

**NIST Technical Note 1799**

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*Rebecca Blank, Acting Secretary*

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*Patrick D. Gallagher, Under Secretary of Commerce for Standards and Technology and Director*

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## **Abstract**

The performance of an upholstery cover fabric in the promotion of smoldering combustion of polyurethane foam (PUF) can be assessed by a previously developed bench scale test. The purpose of the research reported here was to determine whether the test apparatus and the polyurethane foam could be modified to increase the total assembly mass loss (more severe smoldering) while also increasing experimental repeatability.

The results show that the replacement of the non-air-permeable assembly frame with an air-permeable substrate in the test apparatus induces a significant increase in smoldering mass loss and mass loss repeatability. Similar results are achieved by increasing the air permeability of PUF with a process that removes the residual membranes in the foam (reticulation). Ultimately, both the reticulation process of PUF and the modification of the test apparatus aim to promote oxygen transport to the smolder front by natural convection.

These findings indicate the importance of natural convection on ignition, magnitude, and repeatability of smoldering combustion; they might be useful for future development of bench-scale smoldering test methods with improved correlation with full-scale smoldering tests.

## **Keywords**

Polyurethane foam; smoldering; furniture; flammability; SRM 1202

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## List of Acronyms

CPSC	U.S. Consumer Product Safety Commission
$ML_{CPSC}$	Mass loss of the foam expressed as % of the initial mass of the foam; charred material is removed and accounted as mass loss (according to the CPSC proposed regulation) <sup>2</sup>
$ML_{GAS}$	Mass loss of the mockup measured in real time and expressed as % of the initial mass of the foam plus the fabric; charred material is not removed and is not accounted as mass loss
$(ML_{CLOSED})_{GAS}$	Value of $ML_{GAS}$ in the closed mockup configuration
$(ML_{OPEN})_{GAS}$	Value of $ML_{GAS}$ in the open mockup configuration
$(ML_{OPEN}/ML_{CLOSED})_{CPSC}$	Ratio between $ML_{CPSC}$ in the open mockup and $ML_{CPSC}$ in the closed mockup
MLR	Mass loss rate
$ML@TTP$	Value of $ML_{GAS}$ at $t=TTP$
NIST	National Institute of Standards and Technology
PMLR	Peak of mass loss rate
PUF	Polyurethane foam
SRM	Standard Reference Material
SSS	Self-sustained smoldering
TTP	Time to peak of mass loss rate
$\bar{x}$	Average value
$\sigma$	Standard deviation
$\sigma^{rel}$	Relative standard deviation
$(\sigma^{rel}_{CLOSED}/\sigma^{rel}_{OPEN})_{CPSC}$	Ratio between $\sigma^{rel}$ calculated for $ML_{CPSC}$ in the closed mockup and $\sigma^{rel}$ calculated for $ML_{CPSC}$ in the open mockup

## Introduction

The influence of an upholstery cover fabric to promote smoldering in polyurethane foams can be assessed using a foam mockup test.<sup>1</sup> The methodology is based on the test described in the Consumer Product Safety Commission (CPSC) proposed regulation (73 FR 11702).<sup>2</sup> This method requires a polyurethane foam (PUF) with repeatable and well-characterized smoldering. The National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 1202 is a kit that includes a smoldering standard polyether-based polyurethane foam, a denim cover fabric, a cotton fabric, and SRM 1196 cigarettes. The denim fabric supplied in the kit is used to cover the exposed portion of the polyurethane foam in the test method. The denim fabric is a control or a reference for the test, which is used to determine the performance of other fabrics in the promotion of smoldering mass loss of the composite assembly as described on the SRM certificate. In order to assess the smoldering propensity of other cover fabrics, the denim fabric must be replaced with this other fabric. The test measures the mass loss of the foam during a 45 min period. During the development of SRM 1202, the mass loss values drifted drastically from test to test for the same batch of foam and, even more significantly, from batch to batch. The highest repeatable mass loss values were in the low twenties.

The purpose of the research reported here was to determine whether the mockup test device and the polyurethane foam could be modified to increase the total mass loss values (more severe smoldering) while also increasing experimental repeatability.

Numerical simulation and experimental data indicated the key role of oxygen supply on smoldering combustion of PUF.<sup>3,4,5,6,7,8,9,10</sup> We previously reported on foam characteristics that influence smoldering performance.<sup>11</sup> For a foam of given formulation, smoldering is controlled by the cell morphology, in particular, smoldering increases with an increasing fraction of open versus closed cells, and decreasing cell size. Such a foam morphology boosts oxygen supply to the smoldering front by promoting natural convection (open cell structure), and an increase of surface area available for thermo-oxidative reactions (small cell size).<sup>12</sup>

Based on this information, commercial foams were identified that should have higher and more repeatable mass loss values. These foams were standard polyether-based polyurethane foams but, in addition, they were post-processed with a reticulation procedure. The reticulation process removes residual membranes in the foam and provides a highly permeable foam with a homogeneous fully-open cell structure. This morphology is expected to increase smoldering magnitude, due to the increase in air permeability and natural convection, and increase the smoldering repeatability, due to the removal of residual membranes.\*

Here, the SRM 1202 mockup test and the NIST box test<sup>11</sup> have been modified to suppress the limiting effect on natural convection of the wood substrate used as sample holder. As depicted in the schematic drawing of Figure 1, this effect is particularly important for thin foam samples (Figure 1b) rather than thicker foam samples (Figure 1a), where natural convection can still efficiently supply oxygen to the smoldering front. In other words, the closer the smoldering front

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\* In non-reticulated polyurethane foams it is technically impossible to control the fraction of open versus closed cells throughout the same foam batch and between different batches. The resulting variations in air permeability and surface area affect smoldering significantly.

gets to the substrate, the less oxygen reaches the smoldering front by natural convection and, ultimately, the smoldering front might become unstable. Thus, it is reasonable to speculate that the higher the natural convection (controlled by foam thickness, foam air-permeability, substrate permeability and, eventually, fabric permeability) and the higher the smoldering rate and repeatability.

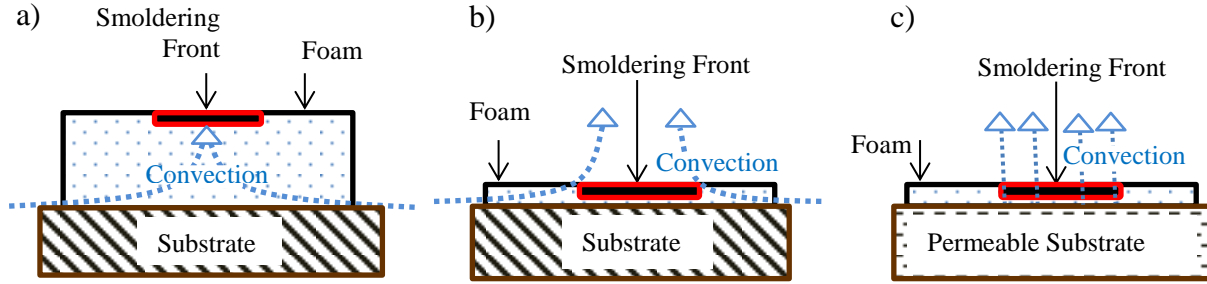


Figure 1. In the presence of a non-air permeable substrate the oxygen supply to the smoldering front is enhanced by natural convection in a thick sample (a), and it is severely limited in a thin foam sample (b); oxygen supply can be promoted by natural convection in thin foam samples replacing the non-permeable substrate with an air-permeable substrate (c).

The aforementioned effect of foam thickness might explain the lack of correlation between bench-scale (*i.e.*, thin foam samples) performance and full-scale smoldering performance (*i.e.*, thick foams samples).<sup>13</sup> This inconsistency can be simply overcome by using an air-permeable substrate that would allow a uniform oxygen supply to the smoldering front through natural convection (Figure 1c).

