



## Thermal Decomposition of Styrenic Polymers Modified with Covalently Bound P- and N-containing Groups: Analysis of the Gaseous-Phase Mechanism

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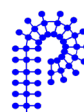
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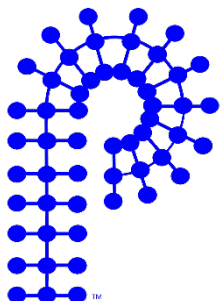
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Fire and Polymers

June 5-8, 2022

Embassy Suites By Hilton Napa Valley

Napa, CA

## Sunday, June 5, 2022

### ARRIVAL AND REGISTRATION

2:30 PM REGISTRATION BEGINS

LECTURE SESSION I	
Session Chair: Jamie Grunlan, Texas A&M University	
3:15 PM	OPENING REMARKS
3:30 PM	<b>Alexander Morgan</b> , University of Dayton Research Institute <i>Studying Smoldering to Flaming Transition in Polyurethane Furniture Sub-Assemblies: Effects of Fabrics, Flame Retardants, and Material Type</i> <b>1</b>
4:00 PM	<b>Mauro Zammarano</b> , NIST <i>Fire Barrier Fabrics in Upholstered Furniture: An Obvious Solution to One of the Most Enduring Problems in Fire Safety</i> <b>2</b>
4:30 PM	BREAK
4:45 PM	<b>Isaac T. Leventon</b> , NIST <i>The NIST Material Flammability Database: Experimental Measurements for Fire Model Calibration and Validation</i> <b>3</b>
5:15 PM	<b>Morgan C. Bruns</b> , St. Mary's University <i>Development of Automated Calibration Tools for Determining Fire Model Input Parameters</i> <b>4</b>
5:45 PM	<b>Natallia Safronava</b> , Federal Aviation Administration <i>Microscale Combustion Calorimetry and Material Change Similarity</i> <b>5</b>
6:15 PM	WELCOME RECEPTION

## Monday, June 6, 2022

7:00 AM BREAKFAST | 7AM – 10 AM IN THE HOTEL'S ATRIUM

LECTURE SESSION II	
Session Chair: Alexander Morgan, University of Dayton Research Institute	
8:30 AM	<b>Anteneh Worku</b> , Pinfa North America <i>The Road to Flame Retardant Commercialization</i> <b>6</b>
9:00 AM	<b>Sabyasachi Gaan</b> , EMPA, Switzerland <i>Hybrid Strategies for Improving the Fire Performance of Epoxy Resin Cured With Aliphatic Hardener</i> <b>7</b>
9:30 AM	<b>Svetlana Tretsiakova-McNally</b> , Ulster University, UK <i>Thermal Decomposition of Styrenic Polymers Modified with Covalently Bound P- and N-containing Groups: Analysis of the Gaseous-Phase Mechanism</i> <b>8</b>



## Monday, June 6, 2022, cont'd

10:00 AM	BREAK	
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10:45 AM	<b>Sabine Fuchs</b> , Hamm-Lippstadt University of Applied Science, Germany <i>Halogen-Free Styrene Copolymers With Intrinsic Flame Retardant Properties</i>	10
11:15 AM	<b>Jacques A. De Beer</b> , University of Maryland <i>Milligram-scale Flame Calorimetry: Development of a Pyrolyzer System used for Accurate Emulation of the Burning Behavior of Non-thermally Thin Samples</i>	11
11:45 AM	END AM SESSION, LUNCH ON YOUR OWN	
<b>LECTURE SESSION III</b>		
<b>Session Chair: Mauro Zammarano, National Institute of Standards and Technology</b>		
4:00 PM	<b>Ramaswamy Nagarajan</b> , University of Massachusetts Lowell <i>Surface functionalization Strategies for Fire Retardant Nylon, Cotton and, Nyco</i>	12
4:30 PM	<b>Bernhard Scharfel</b> , BAM Federal Institute for Materials Research and Testing, Germany <i>Non-vegan Flame-Retardant (Adjuvants in) Biocomposites</i>	13
5:00 PM	<b>Helge-Otto Fabritius</b> , Hamm-Lippstadt University of Applied Sciences, Germany <i>Mechanistic Investigations of Wasp Nest Papers: Towards Environmentally Compatible Flame-Retardant Concepts for Synthetic Materials</i>	14
5:30 PM	END DAILY LECTURES	
6:00 PM	POSTER SESSION END DAILY SESSIONS	

## Tuesday, June 7, 2022

7:00 AM	BREAKFAST   7AM – 10 AM IN THE HOTEL'S ATRIUM	
<b>LECTURE SESSION IV</b>		
<b>Session Chair: Sabyasachi Gaan, EMPA, Switzerland</b>		
8:30 AM	<b>Serge Bourbigot</b> , University of Lille, France <i>Recent Advances in Designing Fire Barriers</i>	15
9:00 AM	<b>Jaime Grunlan</b> , Texas A&M University <i>Water-Based, Environmentally-Benign, Polyelectrolyte-Based Flame Retardant Treatments</i>	16
9:30 AM	<b>Severine Bellayer</b> , University of Lille, France <i>Formulation of Thin and Thick FR Sol-Gel Coatings</i>	17

## Tuesday, June 7, 2022, cont'd

10:00 AM	BREAK	
10:15 AM	<b>Ravi Mosurkal</b> , US Army CCDC <i>Surface Functionalization Strategies for Fire Retardant Nylon, Cotton, and Nyco</i>	18
10:45 AM	<b>Jeffrey Pyun</b> , University of Arizona <i>Polymers Derived From Elemental Sulfur with Enhanced Thermomechanical and Flame Retardant Properties</i>	19
11:15 AM	<b>Yury Brusentsev</b> , Åbo Akademi University, Finland <i>Sulfenamides, Sulfinamides and Sulfonamides as Flame Retardants – Similarities and Differences in the Mechanism of Action</i>	20
11:45 AM	END AM SESSION, LUNCH ON YOUR OWN	
<b>LECTURE SESSION V</b>		
<b>Session Chair: Serge Bourbigot, University of Lille, France</b>		
4:00 PM	<b>Baljinder Kandola</b> , University of Bolton, United Kingdom <i>Effect of Crosslinkers on Charring Efficiency of Lignin-Polyamide Precursors for the Production of Carbon Fibers</i>	21
4:30 PM	<b>Conor McCoy</b> , University of Maryland <i>Modeling of Flame Spread on Charring, Non-charring, and Flame Retardant Polymers In UL-94V</i>	22
5:00 PM	<b>Lorenza Maddalena</b> , Politecnico di Torino-Alessandria campus, Italy <i>Water-Based Processes Exploiting High Aspect Ratio Nanoparticles for the Development of Flame Retardant Flexible Polyurethane Foams</i>	23
5:30 PM	BREAK	
5:45 PM	<b>Vitus Hupp</b> , Bundesanstalt für Materialforschung und -prüfung (BAM), Germany <i>Adhesive Tapes in Bonded Materials - Fire Risk or Protective Layer?</i>	24
6:15 PM	<b>Markus Wiesemann</b> , Hamm-Lippstadt University of Applied Sciences, Germany <i>Halogen-Free Syntheses of Phosphoric Esters Based on Phosphorus Pentoxide</i>	25
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## Wednesday, June 8, 2022

7:00 AM	BREAKFAST   7AM – 10 AM IN THE HOTEL'S ATRIUM	
<b>LECTURE SESSION VI</b>		
<b>Session Chair: Baljinder Kandola, University of Bolton, UK</b>		
8:30 AM	<b>Gaëlle Fontaine</b> , University of Lille, France <i>Mechanistic Aspects of Flame Retarded Polybutylene Succinate</i>	26



**Wednesday, June 8, 2022, cont'd**

9:00 AM	<b><u>Thomas J. Kolibaba</u></b> , NIST <i>Polyelectrolyte Composites for Flame Retardant Additive Manufacturing</i>	<b>27</b>
9:30 AM	<b><u>Igor Jordanov</u></b> , Ss. Cyril and Methodius University, Macedonia <i>Lignin-Based Multilayer Nanocoating for Flame Retardant Cotton Fabric</i>	<b>28</b>
10:00 AM	BREAK	
10:15 AM	<b><u>Bob A. Howell</u></b> , Central Michigan University <i>Iron Additives as Alternatives to Antimony Oxide in Flame-Retardant Formulations</i>	<b>29</b>
10:45 AM	<b><u>Hatsuo Ishida</u></b> , Case Western Reserve University <i>Polybenzoxazines: Development of Very High Performance Noncombustible Polymers without the Need of Flame Retarding Additives</i>	<b>30</b>
11:15 AM	CLOSING REMARKS	

# LECTURE ABSTRACTS

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Fire and Polymers

June 5-8, 2022

Embassy Suites By Hilton Napa Valley

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1.

## **Studying Smoldering to Flaming Transition in Polyurethane Furniture Sub-Assemblies: Effects of Fabrics, Flame Retardants, and Material Type**

*Alexander Morgan<sup>1</sup>, Graham Knapp<sup>2</sup>, Stanislav Stoliarov<sup>2</sup>, Fernando Raffan<sup>2</sup>, Sergei Levchik<sup>3</sup>*

<sup>1</sup>University of Dayton Research Institute, Dayton, Ohio, United States.

<sup>2</sup>University of Maryland, College Park, Maryland, United States.

<sup>3</sup>ICL-Industrial Products, Tarrytown, New York, United States

The transition from smoldering to flaming was studied on fabric, batting, and foam assemblies via an electric spot-ignition source of similar intensity to a cigarette. The materials studied included four different fabrics (cotton, polyester, cotton/polyester blend, flame retardant cotton/polyester blend), two types of batting (cotton, polyester), and three types of polyurethane foam (non-flame retardant, flame retardant by FMVSS 302 testing, flame retardant by BS5852 testing). The results from testing found that materials highly prone to smoldering could propagate smoldering into foams and lead to ignition, whereas materials that tended to melt back from the ignition source did not. Flame retardant fabrics or foam can and do prevent the transition from smoldering to flaming provided sufficient levels of flame retardants are incorporated in the upholstery fabric or foam. Studies on the mechanism of transition to flaming will be discussed, along with heat release measurements on the studied material combinations.

2.

## **Fire Barrier Fabrics in Upholstered Furniture: An Obvious Solution to One of the Most Enduring Problems in Fire Safety**

*Mauro Zammarano, Ickchan Kim, Matthew F. Bundy, Rick D. Davis*

*Engineering Laboratory, National Institute of Standards and Technology (NIST),  
Gaithersburg, MD, US*

*Phone: 301 975 5244, Email: [mzam@nist.gov](mailto:mzam@nist.gov)*

Upholstered Furniture (UF) fires persists as the leading cause of residential fire deaths in US, closely followed by cooking fires. About two thirds of UF fire deaths occur after flashover. Recently, regulations introduced in several US states banned or severely limited the use of flame retardants.

The “Low Heat Release Upholstered Furniture” project at the Fire Research Division (FRD) of National Institute of Standards and Technology (NIST) conducts research aimed at helping US industries’ efforts to reduce the fire losses associated with UF fires [1]. NIST studies demonstrated that, in a furnished compartment containing commercial UF, fire barrier fabrics can delay the time to flashover by over 14 min (from approximately 7 min to 21 min) and significantly increase the time for safe egress time and likelihood for fire fighters to prevent flashover occurrence. Noticeably, this decrease in fire hazard was achieved with no chemical fire retardants in the polyurethane foam, cover, barrier fabric or any other component of the UF.

In this presentation, new chair mockup tests with high performance fire barrier fabrics will be discussed. Fire barriers include oxidized polyacrylonitrile and polysilicic based fabrics. These data will be used to identify possible emerging technologies in fire barriers and expand our set of data to further support the ability of the Cube test, a NIST-developed cone-calorimeter based test, to predict full-scale fire performance of UF [2].

[1] <https://www.nist.gov/el/fire-research-division-73300/flammability-reduction-73304/low-heat-release-upholstered-furniture>

[2] Mauro Zammarano, Fire Performance of Upholstery Materials: Correlation between Cube Test and Full-Scale Chair Mock-Ups, NIST TN 2194, <https://doi.org/10.6028/NIST.TN.2194>

3.

## **The NIST Material Flammability Database: Experimental Measurements for Fire Model Calibration and Validation**

*Isaac T. Leventon\* and Morgan C. Bruns*

*100 Bureau Drive; Building 224, Room A265*

*Gaithersburg, MD 20899*

*(301) 975-6887 [isaac.leventon@NIST.gov](mailto:isaac.leventon@NIST.gov)*

The National Institute of Standards and Technology (NIST) is developing a series of experimental and analytical tools to allow for: (a) calibration of the material properties used as inputs to fire models and (b) the validation of their ability to predict flammability response across a range of configurations and scales (i.e., 0D thermal decomposition of mg-scale samples, 1D gasification and burning of g-scale/coupon-sized slabs, and 2D flame spread over 2.45 m walls). Initial tests have characterized the burning behavior of 17 unique materials (synthetic polymers and copolymers, fiber-reinforced composite materials, porous polymer foams, and natural- and engineered-wood-products) with a wide range of chemistries and burning behaviors (e.g., char formation, sooting tendency, and structural deformations). This presentation provides an overview of the systematic methodology by which these experiments are performed, the measurement data obtained in each experiment, and the infrastructure and metadata needed to maintain this information in a unified database.

