Novel Exposure and Toxicological Methods to Assess Thermal Decomposition and Associated EHS Implications of NEPs

Georgios A. Sotiriou[1]

Dilpreet Singh[1], Fang Zhang[1], Wendel Wohlleben[2] and ***Philip Demokritou[1]***

[1]Department of Environmental Health, Center for Nanotechnology & Nanotoxicology, School of Public Health, Harvard University, 665 Huntington Avenue, 02115 Boston, MA

[2]BASF AG, Ludwigshafen, Germany

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- NSF (grant nr. 1436450 and 1235806)
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SWISS NATIONAL SCIENCE FOUNDATION

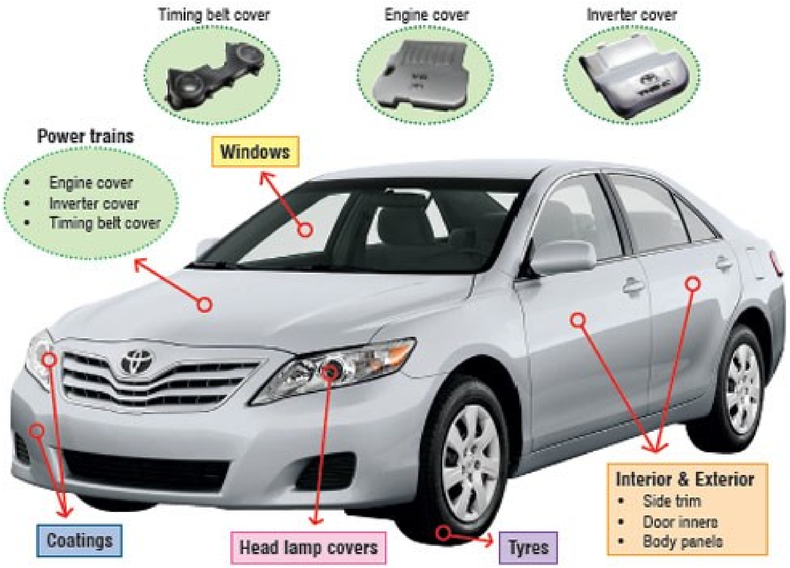
Outline

- I
- Development of "Novel Exposure and Toxicological Methods to Assess Thermal Decomposition and Associated EHS implications of NEPs
- Present preliminary case studies for industry relevant NEPs

Nano-enabled products (NEPs)

- Products that use/incorporate engineered nanomaterials (ENMs)
- Superior performance vs. micron-sized components
  - Increased strength
  - Optoelectronics
  - Antibacterial activity

- Example: Polymer thermoplastic nanocomposites (NCs)[1]
  - Automotive
  - Food Packaging
  - Building materials



[1] BASF Report 2011: Economic, environmental and social performance (2011).

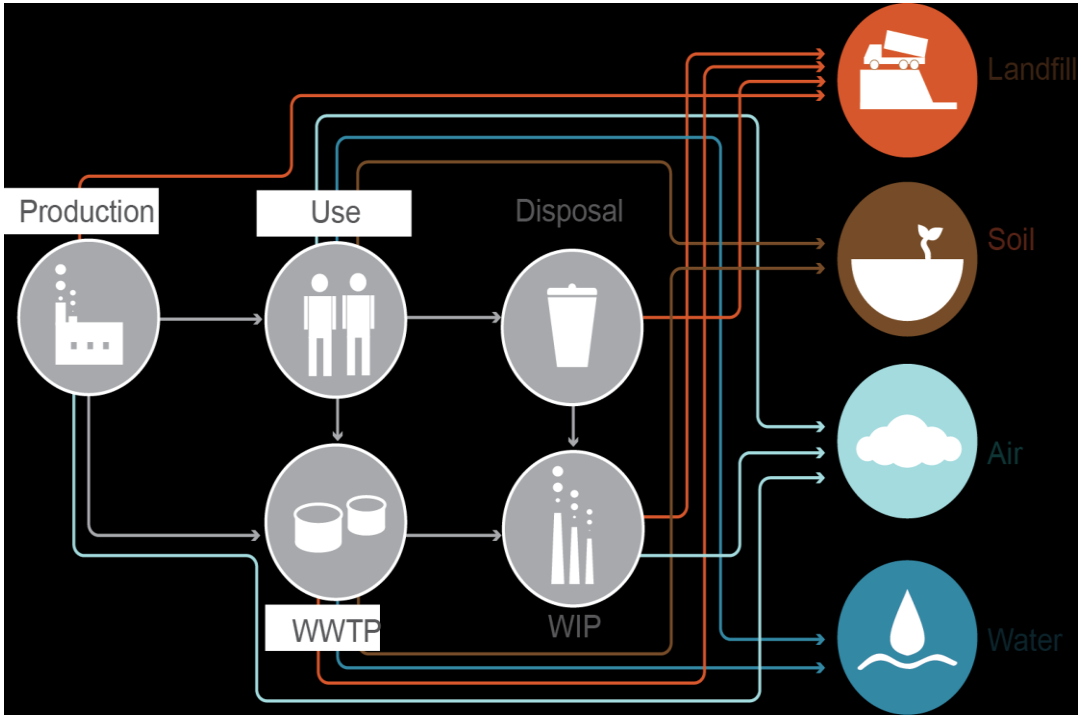
Challenge #1: ENM Production Estimates?

ENM	Future Markets, Inc.[a] Global 2010	Future Markets, Inc.[a] US 2010	Future Markets, Inc.[a] Switzerland 2010	European Commission Global 2010	Piccinno et al. (2012) Global[b] (circa 2011)	Hendren et al. (2011) US (circa 2010)	Gottschalk et al. (2010) Switzerland[c] (several dates)
Ag	360 - 450	180 - 225	3.6-4.5	22	55 (5.5–550)	2.8-20	[1.1][2.3][1.7]
Al_2O_3	18,500 - 35,000	9,250 - 17,500	97 - 183	200,000	55 (55–5,500)		
Carbon Black				9,600,000			
CeO_2	7,500 - 10,000	3,750 - 5,000	39 - 52	10,000	55 (5.5–550)	35-700	
CNT	2,916 - 3,200	1,458 - 1,600	15- 17	500	300 (55–550)	55-1,100	[1.9][2.6][1.2]
Cu	22 - 200	11 -100	0 - 1				
Fe	33,000 - 42,000	16,500 -21,000	173 - 220	100	55 (5.5–5,500)		
Nano-clays	9,200 - 10,400	4,600 - 5,200	48 -55				
SiO_2	82,500 - 95,000	41,250 -47,000	432 - 498	1,500,000	5,500 (55–55,000)		
TiO_2	83,500 - 88,000	41,750 44,000	438 – 461	10,000	3,000 (550–5,500)	7,800-38,000	[114][240][195]
ZnO	31,500 - 34,000	15,750 -17,000	165 - 178	8,000	550 (55–550)		

[b]Median and the 25/75 percentile
[c]Mode, mean and standard deviation

Keller and Lazareva, ES&TL, 2014

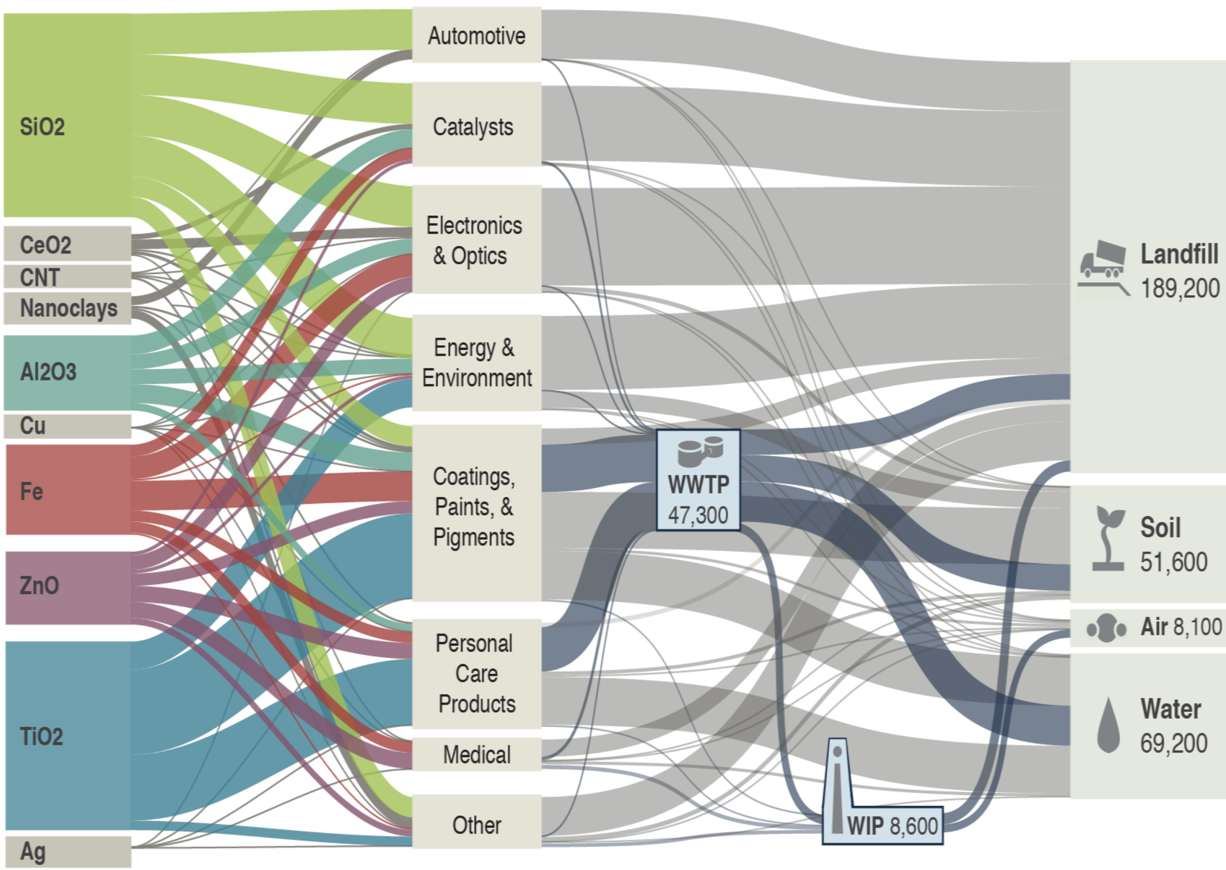
Challenge #2:
Life-cycle considerations of ENMs across value chain and life cycle



- ENM properties change in both value-chain, and **across life cycle of NEPs**
- Limited data on ENM release across LC
- Fragmentary exposure data for both env. media and human populations

Keller and Lazareva, ES&TL, 2014

Nano-waste crisis-
Released ENMs from major apps across life cycle?



- ❑ 60-80 % of ENMs end up in landfills
- ❑ 190,000 m tons/yr of ENMs in landfills
- ❑ 9,000 m. tons/yr in WIP
- ❑ Two apps contribute the most in releases in Env. Media:
  - ❑ Personal care products
  - ❑ Coatings, paints etc

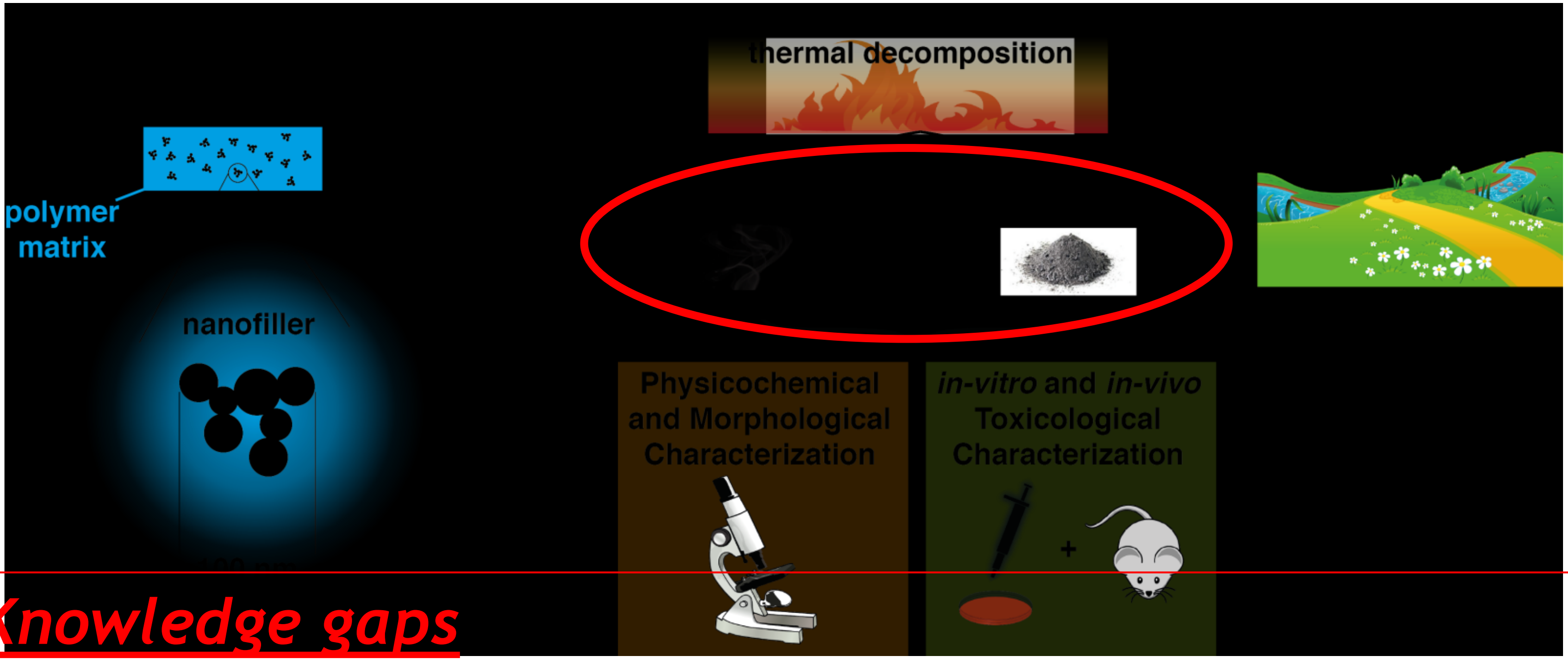
[redacted]

Keller and Lazareva, ES&T, 2014

Outline

- Introduction
- [illegible]
  - Present case studies for thermoplastic based NEPs

Thermal decomposition of NEPs: Possible EHS implications?



