

## Fire Performance Synergies of Metal Hydroxides and Metal Molybdates in Antimony-Free Flexible PVC

Ken Walker<sup>(1)</sup>, Alex Isarov<sup>(2)</sup>, Tong Chen<sup>(2)</sup>

<sup>(1)</sup> The Sherwin-Williams Company, <sup>(2)</sup> J. M. Huber Corporation

### 1. Introduction

Viability of continued use of antimony oxide is among the topics of broad interest to PVC compound suppliers as well as their end users. Existing and emerging regulatory mandates have continued to drive an industry-wide effort to minimize use of antimony oxide in PVC, while being able to maintain adequate fire performance when formulating the low-smoke compounds for a variety of applications such as construction materials and wire and cable products.

Metal hydroxides such as aluminum hydroxide (ATH) and magnesium hydroxide (MDH) are among several alternative “green” fire retardants used to reformulate fire-rated PVC compounds in order to be regulatory compliant. ATH and more recently MDH are widely used to achieve low-smoke flame retardant compounds. Both ATH and MDH function as a flame retardant by decomposing endothermically into water and metal oxide upon heating. The released water vapor, in an amount of about a third of total metal hydroxide used, dilutes the combustible ambience while removing the combustion heat. The oxide by-product formed from the hydroxide decomposition chars on the surface of polymeric materials to prevent heat and oxygen from approaching the polymer.

Molybdate based additives are also used in PVC to both lower smoke generation during combustion and to improve overall FR properties. Molybdates are known to chemically influence the formation of organic char, which effectively removes fuel from the gas phase and thereby lowers smoke and heat release.  $\text{MoO}_3$  has been shown to react with the HCl produced by the pyrolysis of PVC to form  $\text{MoO}_2\text{Cl}_2$ , a potent Lewis acid. This can then promote crosslinking in a number of ways. One likely mechanism is the Friedel-Crafts alkylation of alkene linkages that are formed during PVC thermolysis [1-3].

Kemgard® structured metal molybdates are common smoke suppressants used to achieve low-smoke standards. Kemgard® products utilize a patented process in which molybdates are precipitated on an inert mineral core. This “coated core” approach makes more efficient use of the molybdate species by maximizing the active surface area, and at much lower cost than pure molybdate chemicals.

This paper discusses the results from a recent study on the synergistic use of metal hydroxides and metal molybdates to enable the low-smoke performance for select flexible PVC compositions. Efforts were made to compare the overall FR performance characteristics between an antimony oxide-free compound system and the systems that contain varying amount of antimony oxide. We also examined the interactions between metal hydroxides (both ATH and MDH) and metal molybdates both in presence or absence of the antimony oxide. The performance synergy between a hydroxide and a molybdate was closely investigated in two PVC compositions that are of commercial interest in terms of the type of the plasticizer used. The inclusion of zinc borate for added FR benefits was also explored.

## 2. Experimental

### Materials

**Table 1. Fire retardant ingredients used in this study**

Fire Retardant Ingredients	Grade name	Type	Particle Size (microns)	Surface Area (m <sup>2</sup> /g)
ATH	Micral® 9400	Precipitated	1	4
MDH	Vertex® 100	Synthetic	1	14
Molybdate	Kemgard® HPSS	Synthetic	3	n/a
Zinc Borate	Firebrake® ZB Fine	----	2	n/a
Antimony Oxide	Generic grade	n/a	n/a	n/a

Vertex®, Micral® and Kemgard® are trademarks of J. M. Huber Corporation. Firebrake® is a trademark of RioTinto Minerals.

Micral 9400 and Vertex 100 are fine particle size metal hydroxide materials, which are widely used in flexible PVC formulations as flame retardants and smoke suppressants.

Kemgard HPSS is a basic zinc molybdate/MDH complex manufactured by J.M. Huber Corporation. Kemgard smoke suppressants are produced by a proprietary process that results in a high surface area molybdate precipitated onto an inorganic core. These materials have long been used in both flexible and rigid PVC systems.

### **Test compound formulas, compounding and fire property testing**

PVC compound formulas representative of the commercial applications were used in this study. PVC masterbatch mixes were first made in a high-speed Henschel mixer to incorporate all but flame retardant additives. PVC masterbatch formulations are presented in Table 2.