Ultimately, the two approaches used here, the reticulation process of PUF and the modification of the testing configuration, aim to promote oxygen supply to the smoldering front by natural convection. The findings reported in this work indicate the key role of natural convection on ignition, magnitude and repeatability of smoldering.

## Experimental

Uncertainties are reported as one standard deviation ( $\sigma$ ).

### ***Mockup Designs: Standard (Closed) and Modified (Open) Mockup***

The standard mockup test<sup>1</sup> (closed mockup) was modified to boost natural convection by introducing a 13 mm (about 0.5 in) gap between the foam and the sample holder and by removing part of the fabric (Figure 2 and Figure 3).

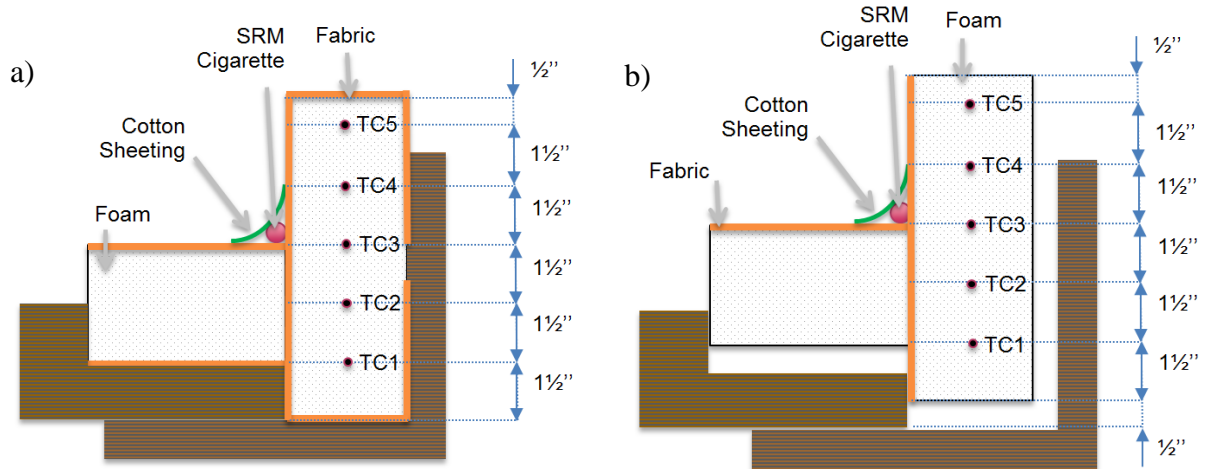


Figure 2. Schematic drawing of the standard (closed) mockup test (a) versus the modified (open) mockup test (b): a gap of 13 mm (about 0.5 in) between the foam and the sample holder and a partial fabric removal promote natural convection in the open mockup. Five thermocouples (TC1 to TC5) are installed in both configurations.

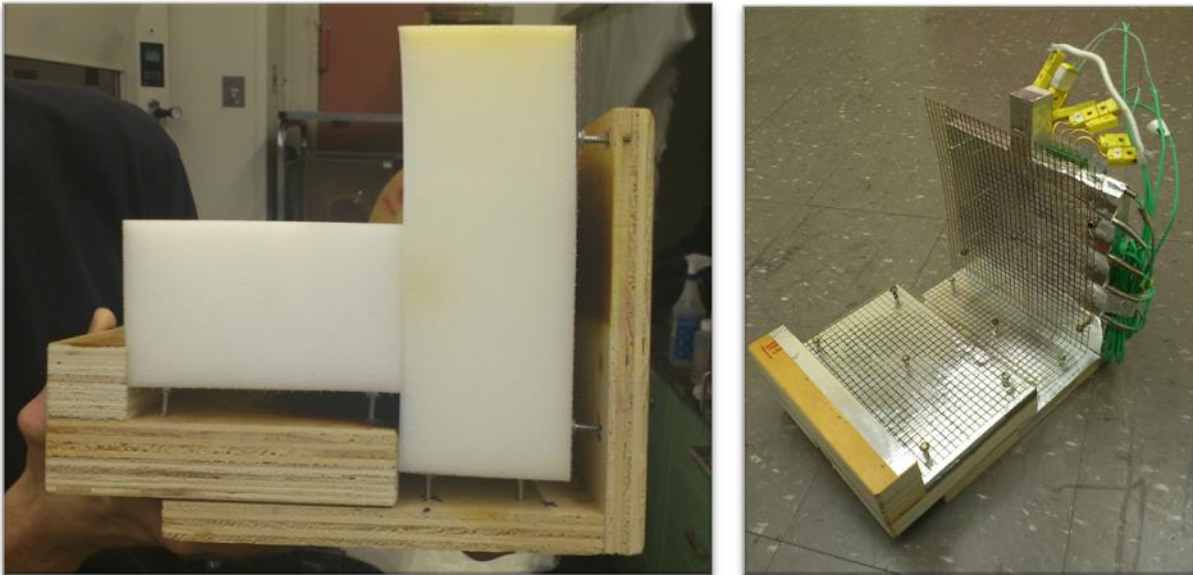


Figure 3. Photos of two sample-holder prototypes for the open mockup test. In the first prototype (left), metal screws and a metal wire mesh are used to suspend the foam at a distance of 13 mm from the wood sample holder. In the second prototype (right), thermocouples are also added to monitor the foam temperature.

An obvious advantage of the open mockup is that the wood sample holder is not exposed to charring and can always be reused, even with highly smoldering foams.

### ***Test Enclosure***

Smoldering tests were run inside polycarbonate enclosures in order to improve the repeatability of the test by:

- minimizing the effect of airflow variations over time in the hood;
- suppressing turbulence.

A schematic drawing of the enclosure is shown in Figure 4. Tests were run with or without the removable lid. The presence of the lid promoted a pure convective laminar flow of the smoke produced by smoldering, and, likely, increased the temperature and the concentration of combustible volatiles in the enclosure.

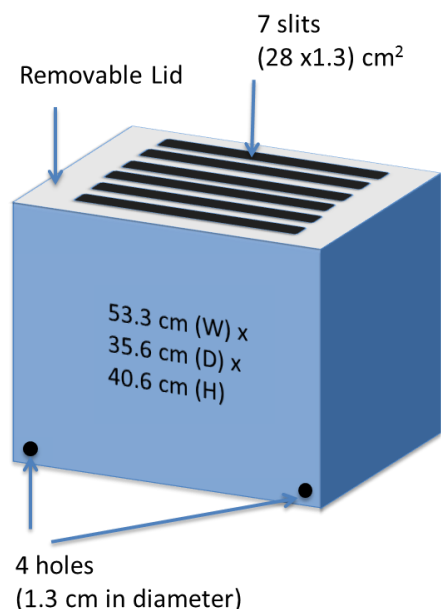


Figure 4. Schematic drawing of the enclosure.

### ***Experimental Setup***

Each mockup with either the standard (closed) or modified (open) set-up was placed inside a polycarbonate enclosure. Tests were run with and without the removable lid. Smoldering was assessed for all mockups as foam mass loss at the end of the test ( $ML_{CPSC}$ ), according to the CPSC proposed regulation.<sup>2</sup> The test duration was 45 min. All charred material was removed from the foam at the end of the test and accounted as mass loss.  $ML_{CPSC}$  was expressed as % of the initial mass of the foam.

In some cases, the mass of each mockup and the temperature of the thermocouples TC1 to TC5 were also recorded in real time throughout the test. The mass loss measured here was due to the volatiles released by both the fabric and the foam ( $ML_{GAS}$ ).  $ML_{GAS}$  was expressed as % of the initial mass of the foam plus the fabric. The charred foam was accounted for mass loss calculations in  $ML_{CPSC}$  but not in  $ML_{GAS}$ , therefore,  $ML_{GAS}$  at  $t=45$  min was different from  $ML_{CPSC}$ . The actual experimental set up is shown in Figure 5.