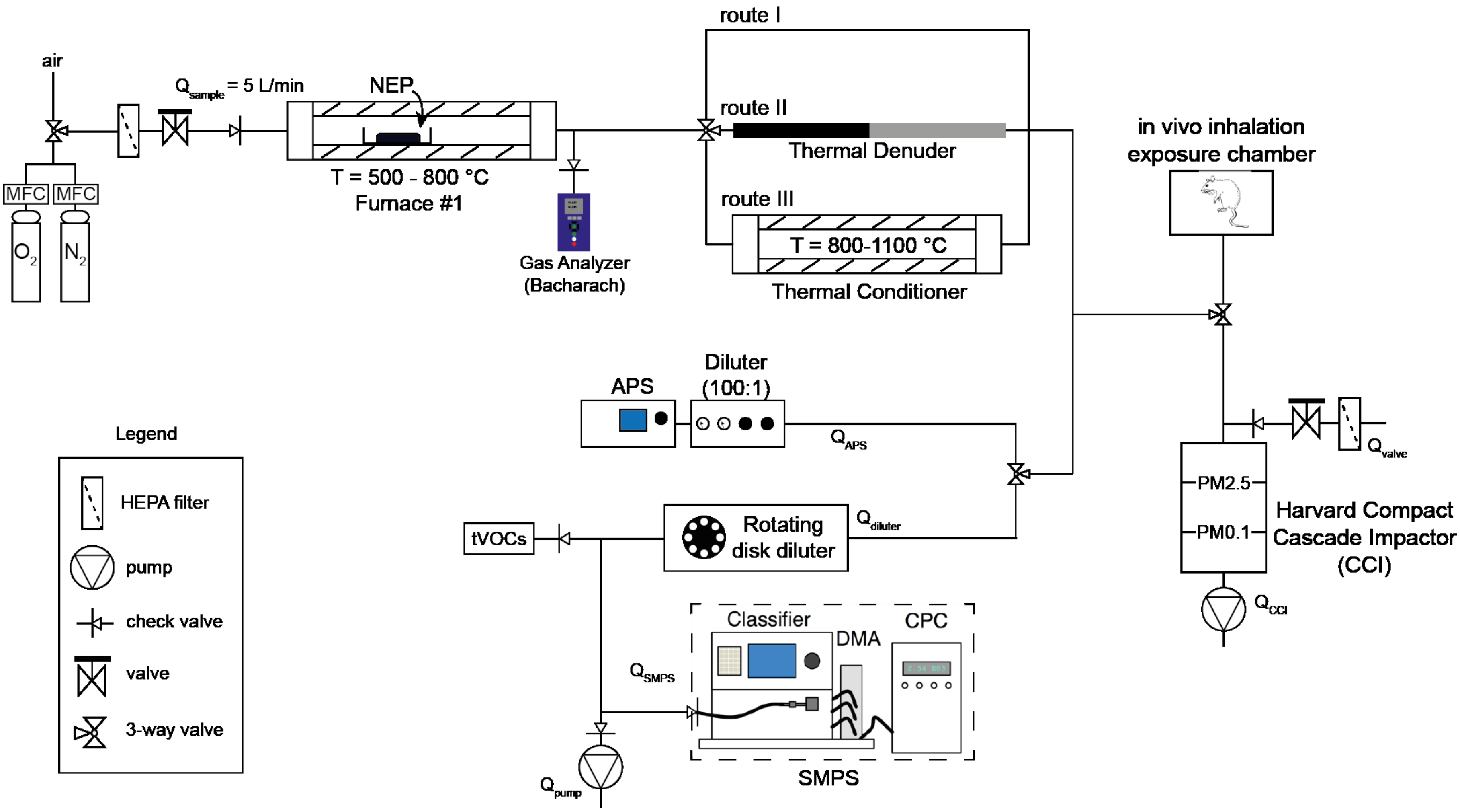
Knowledge gaps

- Lack of a standardized methodology to assess TD of NEPs
- Nanofiller release in the air ?
- Exposure ID: Physico-chemical composition of released aerosol and residual ash
- Fate and transport of by products in env media?
- Link released byproducts to Toxicology and EHS

Project: Thermal decomposition of NEPs- Possible EHS implications

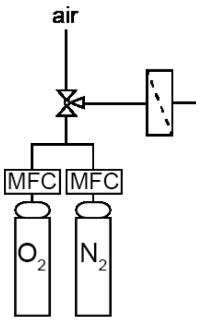
TASK 1	Development Integrated Exposure Generation System for the EHS Characterization of Incinerated NEPs	
TASK 2	Detailed Physicochemical and Morphological Characterization of Byproducts (Released Aerosol **AND** Residual Ash) of Industry Relevant NEPs	
TASK 3	Assessment of EHS Implications of Byproducts (Released Aerosol **AND** Residual Ash)	
	in-vitro and in-vivo Toxicological Characterization	Fate and Transport of Residual Ash in Environment
TASK 4	Safer-by-design Nano-Enabled Products	

Integrated Exposure Generation System (*INEXS*)



Sotiriou et al., ES: Nano, 2015

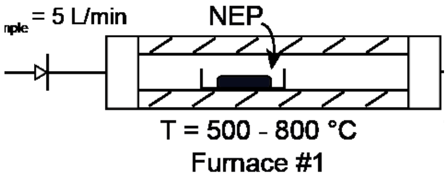
Integrated Exposure Generation System (*INEXS*)



- **controlled combustion conditions (O_2/N_2 ratio)**

Integrated Exposure Generation System (*INEXS*)

- **controlled temperature**



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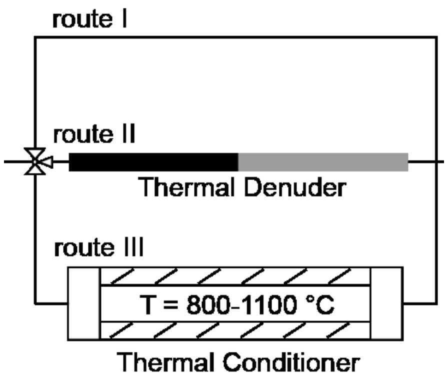


- Thermal denuder (route II) to remove S/VOCs
- Thermal conditioner (route III) to simulate incineration facilities (3s residence time at higher temperatures)

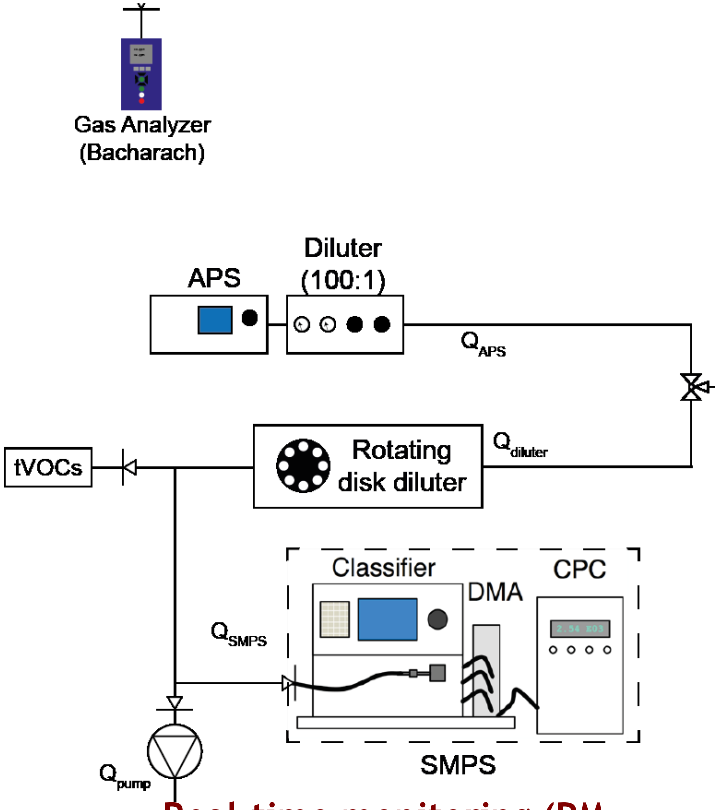
- controlled atmosphere (O_2/N_2 ratio)

Integrated Exposure Generation System (*INEXS*)

- thermal denuder (route II) to remove S/VOCs
- thermal conditioner (route III) to simulate incineration facilities

- controlled temperature

- controlled atmosphere (O_2/N_2 ratio)



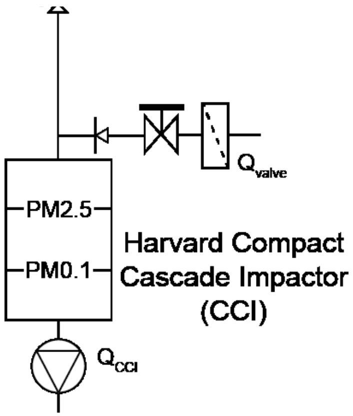
- Real-time monitoring (PM size, concentration, gases, tVOCs)

Integrated Exposure Generation System (*INEXS*)

- thermal denuder (route II) to remove S/VOCs
- thermal conditioner (route III) to simulate incineration facilities

- controlled temperature

- controlled atmosphere (O_2/N_2 ratio)



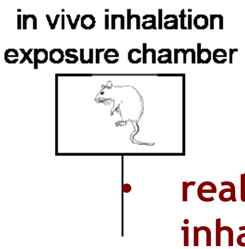
- Sampling of size-fractionated PM
- PCM and in-vitro characterization of PM

- real-time monitoring (size, concentration, gases, tVOCs)

Integrated Exposure Generation System (*INEXS*)

- thermal denuder (route II) to remove S/VOCs
- thermal conditioner (route III) to simulate incineration facilities

- controlled temperature



- real-time in situ inhalation studies

- controlled atmosphere (O_2/N_2 ratio)

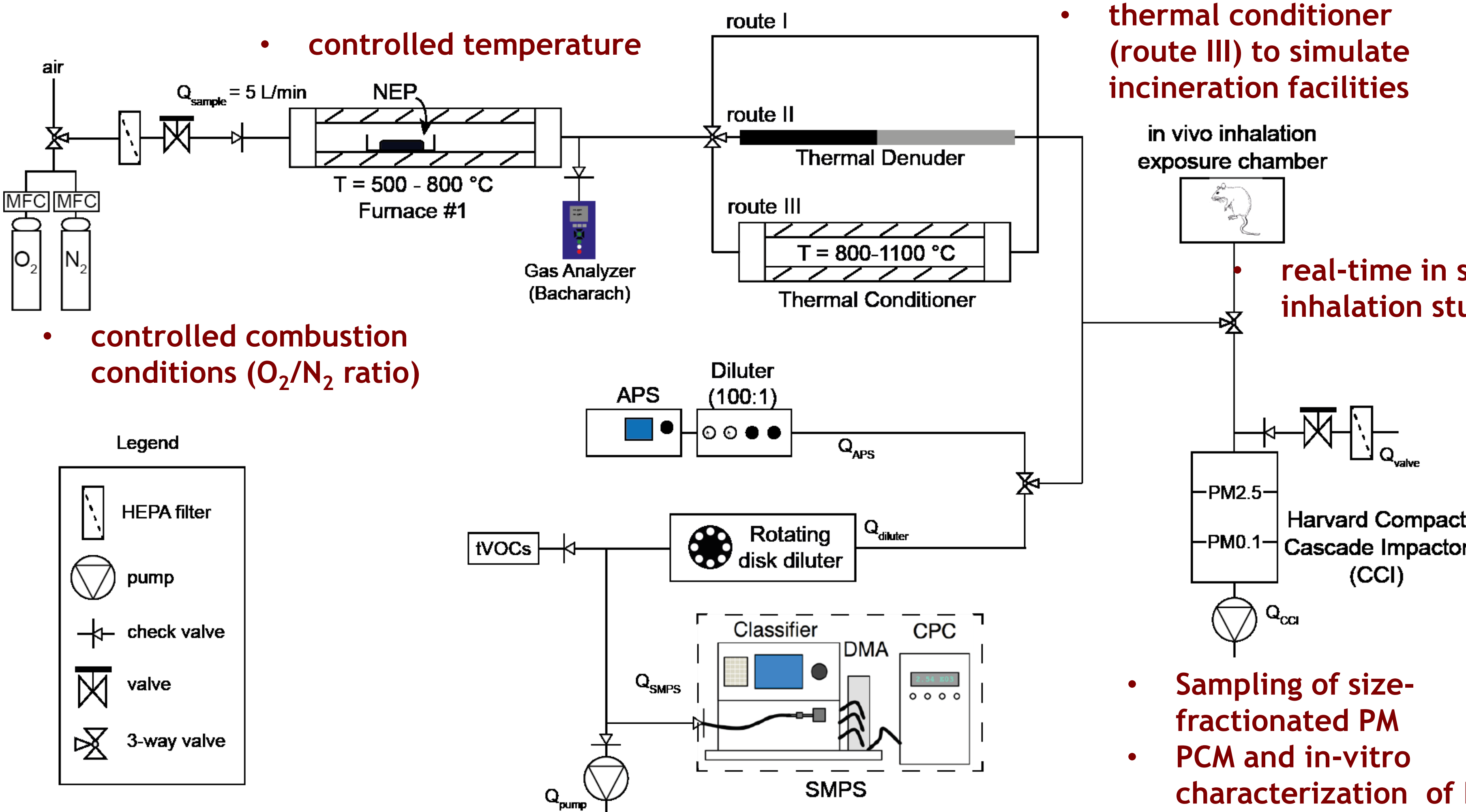
- real-time collection of size-fractionated PM

- real-time monitoring (size, concentration, gases, tVOCs)

Integrated Exposure Generation System (*INEXS*)

- thermal denuder (route II) to remove S/VOCs
- thermal conditioner (route III) to simulate incineration facilities

- controlled temperature

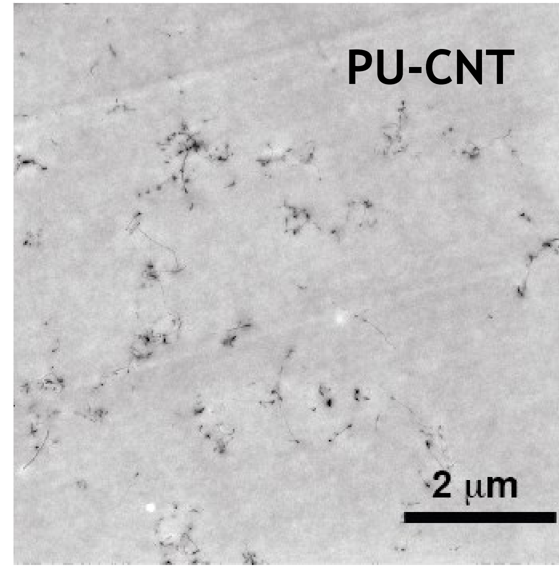


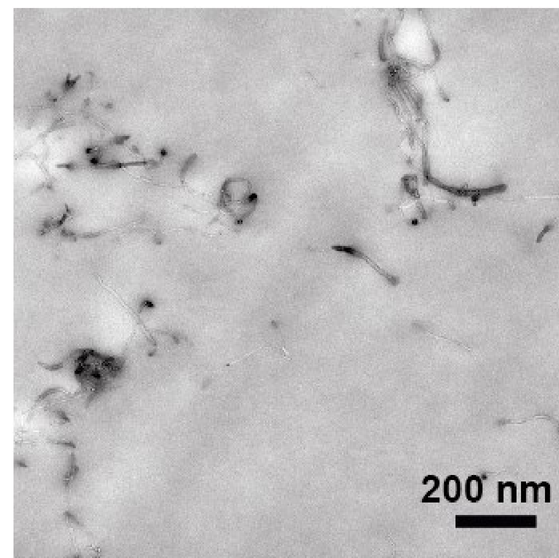
- real-time in situ inhalation studies
- controlled combustion conditions (O_2/N_2 ratio)
- Sampling of size-fractionated PM
- PCM and in-vitro characterization of PM
- real-time monitoring (size, concentration, gases, tVOCs)