The fully formulated compounds were then prepared in a Brabender mixer at about 135°C for 5 minutes by adding the FR ingredients to the masterbatch followed by two-roll milling of the compound mixture to ensure compound homogeneity. The test specimens were compression-molded and die-cut per pertinent ASTM.

**Table 2. Flexible PVC masterbatch used in this study**

Ingredient	Formula 1 (phr)	Formula 2 (phr)
PVC resin (K70)	100	100
Plasticizer - DINP	34	---
Plasticizer - DTDP	10	---
Plasticizer - TOTM	---	44
Ca/Zn Stearate	5	5
Stearic Acid	0.3	0.3

All material testing were performed according to following ASTM procedures,

- ASTM E1354: Cone Calorimeter, 25 kW/m<sup>2</sup> and 50 kW/m<sup>2</sup>
- ASTM E662: NBS Smoke Chamber, flaming and non-flaming as indicated
- ASTM D2863: Limiting Oxygen Index (LOI)

### 3. Results and Discussion

#### 3.1. Partial replacement of antimony oxide with Kemgard HPSS in flexible PVC formulations.

Table 3 shows NBS smoke results for four flexible PVC compounds made with TOTM plasticizer. The first compound denoted as 3-1, containing 50 phr of ATH, 20 phr of MDH and 4 phr of antimony oxide, is based on a known wire and cable formula. The data from the second and third formulas (3-2 and 3-3) show that replacing antimony oxide with Kemgard HPSS significantly lowers the maximum smoke density, and that the reduction improves with loading up to 10 phr. Replacement of 4 phr of antimony oxide with 5 phr of Kemgard HPSS does result in an LOI decreases from 42 to 36. However, increasing the Kemgard to 10 phr limits the LOI loss from 6 units to 4 units.

**Table 3. Effect of antimony oxide replacement with Kemgard HPSS in formulations containing ATH and MDH (Formula 2 – plasticizer TOTM)**

FR Ingredients	3-1	3-2	3-3	3-4
ATH	50.0	50.0	50.0	49.0
MDH	20.0	20.0	20.0	19.0
Antimony Oxide	4.0	0.0	0.0	2.0
KG HPSS	0	5	10	5
<b>NBS Flaming Mode</b>				
D 90 Seconds	23	28	38	31
D 4 Minute	95	97	81	118
D max	210	162	106	178
<b>LOI</b>	42	36	38	40

In the formula 3-4, it seems apparent that some antimony oxide is required to maintain equivalent FR performance. A combination of 2 phr of antimony oxide with 5 phr of Kemgard HPSS increases the LOI to 40, while maintaining a smoke level below that of the control.

**Table 4. Effect of antimony oxide replacement with Kemgard HPSS in formulations containing ATH only (Formula 2 – plasticizer TOTM)**

FR Ingredients	4-1	4-2	4-3
ATH	50.0	70	68
MDH	20.0	0	0
Antimony Oxide	4.0	0.0	2.0
KG HPSS	0	5	5
<b>NBS Flaming Mode</b>			
D 90 Seconds	23	35	27
D 4 Minute	95	104	110
D max	210	198	169
<b>LOI</b>	42	38	40

Table 4 shows results from a similar set of experiments in which the experimental samples contain only ATH as the metal hydroxide (MDH free). Overall, the performance of the experimental samples were very comparable to those of the mixed metal hydroxide system in Table 3. This indicates that in these formulas containing Kemgard HPSS, MDH may be replaced with the lower cost ATH without sacrificing smoke or LOI performance.