4.

## **Development of Automated Calibration Tools for Determining Fire Model Input Parameters**

*Morgan C. Bruns\* and Isaac T. Leventon*

*One Camino Santa Maria*

*Treadaway, Room 143*

*San Antonio, TX 78228*

*(210) 431-6714, mbruns@stmarytx.edu*

Computational fire models such as the Fire Dynamics Simulator have proven to be highly effective at predicting the transport of smoke and heat in building fire scenarios. However, application of these models for predicting fire growth requires the specification of a relatively large number of material properties. Much work has been done to demonstrate methods for estimating these required properties from milligram and gram scale tests, but the analysis of this small-scale data requires a significant amount of human effort. As there are a vast array of flammable polymers being used in our built environment, the determination of these material properties presents a significant challenge. In order to streamline this process, a suite of automated computational tools is being developed. This talk will describe the design and demonstrate the application of these tools for analyzing thermogravimetric analysis, microcombustion calorimetry, and differential scanning calorimetry data of several polymeric materials.



5.

## **Microscale Combustion Calorimetry and Material Change Similarity**

*Natallia Safronava, Richard E. Lyon and Richard N. Walters*

*Federal Aviation Administration*

*W.J. Hughes Technical Center*

*Atlantic City International Airport, NJ 08405*

*Web: [www.fire.tc.faa.gov](http://www.fire.tc.faa.gov)*

Small changes in the composition of certified aircraft cabin constructions are often necessitated by the unavailability, performance characteristics, or environmental regulation of the original constituents-requiring costly recertification of all constructions and assemblies containing these constituents (e.g., adhesives, films, fibers, resins, thermoplastics, coatings, pigments, potting compounds, etc.). In response to this issue, the FAA in cooperation with the aviation industry, developed a microscale method and parameter to measure and compare the intrinsic flammability of constituent materials at the 10 milligram scale. This microscale test method and combustion parameter were codified as ASTM D7309-21b Standard Test Method for Determining Flammability Characteristics of Plastics and Other Combustible Solid Materials Using Microscale Combustion Calorimetry/*MCC*. The *MCC* combustion parameter called the fire growth capacity/*FGC*, includes ignitability and heat release, and was derived from a continuum-level unsteady burning model\*. In this paper we present an empirical microscale/*FGC* criterion for flammability of substitute components of aircraft cabin materials that will provide similar 14 CFR 25 fire performance in bench scale tests. In particular, we demonstrated that the relative change in *FGC* of a substitute component should be similar to the expected variation of fire test results of cabin materials at the 95% confidence level.

\*R.E. Lyon, N. Safronava, S. Crowley and R.N. Walters, A Molecular-Level Fire Growth Parameter, *Polymer Degradation and Stability*, **186**, 109478 (2021).

6.

## **The Road to Flame Retardant Commercialization**

*Anteneh Worku<sup>a,b</sup>*

*<sup>a</sup>Pinfa North America, Califon, NJ, [pinfa-na.org](http://pinfa-na.org)*

*<sup>b</sup>FR Adviser LLC, Lilburn, GA, [aworku@FR-Adviser](mailto:aworku@FR-Adviser)*

Thousands of flame retardant additives, reactives and resins have been discovered and evaluated in academic, government and industry labs over the past several decades. However, only a low percentage has been successfully commercialized. This paper will go through steps and hurdles that a new FR molecule/formulation/idea has to go through before it is commercial. The paper is not a detailed deep drill of each step but will show some critical considerations in discovery, development and commercialization phases. FR R&D is a multidisciplinary effort and requires an all hands on deck approach and collaboration throughout the “idea to commercialization” process. The paper will attempt to bring industry, academia and regulatory bodies to a common understanding of the challenges that each team has to overcome to deliver a flame retardant product that has FR performance while keeping a balance of properties of end-user product, cost and health and environmental aspects.

7.

## Hybrid strategies for improving the fire performance of epoxy resin cured with aliphatic hardener

Aurelio Bifulco<sup>2</sup>, Sabyasachi Gaan<sup>1,\*</sup>

<sup>1</sup>Department of Chemical Materials and Industrial Production Engineering (DICMaPI) University of Naples Federico II, Naples, Italy. +39 348 54 83 896, aurelio.bifulco@unina.it

<sup>2</sup>Additives and Chemistry, Advanced Fibers, Empa Swiss Federal Laboratories for Materials Science and Technology, Lerchenfeldstrasse 5, 9014 St. Gallen, Switzerland. +41 58 765 7611, sabyasachi.gaan@empa.ch

The use of aliphatic amines as hardeners is preferable over the toxic aromatic amines, however, their incorporation increases the flammability of the resin <sup>1</sup>. This presentation will summarize different hybrid strategies (Figure1) which we have recently developed to flame retard bisphenol A diglycidyl ether (DGEBA) resin cured with a cycloaliphatic amine. The synthesis of in-situ sol-gel silica nanoparticles in the epoxy resin followed by incorporation of two DOPO based flame retardants in combination with other synergists or the use of humic acid and ammonium polyphosphate, could help achieve non-dripping V0 classification in UL 94 tests with low phosphorous loadings (e.g. 1, 2 wt%) <sup>2-5</sup>. The formation of a hybrid silica-epoxy network guarantees a better dispersion of more polar additives in the hydrophobic resin, leading to tailored interphases. These strategies enable to boost the flame retardancy of the matrix, without compromise in mechanical and thermal properties of the composites.

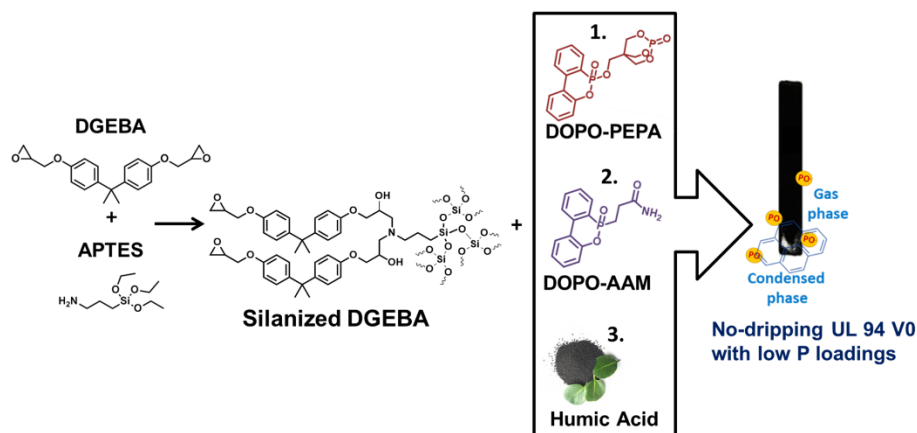


Figure 1. Hybrid routes for flame retardant improvement of epoxy systems

### References

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2. Branda, F.; Bifulco, A.; Jehnichen, D.; Parida, D.; Pauer, R.; Passaro, J.; Gaan, S.; Pospiech, D.; Durante, M., Structure and Bottom-up Formation Mechanism of Multisheet Silica-Based Nanoparticles Formed in an Epoxy Matrix through an In Situ Process. *Langmuir* **2021**, *37* (29), 8886-8893.
3. Bifulco, A.; Parida, D.; Salmeia, K.; Lehner, S.; Stämpfli, R.; Markus, H.; Malucelli, G.; Branda, F.; Gaan, S., Improving Flame Retardancy of in-situ Silica-Epoxy Nanocomposites cured with Aliphatic Hardener: Combined effect of DOPO-based flame-retardant and Melamine. *Composites Part C: Open Access* **2020**, *2*.
4. Bifulco, A.; Parida, D.; Salmeia, K. A.; Nazir, R.; Lehner, S.; Stämpfli, R.; Markus, H.; Malucelli, G.; Branda, F.; Gaan, S., Fire and mechanical properties of DGEBA-based epoxy resin cured with a cycloaliphatic hardener: Combined action of silica, melamine and DOPO-derivative. *Mater Design* **2020**, *193*, 108862-108862.
5. Venezia, V.; Matta, S.; Lehner, S.; Vitiello, G.; Costantini, A.; Gaan, S.; Malucelli, G.; Branda, F.; Luciani, G.; Bifulco, A., Detailed Thermal, Fire, and Mechanical Study of Silicon-Modified Epoxy Resin Containing Humic Acid and Other Additives. *ACS Applied Polymer Materials* **2021**.

8.

## Thermal Decomposition of Styrenic Polymers Modified with Covalently Bound P- and N-containing Groups: Analysis of the Gaseous-Phase Mechanism

*Svetlana Tretsiakova-McNally<sup>1,\*</sup>, Paul Joseph<sup>2</sup>, Aloshy Baby<sup>1</sup>, Doris Pospiech<sup>3</sup>, Eileen Schierz<sup>3</sup>, Alben Lederer<sup>3</sup>, Malavika Arun<sup>2</sup>*

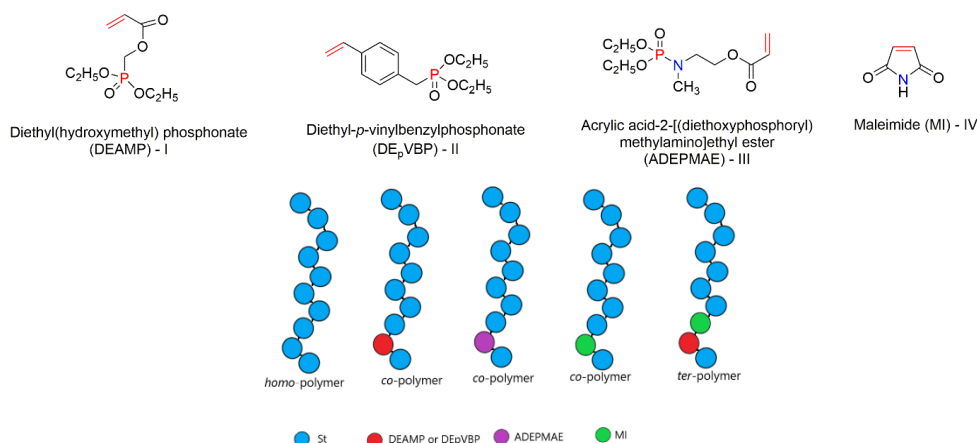
<sup>1</sup> *Belfast School of Architecture and the Built Environment, Ulster University, Shore Road, Newtownabbey, Northern Ireland, UK BT37 0QB*

<sup>2</sup> *Institute for Sustainable Industries and Liveable Cities, Victoria University, PO Box 14428, Melbourne 8001, Victoria, Australia*

<sup>3</sup> *Leibniz-Institute of Polymer Research Dresden, Hohe Str. 6, 01069, Dresden, Germany*

\* +442890366286, [s.treisiakova-mcnally@ulster.ac.uk](mailto:s.treisiakova-mcnally@ulster.ac.uk)

Through the present study, we have modified polystyrene chains by chemically binding nominal amounts of P- and/or N-containing monomers *via* a free radical polymerization. The selected monomers included: diethyl(hydroxymethyl)phosphonate (DEAMP), diethyl-*p*-vinylbenzyl phosphonate (DEpVBP), acrylic acid-2-[(diethoxyphosphoryl)methylamino]ethyl ester (ADEPMAE) and maleimide (MI). The purpose of these chemical modifications was to enhance the fire retardance in the resultant *co*- and *ter*-polymers prepared *via* a solution polymerization technique. Thermogravimetric (TGA) and pyrolysis combustion flow calorimetry (PCFC) investigations found that the modified systems exhibited an improved propensity to form char residues and had lower heat release rates, as compared to the control homopolymer. Furthermore, pyrolysis/GC-MS was employed to identify the major volatile products formed upon the thermal decomposition of the polymers. For instance, ethanol, benzaldehyde, acetophenone triethylphosphate, as well as styrene and styrene oligomers were detected in the gaseous phase emanating from the pyrolysis reaction(s) of the modified polymers, indicating a significantly altered decomposition mechanism.



9.

## **Designing Oligo- and Polymeric Flame Retardants for High Char Yields**

*Todd Emrick, Elizabeth Stubbs, and Chien-Han Chen*

*Polymer Science & Engineering Department, University of Massachusetts,*

*Amherst, MA 01003*

*Phone: 413-577-1613 Email: [tsemrick@mail.pse.umass.edu](mailto:tsemrick@mail.pse.umass.edu)*

This presentation will describe the synthesis of new oligomeric and polymeric compositions which, despite the lack of halogenated or phosphorus-based components, exhibit both exceptionally low heat release properties (by calorimetric measurements) and non-flammability (by vertical burn tests). The ketone-rich aromatic polymers, deoxybenzoins, and related structures will be described were obtained *via* 1) attachment to core molecules to afford small, multifunctional structures and 2) step-growth polymerization chemistry to give linear and branched polymers that may be employed as stand-alone materials or as additives to commodity polymers. Calorimetric measurements show the fire growth capacity (FGC) values of these new structures to be under 100 J/g-K, while several versions are readily integrated into reactive processing methods with polymers containing useful partner functional groups.