Sotiriou et al., ES: Nano, 2015

Industry relevant NEPs

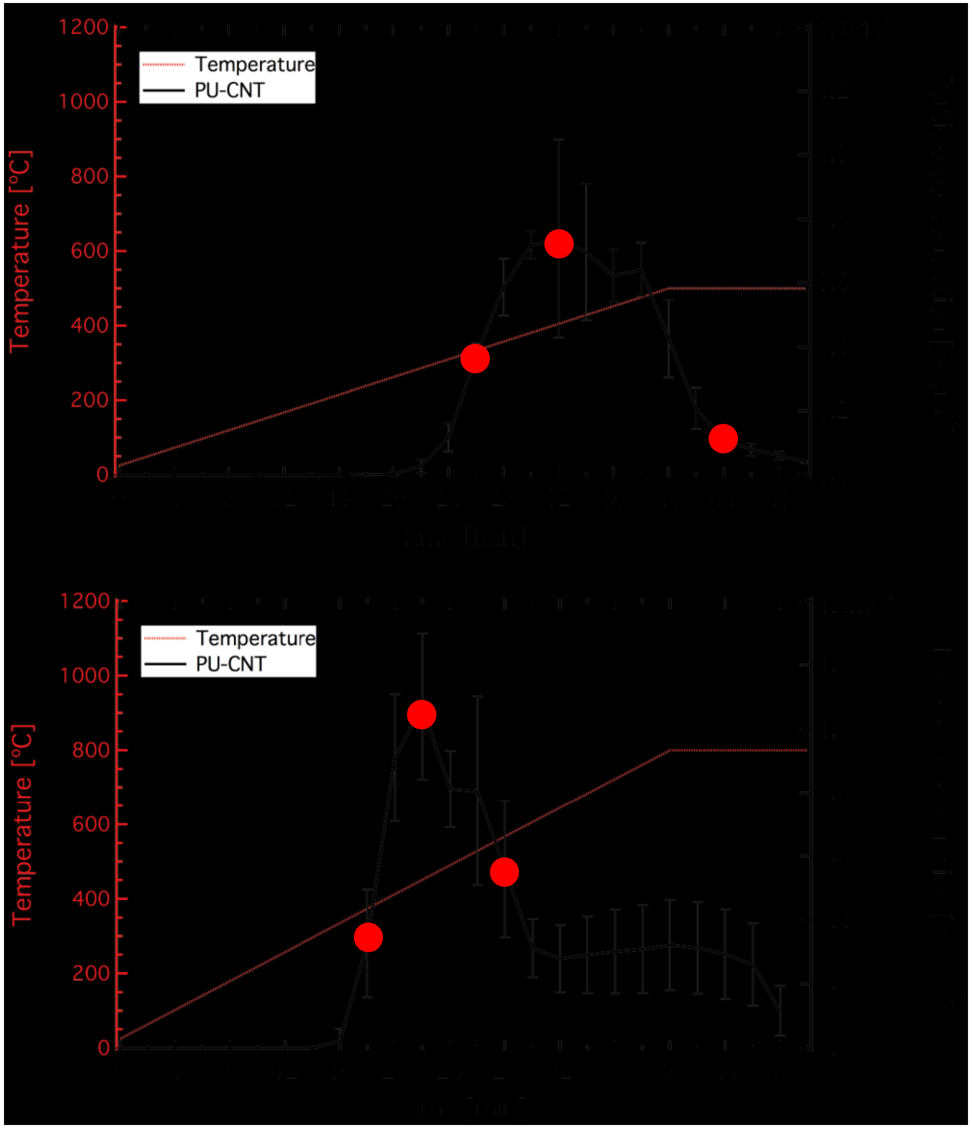
	Matrix	nanofiller	nanofiller loading	application
MARINA	Polyurethane (PU)	-	-	automotive, buildings, textiles
		carbon black (CB)	0.1%	
		carbon nanotubes (CNT)	0.1%	
BASF	Polyethylene (PE)	-	-	packaging, buildings, constructions
		Fe_2O_3	1-5%	
		organic filler	2%	
		organic filler + UV agent	2%	
U Mass	Polycarbonate (PC)	-	-	automotive, electronics
		CNT	3%	
	Polypropylene (PP)	-	-	packaging, electronics
		CNT	3%	
	Ethylene vinyl acetate (EVA)	-	-	packaging, biomedics
		TiO_2	1-15%	
	Medicinal waste	Ag		biomedics

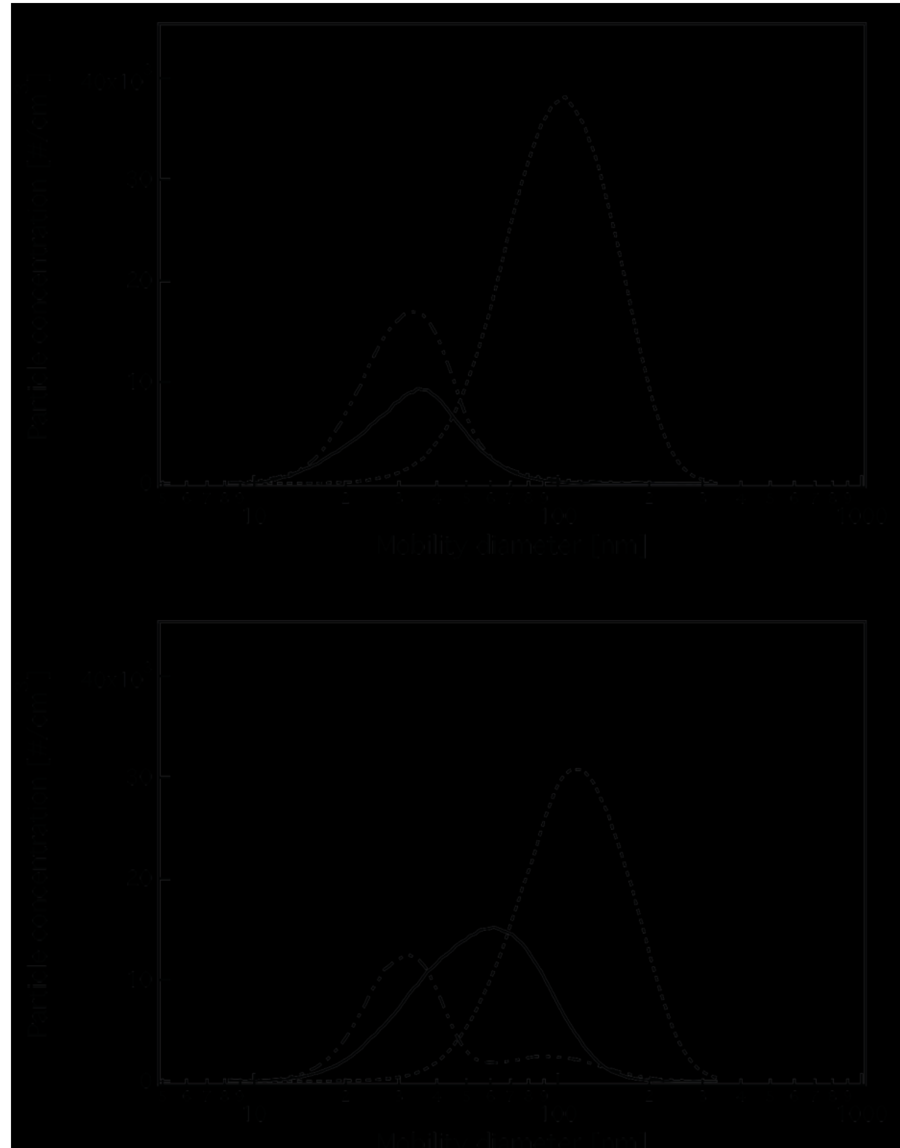




MARINA: **Ma**naging **Ri**sks of **Na**nomaterials (FP7-EU project)

Released aerosol concentration and size (PU-CNT)

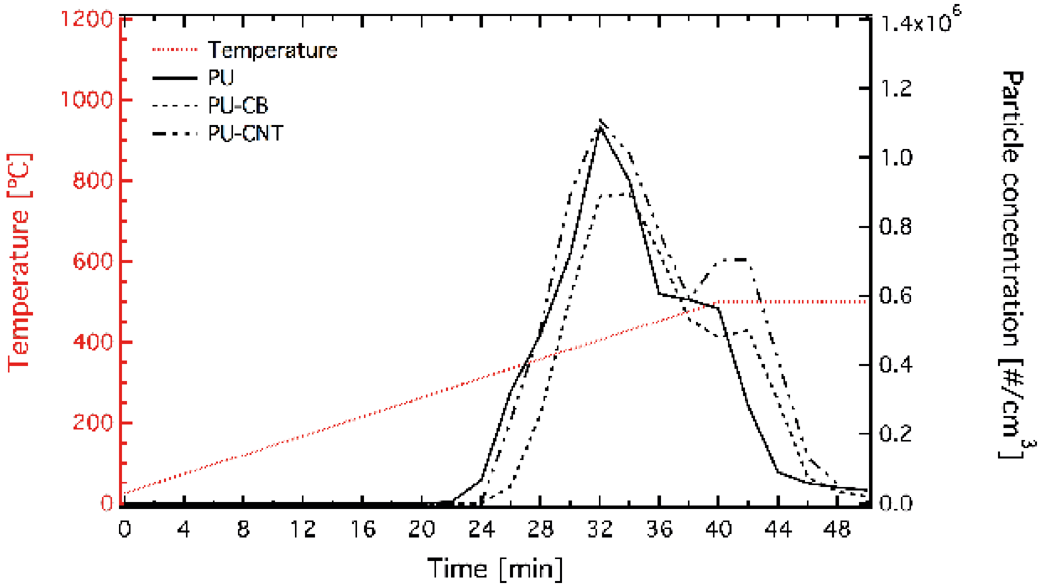


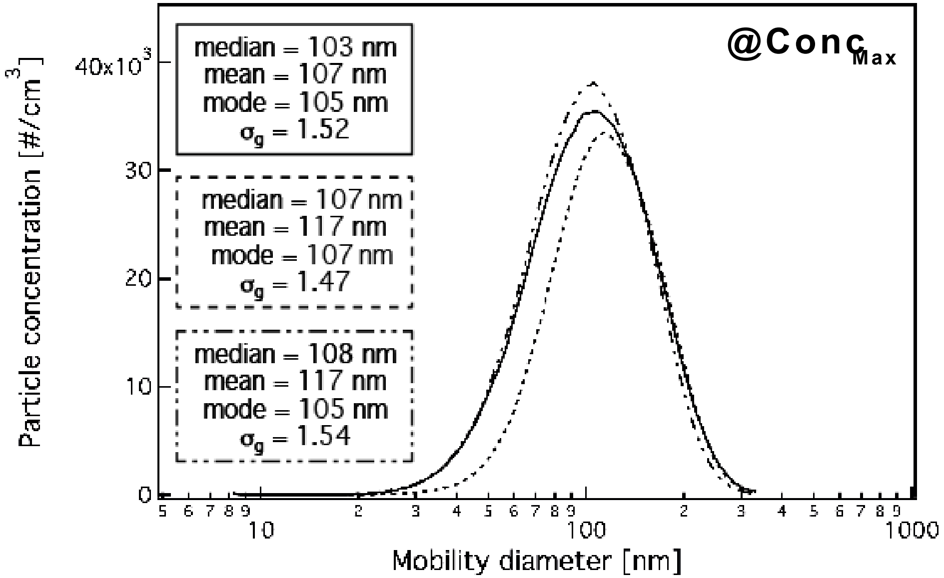


- route 1 (no treatment)

$T_{d,final}$: final thermal decomposition temperature

Does the presence of nanofiller influence the released aerosol concentration & size?





- PU-based NEPs
    - Pure and with two different nanofillers
- Route 1 at 500 °C

RESULTS

- No effect on released aerosol concentration and size due to the nanofiller presence
- Host polymer dictates the released PM

Does the presence of nanofiller influence the chemistry of the released aerosol for carbon based NEPs?

	500 °C		800 °C	
	EC (%)	OC (%)	EC (%)	OC (%)
PU	0.8	99.2	0.8	99.2
PU-CB	0.8	99.2	0.8	99.2
PU-CNT	0.8	99.2	0.8	99.2

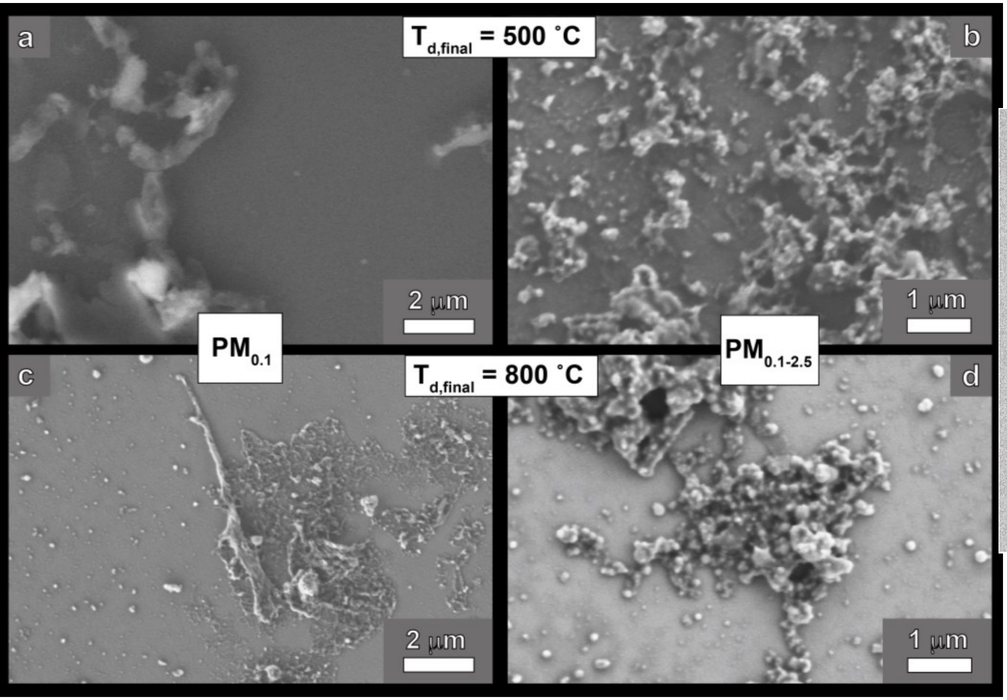
- **Elemental/Organic Carbon (EC/OC) of $PM_{0.1}$**
  - Released aerosol consists primarily of organic carbon ***independent*** of nanofiller
  - No specific nanofiller-related effect forinvestigated NEP compositions and conditions
- **Host polymer matrix dictates the chemical composition of the released aerosol**
  - Different compositions/TD conditions may have different effects
- **TD of polymers generates various organic byproducts[1,2]**
  - Polydispersed aerosols, Aromatic, aralkyl, cycloaliphatic gaseous co pollutants

[1] Matuszak, Frisch. *J. Polym. Sci. Pol. Chem.* **11**, 637 (1973).