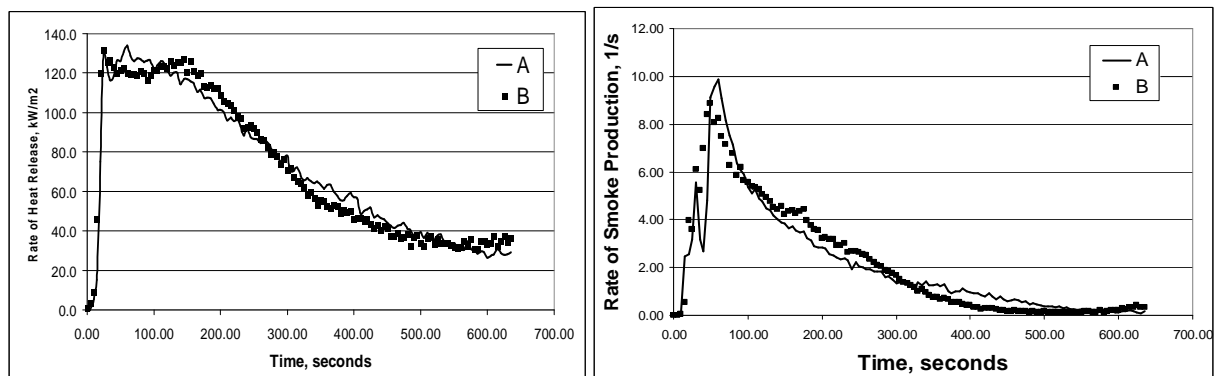
Table 5 shows cone calorimeter results for the control formula containing 4 phr of antimony oxide (5-1) and a formulation containing ATH, Kemgard HPSS and just 2phr antimony oxide (compound 5-2 identical to 4-3). In this example the Peak Rate of Heat Release for both samples were identical. Other cone data (time to ignition, total heat release, effective heat of combustion, etc.) were very comparable as well. At lower hear flux, 25 kW/m<sup>2</sup>, the Kemgard containing formula actually outperforms the control. Reducing antimony oxide from 4 phr to 2 phr and adding 5 phr of Kemgard HPSS lowers the Peak Heat Release Rate from 87 to 80, at the same time also lowering the smoke. Heat Release and Smoke Generation data from the cone calorimeter experiments are shown in Figures 1-1 and 1-2.

**Table 5. Effect of partial antimony oxide replacement with Kemgard HPSS in formulations containing ATH only – cone calorimeter data (Formula 2 – plasticizer TOTM)**

<b>FR Ingredients</b>	<b>5-1</b>	<b>5-2</b>
ATH	50	68
MDH	20	0
Antimony Oxide	4	2
KG HPSS	0	5
<b><u>Cone at 50 kW</u></b>		
Time to Sustained Ignition, seconds	39	34
Peak Rate of Heat Release, kW/m <sup>2</sup>	134	134
Total Heat Released, MJ/m <sup>2</sup>	51	50
Effective Heat of Combustion, MJ/kg	14	15
SEA, m <sup>2</sup> /kg	370	410
<b><u>Cone at 25 kW</u></b>		
Time to Sustained Ignition, seconds	168	144
Peak Rate of Heat Release, kW/m <sup>2</sup>	87	80
Total Heat Released, MJ/m <sup>2</sup>	27	28
Effective Heat of Combustion, MJ/kg	11	11
SEA, m <sup>2</sup> /kg	249	240

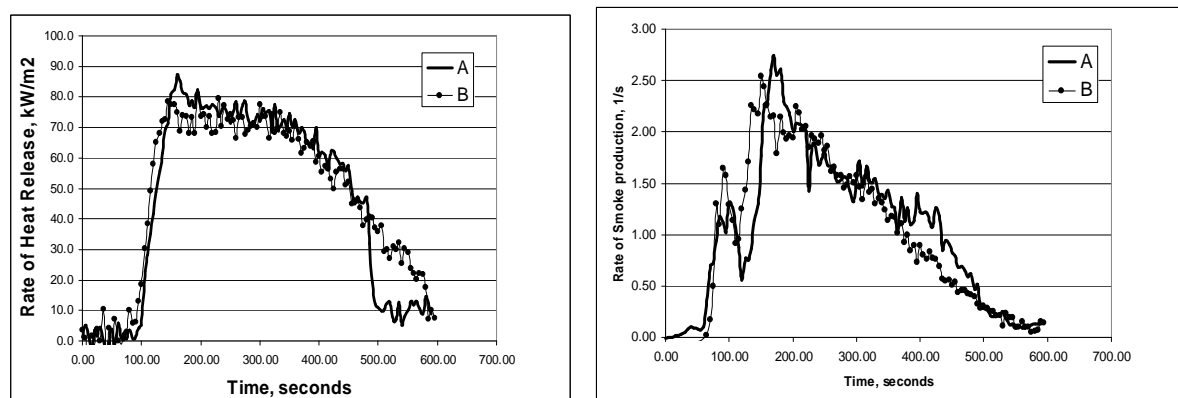
### **3.2. Smoke Suppression Efficiency of ATH and ATH/MDH blends – Effect of Partial Replacement with Kemgard HPSS.**