10.

## Halogen-free styrene copolymers with intrinsic flame retardant properties

*Sabine Fuchs<sup>1</sup>, Michael Luksin<sup>1</sup>, Petra Frank<sup>2</sup>, Ulrich Jonas<sup>2</sup>*

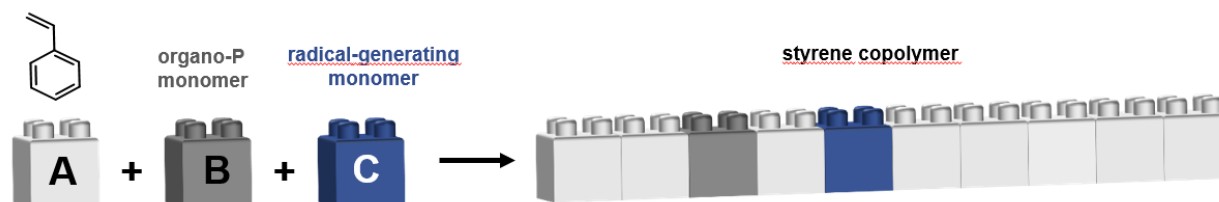
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Equipping styrene homopolymers and copolymers with flame retardant properties is important for a variety of applications. These include polystyrene particle foams (EPS) and extruded foams (XPS) to insulate building facades as well as injection-molded parts made from HIPS, ABS, ASA, etc., for use in the E&E sector. Brominated flame retardants for styrenic polymers [1] are increasingly coming under criticism due to the release of corrosive gases in the event of a fire and a potentially persistent environmental behavior [2]. In comparison, halogen-free flame retardants for styrene (co)polymers are not currently represented in the market because their flame retardant efficiency is either insufficient for the stated applications, or they provide unfavorable properties such as coloring or odors [3].

To avoid the mentioned disadvantages, a novel set of halogen-free styrene copolymers was synthesized in a versatile building-block approach (fig. 1), characterized, and tested for use in B&C applications. Depending on the synthetic route applied, the obtained copolymers exhibited molar masses of 20 – 150 kDa, glass transition temperatures of 83 – 101 °C, decomposition temperatures of 304 - 375 °C, and were able to pass DIN 4102 (B2) flame test without any additional flame retardants added.



**Fig. 1:** Synthetic building-block approach towards halogen-free intrinsically flame retardant styrene copolymers.

<sup>1</sup> Hahn, K.; Kriha, O.; Bellin, I.; Braun, F.; Spies, P.; Sandler, J.; Kurt, W.; Janssens, G.; Fischer, J.; Fleckenstein, C.: „Flame-protected polymer foams“, WO2011/073141 A1, 13.12.2010.

<sup>2</sup> Directive 2006/1907/EC: REACH, *Offic. J. Eur. Union* **2006**, 396, 1-849.

<sup>3</sup> J. Wagner, P. Deglmann, S. Fuchs, M. Ciesielski, C. Fleckenstein, M. Döring, *Polym. Degr. Stability* **2016**, 129, 63-76.



11.

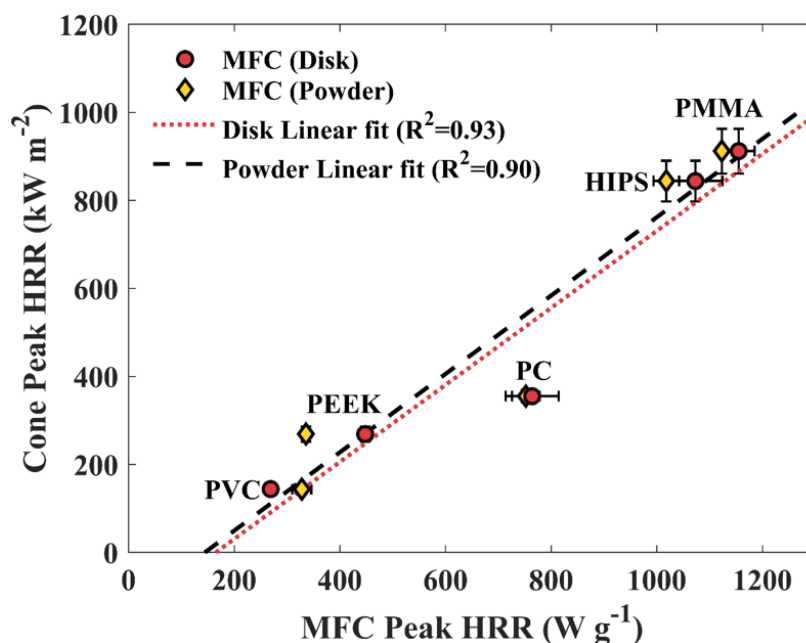
## Milligram-scale Flame Calorimetry: Development of a Pyrolyzer System used for Accurate Emulation of the Burning Behavior of Non-Thermally Thin Samples

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A new Milligram-scale Flame Calorimetry (MFC) pyrolyzer system was developed to more accurately emulate the burning behavior of samples in gram-scale tests, such as cone calorimetry. The pyrolyzer system comprises a flat heating coil operated in a constant power mode closely replicating the constant heater temperature conditions of cone calorimetry. A comparative study using five representative materials was performed in MFC, microscale combustion calorimetry, and cone calorimetry. All methods produced similar final solid residue yields. The correlation between the peak heat release rate (HRR) data from the newly-designed MFC and cone calorimeter was found to be near-linear. This was also the case when comparing the MFC airborne particulate yield and cone average extinction area data. The heat of combustion (HOC) data from MFC and cone calorimetry was nearly identical. The newly-designed MFC generates accurate relative flammability data using samples three orders of magnitude smaller than used in cone calorimetry tests.



12.

## Surface functionalization Strategies for Fire Retardant

### Nylon, Cotton and Nyco

*Sourabh Kulkarni<sup>1,4</sup>, Shiran Yu<sup>2</sup>, Zhiyu Xia<sup>2</sup>, Alexander B. Morgan<sup>5</sup>, Jayant Kumar<sup>3,4</sup>,  
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*<sup>6</sup>Protection Materials Division, Soldier Protection Directorate, US Army DEVCOM -  
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*Ramaswamy\_Nagarajan@uml.edu; Ravi.Mosurkal.civ@army.mil*

A 50/50 blend of nylon and cotton (Nyco) is widely used by the US Armed forces for Army Combat Uniforms (ACU) due to its excellent combination of mechanical properties, comfort, and low cost. Despite these excellent properties Nyco is inherently flammable. The burning behavior is also unique due to the combination of a natural fiber (cotton) and a thermoplastic polymer (nylon) in the fiber blend which gives rise to the scaffolding effect. To address the flammability of Nyco fabric, several approaches have been developed for Nylon and cotton fabrics separately to impart flame retardancy. For Nylon fabric, polyphenols have been explored as char forming flame retardant. Polyphenols such as tannic acid can be coated onto the surface of the fabrics via acid dyeing techniques. The attachment of tannic acid on nylon helps improve the thermal stability and impart flame retardancy. Cellulosic fabrics on the other hand require phosphorus based flame retardant compounds for self-extinguishing characteristics. Various chemistries and processes were developed to covalently functionalize phosphorus based compounds on to cotton fabric. These compounds help in catalyzing the carbonization of cellulose, increasing the char formation, and giving rise to self-extinguishing fabrics with a char length of less than 4 inches in standard vertical flame tests. For Nyco fabrics, the combination of polyphenols along with a phosphorous containing compounds can impart FR characteristics. A systematic approach to functionalizing Nylon, Cotton and Nyco will be presented, and lessons learnt will be discussed. Detailed spectroscopic and thermal characterization of nylon, cotton and Nyco fabric as well as assessment of launder durability will also be presented.

Cancel

## Coffee Biowastes as Sustainable Flame Retardants for Polymers

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Development of biobased and cost-effective flame retardants has attracted the attention of researchers for developing safe and sustainable materials [1]. Various types of biowastes such as oyster shell powder or eggshell have been already incorporated into polymers to control their flammability. In this work, the coffee biowaste was chemically modified with phytic acid and dimethyl phosphite molecules and then incorporated into epoxy and polylactic acid (PLA). PLA and epoxy composites containing different loading percentage of unmodified/modified coffee biowaste were investigated using thermogravimetric analysis (TGA), cone calorimetry and pyrolysis combustion flow calorimeter analysis (PCFC) and UL94 tests. The chemical modification led to a significant increase in the char content up to 60% as detected by TGA. The results clearly showed the effectiveness of the modified coffee biowaste as flame retardant additive, as signaled by a low peak of heat release rate (pHRR) in cone calorimetry and the self-extinguishable character of materials observed in UL94 test.

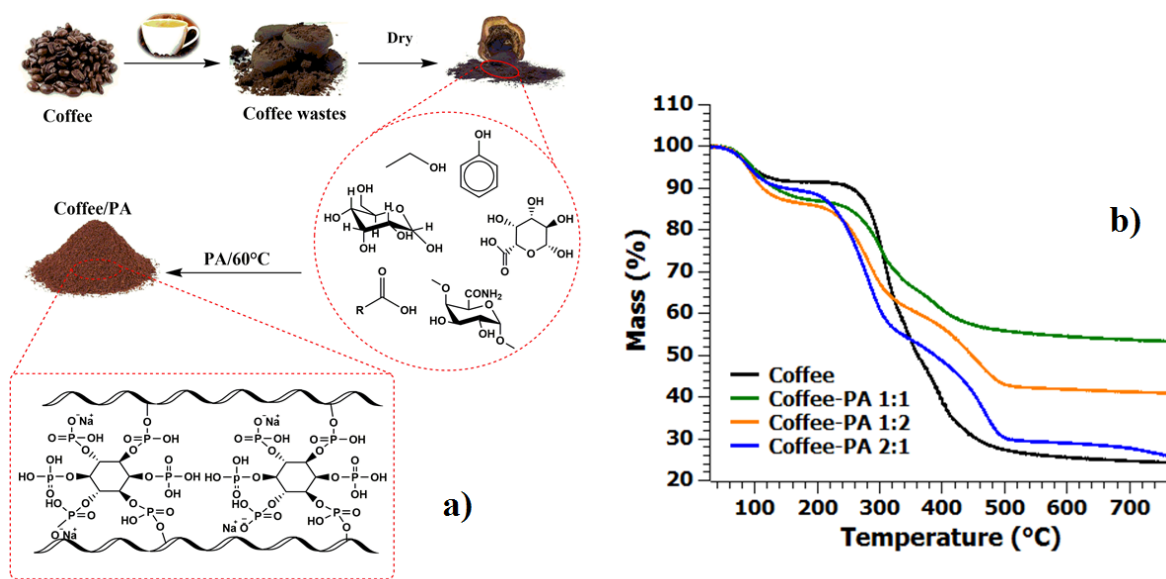


Figure 1: Scheme of chemical modification of coffee waste using phytic acid (a), thermogravimetric analysis (TGA) curves for coffee waste and modified coffee waste with different ratios of phytic acid (b).

### Reference:

[1]. 15. H. Vahabi, F. Laoutid, M. Mehrpouya, M. R. Saeb, Ph. Dubois, Flame retardant polymer materials: An update and the future for 3D printing developments, Materials Science & Engineering R 144 (2021) 100604.

13.

## **Non-vegan Flame-Retardant (Adjuvants in) Biocomposites**

*Bernhard Schartel,<sup>1,\*</sup>*

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Emanating from developing flame retarded biocomposites, we have proposed renewable natural fibers (including keratin) taken from industrial waste as an authentic sustainable approach.[1,2] More recently, we have investigated *non-vegan flame retardant* approaches. This paper loves to give you an insight into our ongoing projects on biogenic industrial wastes like leather, bone meal, and insects.[3-5] Materials were characterized multi-methodically, flame retardant modes of action quantified, decomposition mechanism proposed, and synergisms explained.

Considering the large quantities of leather waste (LW) in industrial-scale production, we underline LW as multifunctional bio-adjuvants. LW enhances the flame retardancy of poly(ethylene-vinyl acetate) (EVA) containing phosphorus flame retardants (P-FR).

Products/by-products of the invertebrate and vertebrate farming, respectively, are promising bio-based adjuvants in flame retarded bio-epoxy thermosets. While the addition of bone meal yields the formation of an inorganic shield, protein-based powders from insects provide an intumescent behavior. In combination with a P-FR superior charring and self-extinguishing are obtained.

Acknowledgement: In part of this work was supported by the Volkswagen Foundation grant “Experiment!” No. 97437.