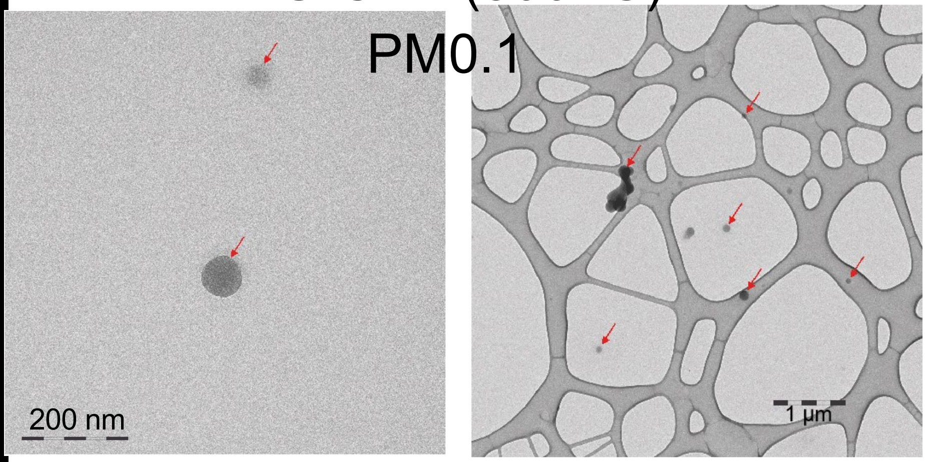
[2] Sotiriou et al., ES: Nano, 2015

Is there "nanofiller" release in the air (1/2)?

- **PU-CNT**



PU-CNT (800 ˚C)
PM0.1



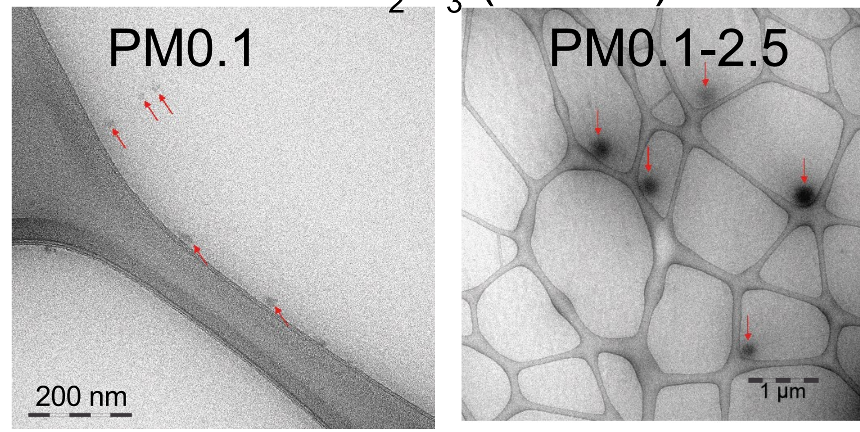
- No CNTs in the released aerosol for both size fractions and temperatures

Sotiriou et al., ES: Nano, 2015

Is there a "nanofiller" release in the air (2/2)?

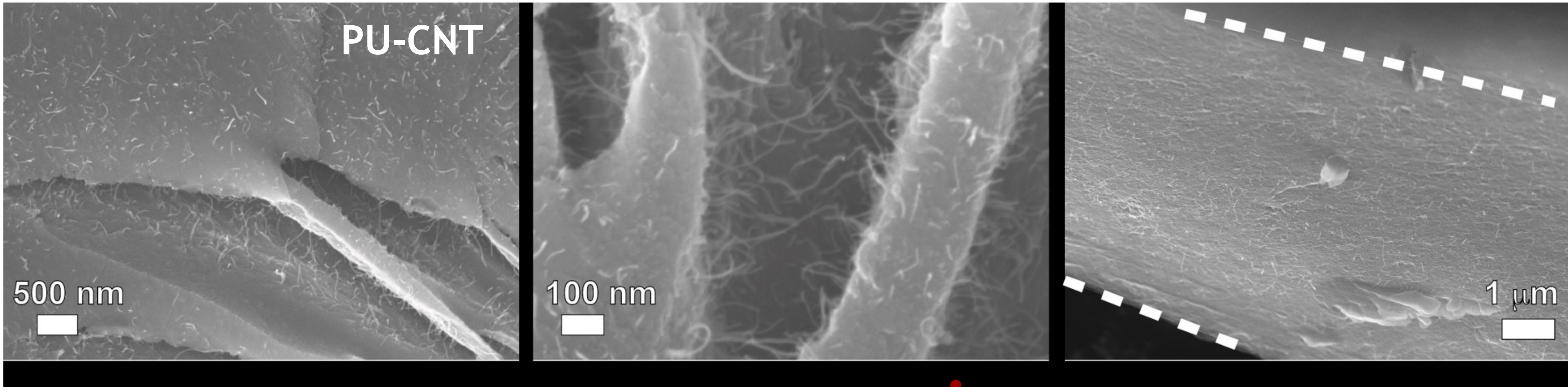
- Is there Fe in the released aerosol?
  - 0.004 % Fe for $T_{d,final}$ = 500 ˚C
  - 0.026 % Fe for $T_{d,final}$ = 800 ˚C

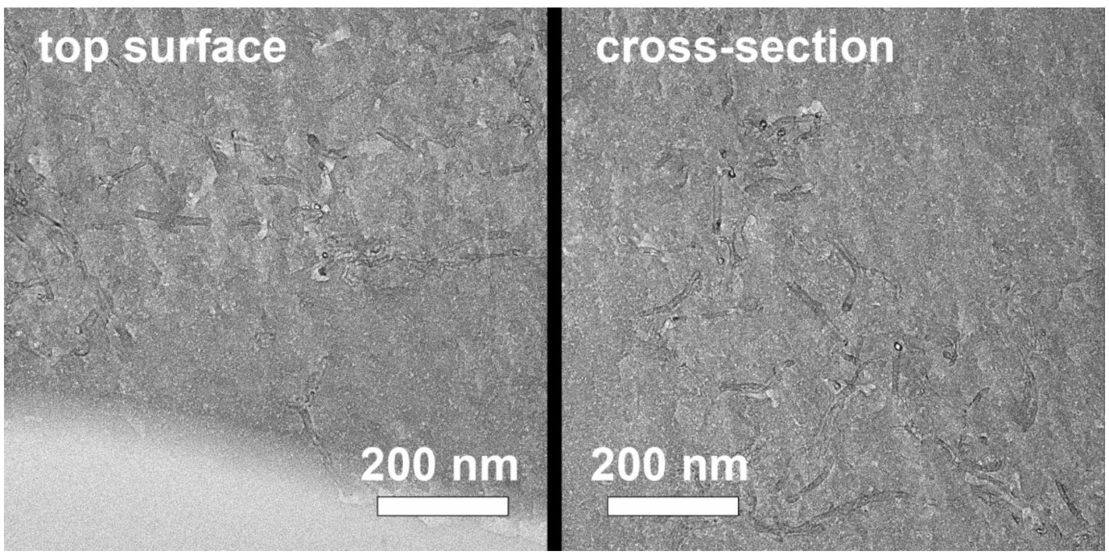
$PE\text{-}Fe_2O_3$ (800 ˚C)



- Release of nanofillers in the air is more likely for the case of inorganic nanofillers (Me/MeOx)

Nanofiller in the residual ash?



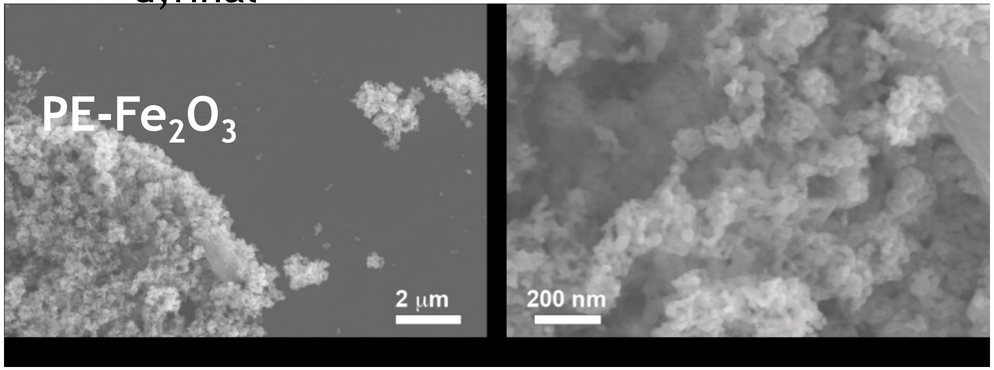


Sotiriou et al., ES: Nano, 2015

- CNTs present in residual ash only for 500 C
- CNTs are homogeneously dispersed throughout the ash
- 18 times higher concentration than pure polymer
- Thermal degradation of polymer results to brittle material with surface bound CNTs

Effect of nanofiller on residual ash composition: Case studies - PE and PU NEPs

- $T_{d,final}$ = 500˚C (PE-/nep



	500 ˚C	
	EC (%)	OC (%)
PE	78	22
PE-org	75	25
PE-Fe_2O_3	-	-

- Presence of Fe_2O_3 facilitates full polymer decomposition
- Catalytic effect of Fe2O3 or more efficient heat dissipation?

- $T_{d,final}$ = 500˚C (PU-/nep

	500 ˚C	
	EC (%)	OC (%)
PU	85	15
PU-CB	77	23
PU-CNT	82	18

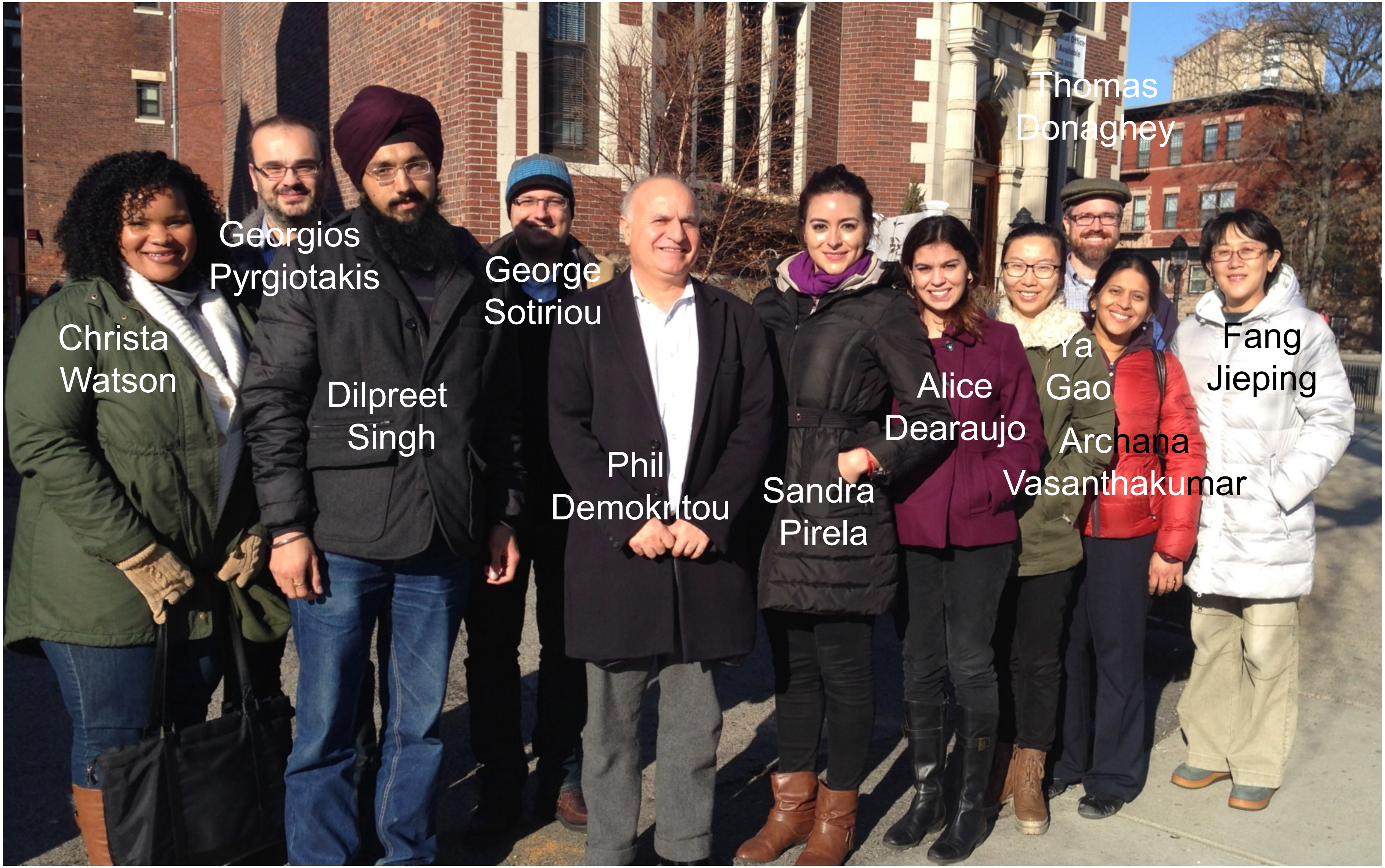
- No chemical changes of ash due to nanofiller presence

Summary

- INEX is a versatile integrated exposure generation system which enables systematic assessment of thermal decomposition of NEPs and associated EHS implications
- The properties of the ***released aerosol*** are dictated by the host polymer matrix
- No release of CNTs for the conditions investigated
- Most likely to have release of ENMs in the air for the case of inorganic nanofillers (Me/Mex)
- Nanofiller mostly remains in ***residual ash***
  - Presence of nanofiller influences residual ash morphology and composition
  - Nanofillers are not strongly held together due to the degradation of the polymer
  - This raises concerns in terms of Fate and transport of byproducts in the environment

Ongoing studies

- Study the thermal decomposition of industry relevant families of NEPs under incomplete combustion scenarios
- Assess the toxicological properties of released aerosol and ash
- Assess the fate and transport of byproducts in environmental media