Table 6 shows comparison of FR properties of three test formulations containing metal hydroxides only, no Kemgard HPSS present (compound 6-1 is a control). One can see that replacement of 4 phr of antimony oxide with 5 phr of metal hydroxide leads to noticeable deterioration of some FR properties of PVC compound, such as 4 min smoke density (non flaming mode), LOI, as well as time to sustained ignition and peak rate of heat release measured by cone calorimeter. It is well known that presence of antimony oxide in PVC formulation significantly reduces flammability of the compound. Partial or complete replacement of antimony oxide with metal hydroxide without negative effect on compound flammability is possible, but it requires higher antimony to hydroxide ratio, such as 5:1 or higher [4].



**Figure 1-1. Cone calorimeter data - heat flux 50 kW/m<sup>2</sup>. Effect of partial replacement of metal hydroxide with Kemgard HPSS on rate of heat release and rate of smoke generation. (Formula 2, plasticizer TOTM)**

**A - ATH – 50 phr, MDH – 20 phr, Sb<sub>2</sub>O<sub>3</sub> – 4 phr  
 B - ATH – 68 phr, KG HPSS – 5 phr, Sb<sub>2</sub>O<sub>3</sub> – 2 phr**



**Figure 1-2. Cone calorimeter data - heat flux 25 kW/m<sup>2</sup>. Effect of partial replacement of metal hydroxide with Kemgard HPSS on rate of heat release and rate of smoke generation. (Formula 2, plasticizer TOTM)**

**A - ATH – 50 phr, MDH – 20 phr, Sb<sub>2</sub>O<sub>3</sub> – 4 phr  
 B - ATH – 68 phr, KG HPSS – 5 phr, Sb<sub>2</sub>O<sub>3</sub> – 2 phr**

At the same time, replacement of 4 phr of antimony oxide with 5 phr of metal hydroxide leads to significant reduction of NBS smoke density measured in flaming mode (6-4). In this case, flammability of the compound is not very important because it is ignited by external flame source.

Comparison of compounds containing ATH only, MDH only and both ATH and MDH (see Table 6) shows that there is some FR synergy between ATH and MDH in flexible PVC. This synergy manifests itself in lower maximum smoke density (non-flaming mode) and lower peak rate of heat release (Figure 2). Additionally, compound containing both ATH and MDH has lower peak rate of smoke generation (Figure 2).

**Table 6. FR properties comparison for ATH and MDH in Formula 1 (Plasticizers DINP + DTDP)**

<b>FR Ingredient</b>	<b>6-1</b>	<b>6-2</b>	<b>6-3</b>	<b>6-4</b>
ATH	50	75	0	38
MDH	20	0	75	38
Antimony Oxide	4	0	0	0
<b><u>NBS – Non Flaming Mode</u></b>				
Ds @ 4 min	63	92	87	92
Ds max	337	306	327	285
<b><u>NBS - Flaming Mode</u></b>				
Ds @ 4 min	212	n/a	n/a	108
Ds max	367	n/a	n/a	175
<b><u>Cone calorimeter - 50 kW</u></b>				
Time to Sustained Ignition, seconds	35	25	29	26
Peak Rate of Heat Release, kW/m <sup>2</sup>	161	203	245	195
Total Heat Released, MJ/m <sup>2</sup>	49	50	49	52
Effective Heat of Combustion, MJ/kg	14	16	16	16
SEA, m <sup>2</sup> /kg	443	566	676	549
<b>LOI</b>	<b>42</b>	<b>34</b>	<b>33</b>	<b>32</b>

The ATH-MDH synergy can probably be explained by difference in their FR action in PVC [5,6]. ATH decomposition temperature is lower than that of PVC dehydrochlorination and therefore ATH FR mechanism is based mostly on cooling the polymer via endothermic decomposition. In contrast, MDH decomposition temperature is higher compared to that of PVC dehydrochlorination and MDH may react with hydrogen chloride interfering with autocatalytic dehydrochlorination process and therefore with char formation.