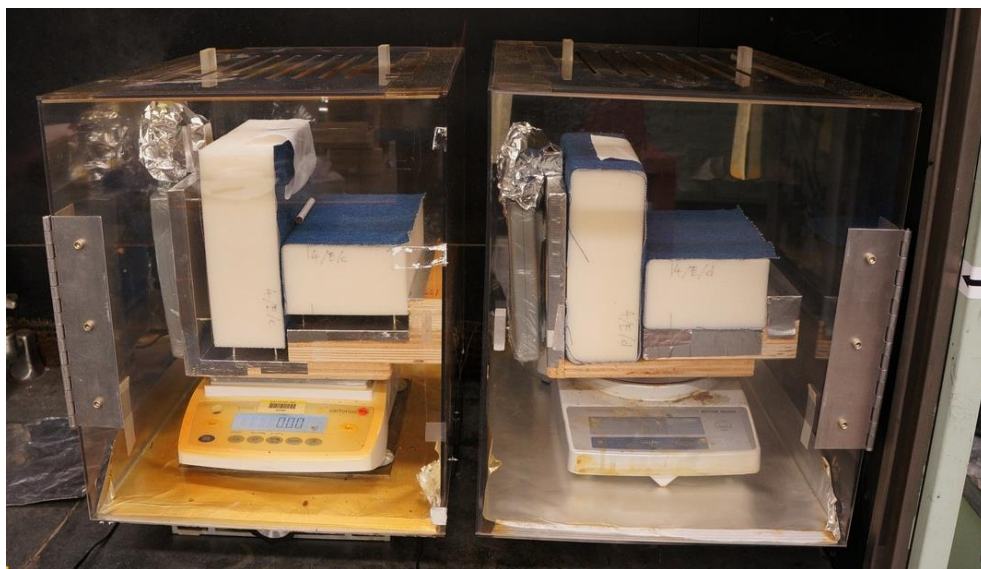


Figure 5. Picture of the actual experimental setup. The mockups (open on the left and closed on the right) are placed inside polycarbonate enclosures. Two scales are used for monitoring in real time the mass loss due to the volatiles released by both the fabric and the foam ( $ML_{GAS}$ ).  $ML_{CPSC}$  was calculated at the end of the test ( $t=45$  min) by first removing all charred foam and then weighing the residual uncharred foam only.

### ***NIST Box Test***

This is a smoldering test method developed at NIST.<sup>11</sup> The foam sample is placed in a wood box and covered with a glass fiber cloth; an electrical heater is used to initiate smoldering (Figure 6). The presence of the box and the fiber glass cloth limit natural convection. Tests on the same foam were run with and without the box to evaluate the effect of the presence of the box on smoldering.

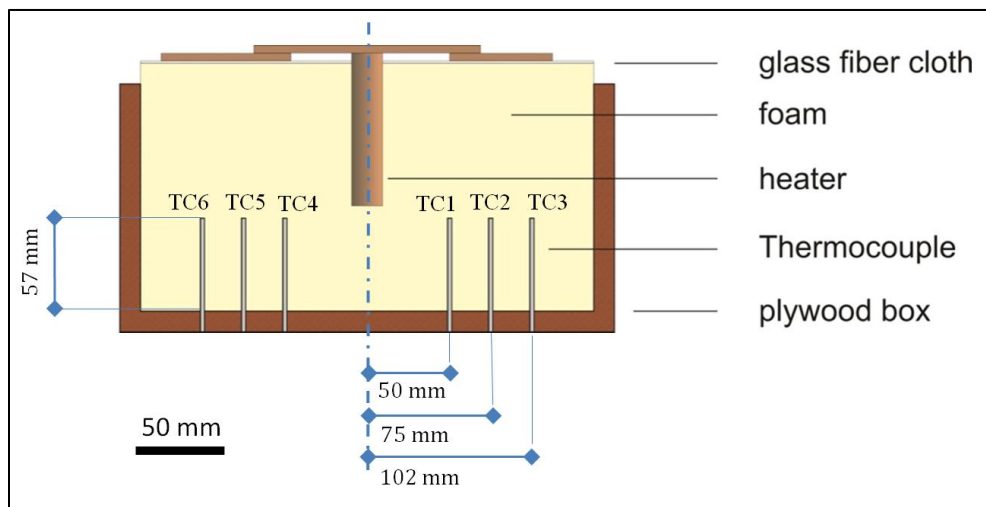


Figure 6. Schematic drawing of the box test. The box test is a smoldering test that does not require the use of a fabric or a cigarette.

## Materials

Three different foams were tested in the mockup test. The foam used in NIST SRM 1202 (SRM 1202 foam, for the remainder) is a slabstock polyether-based polyurethane foam.<sup>1</sup> *Foam C* and *Foam F* are both reticulated polyether-based polyurethane foams. *Foam C* contains carbon black. A polyether-based flexible polyurethane foam (*Foam B11*)<sup>11</sup> was used for the box test. The foam densities were  $(26.7 \pm 0.7, 22.4 \pm 0.3, 22.3 \pm 0.3$  and  $29.2 \pm 0.6)$  kg·m<sup>-3</sup> for SRM 1202 foam, *Foam C*, *Foam F* and *Foam B11*, respectively.

## Results

### Mockup Smoldering Tests Run in the Enclosure without a Lid

Smoldering tests were run in the closed and open mockup configuration in the enclosure without a lid. Mass loss was calculated on the foam only according to the CPSC proposed regulation<sup>2</sup> (ML<sub>CPSC</sub>). The results are summarized in Table 1.

Table 1. Mass loss measured according to CPSC's proposed regulation<sup>2</sup> (ML<sub>CPSC</sub>) for the closed and open mockup.

	SRM 1202 Foam (Non-reticulated)		<i>Foam C</i> (Reticulated)		<i>Foam F</i> (Reticulated)	
	Mockup setup Closed	Open	Mockup setup Closed	Open	Mockup setup Closed	Open
ML <sub>CPSC</sub> (%)	17.1	48.9	19.5	57.8	67.5	92.4
$\sigma$ (%)	13.0	10.8	4.2	3.0	6.0	0.9
$\sigma^{\text{rel}}$ (%)	76.1	22.1	21.5	5.2	8.9	1.0
Number of Tests	12	4	4	4	4	3
(ML <sub>OPEN</sub> /ML <sub>CLOSED</sub> ) <sub>CPSC</sub>	2.9		3.0		1.4	
( $\sigma^{\text{rel}}_{\text{CLOSED}}/\sigma^{\text{rel}}_{\text{OPEN}}$ ) <sub>CPSC</sub>	3.4		4.1		8.9	

$\sigma$ : standard deviation.

$\sigma^{\text{rel}}$ : relative standard deviation.

(ML<sub>OPEN</sub>/ML<sub>CLOSED</sub>)<sub>CPSC</sub>: ratio between ML<sub>CPSC</sub> in the open mockup and closed mockup.

( $\sigma^{\text{rel}}_{\text{CLOSED}}/\sigma^{\text{rel}}_{\text{OPEN}}$ )<sub>CPSC</sub>: ratio between  $\sigma^{\text{rel}}$  calculated for ML<sub>CPSC</sub> in the open mockup and closed mockup.

The data of Table 1 for SRM 1202 foam and *Foam C* indicate that:

1. In both the open and standard mockup test, the average mass loss for the *Foam C* is about 15 % higher than the average mass loss for SRM 1202 foam. This suggests that relative smoldering performance between different foams is not affected by the test configuration.
2. In both configurations, the relative standard deviation for *Foam C* is 3-4 times smaller than the relative standard deviation for SRM 1202 foam. This indicates that a reticulated foam with its regular open cell structure induces a more repeatable smoldering.
3. The average mass loss increases by a factor of about 3 for both SRM 1202 foam and *Foam C* when the open mockup test is used rather than the standard closed mockup test. The open test configuration induces a proportional variation in average mass loss in both foams.