[1] S Rabe, G Sanchez-Olivares, R Pérez-Cháves, B Schartel. Natural Keratin and Coconut Fibres from Industrial Wastes in Flame Retarded Thermoplastic Starch Biocomposites. *Materials* 12, 344, 2019

[2] G Sanchez-Olivares, S Rabe, R Pérez-Chávez, F Calderas, B Schartel. Industrial-waste agave fibres in flame-retarded thermoplastic starch biocomposites. *Compos. Part B* 177, 107370, 2019

[3] A Battig, G Sanchez-Olivares, D Rockel, M Maldonado-Santoyo, B Schartel. Waste not, want not: The use of leather waste in flame retarded EVA. *Maters Design* 210, 110100, 2021

[4] A Battig, KI Garfias González, B Schartel. Valorizing “non-vegan” bio-fillers: synergists for phosphorus flame retardants in epoxy resins. submitted

[5] FR Gleuwitz, A Battig, B Schartel. Tenebrio molitor beetle as nonvegan adjuvant in flame-retarded tannic acid-based epoxy thermosets. in preparation.

14.

## Mechanistic investigations of wasp nest papers: Towards environmentally compatible flame-retardant concepts for synthetic materials

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Fire is common in many ecosystems and has led to evolutionary adaptations of organisms and their structures. Wasps build nests from paper-like materials consisting of chewed wood particles and their protein-rich saliva, whose composition influences the properties of their building material. We show that the flammability of these bio-papers is significantly inhibited compared to synthetic papers. The microstructure of egg-cells and shells built by the animals differs in saliva quantity and how densely it covers the wood particles (Fig. 1). This leads to different flame-retardancy properties and influences the stability of the charred residues after flame testing. Investigation of biomimetic papers synthesized using various amounts of commercial proteins like gluten and wood particles from different tree species indicate a similar role of the proteins. First transfer attempts to synthetic materials by incorporating the design principles of wasp papers into wood-plastic composites led to significant changes of their drip off-behavior during combustion.

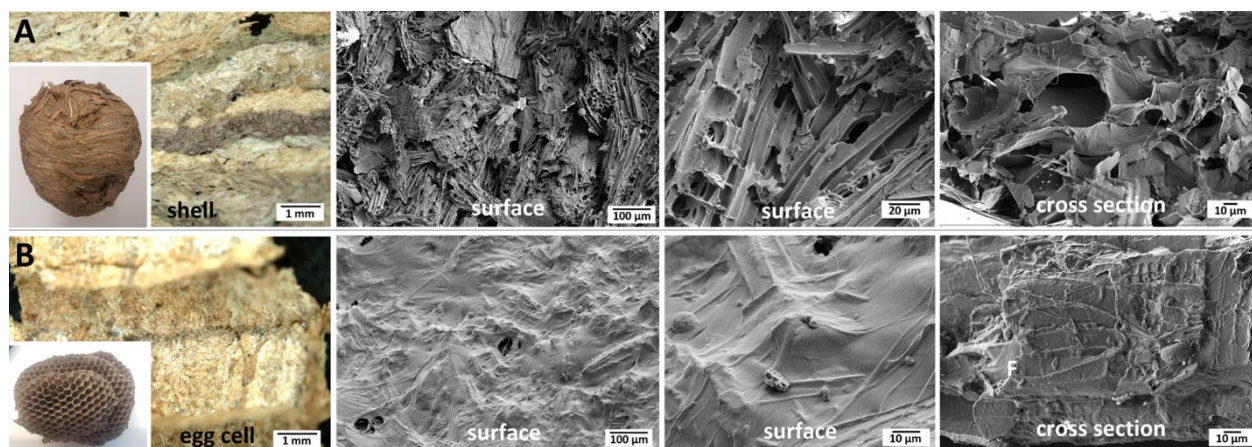


Fig. 1: Macro- (light microscopy) and microstructure (scanning electron microscopy) of (A) shell material and (B) egg cells from a *Vespula germanica* nest.



15.

## Recent advances in designing fire barriers

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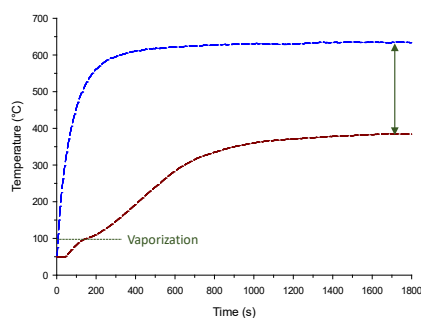
<sup>2</sup>*Institut Universitaire de France, Paris, France*

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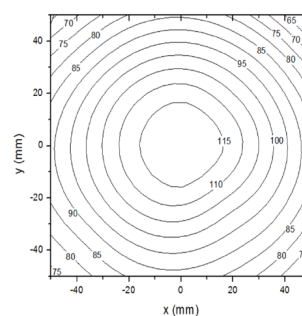
In case of fire, people must be protected by materials confining and stopping fire. It is the goal of this research to design materials and assembly of materials exhibiting low flammability, protecting substrates and limiting fire spread. An approach was to prepare foamed geopolymers (GPs) as fire barrier to protect a substrate. GP foam was coated on steel plate as a substrate and was evaluated using a burn-through test (Figure 1-(a)) delivering heat fluxes as high as  $116 \text{ kW/m}^2$  (Figure 1-(c)). The temperature reached on the backside of the steel plate is much lower for the GP foam than that of the virgin steel (Figure 1-(b)). In the steady state, the temperature difference is about  $250^\circ\text{C}$ . Other fire barriers will be considered such as intumescent coating and multilayered materials (e.g. intumescent coating/aluminum foil). Examples will be shown in the talk in the conditions of jetfire and burn through testing respectively.



(a)



(b)



(c)

**Figure 1:** (a) Flame impinging GP foam during burn-through test, (b) comparison of the time/temperature curves of virgin steel plate (in blue) and steel coated by GP foam (in red) and (c) mapping of heat flux (in  $\text{kW/m}^2$ ) at the surface of the plate



16.

## Water-Based, Environmentally-Benign, Polyelectrolyte-Based Flame Retardant Treatments

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Flame retardants mitigate the threat of fire from inherently flammable materials responsible for sustaining a high standard of living. Although bulk flame retardants have proven effective for many years, there is now increased interest in the use of surface treatments to localize flame retardant chemistry at the exterior of a material, where combustion occurs. These water-based coatings preserve desirable bulk properties and minimize the amount of additive needed. The success of these treatments depends on the scalability, durability, and efficacy.

Our work in the fields of layer-by-layer (LbL) assembly and polyelectrolyte complexation has provided new water-based coating technologies for imparting effective flame retardancy to polymeric materials without using environmentally harmful chemistries [1][2]. These water-based coatings are very thin (typically < 500 nm thick) and conformal. The ability to place flame retardant chemistry exclusively at the surface prevents loss of beneficial bulk properties and reduces the amount of flame retardant required to achieve self-extinguishing behavior.

### References

- [1] S. Lazar, T. J. Kolibaba, J. C. Grunlan, *Nature Reviews Materials* 2020, 10, 259-275.
- [2] K. M. Holder, R. J. Smith, J. C. Grunlan, *J. Mater. Sci.* 2017, 52, 12923-12959.

17.

## Formulation of thin and thick FR sol-gel coatings

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Sol-gel coatings are used for a large variety of applications and have the potential to fulfil each and every expectation of the end user in terms of cost effectiveness, environmental friendliness and functional properties. In this work, thin and thick flame retardant (FR) sol-gel coatings were formulated and evaluated to fire protect foams, textiles and wood panels. The coatings developed are mainly based on a mix of silane monomers in an ethanol/water solution with diethylphosphite or eco-friendlier FR molecules.

Thin sol-gel coatings were deposited on foams and textiles and the resulting materials led to self-extinguishment when exposed to a flame. They also exhibited a very interesting intumescent phenomenon. Thick transparent sol-gel coatings were deposited on wood panels. The resulting materials were tested under mass loss cone test ( $50 \text{ kW/m}^2$ ), furnace test and under a mini Single Burning Item (SBI) test (Figure 1) set up in our lab.

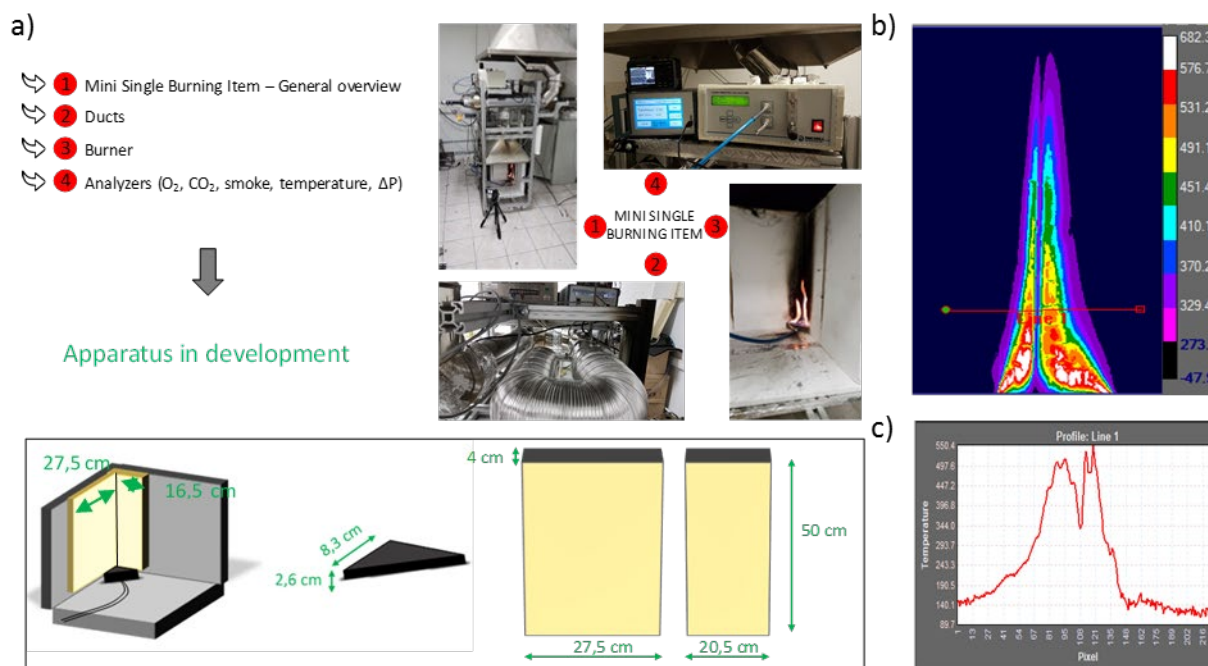


Figure 1 : Scheme of the Mini Single Burning Item (M-SBI) (a), infrared image of a burning sample (b) and the corresponding temperature profile (c)

18.

## Surface functionalization Strategies for Fire Retardant

### Nylon, Cotton and Nyco

*Sourabh Kulkarni<sup>1,4</sup>, Shiran Yu<sup>2</sup>, Zhiyu Xia<sup>2</sup>, Alexander B. Morgan<sup>5</sup>, Jayant Kumar<sup>3,4</sup>,  
Ramaswamy Nagarajan<sup>2,4\*</sup>, Ravi Mosurkal<sup>4,6\*</sup>*

*Departments of<sup>1</sup>Mechanical Engineering, <sup>2</sup>Plastics Engineering, <sup>3</sup>Physics and Applied  
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*<sup>5</sup>Center for Flame Retardant Materials Science, University of Dayton Research Institute,  
Dayton, Ohio 45469, USA*

*<sup>6</sup>Protection Materials Division, Soldier Protection Directorate, US Army DEVCOM -  
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*Ramaswamy\_Nagarajan@uml.edu; Ravi.Mosurkal.civ@army.mil*

A 50/50 blend of nylon and cotton (Nyco) is widely used by the US Armed forces for Army Combat Uniforms (ACU) due to its excellent combination of mechanical properties, comfort, and low cost. Despite these excellent properties Nyco is inherently flammable. The burning behavior is also unique due to the combination of a natural fiber (cotton) and a thermoplastic polymer (nylon) in the fiber blend which gives rise to the scaffolding effect. To address the flammability of Nyco fabric, several approaches have been developed for Nylon and cotton fabrics separately to impart flame retardancy. For Nylon fabric, polyphenols have been explored as char forming flame retardant. Polyphenols such as tannic acid can be coated onto the surface of the fabrics via acid dyeing techniques. The attachment of tannic acid on nylon helps improve the thermal stability and impart flame retardancy. Cellulosic fabrics on the other hand require phosphorus based flame retardant compounds for self-extinguishing characteristics. Various chemistries and processes were developed to covalently functionalize phosphorus based compounds on to cotton fabric. These compounds help in catalyzing the carbonization of cellulose, increasing the char formation, and giving rise to self-extinguishing fabrics with a char length of less than 4 inches in standard vertical flame tests. For Nyco fabrics, the combination of polyphenols along with a phosphorous containing compounds can impart FR characteristics. A systematic approach to functionalizing Nylon, Cotton and Nyco will be presented, and lessons learnt will be discussed. Detailed spectroscopic and thermal characterization of nylon, cotton and Nyco fabric as well as assessment of launder durability will also be presented.

19.

