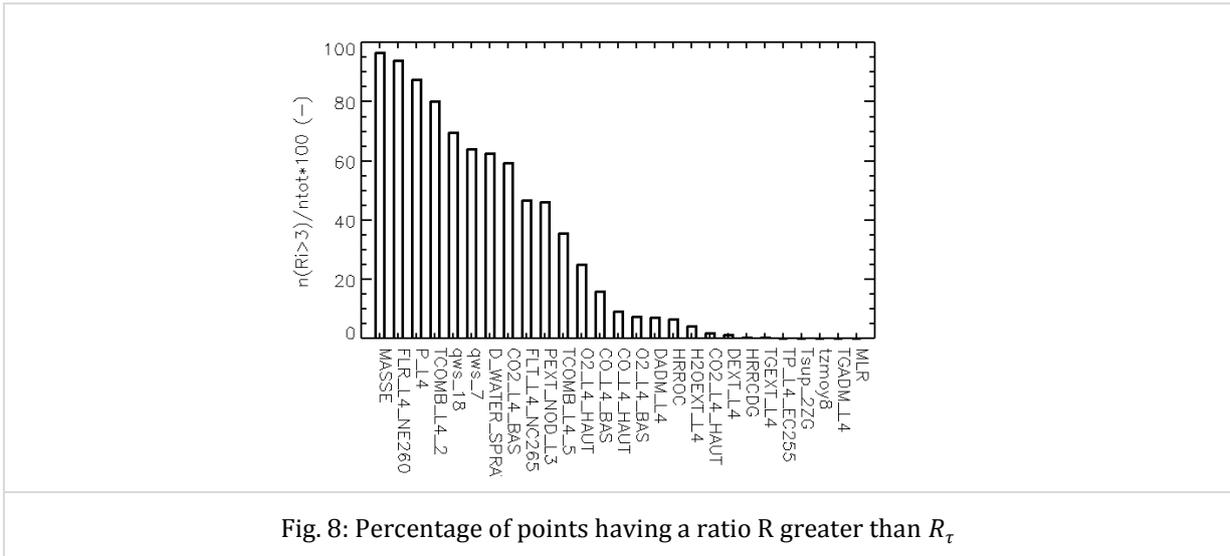


Fig. 7: Time variation of the metric R for 12 representative sensors ($\#R_i > R_\tau = 3$ means “number of point having R_t greater than R_τ ”); the horizontal line corresponds to the limit $R_i = R_\tau$

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CONCLUSION

This study proposes a repeatability analysis of large scale fire test involving a 400 kW oil pool fire in a 42 m² mechanically ventilated enclosure with the activation of water spray system. The study, based on two trials, compares a set of 27 variables directly measured or computed from measurements, selected such as they characterize the whole fire scenario (fire source, gas phase, walls, ventilation network and water spray system). For each variable, metrics are computed and give the level of repeatability of this fire scenario. Conclusions obtained from the results are the followings.

- For a fire test scenario including water spraying, the repeatability assessment is similar as in previous studies [6], [7], [8] for gas temperature, species concentrations or mass loss rate. The consideration of water spraying in the fire test scenario induces pressure variations that are the most difficult quantity to repeat between trials.
- The study points out that repeatability levels are closely related to the type of variable considered. Oxygen concentration measured with analyser or gas temperature measured with thermocouples gives the most repeatable quantities. On the opposite, water spray characteristics or ventilation features (pressure and air flowrates) are more difficult to reproduce.
- The importance of uncertainty when assessing repeatability is highlighted and discussed from the use of a new parameter R defined for each experimental measurement. This new metric is the ratio between precision assessed from trials of fire test and the uncertainty assessed on controlled conditions (calibrator and reference apparatus). If the ratio is lower or equal to a given criterion, precision is identical to uncertainty and the uncertainty is appropriate to characterize the range in which the true value is asserted to be. If the ratio R is greater than the criterion, precision is larger than uncertainty.
- From the perspective of comparison between a numerical simulation and experimental data, this analysis demonstrates that two types of situations can be encountered. The first one concerns variables for which variations due to repeatability are lower than those due to sensor uncertainty ($R^k < R_\tau$). For those measurements, code validation can be based on one test, using the sensor uncertainty as the critical distance considering the simulation as validated. The second situation concerns variables for which variations due to repeatability are greater than those due to sensor uncertainty ($R^k > R_\tau$). In this case, comparison between the numerical simulation and the measured signal cannot be

1 based on the sensor uncertainty only but on a larger critical distance that takes into ac-
2 count the variation due to repeatability.

- 3 • From the present work, examples of measured variables whom ranges of uncertainty
4 and repeatability are similar, are gas temperature, oxygen concentration, fuel mass loss
5 rate in case of liquid pool fire. On the opposite, measures variables that need repeatable
6 tests in order to assess the range of variability are room pressure, fuel temperature,
7 radiative heat fluxes, variables related to water spray system. Nevertheless, these con-
8 clusions have been obtained with a set of only two trials which is not enough to give con-
9 clusive remarks about repeatability. Future work should integrate larger number of tri-
10 als.

11 The repeatability is an issue when performing large scale fire test. For scenario involving com-
12 plex phenomenon such as complex fire source (furniture, cables, electrical cabinet,..), or under-
13 ventilated unstable combustion regime, issue of repeatability have to be treated. The phenom-
14 ena of fire growth and fire propagation as well as the under-ventilated combustion are difficult
15 to be fully controlled during the experiment. For fire tests dealings with such topics, campaign of
16 repeatability tests should be carried out in the perspective of code validation.

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- 18
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