4. The relative standard deviation decreases by a factor of 3 to 4 when the open mockup is used (3.4 for SRM 1202 foam and 4.1 for *Foam C*). In the standard mockup the smoldering front might become unstable when approaching the sample holder due to insufficient oxygen supply; this phenomenon might affect the repeatability of the test.

The results for *Foam F* in Table 1 show qualitatively the same trend observed for SRM 1202 foam and *Foam C*, *i.e.*, an increase in smoldering mass loss and a decrease in the relative standard deviation when the open mockup configuration is used. However, the magnitude of these variations was different. There was only a 1.4 fold increase (instead than about 3 fold increase as for *Foam C* and SRM 1202 foam) in mass loss because *Foam F* already lost most of its mass (about 67 %) in the closed mockup. Similarly, the relative standard deviation in the open mockup is particularly low because smoldering was close to 100 % after 45 min, however the mass loss rate might vary significantly between one test and the other.

Mass loss, measured as  $ML_{GAS}$ , was recorded in real time on three *Foam F* samples (same formulation as the *Foam F* used in Table 1 but different batch) in a closed mockup configuration. Figure 7 shows the  $ML_{GAS}$  profiles measured for these samples.  $ML_{GAS}$  at  $t = 45$  min is obviously different from the mass loss measured according to the CPSC proposed regulation ( $ML_{CPSC}$ ), where only the mass loss in the foam is measured and all charred foam is accounted as mass loss. As an example, the three tests of Figure 7 have an average  $ML_{CPSC}$  of  $(81.7 \pm 3.1) \%$  and an average  $ML_{GAS}$  of  $(42.6 \pm 7.4) \%$ .

Figure 8 shows the mass loss rate ( $MLR_{GAS}$ ) calculated as the time derivative of  $ML_{GAS}$  for the same samples of Figure 7. Self-sustained smoldering (SSS) is defined here as persisting smoldering after the removal of the heat generated by the ignition source. In the mockup test, SSS can be unambiguously identified by increasing values of  $MLR_{GAS}$  after the complete consumption of the ignition source; in fact, at this stage, there is no more heat generated by the cigarette, and an increase in  $MLR_{GAS}$  can be only induced by an increase in heat generated by smoldering of the foam and/or the fabric. For the ignition source used here (a NIST SRM 1196 cigarette), complete consumption is achieved in 30 min (typically between 25 min and 28 min).

All three tests in Figure 8 showed SSS, in fact,  $MLR_{GAS}$  kept increasing for all samples after  $t = 30$  min and the peak of  $ML_{GAS}$  (PMLR) occurred at  $t > 30$  min. These closed mockup tests were run with highly permeable reticulated foams. In general, no SSS was observed when the air permeability of the foam was below a threshold value, and  $ML_{CPSC}$  was lower than 0.2 %.<sup>11,†</sup> In other words, when natural convection was suppressed by reducing the air permeability of the foam, SSS did not occur and the smoldering mass loss was significantly lower.

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<sup>†</sup> In this study SSS was assessed by smoke production, *i.e.*, no visible smoke production at  $t > 30$  min implies no SSS.

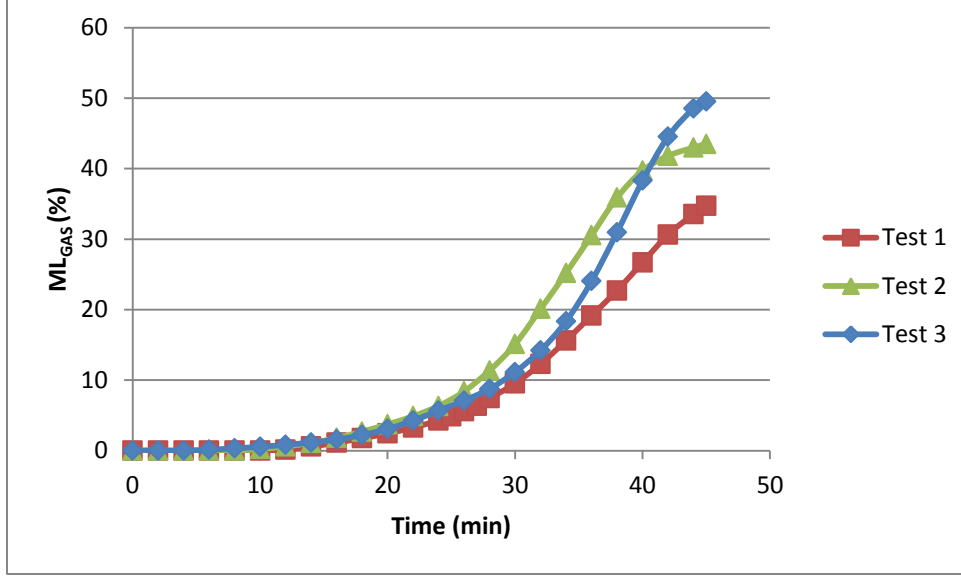


Figure 7.  $ML_{GAS}$  (mass loss due to the volatiles released by both the fabric and the foam, normalized by the total mass of the fabric and the foam) for three *Foam F* samples in a closed mockup.

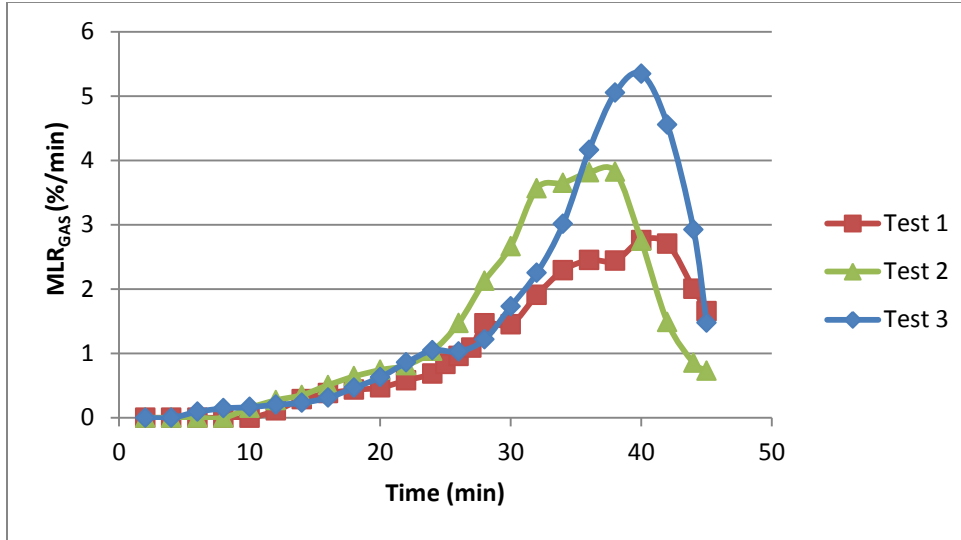


Figure 8. Mass loss rate calculated as the time derivative of  $ML_{GAS}$  for the samples of Figure 7.

The values of time to PMLR (TTP), PMLR and  $ML_{GAS}$  at  $t=TTP$  ( $ML@TTP$ ) are summarized in Table 2. The relative standard deviation ( $\sigma_{rel}$ ) for TTP,  $ML@TTP$  and PMLR are about 3 %, 18 % and 33 %. The relative standard deviation for  $ML_{CPSC}$  in the same set of foam samples is about 4 %. This implies that even if the  $ML_{CPSC}$  values are similar, the maximum smoldering rate (that is proportional to PMLR), might vary significantly between one foam sample and another.