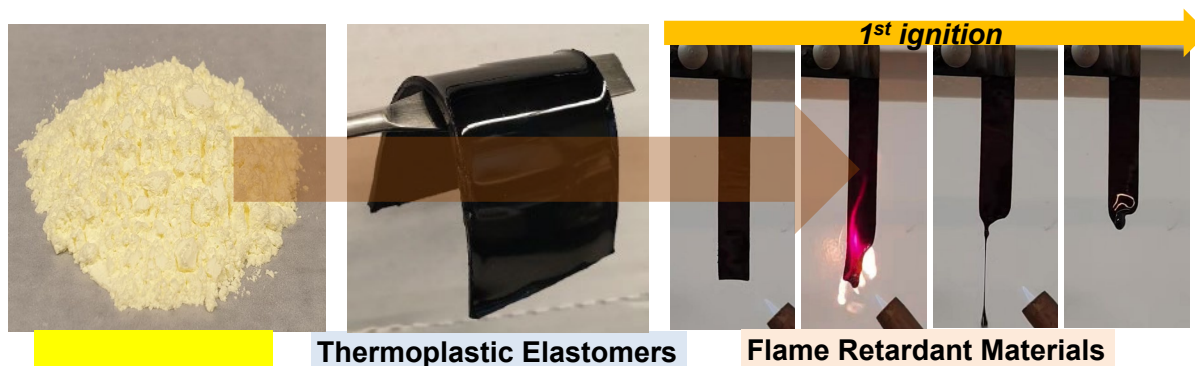
## Polymers Derived From Elemental Sulfur with Enhanced Thermomechanical and Flame Retardant Properties

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The production of elemental sulfur ( $S_8$ ) from petroleum refining has created a technological opportunity to increase the valorization of elemental sulfur by the creation of high performance sulfur based plastics with improved thermomechanical properties, elasticity and flame retardancy. We will discuss our recent efforts on the preparation segmented multi-block polyurethanes (SPUs) and thermoplastic elastomers derived from  $S_8$  that incorporate an appreciable amount of sulfur into the final target material. These sulfur based polyurethanes were readily solution processed into large area free standing films where both the tensile strength and elasticity of these materials were controlled by variation of the sulfur polyol composition. SPUs with both high tensile strength (13-23 MPa) and ductility (348% strain at break) were prepared, along with SPU thermoplastic elastomers (578% strain at break) which are comparable values to classical thermoplastic polyurethanes (TPUs). The incorporation of sulfur into these polyurethanes, we observe enhanced flame retardancy in comparison to classical TPUs, which points to the opportunity to impart new properties to polymeric materials as a consequence of using elemental sulfur.



20.

## **Sulfenamides, sulfinamides and sulfonamides as flame retardants – similarities and differences in the mechanism of action**

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Several sulfur-nitrogen compounds have proven their potential as flame retardants for polymeric materials.<sup>1-3</sup> In the current work we have investigated the flame retardant activity of three different sulfur-nitrogen derivatives: 1) sulfenamides, 2) sulfinamides and 3) sulfonamides. The flame retardant mechanism and efficacy were investigated by performing standard fire tests such as DIN4102 and LOI tests in combination with thermal analysis (TGA/DSC) and chemical analysis of the decomposition products of the neat sulfur-nitrogen compounds. Despite the structural similarities some differences in efficacy and mode of action for these compounds were observed for flame retardancy of polypropylene. Here we present our preliminary findings on the activity differences of these 3 groups of sulfur-nitrogen compounds with respect to flame retardant efficacy in polypropylene films.

1. A. Mountassir; T. Tirri; P. Sund; C-E. Wilén, Sulfenamides as Standalone Flame Retardants for Polystyrene, Polymer Degradation and Stability, Volume 188, June 2021, 109588.
2. Teija Tirri, Melanie Aubert, Humayun Aziz, Yury Brusentsev, Weronika Pawelec, Carl-Eric Wilén, Sulfenamides in synergistic combination with halogen free flame retardants in polypropylene, Polymer Degradation and Stability, Volume 164, June 2019, 75.
3. C-E Wilén; M. Aubert; T. Tirri; W. Pawelec, WO2015067736A1, 2015.

21.

## **Effect of crosslinkers on charring efficiency of lignin-polyamide precursors for the production of carbon fibers**

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There is a continuous increase in the demand for carbon fibres in the global market despite their high costs of manufacturing, which is mainly associated with those derived from precursor polyacrylonitrile fibres. This route is partly the reason that carbon fibres are expensive and involve a large carbon foot print in their manufacture. Lignin, a biobased polymer, owing to its high carbon content (> 60%), excellent char-forming ability and a potential to be spun into fibres, offers itself as a possible alternative precursor. There are however multiple technical challenges to produce lignin precursor fibers, the main ones being compounding/spinning the more processable, lower molecular weight lignins and long thermal processing times required for carbonisation. In order to address the first challenge, the lignin can be blended with a wide range of thermoplastic polymers and the resulting blends melt spun into fibers. Another challenge is to increase the char yield of the lignin-based precursors for carbon fiber production. To date, the lignin based systems have shown considerably lower char yields than commercial tar pitch char yields under a nitrogen atmosphere, which is further reduced when lignin is blended with other polymers. This can be addressed by adding crosslinkers and char promoters in the blends, which however can affect the processability of the blends.

In our recent research we have successfully blended a hydroxypropyl modified organosolv lignin with a bio-based polyamide, PA 1010, and extruded into fibres. This study aims to explore the enhancement in charring efficiency of the blends by using a number of crosslinkers and char promoters either as additives prior to melt spinning fibres or as surface treatments of the extruded fibres. The charring efficiency of the blends has been investigated by thermal analytical techniques (e.g. TGA, DSC, DMA) at various stages of heat treatments used for thermal stabilisation and carbonisation of the fibres. The flammability of blended polymers has been studied by UL-94 test, where V-2 rating could be achieved for blends containing 20 – 40 wt% lignin compared to ‘no-rating’ for the polyamide. The effect of crosslinkers on the flammability of the extruder fibres is being investigated and will be presented in the conference.

**Acknowledgements:** This work is part of the project funded from the BioBased Industries Joint Undertaking under the European Union’s Horizon 2020 research and innovation programme under grant agreement No 720707rs.



22.

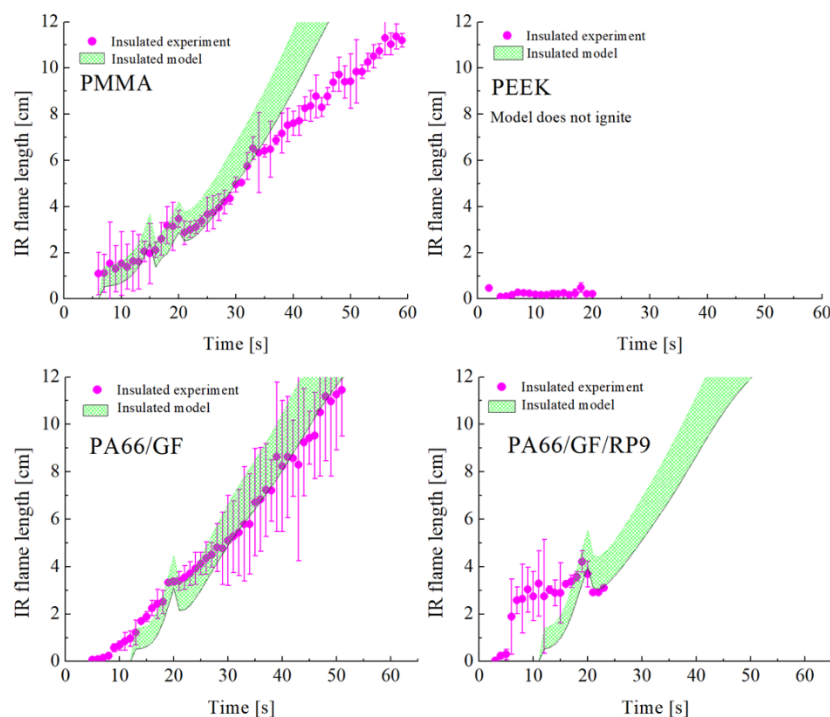
## Modeling of Flame Spread On Charring, Non-charring, and Flame Retardant Polymers In UL-94V

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The UL-94V test is widely used to assess the flammability of polymers in a vertical configuration; accurate modeling of it could facilitate the development of polymers safer from fire. In this work, flame spread in slightly modified UL-94V tests was tracked and modeled on several polymers including poly(methyl methacrylate) (PMMA), poly (ether ether ketone) (PEEK), and glass-fiber reinforced polyamide 6,6 (PA66/GF) with and without flame retardant red phosphorous (RP). The model, implemented via a numerical pyrolysis solver, ThermaKin, couples previously developed and validated pyrolysis models with submodels representing the burner and polymer flames. A few model predictions compared with experimental data are shown in Fig. 1. Model agreement is good apart from the model's inability to predict the extinction of the PA66/GF/RP9 flame due to gas-phase effects which were not included.



**FIGURE 1.** Comparison of experimental flame length data and model predictions. The shaded area accounts for the uncertainty in scaling the simulated results.

23.

## Water-based processes exploiting high aspect ratio nanoparticles for the development of flame retardant flexible Polyurethane Foams

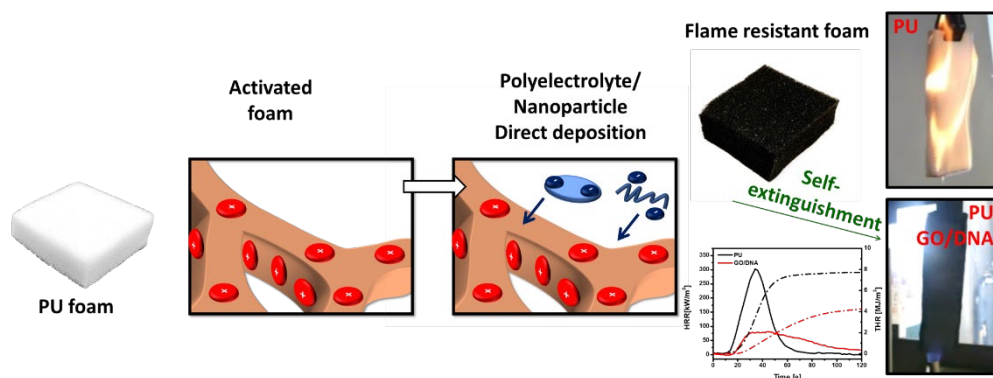
Lorenza Maddalena<sup>1</sup>, Paolo Bettotti<sup>2</sup>, Marina Scarpa<sup>2</sup>, Alberto Fina<sup>1</sup>, Federico Carosio<sup>1</sup>

<sup>1</sup>Politecnico di Torino-Alessandria campus, viale Teresa Michel 5, 15121, Alessandria, Italy

<sup>2</sup> Nanoscienze laboratory, Dipartimento di Fisica, Università di Trento, Via Sommarive 14, Povo, 38123, Trento, Italy

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Recent societal concerns associated to the safety of conventionally used flame retardant additives resulted in the need to find new, sustainable and high performing solutions to reduce the fire threat of common polymers. In this contribution, waterborne self-assembled coatings comprising 2D nanoparticles are employed as promising route to improve the fire safety of flexible polyurethane foams (PU). Different 2D nanoparticles (graphite oxide, montmorillonite clay MMT, kaolinite KA) have been selected and combined with natural polyelectrolytes (alginates, chitosan, deoxyribonucleic acids).<sup>1</sup> Polyelectrolyte/nanoparticle complexation, forced self-assembly or in-situ assembly are employed to deposit nanostructured coatings characterized by high flame retardant efficiency. Few deposition steps (one or two) were found sufficient to produce PU characterized by self-extinguishing behaviour and low heat and smoke release, evaluated by flammability and cone calorimetry test, respectively. The achieved results make it possible for the development of industrially viable approaches where the efficiency of the process and the flame retardant results are maximised.



<sup>1</sup> L. Maddalena, F. Carosio, A. Fina, Advanced Materials and interfaces, 8, 21, 2101083, 2021

**Acknowledgment:** The financial support from Italian Ministry of University (MUR) call PRIN 2017 with the project 2017LEPH3M “PANACEA” is acknowledged.

24.