Thomas Donaghey
Georgios Pyrgiotakis
George Sotiriou
Christa Watson
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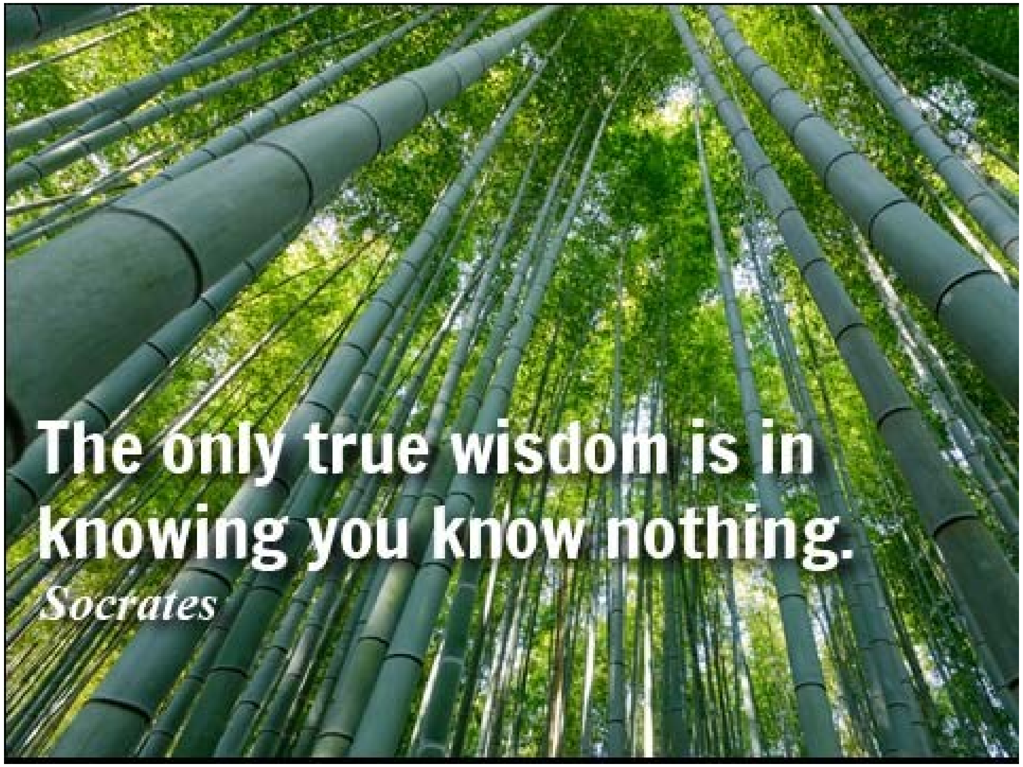
Phil Demokritou
Sandra Pirela
Alice Dearaujo
Ya Gao
Archana Vasanthakumar
Fang Jieping

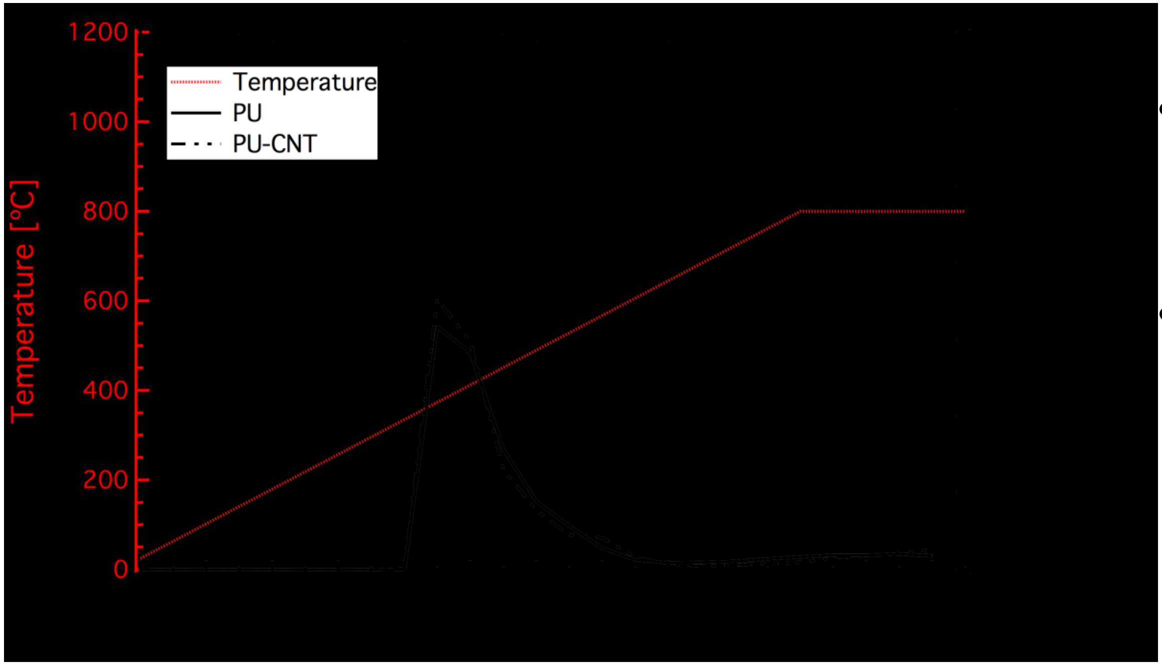

The only true wisdom is in knowing you know nothing.
Socrates

THANK YOU!

Released aerosol & residual ash: Knowledge gaps

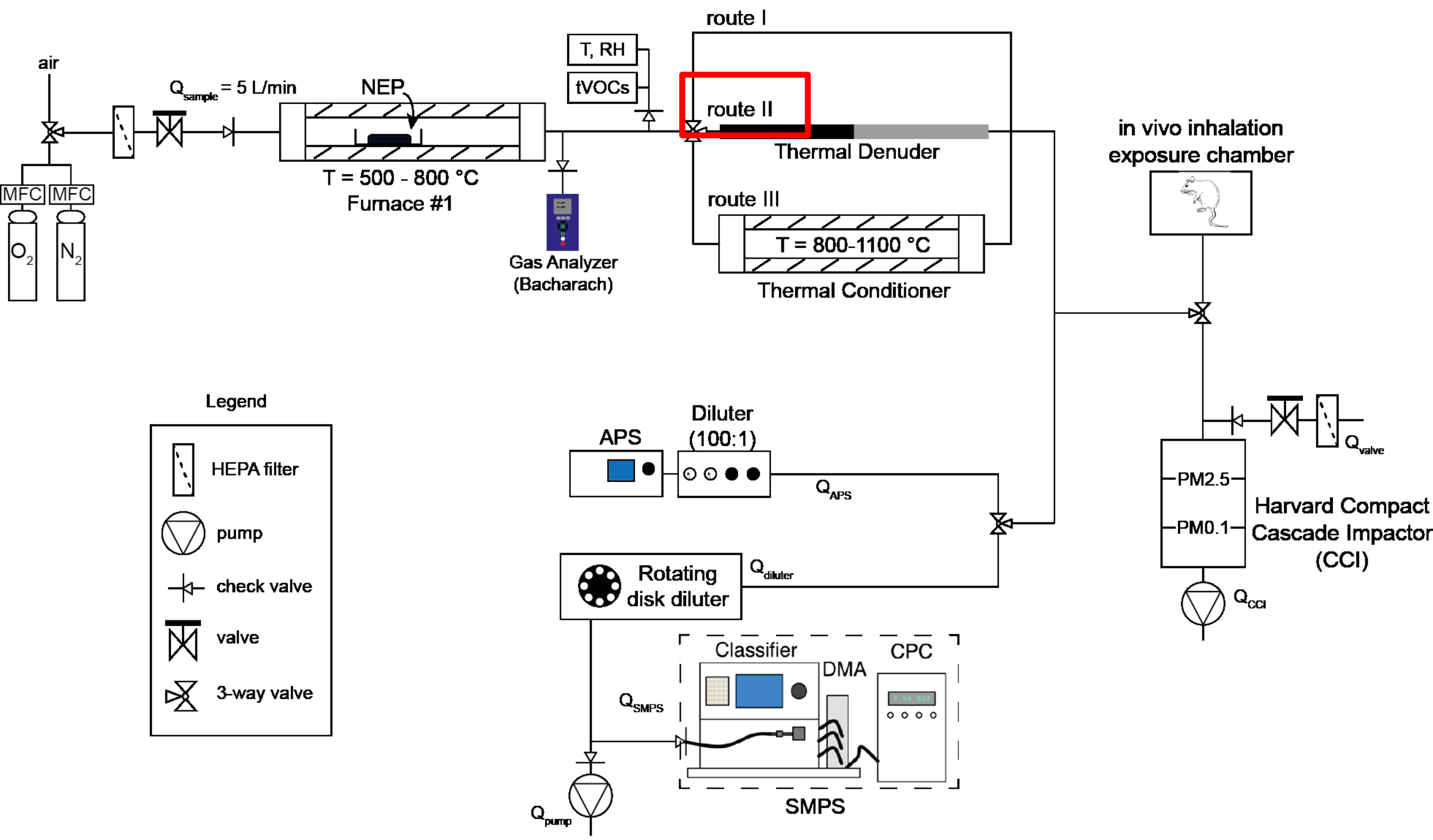
1. What are the physicochemical and morphological properties of the released aerosol during TD of industry relevant NEPs?
2. Are any nanofillers released from NEP and under what TD process conditions ?
3. How does the presence of s/VOCs from combustion of matrices used in the synthesis of NEPs influence the released aerosol chemical composition and toxicity?
4. What is the physicochemical and morphological characterization of the residual ash ? Are there nanofillers remained in the residual ash after TD and at what concentration and condition?
5. How does the properties of nanofillers and matrices used in the synthesis of NEPs influence the physicochemical,morphological and toxicological properties of the byproducts
6. What is the toxicological profile of the released aerosol and the residual ash? Is there a nanofiller-specific effect?
7. What is the fate and transport of the residual ash in the environment?

Released aerosol during thermal decomposition of PU-CNT



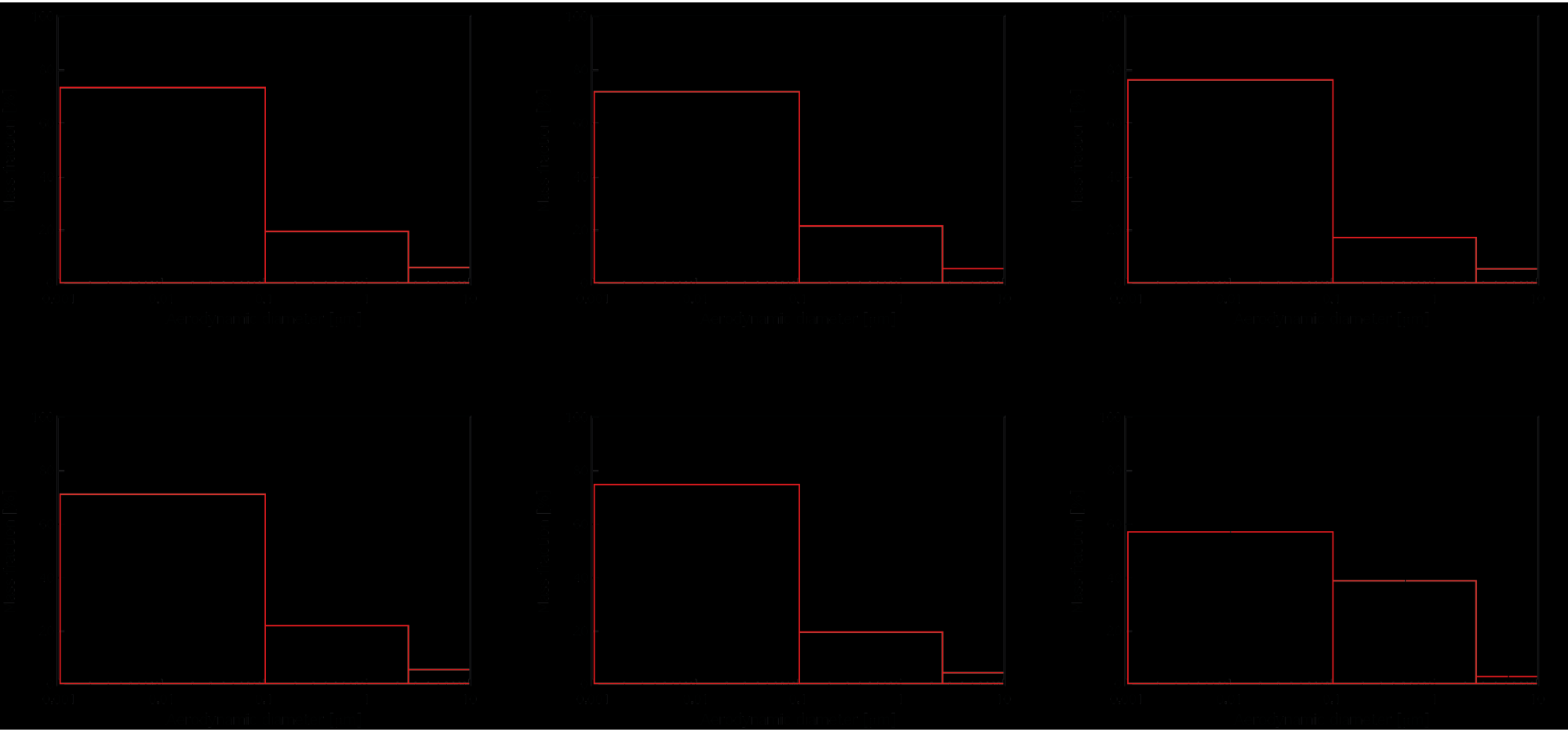
- Released aerosol passing through thermal denuder (**ROUTE 2 @ 800˚C**)
- Similar aerosol release independent of nanofiller presence