In Figure 8, the reduction in  $MLR_{GAS}$  for  $t > TTP$  ( $\approx 40$  min) indicates a reduction in smoldering rate. It can be argued that for foams with high values of  $ML_{CPSC}$ , like *Foam F*, the test duration should be decreased to prevent a reduction in smoldering rate due to sample size limitations (*i.e.*,

foam depletion and/or approach of the smoldering front to the sample holder). For  $t < \text{TTP}$ ,  $\text{MLR}_{\text{GAS}}$  is still increasing, the differences in mass loss (measured as  $\text{ML}_{\text{GAS}}$ ) between different samples might not be significant and the mass loss ranking of the samples might be different from the mass loss rate ranking at  $t = 45$  min. For example, at  $t = 30$  min,  $\text{ML}_{\text{GAS}}$  values are 9.5 %, 15.1 % and 11.1 % for test 1, test 2 and test 3, respectively. At  $t = 45$  min,  $\text{ML}_{\text{GAS}}$  values are 34.7 %, 43.5 % and 49.5 % for test 1, test 2 and test 3, respectively (see Figure 7). In general, a prolonged smoldering time is preferable in terms of sensitivity but increases the aforementioned effect of sample size limitations. As a result, the selection of an optimal testing time for  $\text{ML}_{\text{CPSC}}$  type calculations (where the test needs to be stopped to remove the char and calculate the mass loss at a given time) remains questionable and a continuous real-time mass-loss measurement, as  $\text{ML}_{\text{GAS}}$ , appears to be generally more robust and meaningful.

The PMLR calculated from  $\text{ML}_{\text{GAS}}$  might be a better indicator for smoldering propensity than  $\text{ML}_{\text{CPSC}}$ , in particular for evaluating the probability of smoldering-to-flaming transition.<sup>14</sup> The severity of smoldering increases with an increase in PMLR and  $\text{ML@TTP}$ , and decreases with an increase in TTP.

Table 2. Average ( $\bar{x}$ ), standard deviation ( $\sigma$ ) and relative standard deviation ( $\sigma_{\text{rel}}$ ) values for the peak of  $\text{MLR}_{\text{GAS}}$  (PMLR), time to PMLR (TTP), and  $\text{ML}_{\text{GAS}}$  at  $t=\text{TTP}$  ( $\text{ML@TTP}$ ) calculated for the three tests of Figure 7 and Figure 8.

	TTP (min)	PMLR (%/min)	ML@TTP (%)
$\bar{x}$	39.3	4.0	33.6
$\sigma$	1.2	1.3	6.1
$\sigma_{\text{rel}}$	2.9	32.9	18.2

#### ***Mockup Smoldering Tests Run in the Enclosure with Lid***

The previous paragraph has shown the importance of natural convection on smoldering in terms of both magnitude and repeatability. In this section the closed and open mockup tests were run in a similar configuration to the one used before with the exception of the enclosure that, instead of being open on the top, was closed with a lid (Figure 4 and Figure 5). An open and a closed mockup test were run in parallel with *Foam F*. Figure 9 shows the two samples at about 39 min to 40 min from the beginning of the test. In the open mockup (Figure 9, on the left), the amount of smoke in the enclosure was observed to be larger and the smoldering front reached the side of the foam. These observations indicate a higher smoldering rate for the open mockup test.



Figure 9. Photograph of the closed (right) and open (left) mockups after about (39 to 40) min from the beginning of the test. *Foam F* is used for both mockups.

This conclusion was supported by the values of mass loss and temperature of the thermocouples (Figure 10 and Figure 11) that were higher in the open mockup test than the closed mockup test. At  $t = 40$  min, the mass loss in the closed mockup,  $(ML_{\text{CLOSED}})_{\text{GAS}}$ , was 13.3 % and the mass loss in the open mockup,  $(ML_{\text{OPEN}})_{\text{GAS}}$ , was 45.8 %. The ratio between  $ML_{\text{GAS}}$  in the open mockup and  $ML_{\text{GAS}}$  in the closed mockup,  $(ML_{\text{OPEN}}/ML_{\text{CLOSED}})_{\text{GAS}}$ , was about 3. The temperature measured by thermocouples TC1 to TC5 reaches a maximum of 390 °C for the closed mockup and about 670 °C for the open mockup, enough to induce autoignition. Transition to flaming was observed at  $t \approx 44$  min and the sample was suppressed with a CO<sub>2</sub> fire extinguisher after about 10-15 s from the initiation of flaming ignition. Interestingly, the temperatures of all thermocouples appeared to decrease rather than increase after ignition, possibly, due to the oxygen depletion inside the foam (no more heat produced in the foam due to smoldering) and the low thermal conductivity of the charred foam (the increase in temperature due to the fire is negligible in the foam core, where the thermocouples are placed).

Transition to flaming was never observed in the open mockup test without the enclosure lid (eight tests). Even though more validation tests are necessary, this result suggests that the enclosure lid promotes transition to flaming, likely, by increasing the temperature and the concentration of combustible volatiles in the enclosure. Also, the presence of the enclosure lid helped to decrease the rate of combustion by limiting the amount of oxygen available to the smoldering front, another beneficial effect of the lid.

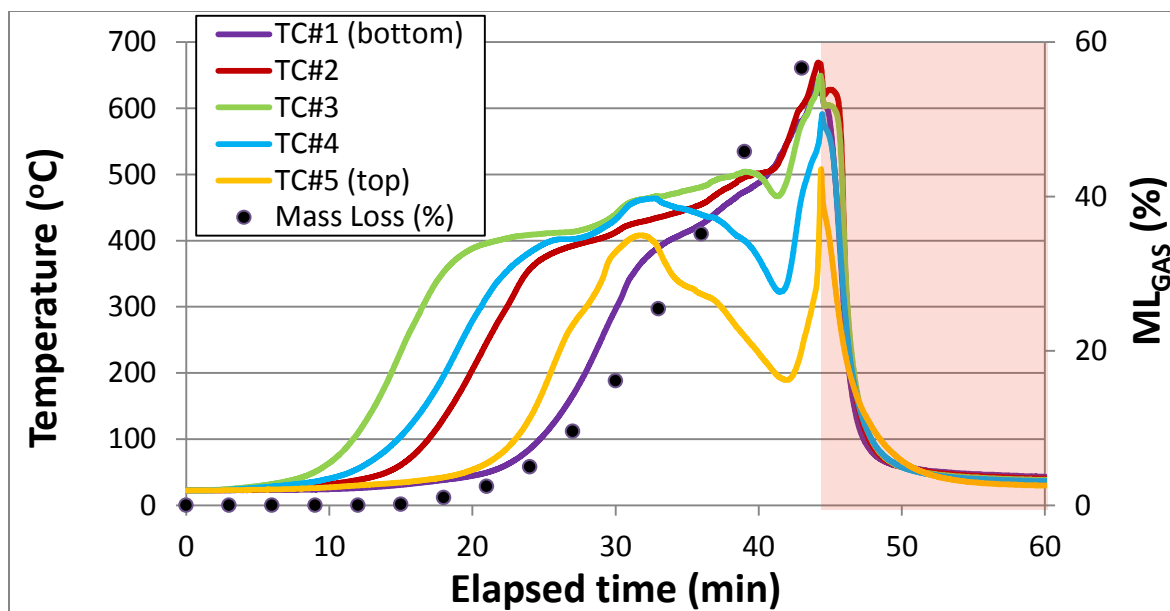


Figure 10. Temperature and mass loss profiles for a sample of *Foam F* in the open mockup test with enclosure lid. Transition to flaming was observed at about  $t = 44$  min.