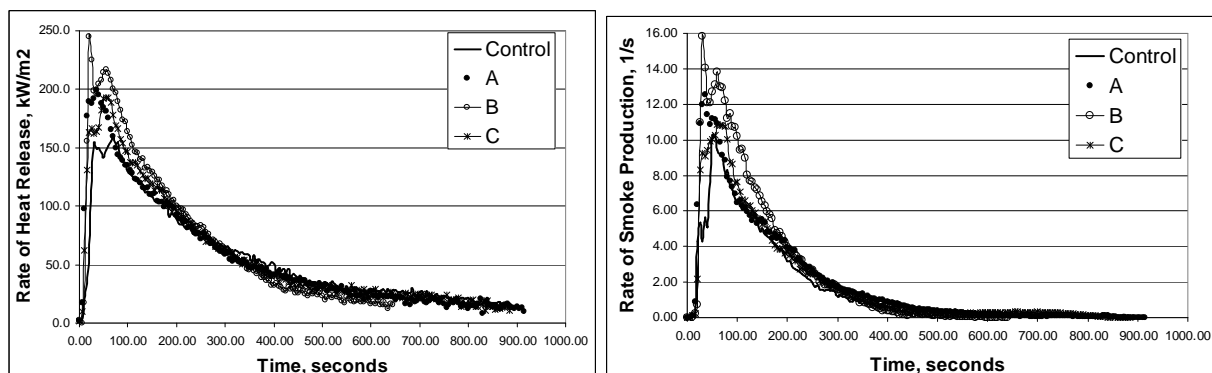
In earlier work [4] no FR synergy between ATH and MDH was observed in flexible PVC formulation containing ground calcium carbonate. Both MDH and calcium carbonate have decomposition temperatures higher than the temperature of PVC dehydrochlorination [5, 6] and both are capable of reacting with HCl thus interfering with PVC decomposition process. This is probably why ATH/MDH synergy is difficult to observe in the formulations containing calcium carbonate.

Data presented in Table 7 shows effect of partial replacement of metal hydroxides with Kemgard HPSS in a flexible PVC formulation.

If starting formulation contains only ATH (compound 7-1), replacement of 5 phr of ATH with 5 phr of Kemgard HPSS leads to significant improvement of FR properties (compound 7-3). Kemgard HPSS lowers NBS smoke density (non flaming mode), peak rate of heat release and increases LOI by two units.

Cone calorimeter charts for samples containing 75 phr ATH and 70 phr ATH + 5 phr Kemgard HPSS (compounds 7-1 and 7-3) are presented on Figure 3. One can see that presence of Kemgard HPSS reduces peak rate of heat release and peak rate of smoke production. Simultaneously, both peaks are delayed. This effect can probably be explained by better char formation on the surface of polymer in the presence of zinc molybdate.

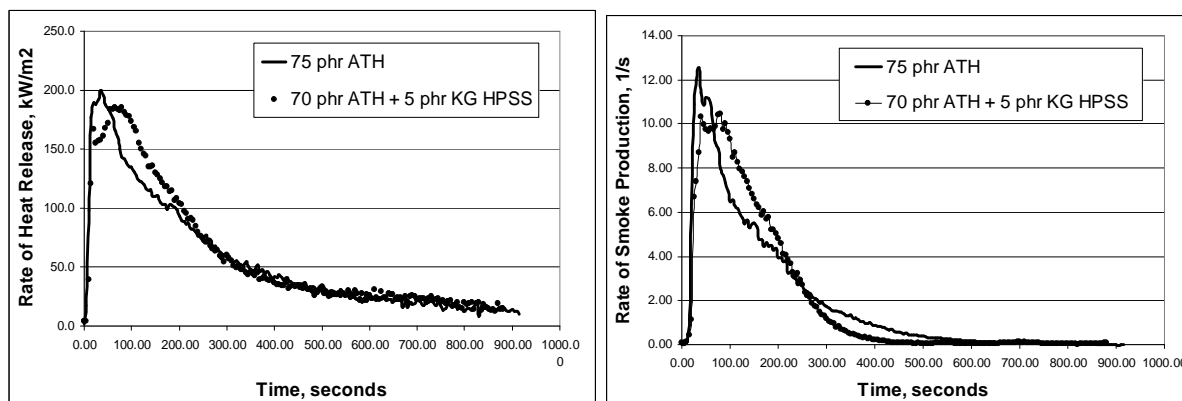
At the same time, if a starting formulation contains both ATH and MDH (compound 7-2), replacement of 5 phr of metal hydroxide with 5 phr of Kemgard HPSS (compound 7-4) has less effect on FR properties.