Experimental setup

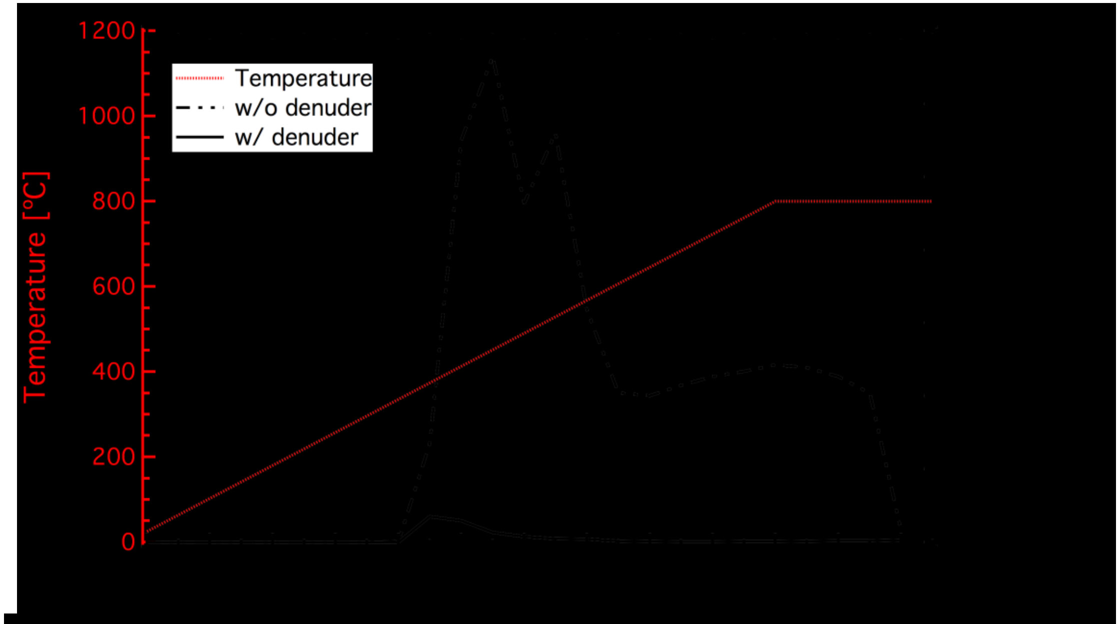


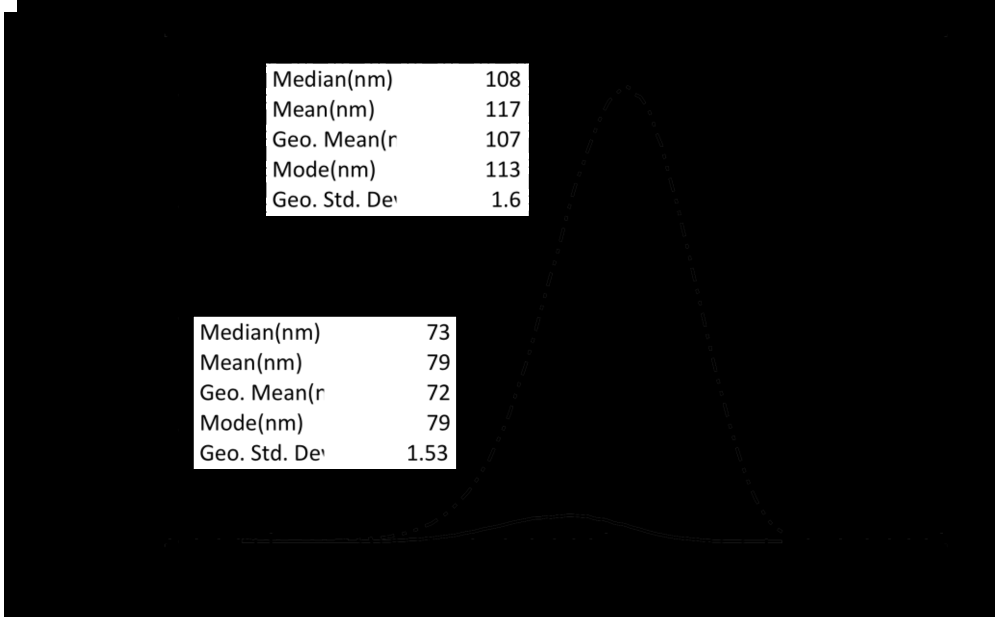
Mass particle size distributions (route 1)

500 ˚C **PU** **PU-CB** **PU-CNT**



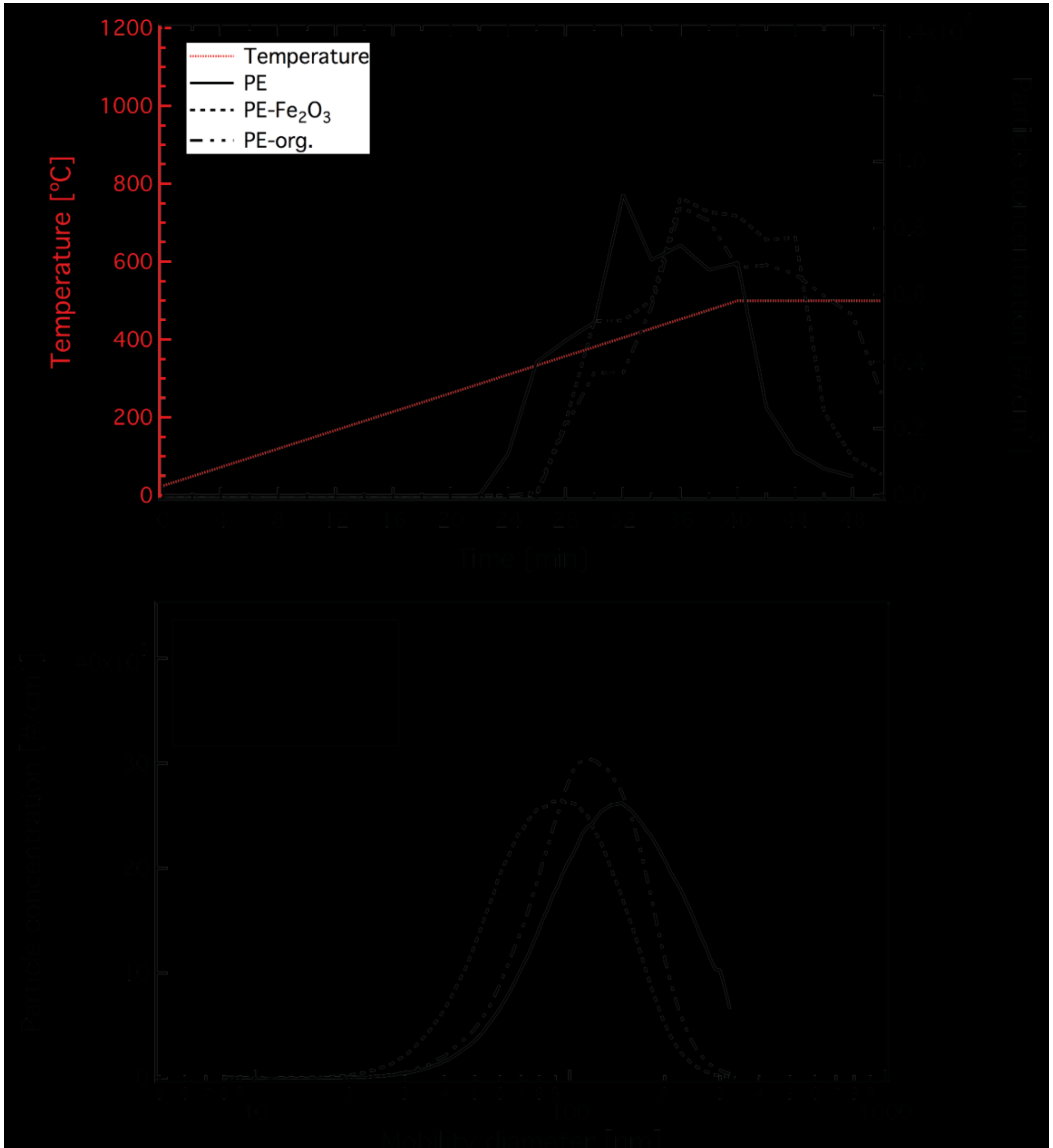
Released aerosol during thermal decomposition of PU-CNT





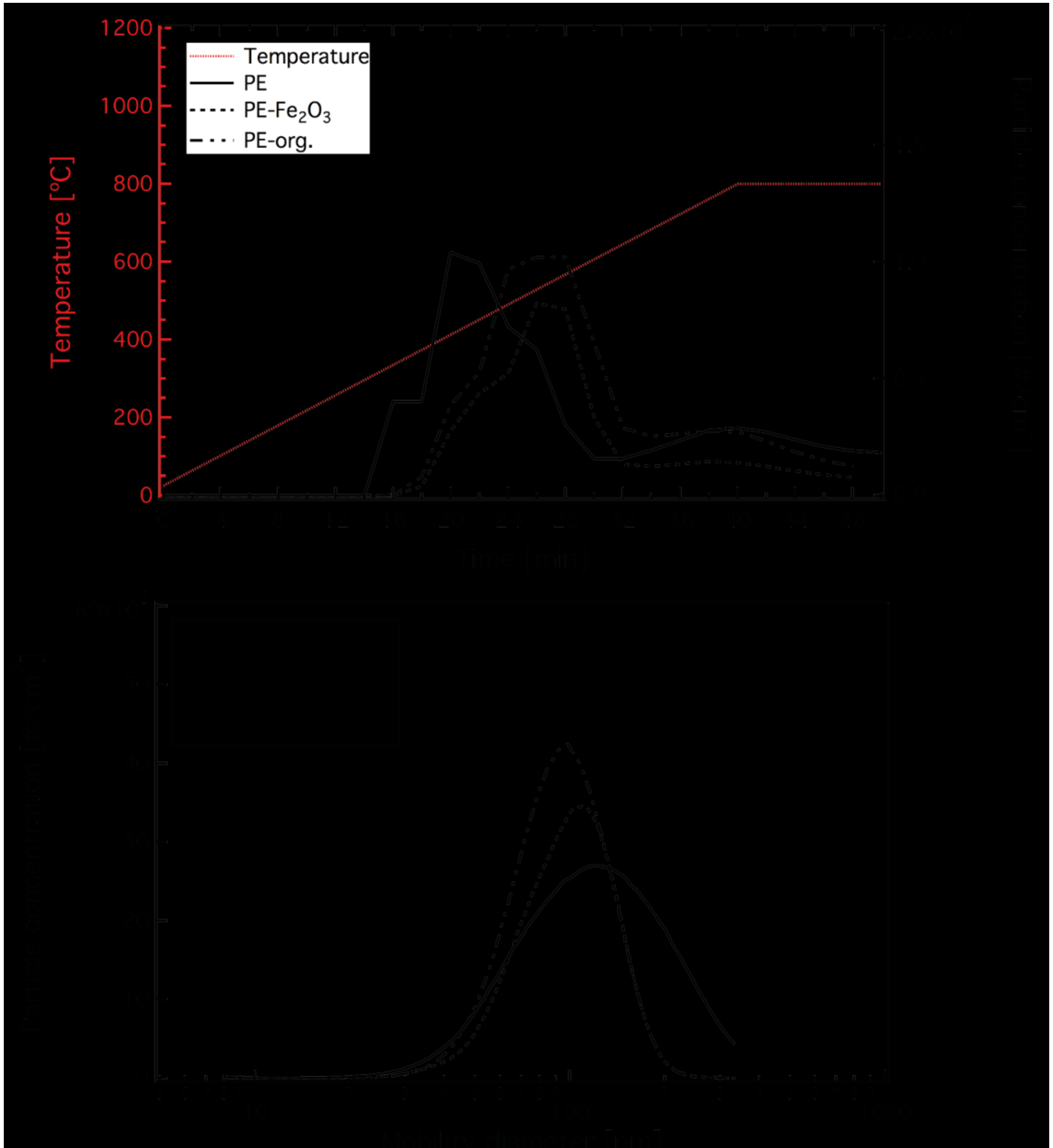
- Released aerosol passing through thermal denuder (**ROUTE 2 @ 800˚C**)
- Less particles in the released aerosol through denuder
  - Smaller
- Denuder removes S/VOCs (semi/volatile organic compounds)

Released aerosol during thermal decomposition of PE



- **ROUTE 1**
- **All three** PE-based polymers
  - Pure
  - PE-Fe_2O_3 (5 wt%)
  - PU-Org. filler (2 wt%)
- Dilution factor = 100
- T_{max} = 500˚C
- Sample (**~100 mg**) decomposition starts ~400˚C
- Similar size distributions and concentrations independent of nanofiller

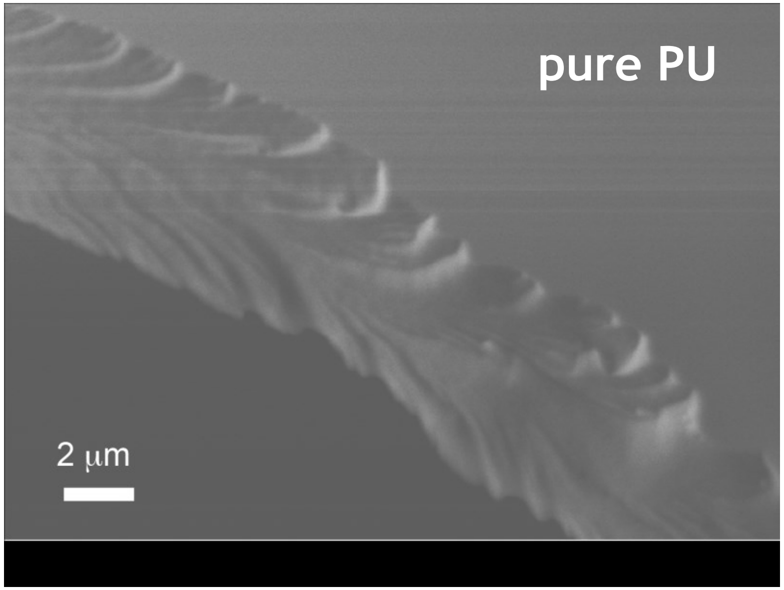
Released aerosol during thermal decomposition of PE



- **ROUTE 1**
- **All** three PE-based polymers
  - Pure
  - PE-Fe_2O_3
  - PU-Org. filler
- Dilution factor = 100
- T_{max} = 800˚C
- Sample (**~100 mg**) decomposition starts ~400˚C
- Similar size distributions and concentrations independent of nanofiller
- In agreement with decomposition at 500˚C

Is there nanofiller in the residual ash?