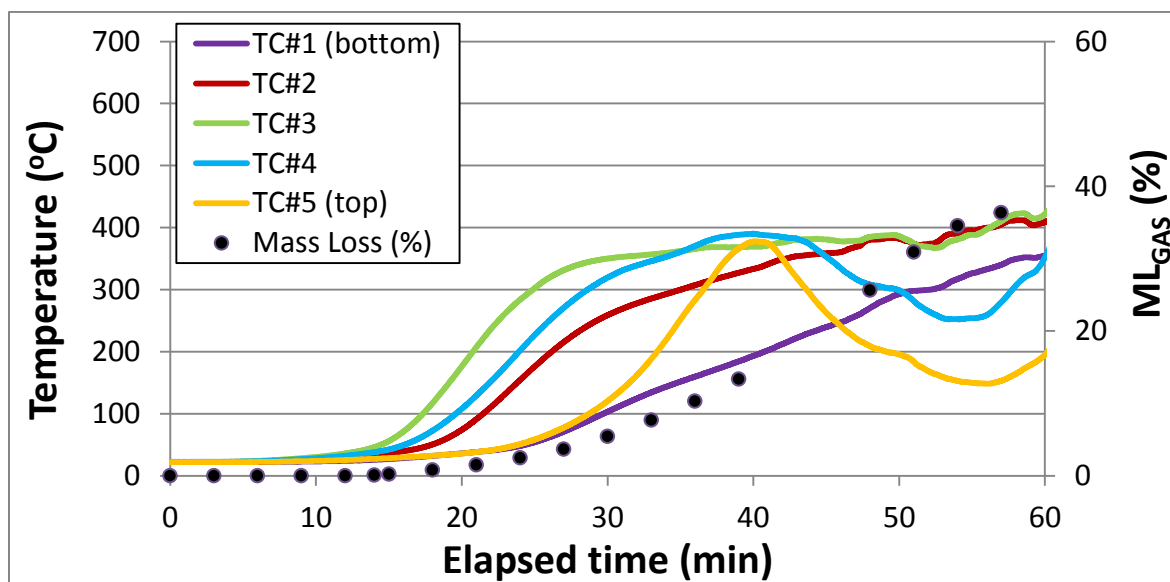


Figure 11. Temperature and mass loss profiles for a sample of *Foam F* in the closed mockup test with enclosure lid during the first 60 min.

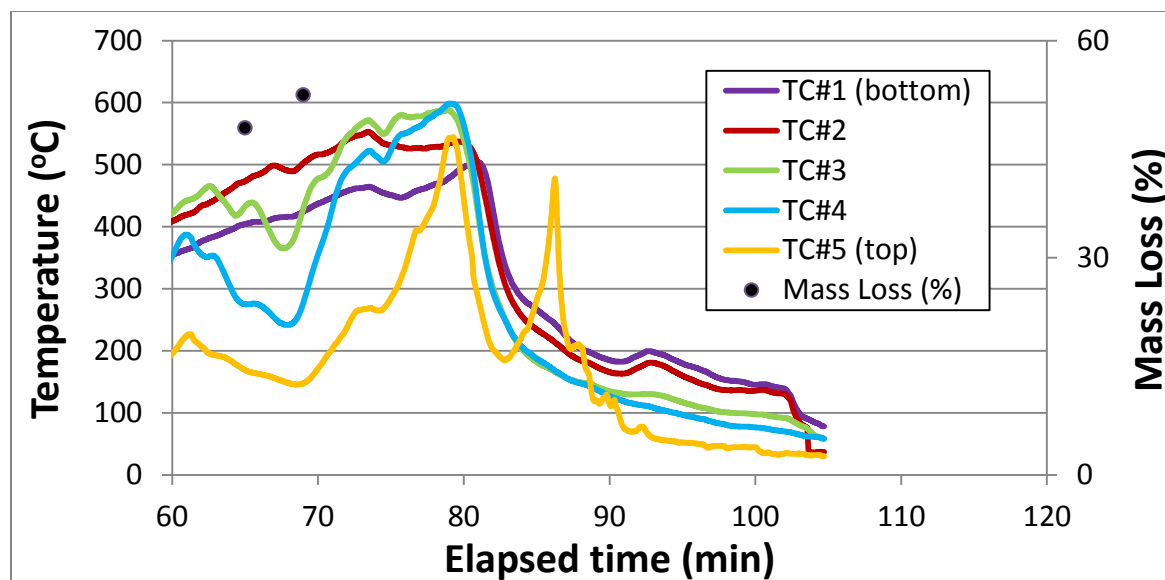


Figure 12. Temperature and mass loss profiles for *Foam F* in the closed mockup test with enclosure lid after  $t = 60$  min.

For the closed mockup, the test duration was about 100 min. In Figure 12 the temperature and mass loss profiles for  $t > 60$  min are shown (mass loss data reading became unreliable after 70 min). The temperature of TC1 (closest thermocouple to the bottom of the sample holder) is the lowest throughout the test. The temperature of thermocouples TC3 to TC5 started decreasing after  $t = 60$  min and started rising again at about  $t = 70$  min, when the smoldering fabric reached the bottom of the vertical foam and induced some charring in the foam in contact with the sample holder (Figure 13). The rapid increase in smoldering observed at this stage might be due to the formation of an air gap between the sample holder and the bottom corners of the vertical foam slab; in fact, such an air gap might promote natural convection. The final foam residues in the closed and open mockups are compared in Figure 14.

The temperature of the thermocouples, TC3 and TC4, reached a maximum temperature of about  $600\text{ }^{\circ}\text{C}$  at  $t = 80$  min in the closed mockup test (maximum temperature in the open mockup  $670\text{ }^{\circ}\text{C}$ ), therefore, autoignition and transition to flaming cannot be excluded in this test configuration, even though it would require more time. The temperature peak for TC5 at  $t = 86$  min ( $478\text{ }^{\circ}\text{C}$ ) occurred when the smoldering front on the fabric reached the top of the vertical foam.

The data of Figure 11 and Figure 12 show also that the foam temperature can increase significantly even without a significant  $ML_{\text{GAS}}$ . For example in Figure 11 at  $t = 12$  min, the TC#3 thermocouple reached a temperature of about  $120\text{ }^{\circ}\text{C}$  without any significant  $ML_{\text{GAS}}$ . This suggests that temperature measurements rather than mass loss measurements are preferable in terms of sensitivity.