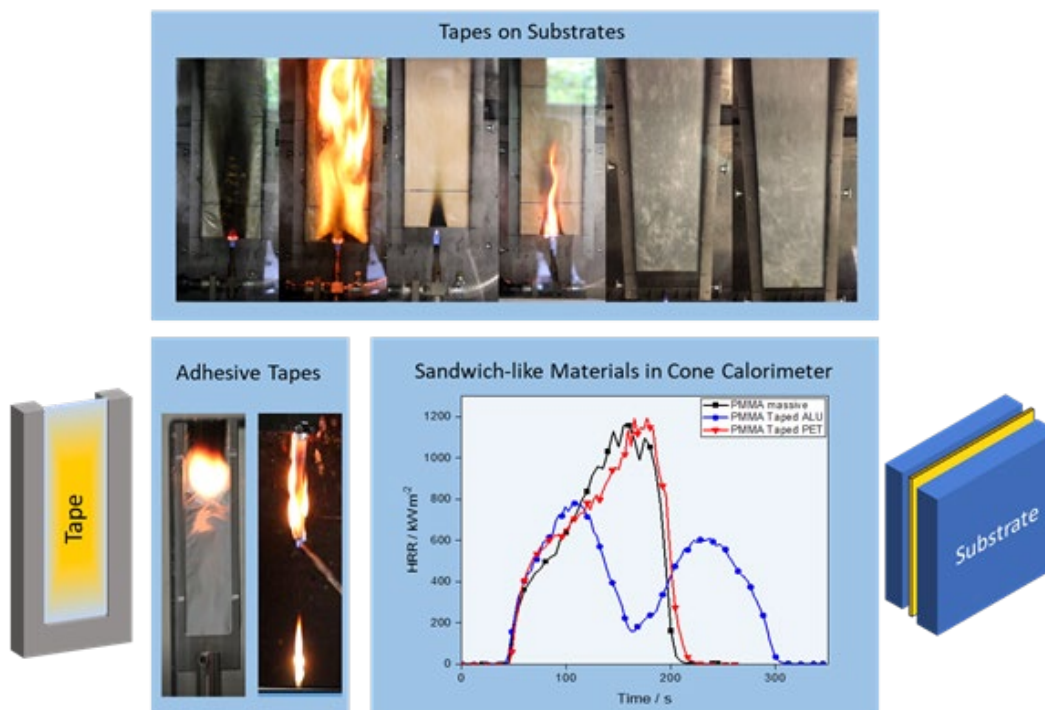
## Adhesive tapes in bonded materials - fire risk or protective layer?

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In the recent years, more and more products in construction and automotive industry are bonded by adhesive tapes instead of mechanical fasteners but there is no sufficient understanding of how these bonded, layered materials behave in fires. Our research project gives an insight of how adhesives and substrates interact with each other in different fire scenarios and how flame retardants function in pressure sensitive adhesive (PSA) tapes. A systematic investigation on the burning behavior of PSA tapes as free-standing films, as top layers on different substrates and as sandwich-like adhesive joints was performed. The burning behavior of free-standing PSA tapes and those used as a coating was significantly improved by using phosphorus-based flame retardants. Furthermore, it was shown that, depending on tape structure and substrate, the PSA tape can lower the fire risk by acting as an intermediate protection layer in bonded materials.



25.

## Halogen-free syntheses of phosphoric esters based on phosphorus pentoxide

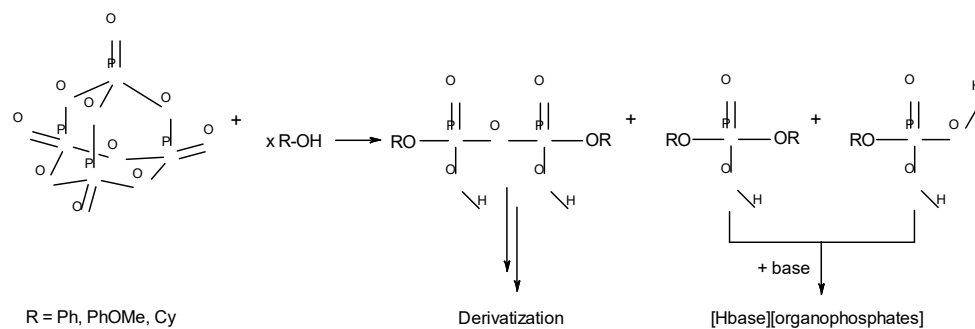
Markus Wieseemann<sup>a</sup>, Sabine Fuchs<sup>a</sup>, Mateusz Andruschko<sup>a</sup>

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The development of halogen-free phosphorus-based compounds is an omnipresent strategy to achieve the goal of an environmentally friendly flame retardancy in thermoplastics. Although numerous and efficient examples are broadly utilized, the syntheses of those flame retardants (FRs) frequently include halogenated intermediates and starting materials, which are hazardous and in form of contaminants corrosive to modern electronic devices.<sup>[1]</sup> Flame retardants like melamine polyphosphate or red phosphorus, which renounce halogenated compounds in their production, lack derivatization ability for the development of tailor-made FRs.

Phosphorus pentoxide represents a halogen-free, albeit due to its insolubility and multi-center reactivity challenging, starting material for the synthesis of phosphate esters (Scheme 1).



**Scheme 1:** Alcoholysis of phosphorus pentoxide.

However, in dependence on the reaction conditions the alcoholysis of phosphorus pentoxide results in the formation of mono- and diesters of phosphoric acid as well as pyrophosphates.<sup>[2]</sup> Subsequent to separation, the derivatization and reaction with bases enables a convenient and entirely halogen-free synthesis of potential FRs.

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26.

## Mechanistic aspects of flame retarded polybutylene succinate

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Among the biobased polymers polybutylene succinate (PBS) is an attractive one. It can replace petrochemical polymers for different applications, indeed, it has a good processability, a controlled biodegradability and quite good thermal and mechanical properties. Unfortunately, its high flammability reduces its application in various field where flame retardancy is needed. Therefore, a lot of efforts are made to improve the reaction to fire of PBS [1]. As an example, PBS can be flame retarded by an intumescence approach using ethylenediamine phosphate (EDAP) and synergists (Figure 1) [2]. In this talk, the different approaches developed to reduce flammability of PBS will be presented and a focus will be made on the mechanistic aspects.

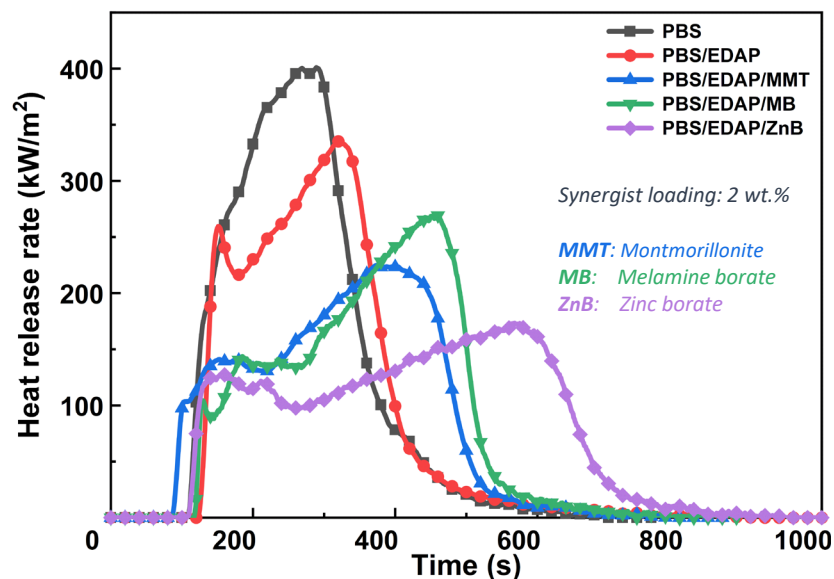


Figure 2: Flame retardancy of intumescent PBS evaluated by Mass Loss Cone

[1] F. Xiao, G. Fontaine, S. Bourbigot, Recent developments in fire retardancy of polybutylene succinate, *Polym. Degrad. Stab.* 183 (2021) 109466.

[2] Fei Xiao, Gaëlle Fontaine, Serge Bourbigot, Intumescent polybutylene succinate: ethylenediamine phosphate and synergists, *Polymer Degradation and Stability*, 2021, 192: 109707.

27.

## **Polyelectrolyte Composites for Flame Retardant Additive Manufacturing**

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Additive manufacturing, also called 3D printing, is a rapidly maturing technology that has found widespread use for prototyping parts and recently for mass-produced 3D printed items. Filament-based additive manufacturing is the most widespread form of 3D printing, forming objects by the extrusion of molten thermoplastics. The inherent flammability of these thermoplastics limits the applications of additively manufactured parts and is a barrier to the commercial viability of 3D printing for mass production. Polyelectrolyte coatings have risen to prominence in recent years as effective flame retardant treatments for a wide variety of materials, but are impractical for use in 3D printing filaments. However, polyelectrolyte complexes (PECs) are effective flame retardants for thermoplastics when mixed as bulk additives. Incorporation of bulk PECs preserves the printability of polylactic acid and polyamide while simultaneously yielding flame retardant filaments and parts. Reduction of part flammability without altering processing presents an opportunity for a scalable and cost-effective method to improve the safety of 3D printers and 3D printed parts.



28.

## Lignin-based multilayer nanocoating for flame retardant cotton fabric

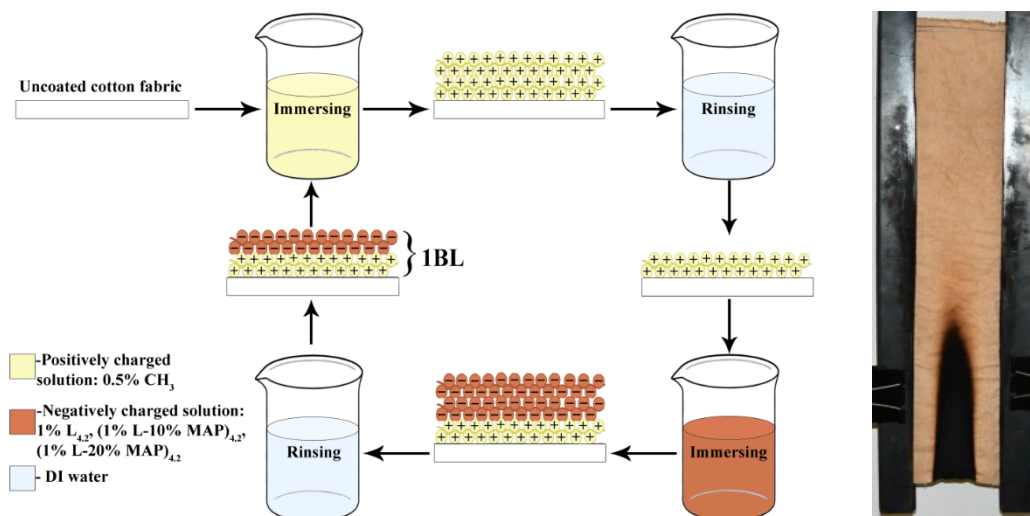
Igor Jordanov,<sup>\*1</sup> Jovana Petkovska,<sup>1</sup> Maja Radetić,<sup>2</sup> Jaime C. Grunlan<sup>3</sup>

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Layer-by-layer (LbL) assembly is a simple, inexpensive, and highly tailorable water-based technique, performed by alternate exposure of a substrate to oppositely-charged solutions or suspensions at room temperature, giving rise to a multilayer nano-film. It is one of the techniques for textile finishing that uses polyelectrolytes, nanoparticles, and bio-macromolecules, possible to design an unlimited combination of assemblies with impressive functionality. Here we are producing lignin-based multilayered nanocoating composed of magnesium lignosulfonate (L), chitosan (CH), and monoammonium phosphate (MAP) that give self-extinguishing cotton fabric with less than 5 bilayers. 5 BL of CH<sub>3</sub>/(L-20% MAP)<sub>4.2</sub> imparted exceptional flame retardancy with only 15.5 wt% weight gain. This sample has 35 vol% LOI, 30.9 wt% residue at 600°C, and a 67.2 % reduction in heat release rate. In this intumescent system, lignin and chitosan are char-forming, while monoammonium phosphate, with its decomposing components ammonia and phosphoric acid, acts as a blowing agent and acid source.



29.

## **Iron Additives as Alternatives to Antimony Oxide in Flame -retardant Formulations**

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Antimony oxide has long been used as an adjuvant in organohalogen flame-retardant formulations. Antimony oxide is neither a flame retardant nor a synergist. In the degrading polymer/flame retardant matrix it is converted to volatile antimony trihalide and oxyhalides which escape to the gas phase where they effectively scavenge combustion propagating radicals. Thus, the antimony halides and hydrogen halide from the decomposing flame retardant act in parallel to suppress combustion. Antimony oxide has been used in a similar way in halogenated polymers, in particular, plasticized poly(vinyl chloride) [PVC]. Unformulated PVC is effectively noncombustible (LOI 45). However, to be processed, it must be strongly plasticized. The presence of plasticizer often imparts two negative characteristics, toxicity and flammability. To combat flammability, antimony oxide is often added during processing. PVC degrades by thermally-induced dehydrochlorination. In the degrading polymer containing antimony oxide volatile antimony chlorides are formed which suppress gas-phase combustion. With the increasing awareness of the toxicity of antimony oxide [*Int. J. Environ. Res. Public Health*, **2019**, 19, 4474] alternatives have been sought [*Int. J. Mater. Res. Sci. Tech.*, **2020**, 1(1), 15-20]. Commercial replacements for antimony oxide are now available for use in some applications [R. J. Marshall Company]. However, the search for a general replacement continues. Iron compounds are widely available and low in cost. PVC formulations containing various iron compounds at 2 and 10 parts-per-hundred have been generated. The thermal degradation and flammability of these materials have been evaluated utilizing thermogravimetry (TGA) and limiting oxygen index (LOI).