**Figure 2. Cone calorimeter data: Effect of metal hydroxide on rate of heat release and rate of smoke generation.** Control - (ATH – 50 phr, MDH – 20 phr, Sb<sub>2</sub>O<sub>3</sub> – 4 phr)  
 A - sample 1 (ATH – 75 phr)  
 B - sample 2 (MDH – 75 phr)  
 C - sample 3 (ATH – 37.5 phr, MDH – 37.5 phr)

**Table 7. Effect of partial replacement of metal hydroxide with Kemgard HPSS on FR properties of flexible PVC in Formula 1 (Plasticizers DINP + DTDP)**

Compound ID	7-1	7-2	7-3	7-4
<u>FR Ingredient</u>				
ATH	75	38	70	35
MDH	0	38	0	35
KG HPSS	0	0	5	5
<b><u>NBS - Non Flaming Mode</u></b>				
Ds @ 4 min	92	92	75	80
Ds max	306	285	224	343
<b><u>NBS - Flaming Mode</u></b>				
Ds @ 4 min	n/a	108	126	n/a
Ds max	n/a	175	170	n/a
<b><u>Cone calorimeter - 50 kW</u></b>				
Time to Sustained Ignition, seconds	25	26	27	29
Peak Rate of Heat Release, kW/m <sup>2</sup>	203	195	186	199
Total Heat Released, MJ/m <sup>2</sup>	50	52	52	51
Effective Heat of Combustion, MJ/kg	16	16	16	16
SEA, m <sup>2</sup> /kg	566	549	533	565
<b>LOI</b>	34	32	36	36



**Figure 3. Cone calorimeter data: Effect of partial replacement of ATH with Kemgard HPSS on rate of heat release and rate of smoke generation. (Formula 1, plasticizers DINP and DTDP)**

Presence of MDH in flexible PVC formulation appears to reduce char forming and smoke suppression efficacy of zinc molybdate based Kemgard HPSS. In fact, partial replacement of ATH/MDH blend leads to higher NBS smoke density in non-flaming mode (compound 7-4). This finding is consistent with data we reported earlier [6].

### **3.3. Effect of Zn Borate on FR properties of flexible PVC compound containing metal hydroxides and Kemgard HPSS.**

In addition to molybdates, zinc borate is often added to PVC compounds to promote char formation and reduce afterglow. While molybdates promote organic char via a reductive coupling mechanism, borates are believed to promote an inorganic char because of the vitreous nature of borates. Because of this, we also evaluated zinc borate as a co-additive with Kemgard HPSS. Table 8 shows NBS smoke and cone calorimeter results for 4 samples from this study. The control (8-1) contains 75 phr ATH as the only flame retardant additive. Replacing 5 phr ATH with 5 phr Kemgard HPSS dramatically improves FR properties (8-2). Peak Heat Release Rate is lowered from 203 to 186, while the LOI increases from 34 to 36. NBS smoke (Non-flaming mode) is also lowered. This clearly demonstrates the FR and smoke suppressant effectiveness of Kemgard HPSS. Addition of 3 phr of zinc borate may have actually diminished FR performance. The LOI was lowered from 36 to 34 and the Peak Rate of Heat Release not improved. Smoke in both the cone and NBS smoke chamber (flaming mode) were increased. The fourth compound shown in Table 8 (8-4) doubled the level of Kemgard HPSS while maintaining 3 phr zinc borate. This change further diminished FR performance (increased Peak Rate of Heat Release). It also caused an increase in maximum smoke density in the NBS smoke (flaming mode) although the 4 minute smoke was decreased. These results suggest that addition of zinc borate to the current set of formulations provides little benefit and may actually diminish FR performance. It is well known that high levels of zinc additives in PVC can actually reduce FR and increase smoke by “char cracking”. This process may be responsible for loss of FR properties for compound 8-4 (Table 8).