- $T_{d,final}$ = 500˚C
  - Residual ash from all samples
  - PU-based NEPs



- $T_{d,final}$ = 800 ˚C
  - Residual ash only from NEPs with inorganic components (e.g. Fe_2O_3)
  - CNTs fully decompose

Research Strategy

TASK 1	Development Integrated Exposure Generation System for the EHS Characterization of Incinerated NEPs	
TASK 2	Detailed Physicochemical and Morphological Characterization of Byproducts (Released Aerosol **AND** Residual Ash) of Industry Relevant NEPs	
TASK 3	Assessment of EHS Implications of Byproducts (Released Aerosol **AND** Residual Ash)	
	in-vitro and in-vivo Toxicological Characterization	Fate and Transport of Residual Ash in Environment
TASK 4	Safer-by-design Nano-Enabled Products	

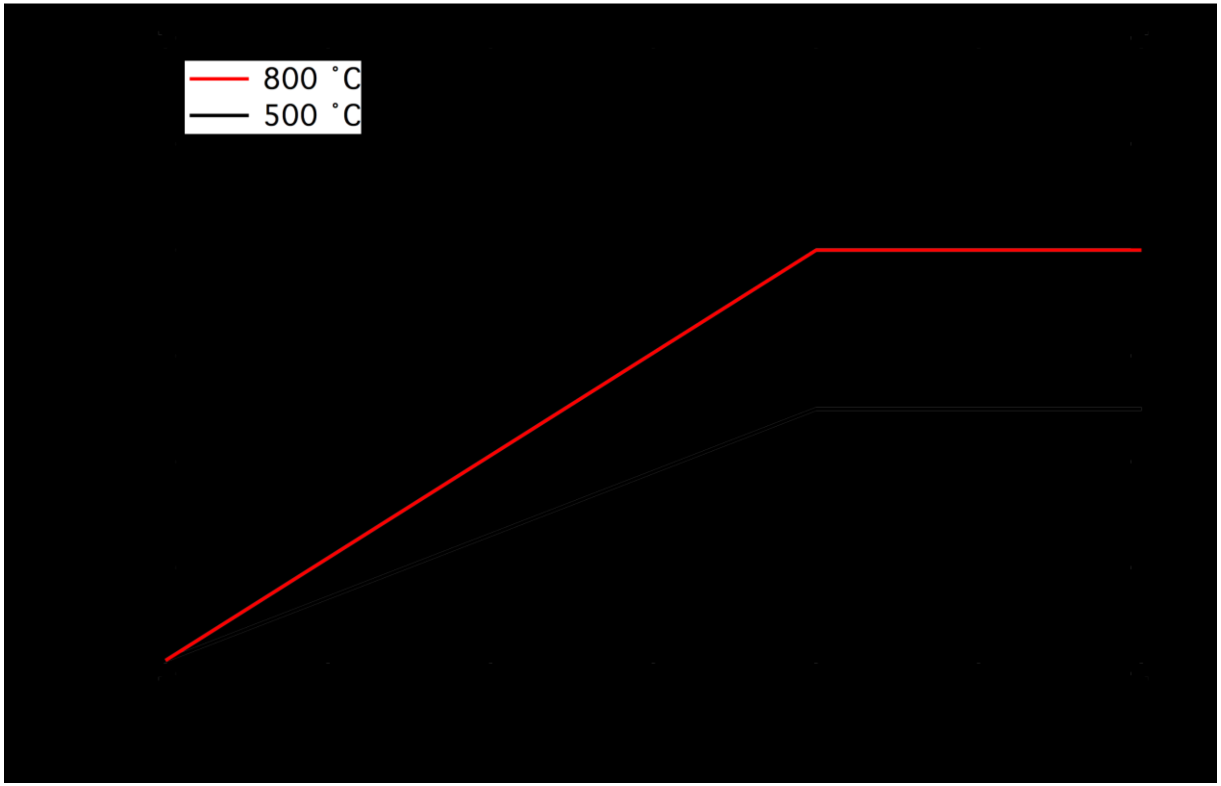
Nano-release during end-of-life of NEPs

- End-of-life
- Thermal decomposition/Incineration

[1] Nowack, David, Fissan, Morris, Shatkin, Stintz, Zepp, Brouwer. *Environ. Int.* **59**, 1 (2013).

[2] W. Wohlleben, M.W. Meier, S. Vogel, R. Landsiedel, G. Cox, S. Hirth, Z. Tomovic. *Nanoscale* **5**, 369 (2013).

Effect of final thermal decomposition temperature

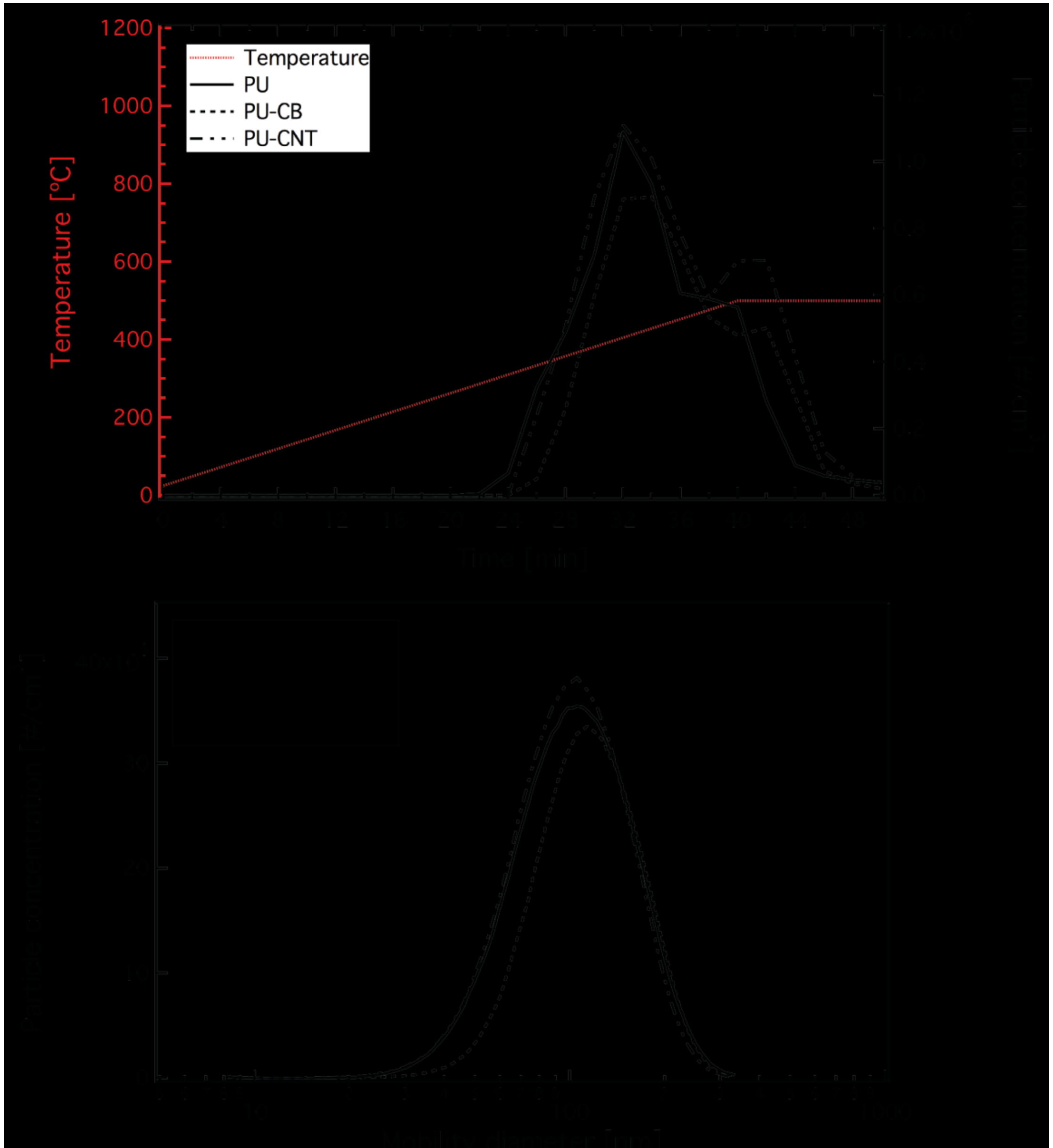


- Temperature increase in constant rate
  - 20˚C/min
    - 800 ˚C
  - 12.5 ˚C/min
    - 500 ˚C

  Thermal decomposition of polymers ~500 ˚C

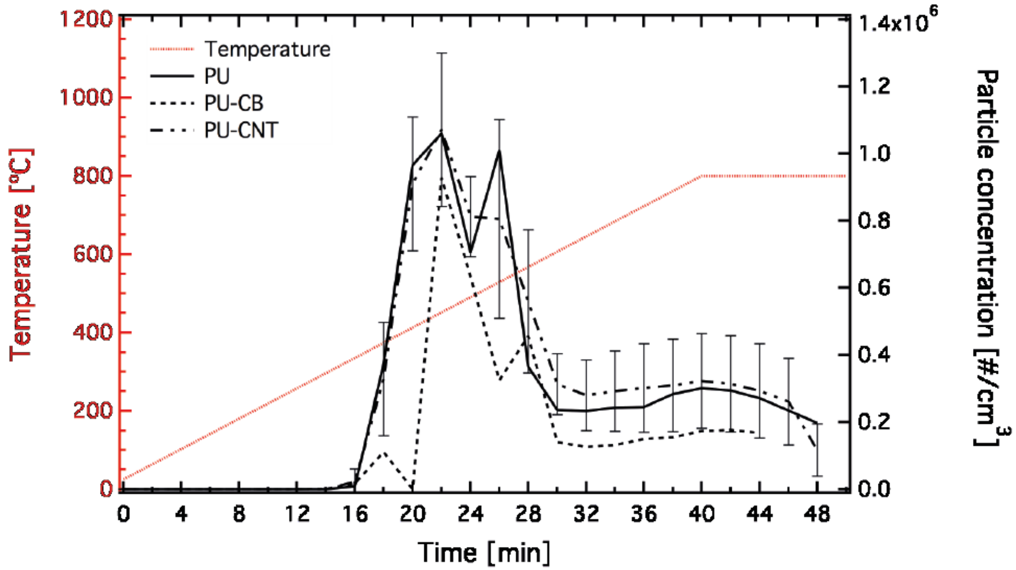
  Interesting to see how decomposition progresses from 500℃ to 800℃

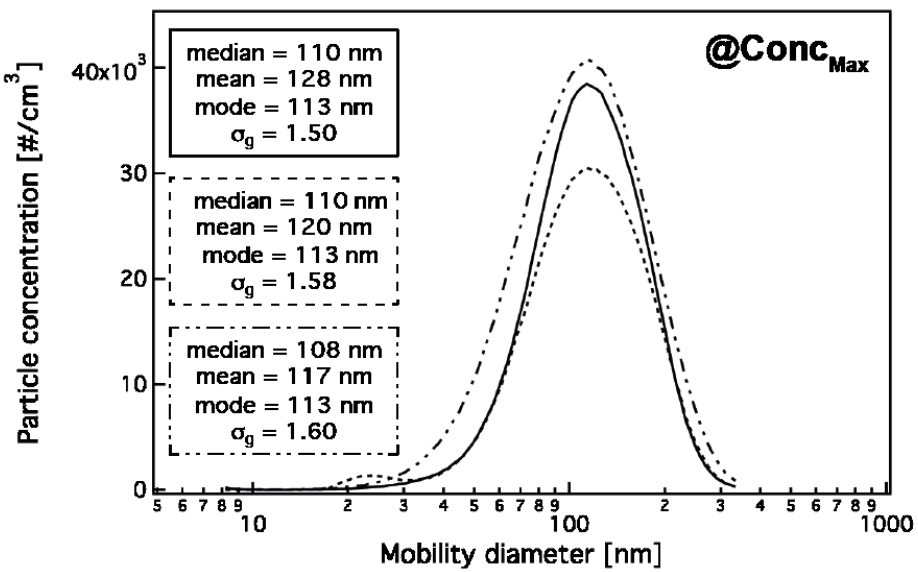
Released aerosol during thermal decomposition of PU



- **ROUTE 1 (No treatment)**
- **All** three PU-based polymers
  - Pure
  - PU-CB
  - PU-CNT
- Dilution factor = 100
- T_{max} = **500˚C**
- Sample (**~100 mg**) decomposition starts ~400˚C
- Similar size distributions and concentrations independent of nanofiller presence
- In agreement with decomposition at 800˚C

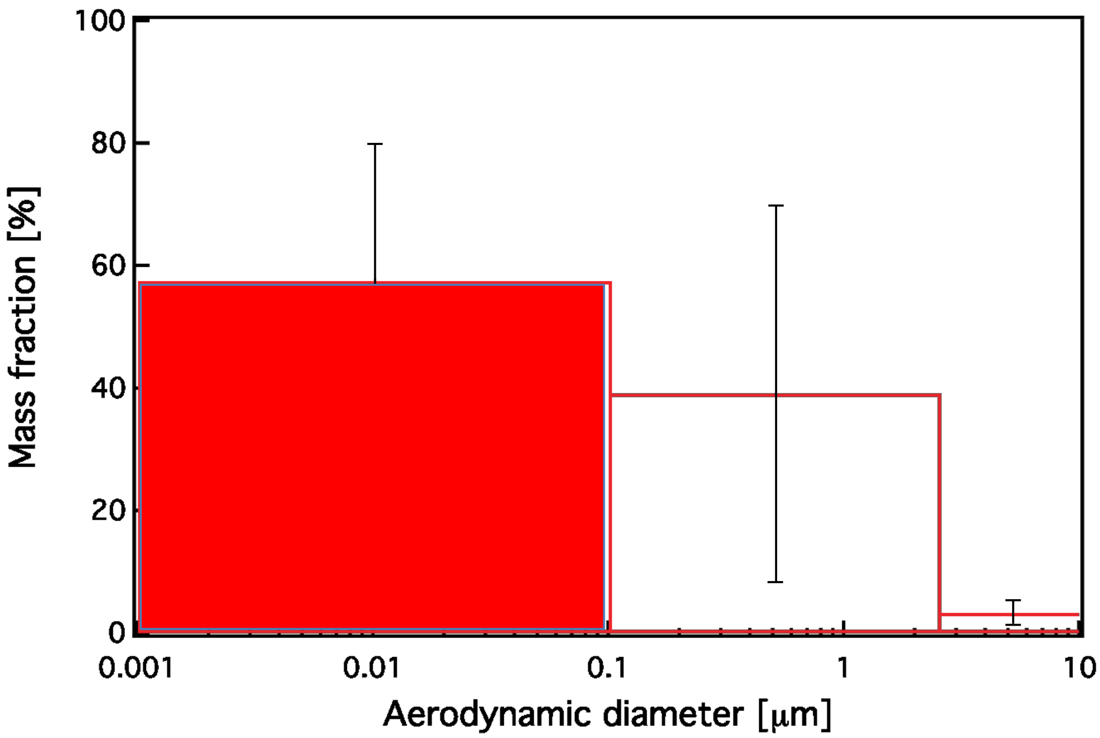
Released aerosol concentration: Nanofiller presence