30.

## **Polybenzoxazines: Development of Very High Performance Noncombustible Polymers without the Need of Flame Retarding Additives.**

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Polymers are often used with flame retarding additives. Traditionally used flame retardants are often toxic, lead to toxic byproducts or cause adverse effects by the addition of secondary materials. More recently, natural renewable additives or green methodologies are attracting strong attention. As part of this environmentally benign approach, development of intrinsically noncombustible polymers offers non-toxic products and the ability to sustain the originally developed polymer properties. Polybenzoxazine is the newest rare class of polymers that has been commercialized. Polybenzoxazines offer extremely high molecular design flexibility, can be synthesized from readily available commercial raw materials, polymerize with near-zero shrinkage, and exhibit excellent mechanical, thermal and electrical properties. Being able to synthesize a fire-smart structure is one of the advantageous consequences of this excellent molecular design flexibility. In this lecture, we will introduce fire smart polymers that can exhibit  $T_g$  greater than 350°C, a constant  $G'$  property in a very wide temperature range (R.T.-400°C) with heat release capacity less than 100 J/g.K (noncombustible).

Cancel

## **Formulation of Flexible Polyurethane Foams with Significantly Reduced Flammability**

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*321-674-8480, [nelson@fit.edu](mailto:nelson@fit.edu)*

This study focused on the development of a family of highly flame retardant, environmentally friendly, flexible polyurethane foams. FR package is non-halogen, bound-in, meaning it is non-migrating, of low VOC, resolving key issues for stakeholders. Goal was to exceed fire retardancy of BX265 NASA SOFI rigid foam (354 Peak Heat Release Rate by Cone Calorimeter at 50kW/m<sup>2</sup> external flux, 1-inch thickness). Foams achieved down to 140 PHRR (40% of SOFI)(92% reduction in PHRR versus 1670 for base foam). Foams meet Cal133, BS5852, and FAA Oil Burner Test standards for seating; 16CFR1633, Cal129, and NFPA 267 (Navy Modification) standards for mattresses. Some foams meet US Air Force dynamic cushioning test for packaging. Foams made to any needed static stress performance, useful for energy absorption foams for automotive or aerospace. Some foams show 25% improvement in cryogenic insulating performance. Foams under 3.0 pcf available, foams in five applications are highlighted.

# POSTER PROGRAM

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Fire and Polymers

June 5-8, 2022

Embassy Suites By Hilton Napa Valley

Napa, CA

## MONDAY, JUNE 6, 2022

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# POSTER ABSTRACTS

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Fire and Polymers

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1.

## SENSITIVITY ANALYSIS OF THE PYROLYSIS MODEL OF NON-CHARRING AND CHARRING MATERIALS USING MORRIS SCREENING METHOD

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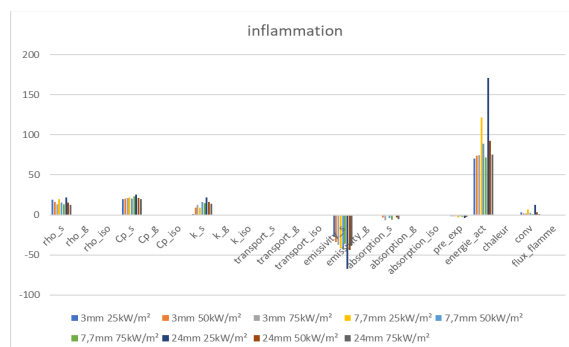
<sup>b</sup> Univ. Lille, CNRS, INRAE, Centrale Lille, UMR 8207 - UMET - Unité Matériaux et Transformations, F-59000 Lille, France

<sup>c</sup> Institut Universitaire de France (IUF)

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Sensitivity Analysis allows to determine the most influential input parameters of a numerical model. It was applied for the analysis of pyrolysis models but those methods were ‘local methods’, i.e., they do not consider the influence of a parameter in the whole domain of possibilities. Also, these methods do not highlight the possible interactions between the parameters. In this study, we propose to fill the gap by using a powerful screening method: the Morris method. We applied Morris method using the pyrolysis code, ThermaKin and we examined two materials in the conditions of cone calorimetry: the PMMA a non-charring material, and the PVC a charring one. The most influential parameters are the activation energy and emissivity. The second most influencing parameters are conductivity, heat of capacity and density. Then, the other parameters without any influence on the output parameters, like the gas properties (**Figure 1** for illustration on the influence of the input parameters on time to ignition).

The method of Morris and its advantages will be presented in detail. The results of the study will be discussed, and the focus will be on the ability of the method to methodically perform sensitivity studies and to highlight the possible interactions between input parameters.



**Figure 3:** Influence of the input parameters on the inflammation (PMMA, different thicknesses and incident heat fluxes). The result Morris method allows to distinguish the input parameters from the most influential to the lesser ones. It allows also to determine in which sense and to point out potential interactions.



2.

## Development of Computational Fluid Dynamics Models for Flame Retardant Thermoplastics in Electric Vehicle Applications

*Lei Chen, Byeongjin Baek, Scott Corneillie, Cheryl Patchett, Amol Prabhakar Avhad, Swamy SM, Han Goossens, Sreekanth Pannala*

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The rapid development of electric vehicle (EV) technology with anticipated growing electric or hybrid automotive market share [1] poses both opportunities and challenges on high-strength, lightweight, and flame retardant (FR) thermoplastic composite materials. Comprehensive computational fluid dynamics modeling approaches were developed with ANSYS Fluent and Fire Dynamics Simulator (FDS) to investigate external flame, polymer pyrolysis, intumescence and char formation, as well as the thermal and chemical interactions between fire and polymer. The polymer pyrolysis kinetic schemes were developed from thermogravimetric and calorimetric analysis of FR polypropylene samples. User defined scalars and functions were developed to model the polymer and char volume fractions, as well as the thermal property changes. The model was validated against experimental data in plaque-scale flame tests to provide insights into the behavior of FR thermoplastics with flame exposure, and can be used to predict the FR performance in thermal abuse events for EV battery packing applications.

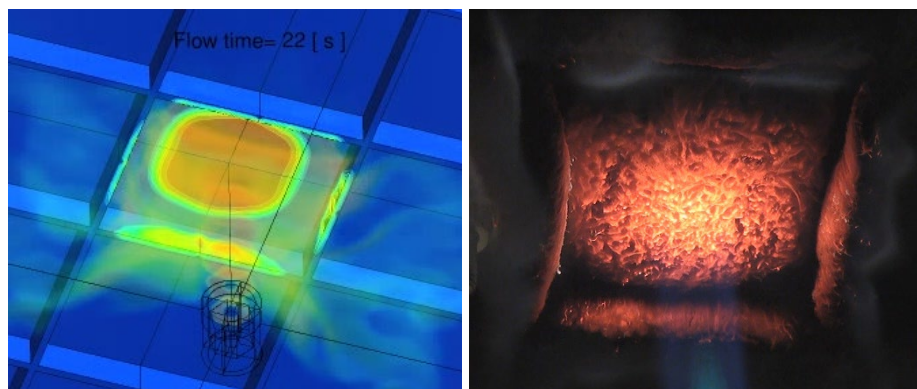


Figure: Comparison of the three-dimensional transient CFD modeling results of char volume fraction on the surface of the Flame Retardant Polypropylene (left), and the flame test experiments image (right).

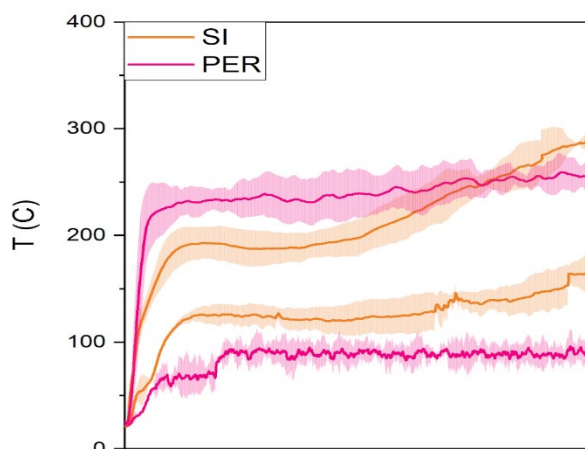
[1] Fortune Business Insights, Market Research Report ID: FBI101678, Published Feb 2021

3.

## **Tannic acid-based super-intumescent coatings for prolonged fire protection of cardboard and wood**

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Tannic acid (TA) has recently gained recognition for its application in formulating environmentally friendly fire retardants. TA-based intumescent composites (SI) were developed and evaluated against control composites containing pentaerythritol (PER), a common intumescent char-forming agent. Components of the formulation were analyzed individually to provide a necessary baseline for comparison. The components were then compounded in epoxy resin to create intumescent coatings. The SI system produces highly expansive coatings which significantly outperforms the PER system in both heat dissipation and time-to-failure. Quantitative analysis followed using cone calorimetry. TA composites displayed lower peak heat release values (211 vs. 108 kW/m<sup>2</sup>s<sup>-1</sup>), lower total heat release values (37.2 vs. 24.4 MJ/m<sup>2</sup>), and lower fire growth rates (2.43 vs. 1.27 kW/m<sup>2</sup>) relative to PER composites. To complement cone calorimetry data, a number of structural analyses were performed on the resultant char to provide a structure/property understanding. These techniques include compressive testing, XPS, BET, and Raman spectroscopy. Support from Underwriters Laboratories is gratefully acknowledged.



4.

## **Analysis of Thermal Exposure and Ignition of Western Red Cedar Subject to Glowing Firebrand Piles**

*Jacques A. De Beer<sup>a</sup>, Joseph A. Alascio<sup>a</sup>, Stanislav I. Stoliarov<sup>a</sup>, Emily L. Dietz<sup>a</sup>, Michael J. Gollner<sup>b</sup>*

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The prevalence and severity of wildland-urban interface fires leading to destruction of communities across the world has been continuously increasing. Post-fire studies indicate that firebrand exposure is responsible for a large percentage of structure losses during these wildfire events. In this work, a bench-scale wind tunnel setup was employed to analyze the mechanisms contributing to the ignition of a typical exterior structural fuel, Western Red Cedar (WRC) when exposed to glowing firebrands. Two types of ignition events were identified: direct ignition of the firebrand pile and surface ignition of the WRC board, with the WRC surface ignition event more likely to lead to further fire growth. Most of the WRC surface ignition events originated upwind from the air-flow-facing edge of the firebrand pile. Back surface temperature measurements, obtained with an infrared camera, were used to quantify the firebrand pile thermal exposure to an inert substrate using a thin ceramic fiber insulation board (Kaowool PM). Increasing the firebrand pile size increased the thermal exposure and the WRC surface ignition probability. Increasing air flow, up to 2.4 m s<sup>-1</sup>, increased the thermal exposure and the WRC surface ignition probability. Further, increases in the air flow speed decreased both quantities. This decrease was attributed to competition between an increased supply of oxygen promoting solid-phase firebrand combustion and increased convective cooling. Time-resolved CO<sub>2</sub> and CO concentration measurements were used to compute heat release rate profiles and identify the nature of the combustion process. Smoldering was found to be the dominant mode of combustion for the WRC-firebrand pile systems.

5.

## **Development of silica microfibres and application as flame retardant additives in poly(lactic acid)**

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Silane-based reactive surface modification of natural fibres is generally performed to improve the fibre-matrix interaction in polymeric composites. Surface treatment of reinforcing natural fibres was also found to effectively promote the charring and improve the fire resistance of intumescent flame retardant (IFR) systems. Nevertheless, various forms of silica-based additives have proven synergistic efficacy in phosphorus-based flame retardant systems. In this study, neat silica microfibers and silane-treated polysaccharide microfibers were prepared using a solvent-based high-speed electrospinning technique and then applied as potential synergists in the IFR system besides melamine polyphosphate to obtain flame retarded poly(lactic acid) composites. The effect of the silica microfibres, differing in dimensions and chemical composition, was comprehensively investigated based on morphological, spectroscopic and thermal analyses, flammability (cone calorimetry, LOI, UL-94) and mechanical testing of the composites.

6.

## **Experimental measurements of full-scale fire growth for fire model validation**

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A series of full-scale flame spread experiments was conducted to assess the impact of material composition on flammability response. In each test, two parallel panels, each with dimensions 2.45 m tall and 0.3 m wide, were spaced 0.3 m apart to support one of 17 unique materials with a wide range of chemical compositions and burning behaviors (charring, sooting, deformation, and ignitability). Samples were ignited at their base (60kW burner) allowing for upward flame spread. Measurement data collected in these experiments include: flame-to-surface heat flux, heat release rate, species yields, total mass loss, and visual recordings. Final datasets will be archived in a comprehensive, searchable, and freely-available database, which can be used for validation of CFD flame spread simulations. This poster provides a summary of the methodology by which these full-scale experiments were performed, how the measurement data was collected, and how this data was analyzed and processed for end-users.

7.