### **3.4. Plasticizer effect: TOTM vs. DINP/DTDP**

Two plasticizer systems were used in this study. One system was a combination of DINP (di-isononyl phthalate) and DTDP (ditridecyl phthalate), another was TOTM (tri-2-ethylhexyl trimellitate). The total amount of the plasticizers was kept constant, i.e., 44 PHR, in both cases.



**Table 8 Effect of zinc borate on FR performance of flexible PVC containing combination of metal hydroxides and Kemgard HPSS (plasticizers DINP and DTDP)**

<b>FR Ingredient</b>	<b>8-1</b>	<b>8-2</b>	<b>8-3</b>	<b>8-4</b>
ATH	75	70	68	64
MDH	0	0		
KG HPSS	0	5	4	8
Zinc Borate	0		3	3
<b><u>NBS - Non Flaming Mode</u></b>				
Ds @ 4 min	92	75	83	83
Ds max	306	224	225	231
<b><u>NBS - Flaming Mode</u></b>				
Ds @ 4 min	n/a	126	160	138
Ds max	n/a	170	189	234
<b><u>Cone calorimeter - 50 kW</u></b>				
Time to Sustained Ignition, seconds	25	27	28	27
Peak Rate of Heat Release, kW/m <sup>2</sup>	203	186	188	208
Total Heat Released, MJ/m <sup>2</sup>	50	52	51	49
Effective Heat of Combustion, MJ/kg	16	16	16	16
SEA, m <sup>2</sup> /kg	566	533	584	573
<b>LOI</b>	34	36	34	35

The DINP/DTDP combination is reportedly suitable for use in such PVC applications as flooring, profile extrusion or sheeting, building/automotive wire or low-voltage cable. On the other hand, TOTM is more suitable for communications cable insulation compounds as well as automotive interior. Since the type of application determines the FR performance requirements, an effort was made to investigate the effect of the molybdate on the FR characteristics of the compound that contained each of the two plasticizer systems.

Table 9 compares the DINP/DTDP vs. TOTM in the absence of the molybdate, but containing antimony oxide as an FR synergist. It is evident that TOTM helps make the compound more fire retardant than the DINP/DTDP combination, as indicated by significant differences in heat release and smoke density measurements. In industrial practices, it is common that plasticizer selection often affects the compound formulation such that one is able to optimize the performance/cost by minimizing use of plasticizer and flame retardants.

Table 10 compares the two plasticizer systems in the presence of the Kemgard molybdate but without antimony oxide. The results show that, use of the Kemgard HPSS is able to retain the FR robustness enabled by TOTM for an antimony-free PVC composition. However, unlike the case of antimony-containing system as shown in Table 9, when Kemgard HPSS was used to completely displace antimony, the smoke density measured by NBS smoke chamber showed only marginal difference between the two plasticizers.

**Table 9. Comparison of plasticizers – no Kemgard but with antimony**

<b>FR ingredients</b>	<b>9-1</b>	<b>9-2</b>
ATH	50.0	50.0
MDH	20.0	20.0
<b>DINP</b>	<b>34.0</b>	
<b>DTDP</b>	<b>10.0</b>	
<b>TOTM</b>		<b>44</b>
Antimony Oxide	4.0	4.0
KG HPSS	0	0
<b><u>NBS - Flaming mode</u></b>		
Ds @ 4 min	212	95
Dmax	367	210
<b><u>Cone calorimeter @ 50kW</u></b>		
Time to Sustained Ignition, seconds	35	38.6
Peak Rate of Heat Release, kW/m <sup>2</sup>	161	133
Time of Peak RHR, seconds	75	60
SEA, m <sup>2</sup> /kg	443	370
Time of Peak SEA, seconds	22.5	40
<b>LOI</b>	<b>42</b>	<b>42</b>