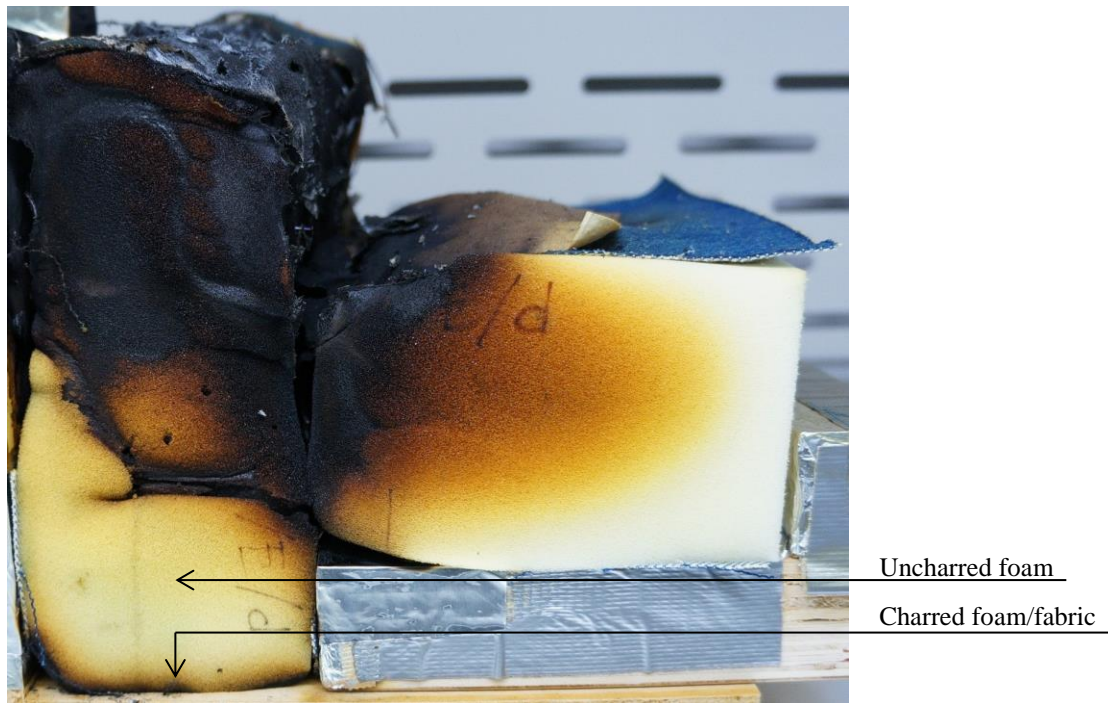


Figure 13. Side view of the closed mockup after testing. The bottom of the vertical foam slab in contact with the sample holder shows sign of charring (labeled as charred foam/fabric). Charring in this region was generated by a smoldering front propagating on the fabric and around uncharred foam. At this point ( $t = 70$  min), the temperature in all thermocouples increased rapidly possibly due to an increase in the foam-substrate gap (especially at the bottom corners of the vertical foam slab), that promoted natural convection.

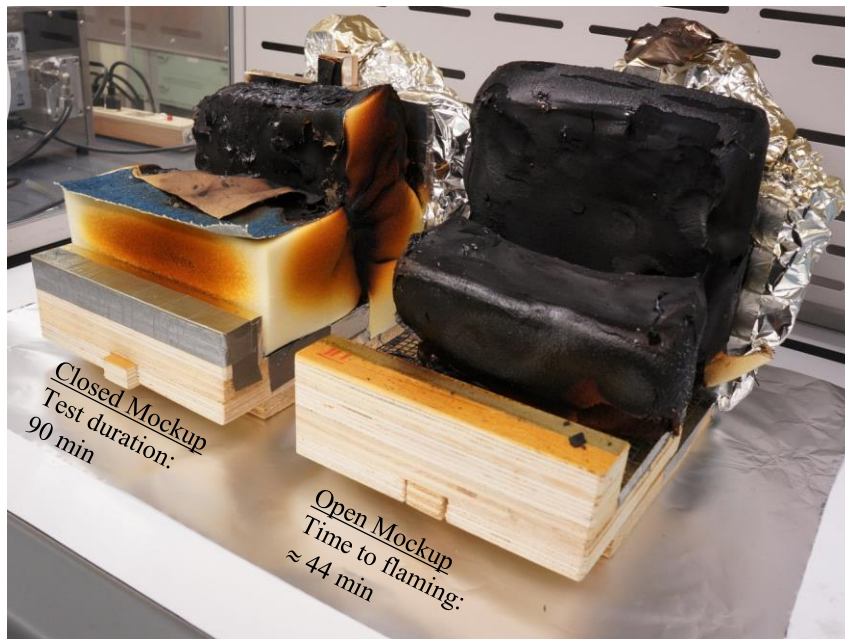


Figure 14. Photograph showing the residues for the foams tested in the open mockup (right) and closed mockup (left). The test duration was about 100 min in the closed mockup. In the open mockup, transition from smoldering to flaming occurred at about  $t = 44$  min.

### Smoldering in the NIST Box Test

The effect of natural convection on smoldering was also investigated with the NIST box test. Tests on the same type of foam were run with and without the box to evaluate the effect of the presence of the box on smoldering (Figure 6). The temperature of the electric heater, used as the smoldering ignition source, was set to 330 °C or 340 °C. Three tests were run per each combination of temperature and testing configuration (with or without box) for a total of 12 tests.

Figure 15 shows a comparison between the temperature profiles of the thermocouples with and without the box with the source set to 340 °C. A sample shows unambiguously self-sustained smoldering (SSS) in the box test if the temperature of at least one thermocouple is higher than the temperature of the heater (in blue) at any time during the test; in this scenario smoldering is not driven by the heater but is self-sustained by the heat generated in the foam by char oxidation.<sup>14</sup> According to this definition, without box, 100 % of the samples showed SSS, however, with a box, only 33 % and 66 % of the samples showed SSS at a heater set temperature of 330 °C and 340 °C, respectively. Independent of the heater temperature, 50 % of the total samples tested with the box demonstrated SSS behavior. The results are summarized in Table 3.

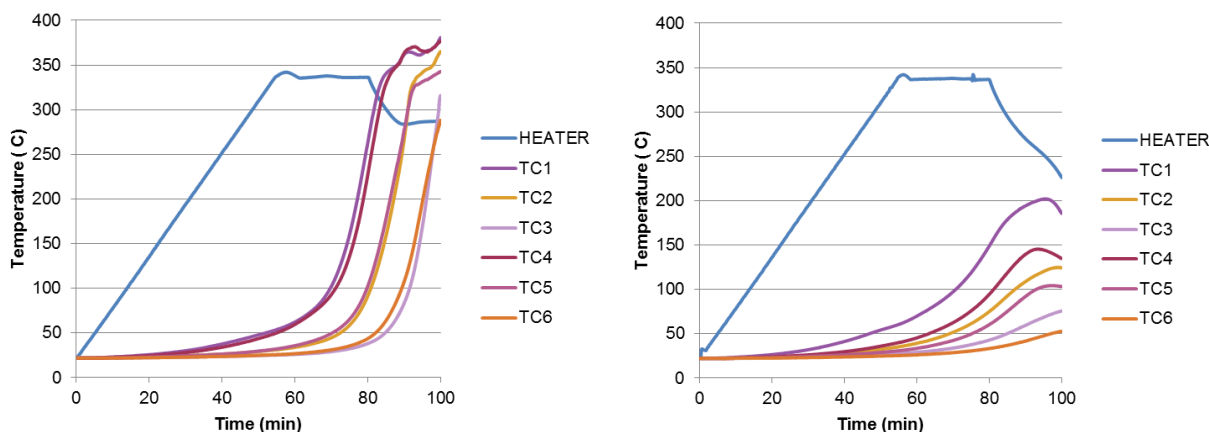


Figure 15. Comparison between the temperature profiles of the thermocouples in the box test without box (left) and with the box (right). A sample shows unambiguously sustained smoldering (left only) if the temperature of at least one thermocouple is higher than the temperature of the heater (in blue) at any time during the test.

Self-sustained and non-self-sustained smoldering samples showed an average mass loss value of  $(8.0 \pm 3.1) \%$  (9 tests) and  $(2.7 \pm 0.8) \%$  (3 tests), respectively; thus, when natural convection was suppressed by reducing the air permeability of the test apparatus, sustained smoldering was less likely to occur and the mass loss was significantly lower. As already mentioned, the air permeability of the foam had a similar effect on SSS in the mockup test.

Data in Table 3 suggest that the average mass loss at both 330 °C and 340 °C increases when the box is removed. This difference in mass loss increased with the heater temperature. More replicate tests are needed to verify that these differences in mass loss are significant (unknown uncertainty for smoldering mass loss in presence of the box).



Table 3. Mass loss, sustained smoldering and  $\Delta T_{av}/T_{av}$ .

Heater Temperature (°C)	Samples with Self-Sustained Smoldering (%)		Average Mass Loss in Samples with SSS (%)		$\Delta T_{av}/T_{av}$ in Samples with SSS	
	Without Box	With Box	Without Box	With Box	Without Box	With Box
340	100	66	12.0±1.3	6.8*	0.25±0.11	0.48*
330	100	33	7.3±2.8	4.2*	0.28±0.10	0.33*

\*Data with unknown uncertainty (less than three samples with SSS are available).