## **Flame retardancy investigations on composites for lightweight electric vehicle battery housings**

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The automotive sector increasingly demands safety technologies such as flame-retarded materials used for electric vehicles. Suitable materials are needed for the fire protection of a rechargeable energy storage system (REESS) - including battery, housing and control electronics - against an external source of damage such as a fuel fire outside the car, and also against internal technical failure of the REESS such as an internal fire and (in the worst case) thermal-runaway of the entire REESS. To meet the requirements, the flame retardancy of the REESS housing materials is of great importance.

Here, we report the flame retardancy behavior of thermoplastic and thermoset composites in the event of an external fire, studied by a bench-scale fuel fire test which simulates the fire treatment of the UNECE-R100-8E on component level.

8.

## **Scale-up and Testing of New Self-Extinguishing Polymer**

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We will present the scale-up and testing a new flame-resistant polymer. The issues of scale-up from laboratory scale to pre-production scale will be discussed. With the production of the polymer on the 1-kilogram scale, testing is the next priority. We will present the tests and testing involved as the polymer is scaled.



## **Combustion Kinetics of Hydrothermally Carbonized Lignocellulosic Biomass by Cone Calorimeter**

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This study focused on converting corn stover into carbon-rich biopolymer through Hydrothermal Carbonization (HTC) and evaluating the combustion kinetics in cone calorimeter at three heat fluxes (30-50 kW/m<sup>2</sup>). The biomass goes through HTC at 200, 230, and 260 °C for 30 mins. Resulting solid, also known as hydrochar, possess higher lignin but lower cellulose/hemicellulose biopolymers than biomass. The O/C and H/C ratios are significantly reduced augmenting heating value. The hydrochars are combustible at lower critical heat flux and ignition temperature. However, hydrochars also show higher ignition time and thermal response because of high lignin content. The combustion of hydrochar is mostly driven by the loss of volatile matter than the fixed carbon. Activation energy for oxidation of fixed carbon and volatile matter are significantly reduced through HTC, suggesting smoother combustion of biopolymers. The combustion of hydrochar follows first order kinetics. Hydrochars, overall, shows an increased combustibility than raw biomass.

**Keywords:** Hydrothermal Carbonization; Hydrochar; Biopolymers; Reaction Kinetics; Combustion; Cone calorimeter;

10.

## **Simple Surface Functionalization Method for Multifunctional Textiles with Flame and Vector Protection**

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Nylon-cotton (Nyco) blends are currently used in a wide range of civilian and military textile applications because of their excellent strength and abrasion resistance provided by nylon, and comfort provided by cotton. However, there is a need to address the inherent flammability of Nyco and also impart insect repellent characteristics to the fabric. Nyco has a potential fire risk because cotton fibers catch fire at relatively low temperatures (ignition point ~ 350 °C) while Nylon 66 fibers tend to melt and burn continuously, adhering to the char formed by the cotton. Currently, there are very few cost-effective and durable flame retardants (FR) and insect repellent (IR) solutions available for Nyco fabrics. A novel method to impart safer & durable flame retardant (FR) characteristics and insect repellency to Nylon-cotton blends through covalent functionalization is explored. This involves the use of a biobased phosphorus-containing compound, phytic acid which is covalently attached to hydroxyl groups in Nyco. The FR functionalized fabric is then treated with insect repellent permethrin using plasma assisted crosslinking. The surface of the functionalized fabric was characterized using Fourier transform infrared spectroscopy, the thermal analysis and FR performance of the functionalized fabric was performed using thermogravimetric analysis, microscale combustion calorimetry, and vertical flame test. The insect repellency effects of the treated fabric were also studied using a modified World Health Organization Susceptibility Test. Detailed characterization of FR performance and insect repellent characteristics of this multifunctional fabric will be discussed.

11.

## **Polymeric Coacervate Coating for Flame Retardant Paper**

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Cellulosic paper (from wood fibers) is a highly flammable material that is used in corrugated carboard, packaging, printing, and construction. While there is significant work focused on depositing a flame retardant coating onto the individual wood pulp fibers, there are very few studies that apply flame retardant coatings to already-cast paper. In an effort to improve the flame retardant properties of paper, a polymer-dense coacervate composed of polyethylenimine (PEI) and poly(sodium phosphate) (PSP) was deposited in a single step and subsequently crosslinked with glutaraldehyde. In a vertical flame test, the crosslinked PEI/PSP coacervate-coated paper achieves self-extinguishing behavior, and an average char length of 3.4 in, with only a 35% weight gain. Additionally, the crosslinked coating retains its flame retardant properties after water immersion and conditioning tests. This coacervate system is the first polymeric coating to be successfully deposited onto commercially available cellulosic paper for the purpose of flame retardancy.

12.

## **Phytic Acid-rich Flame Retardant UV-Curable Coatings for Metal Substrates**

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We propose a formulation principle to include phytic acid in organic coating resins usable on steel substrates. Phytic acid (PA), a bio-based phosphorous containing functional molecule, is highly hydrophilic in nature, and incorporation of this molecule into organic fire-retardant organic coatings is a challenging task. We developed a UV curable polymeric material, which is prepared by reacting isophorone diisocyanate with PA first, to form a poly-isocyanate that was further reacted with hydroxymethyl acrylate to form methacrylated urethane resin. These phytic acid rich urethane-acrylate coatings were chemically characterized by <sup>1</sup>H NMR, FTIR and XPS. We fabricated coatings on steel panels using these phyto-urethane-acrylate (PUA) resins via UV-curing using a photo initiator, Omnirad 1173. Coatings prepared using the PUA resin showed superior coating properties and higher glass transition temperature ( $T_g$ ) compared to that of a commercially available resins. Our preliminary studies demonstrated that PUA based coatings showed 30% lower peak heat release rate (PHRR), and augmented fire-retardant properties as compared to control coatings.

13.

## **Renewable Nanocoating for Flame-Retardant Cottonid Paper**

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Cottonid based-materials, made of 100% cellulose, have gained great interest in the bio-architecture field due to their comparable mechanical properties to wood and some technical plastics. These materials are manufactured by a parchmentizing process, in which several sheets of raw cotton-based paper (or cottonid paper) are joint together through a chemical reaction. Unfortunately, much like wood and other cellulose-based materials, cottonid is highly flammable. In an effort to reduce flammability, thin films of fully renewable and environmentally benign polyelectrolytes [chitosan (CH) and phytic acid (PA)] were deposited on cottonid paper via layer-by-layer (LbL) assembly. Only 4-bilayers of the CH/PA coating are required to achieve self-extinguishing behavior. Microcombustion calorimetry confirmed that coated cottonid paper reduces peak heat release rate and total heat release by at least 43% and 75%, respectively, relative to the uncoated control. These results demonstrate that this renewable intumescent LbL assembly provides an effective flame retardant treatment for these environmentally-friendly, climate-adaptive construction materials.

14.

## **Bioinspired Routes Towards Flame Protection of Wood-Plastic-Composites**

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To overcome problems such as environmental pollution and the release of hazardous byproducts during combustion known from typically used flame retardant additives, organisms and biological structures which have evolutionarily adapted to fire-prone habitats are considered promising candidates for the development of biogenic and bioinspired alternatives.<sup>[1],[2],[3]</sup>

Thus, synthetical polymer-based materials mimicking the composite used by wasps for nest construction were prepared by extrusion and injection molding. Various natural proteins as well as different wood species were incorporated into polymeric matrices at several loadings to investigate their influence on the polymer's combustion behavior through modified versions of common flammability tests, e.g. UL94 or B2. Furthermore, the thermal behavior of the composite materials and each individual component was determined by TG-FTIR focusing on possible synergistic effects regarding thermal decomposition. Ultimately, the morphology of the material before and after combustion as well as the structural influence on the flammability was investigated by scanning electron microscopy.

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15.

## **Synthetic papers mimicking structure, composition and flame-retardancy mechanisms of wasp papers**

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In order to find toxicologically less harmful and more environmentally friendly flame retardants, we investigate the natural flame protection mechanisms incorporated in wasp papers from different parts of the wasp nests. Throughout our investigations we separated structural and compositional influences to find and better understand biological mechanisms that are able to reduce the flammability of paper like materials.

For this, we produced biomimetic papers from wood particles of different tree species and used various commercial proteins that mimic the main component of the wasp saliva. The diversely processed papers were flame tested and investigated by TG-FTIR to classify their combustion behavior. The papers as well as their burnt residues were structurally characterized and compared with common papers and wasp papers. Thereby we confirm the influence of quantity and distribution of proteins on the flame retardancy properties of the biological blueprint.



16.

## **Bio-sourced Multilayer Nanocoating for Self-Extinguishing Nylon-Cotton Blend Fabric**

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In 2020, 7,169 clothing related burn injuries were reported in the United States with the average total treatment cost being \$73,532 per patient. Nylon-cotton blended fabric (NYCO), commonly used in military uniforms for its comfort and resilience, presents an inherent fire risk with its high flammability and high heat release. There are few effective flame retardant treatments for NYCO that are environmentally-benign and maintain the hand of the fabric. A layer-by-layer (LbL) assembled 15 quadlayer (QL) coating consisting of chitosan (CH), phytic acid (PA), and tannic acid (TA) was applied to NYCO. While individually TA and PA paired with CH are not self-extinguishing, they work synergistically in the QL system to create an effective intumescent coating. This completely bio-sourced coating self-extinguishes in a vertical burn test (ASTM D6413) with only 16.6% weight added, yielding 91.4% post-burn residue and a significant decrease in peak heat release rate. This novel coating highlights the potential of green materials to replace less environmentally-benign flame retardant treatments.

17.

## **Polymeric Materials in Under-ventilated and Vitiating Environments - An investigation into control variable sensitivity for the controlled atmosphere cone calorimeter**

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The controlled atmosphere cone calorimeter (CACC) is a bench scale apparatus addressing some of the limitations of the traditional cone calorimeter (CC) design, namely its inability to replicate later stage enclosure fires of equivalence ratio  $\geq 1$  where fire behaviour becomes ventilation controlled. Cone calorimetry provides an important link between polymer analysis and fire science. The addition of a controlled chamber offers an opportunity to examine worst case fire conditions, considering the toxic and irritant yields, for many materials. However, academic exploration on the sensitivity of control variables to collected results has been limited (both in terms of number of papers and materials explored). Therefore, this work builds upon the work of a previously published paper to examine the influence of inflow rate of air/nitrogen mixture into the CACC chamber. The current work expands on the method of oxygen reduction (flow rates causing both vitiation and under-ventilation), irradiance and fuel type. Experiments were conducted using a CACC at 30, 50 and 65 kW/m<sup>2</sup> irradiance levels. Flow rates of 5, 10 and 20 L/min were used to investigate under-ventilated conditions whilst flow rates of 100, 150 and 180 L/min were used for vitiated tests. Vitiated tests were conducted in atmospheres with 17.5 and 20.95 vol% O<sub>2</sub>. This study has broadened the investigation to include 6 mm HDPE, PMMA, plywood, as well as electric cables (EQQ [S05Z1Z1-U] B2ca in accordance with EN13501-6) and liquid fuel (isopropanol IPA-1000). The fuels represent a wide range of potential subjects for CACC experimental research.

18.

## **Acid-Doped Biopolymer Nanocoatings for Flame Retardant Polyurethane Foam**

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Soft furnishing fires contribute to 29% of fire casualties and \$8.7 billion in direct property damage annually in the United States. Polyurethane foam (PUF), a common component in soft furnishings known for its comfort and flexibility, can emit toxic gases and propagate fires due to melt dripping when ignited. Various acid salts were added to a layer-by-layer assembled nanocoating, consisting of chitosan and carboxymethyl cellulose, to improve PUF flame retardancy and to understand the influence of salt-doping on flammability. The 20-bilayer phosphoric acid-doped coating exhibits self-extinguishing behavior, with a 67% reduction in peak heat release rate, while maintaining the structural integrity of the foam. By depositing this completely environmentally-sourced coating on polyurethane foam, the inherent danger of soft furnishing fires can be significantly reduced in a non-toxic manner.

19.

## Halogen-Free Flame-Retardant Finishings for Textiles

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Among all technical textiles, fabrics with a low flammability are often desirable. Nature-based compounds, involving phytic acid or keratin, can be used for flame-retardant coatings of different textile carrier materials such as cotton, polyester/cotton blends or polyester. Both substances may be obtained from renewable or industrial waste products and were used for water-based textile coatings. Artificial and water-soluble flame retardants, synthesized from cyclophosphazene, also enable waterborne textile finishings. Since nylon-cotton blends are known to be challenging substrates regarding their flame-retardant functionalization and its durability, Nyco was finished with two different cyclophosphazene derivatives. An extensive investigation of the flame-retardant performance and mechanism of the different textile finishings and coatings was conducted.

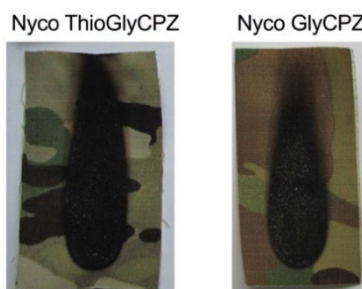


Figure 1. Flame tests of washed samples (10 times at 80 °C), according to ISO 15025.

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