**Table 10. Comparison of plasticizers – with Kemgard but no antimony**

<b>FR ingredients</b>	<b>10-1</b>	<b>10-2</b>
ATH	70.0	70.0
<b>DINP</b>	<b>34.0</b>	
<b>DTDP</b>	<b>10.0</b>	
<b>TOTM</b>		<b>44</b>
KG HPSS	5	5
<b><u>NBS - Flaming mode</u></b>		
Ds @ 4 min	126	104
D max	170	198
<b><u>Cone calorimeter @ 50kW</u></b>		
Time to Sustained Ignition, seconds	27	37.4
Peak Rate of Heat Release, kW/m <sup>2</sup>	186	156
Time of Peak RHR, seconds	70	82
SEA, m <sup>2</sup> /kg	533	396
Time of Peak SEA, seconds	25	52
<b>LOI</b>	<b>36</b>	<b>38</b>

## 4. Conclusions

1. Replacement of antimony oxide with Kemgard HPSS in flexible PVC formulation containing metal hydroxides significantly reduces maximum smoke density (NBS – flaming mode), but at the same time diminishes LOI. Increase in Kemgard HPSS loading level can limit LOI loss.
2. Partial replacement of antimony oxide with Kemgard HPSS in flexible PVC formulation containing metal hydroxides is possible with minimum or no loss of FR properties.
3. In the absence of MDH, partial replacement of an ATH with Kemgard HPSS leads to significant improvement of FR properties indicating FR synergy between the two materials. No similar synergy was observed between ATH/MDH blend and Kemgard HPSS.
4. Addition of zinc borate to flexible PVC formulations containing metal hydroxides and Kemgard HPSS does not improve FR properties.
5. TOTM enhances PVC compound FR robustness when compared to the DINP/DTDP combination. This offers a means to potentially reducing the total FR use for the TOTM plasticized systems.
6. Using Kemgard HPSS to replace antimony oxide can sustain the differentiated FR characteristics that results from use of TOTM.

## Acknowledgements

The authors wish to thank Mr. David Temples and Mr. Jonathan Parker of J.M. Huber Corporation for their fine laboratory support of this work.

## References

1. W.H. Starnes, Jr., R.D. Pike, J.R. Cole, A.S. Doyal, E.J. Kimlin, J.T. Lee, P.J.Murray, R.A. Quinlan and J. Zhang, "Cone Calorimetric Study of Copper-Promoted Smoke Suppression and Fire Retardancy of Poly(vinyl chloride): Recent Progress", Proceedings, Additives 2004 Conference.
2. W.H. Starnes Jr. and E. Edelson, *Macromolecules* 12(5) 797-802 (1979)
3. W.H. Starnes Jr., "Mechanism of Polyvinyl Chloride Flame Retardance by Molybdenum (VI) Oxide" in Polymer Additives, J.E. Kresta (ed) Plenum Press, New York (1984).
4. T. Chen, "Low-smoke Flexible PVC Compounds via Metal Hydroxide as Flame Retardants", SPE Vinyltec 2006 Proceedings, Atlanta, Georgia
5. Chen, T. and Isarov, A. New Magnesium Hydroxides Enabling Low-Smoke Cable Compounds. Proceedings of the 56<sup>th</sup> IWCS Conference, Lake Buena Vista, FL 2007.
6. Walker, J.K., Luke, E., Chen, T., Ivarov, A.: Synergies of Metal Hydroxides and Metal Molybdates in Low-Smoke Flexible PVC. Proceedings of the 57<sup>th</sup> IWCS Conference, Providence, RI 2008.

## Authors

**Ken Walker** is a staff scientist with the Sherwin-Williams Co. He graduated from Boston University in 1980 with a Ph.D. in physical chemistry and has 30 years of industrial research experience with both Diamond Shamrock Corp and Sherwin-Williams. From 1999 – 2010, Ken directed the R&D effort for the Kemgard product line at Sherwin-Williams.

**Alex Isarov** is a Technology Manager for Surface Chemistry at Engineered Materials Division of J. M. Huber Corporation. He received Ph.D. degree in Chemistry (1991) from the Institute of Surface Chemistry (Kiev, Ukraine), and completed a Postdoctoral Fellowship at the University of Toledo, Ohio. Currently Alex is involved in development of metal hydroxide based flame retardants for polymer applications.

**Tong Chen** is Director of Technology with Huber Engineered Materials Division of J. M. Huber Corporation. He is responsible for development of new metal hydroxide flame retardant products and related industrial application technologies. He received his Doctor of Science degree in chemical engineering/polymer materials science from MIT, MS in applied chemistry and BS in chemical engineering from Tianjin University, China.