The asymmetry of the smoldering front can be used to evaluate the repeatability of the smoldering process in a specific scenario (*i.e.*, with or without box). The differences in temperature between the thermocouples at the same distance from the heater (TC1 and TC4, TC2 and TC5, TC3 and TC6) are used to evaluate the asymmetry of the smoldering front. In smoldering samples, the asymmetry of the smoldering front can be evaluated by the following expression:

$$\Delta T_{av}/T_{av} = \frac{\text{Abs}(T_{TC1}(t) - T_{TC4}(t)) / ((T_{TC1}(t) + T_{TC4}(t))/2) + \text{Abs}(T_{TC2}(t) - T_{TC5}(t)) / ((T_{TC2}(t) + T_{TC5}(t))/2) + \text{Abs}(T_{TC3}(t) - T_{TC6}(t)) / ((T_{TC3}(t) + T_{TC6}(t))/2)}{3}$$

where  $T_{TCi}(t)$  is the temperature of the generic thermocouple  $TC_i$  (with  $i$  integer between 1 and 6) at a generic time  $t$ . For a perfectly symmetric smoldering front  $\Delta T_{av}/T_{av} = 0$ .

At a heater temperature of 330 °C, the foam was barely smoldering in presence of the box and the test configuration had an insignificant effect on asymmetry of the smoldering front; however  $\Delta T_{av}/T_{av}$  increased by almost a factor of two at a heater temperature of 340 °C when the box was used. More replicate tests are necessary for calculating standard deviation values and confirm these preliminary data.

## Conclusions

We identified new commercial foams that have higher and more repeatable mass loss values as compared to SRM 1202 foam in the CPSC mockup test. These foams were standard polyether-based polyurethane foams post-processed with a reticulation procedure which removes residual membranes in the foam and provides high permeability foams with a homogeneous fully-open cell structure. This morphology is expected to increase the magnitude and repeatability of smoldering mass loss in the mockup test by promoting natural convection and suppressing air permeability variation in PUF.

The use of substrates impermeable to air prevents natural convection and generates instability in the smoldering front in the proximity of the substrate due to oxygen “starvation.” This effect is particularly important for thin foam samples rather than thicker foam samples, in which natural convection can efficiently supply oxygen to the smoldering front. In general, the higher the natural convection (controlled by foam thickness, foam air-permeability, substrate permeability

and fabric permeability) and the higher the smoldering rate, percentage of self-sustained smoldering samples and repeatability.

The aforementioned effect of foam thickness is also important, because it might explain the lack of correlation between bench-scale (*i.e.*, thin foam samples) performance and full-scale smoldering performance (*i.e.*, thick foams samples) whenever air-impermeable substrates are used. A better correlation might be achieved using a more realistic test configuration by the incorporation of air-permeable substrates in the test, allowing a uniform oxygen supply to the smoldering front through natural convection, ultimately producing a more intense and repeatable smoldering.

Here, the mockup test and the NIST box test have been modified to suppress the limiting effect on natural convection of the wood substrate, used as the sample holder. In the mockup test the wood substrate is replaced with a metal wire mesh and in the NIST box test the wood box is removed.

The findings from this research show that:

- the reticulated foams used here have a more repeatable smoldering behavior (3- to 4-fold reduction in relative standard deviation for mass loss) and a higher average mass loss (2- to 3-fold increase in mass loss) as compared to SRM 1202 foam;
- the use of a permeable substrate in the open mockup test induced roughly a 3-fold increase in smoldering mass loss;
- smoldering is more repeatable when a permeable substrate is used in the mockup test (the relative standard deviation for smoldering mass loss decreases by a factor of 3 to 4);
- the combination of a permeable substrate, an external enclosure and a reticulated foam promoted the transition from smoldering to flaming in the mockup test;
- in the NIST box test the percentage of self-sustained smoldering samples decreases from 100 % to 50 % when natural convection was limited by the wood substrate, used as sample holder;
- continuous real-time mass-loss and temperature monitoring appears to be a more meaningful, sensitive and robust approach for smoldering evaluation than a single mass loss calculation at an arbitrarily defined length of time.

These findings indicate the importance of natural convection on ignition, and the magnitude and repeatability of smoldering combustion. This information will be useful for the future development of bench-scale smoldering tests with an improved correlation of the rate of smoldering with full-scale smoldering tests using actual furniture.

## References

1. Davis R.D., Zammarano M., Matko S., Kraemer R.H. NIST TN 1775: Standard Operating Procedures for Smolder Ignition Testing of Upholstery Fabrics, National Institute of Standards and Technology Technical Note 1775, November 2012, 24 pgs. available at [http://www.nist.gov/manuscript-publication-search.cfm?pub\\_id=912584](http://www.nist.gov/manuscript-publication-search.cfm?pub_id=912584)
2. Proposed standard for the flammability of upholstered furniture, CPSC 1634, 73 FR 11702 (March 4, 2008).
3. Rogers F.E., Ohlemiller T.J., Kurtz A., and Summerfield M., Studies of the smoldering combustion of flexible polyurethane cushioning materials. *Journal of Fire and Flammability*, 1978, **9**, p. 5-13.
4. Dodd A.B., Lautenberger C., and Fernandez-Pello C., Computational modeling of smolder combustion and spontaneous transition to flaming. *Combustion and Flame*, 2012. **159**(1): p. 448-461.
5. Ortiz-Molina M.G., Toong T-Y., Moussa N.A., and Tesoro G.C., Smoldering combustion of flexible polyurethane foams and its transition to flaming or extinguishment. Symposium (International) on Combustion, 1979. **17**(1): p. 1191-1200.
6. Rein G., Lautenberger C., Fernandez-Pello A.C., Torero, J.L., and Urban, D.L., Application of genetic algorithms and thermogravimetry to determine the kinetics of polyurethane foam in smoldering combustion. *Combustion and Flame*, 2006. **146**(1-2): p. 95-108.
7. Torero J.L. and Fernandez-Pello A.C., Forward smolder of polyurethane foam in a forced air flow. *Combustion and Flame*, 1996. **106**(1-2): p. 89-109.
8. Rein G., Smoldering combustion phenomena in science and technology. *International Review of Chemical Engineering*, 2009, p. 3-18.
9. Torero J.L., Fernandez-Pello A.C., Natural Convection Smolder of Polyurethane Foam, Upward Propagation, *Fire Safety Journal*, 1995, 24, 35-52.
10. Bar-Ilan A., Rein G., Walther D.C., Fernandez-Pello A.C., The Effect of Buoyancy on Opposed Smoldering, *Combust. Sci. and Tech*, 2004, 176 2027-2055.
11. Zammarano M., Matko S., Kraemer R.H., Davis R.D., Gilman J.W., Mehta S.N. NIST TN 1747: Factors Influencing the Smoldering Performance of Polyurethane Foam, National Institute of Standards and Technology Technical Note 1747, July 2012, 89 pgs. available at <http://dx.doi.org/10.6028/NIST.TN.1747>
12. Zammarano M., Matko S., Kraemer R.H., Davis R.D., Gilman J.W., Sung Li Piin, Fox D.M., Mehta S.N., Smoldering in Flexible Polyurethane Foams: The Effect of Foam Morphology, in *Fire and Polymers VI: New Advances in Flame Retardant Chemistry and Science* Chapter 29, pp 459–479, ACS Symposium Series, Vol. 1118, December 18, 2012, American Chemical Society.
13. 16 CFR Part 1634, Upholstered Furniture Fire Safety Technology Meeting and Request for Comments (March 1 2013), available at <http://www.cpsc.gov/Global/Newsroom/FOIA/CommissionBriefingPackages/2013/upholstmeetF R.pdf>
14. Chai C. Y. H., Wang J. H., Transition from Smoldering to Flaming Combustion of Horizontally Oriented Flexible Polyurethane Foam with Natural Convection, *Combustion and Flame* 127, 2001, p. 2252-2264.