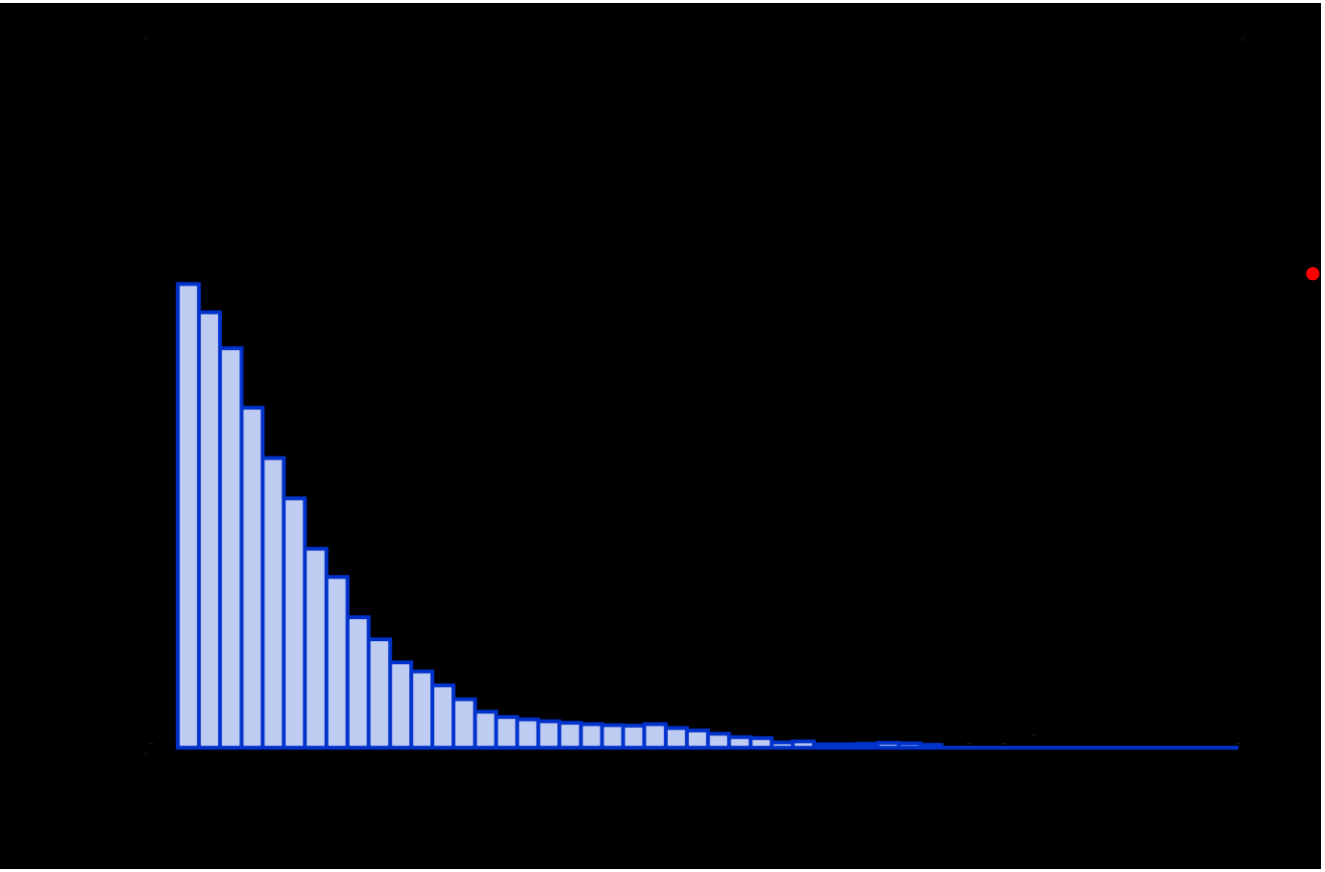
- **ROUTE 1 (No treatment)**
- **All** three PU-based polymers
  - Pure
  - PU-CB
  - PU-CNT
- Dilution factor = 100
- **T_{max} = 800˚C**
- Sample (**~100 mg**) decomposition starts ~400˚C
- Similar size distributions and concentrations independent of nanofiller presence

Aerodynamic mass particle size distribution



- **ROUTE 1 @ 800˚C**
  - PU-CNT
- Measured gravimetrically from the (CCI) impactor stages
- Bulk of the mass collected in $PM_{0.1}$ range
- Organic carbon ($PM_{0.1}$)
  - 99.2%

Released aerosol during thermal decomposition of PU

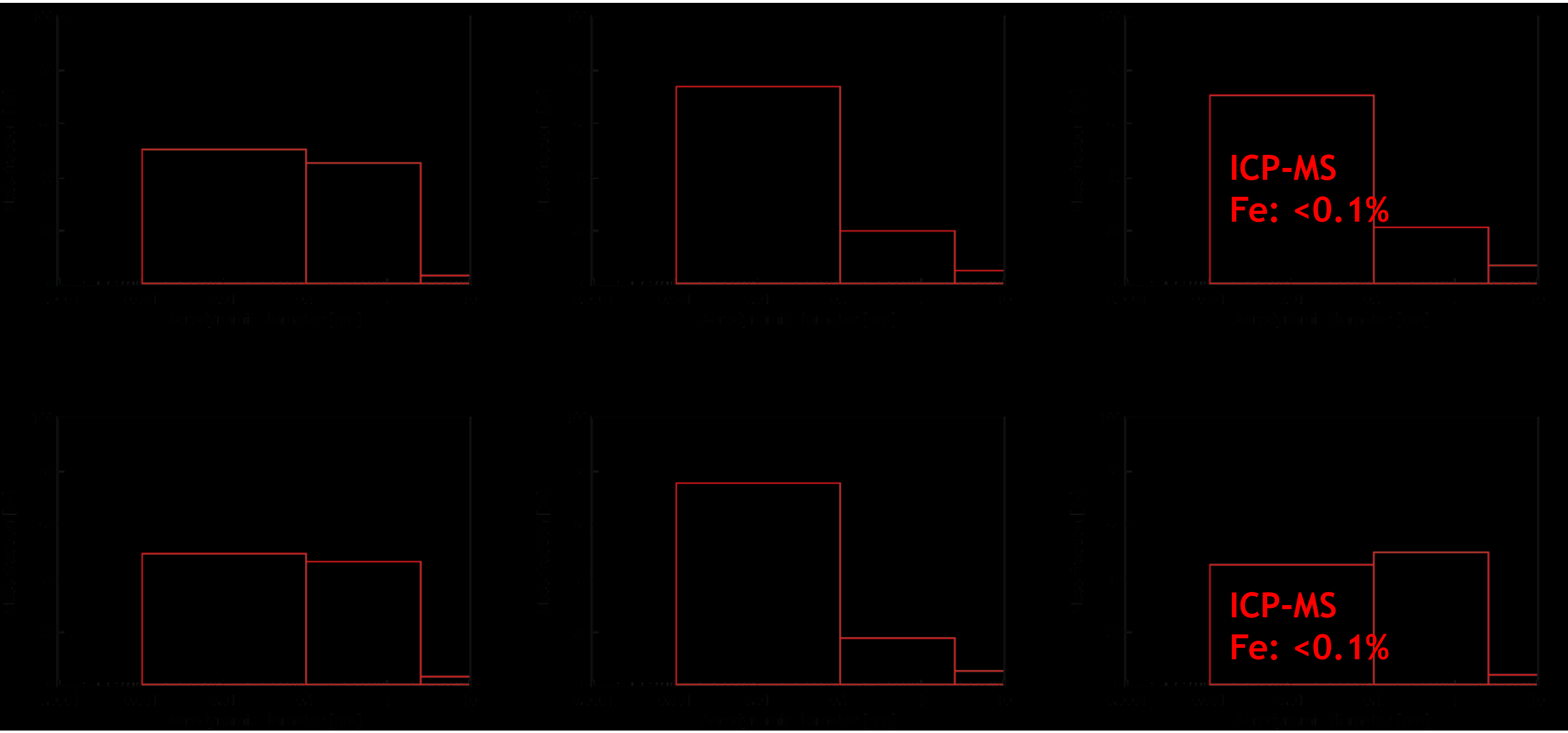


- **ROUTE 1 @ 800 ˚C**
PU-CNT
Dilution factor = 100

Mass particle size distributions for PE (ROUTE I)

500 ˚C

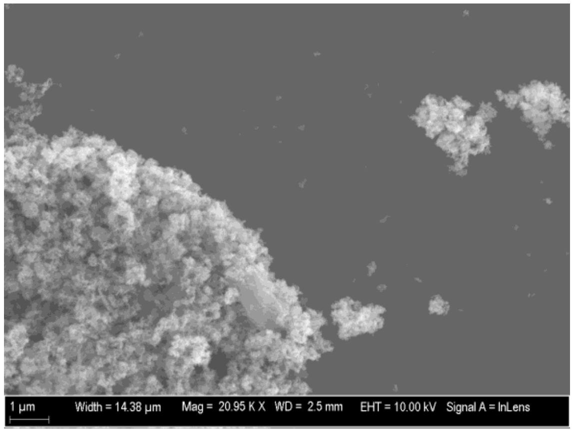
PE | **PE-ORG** | **PE-Fe_2O_3**

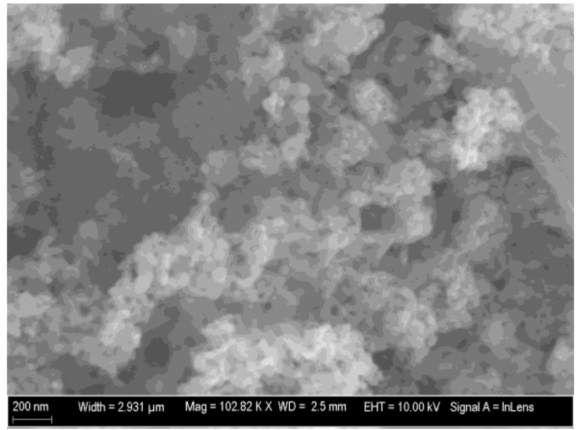


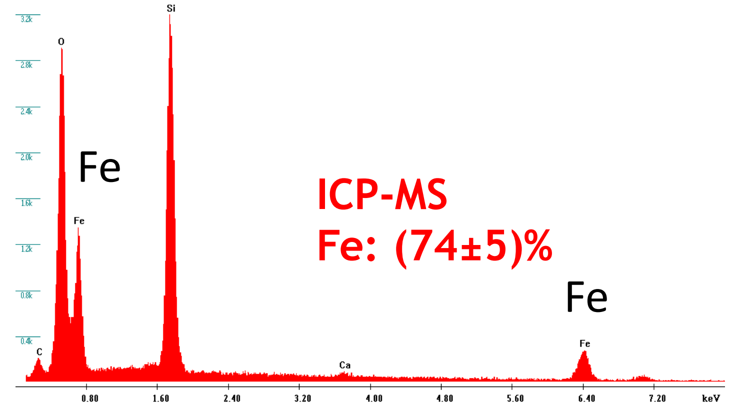
OC content for all samples ($PM_{0.1}$): 99.6% ± 0.2%

Residual ash @500˚C and 800˚C of PE-Fe_2O_3: SEM

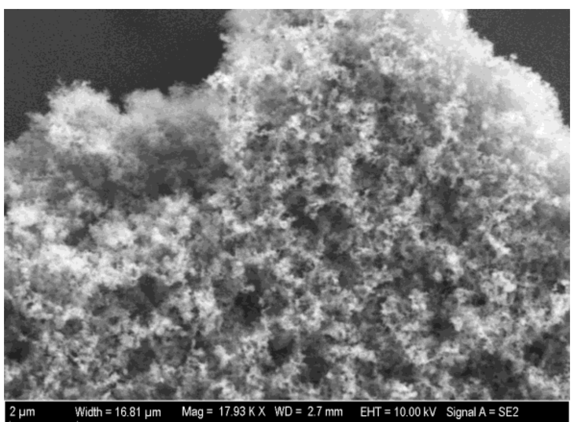
@500˚C

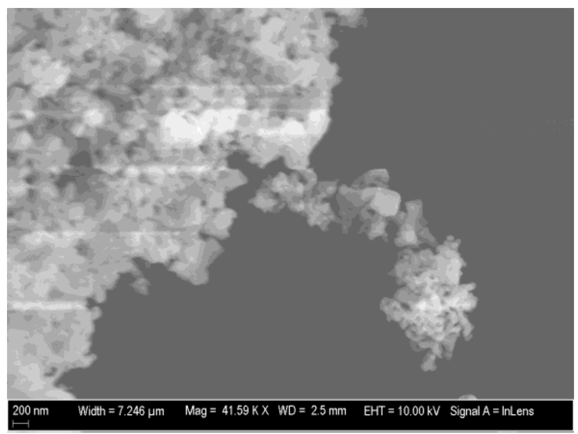


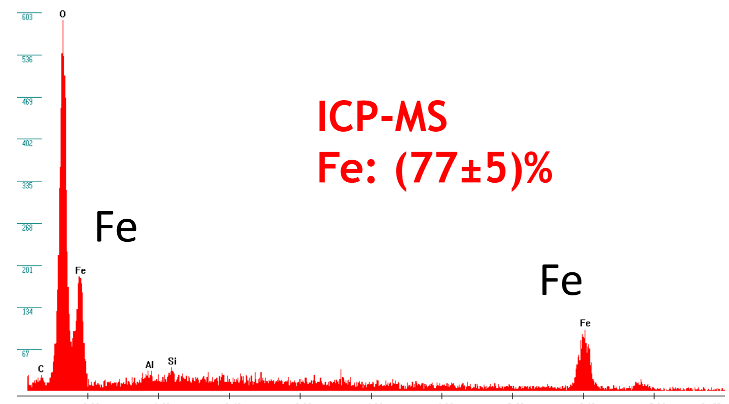




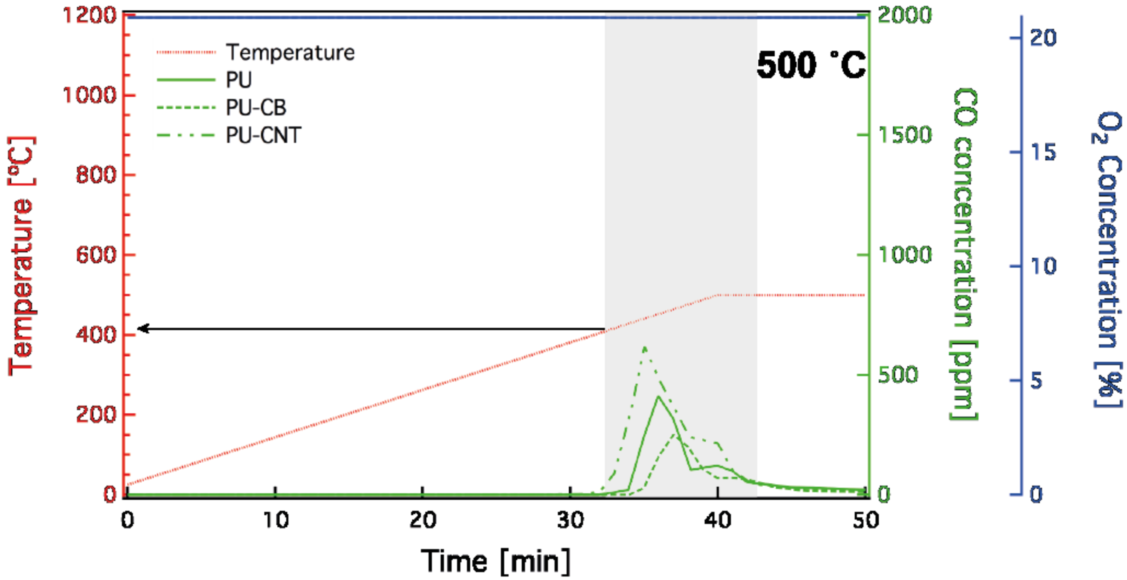
@800˚C

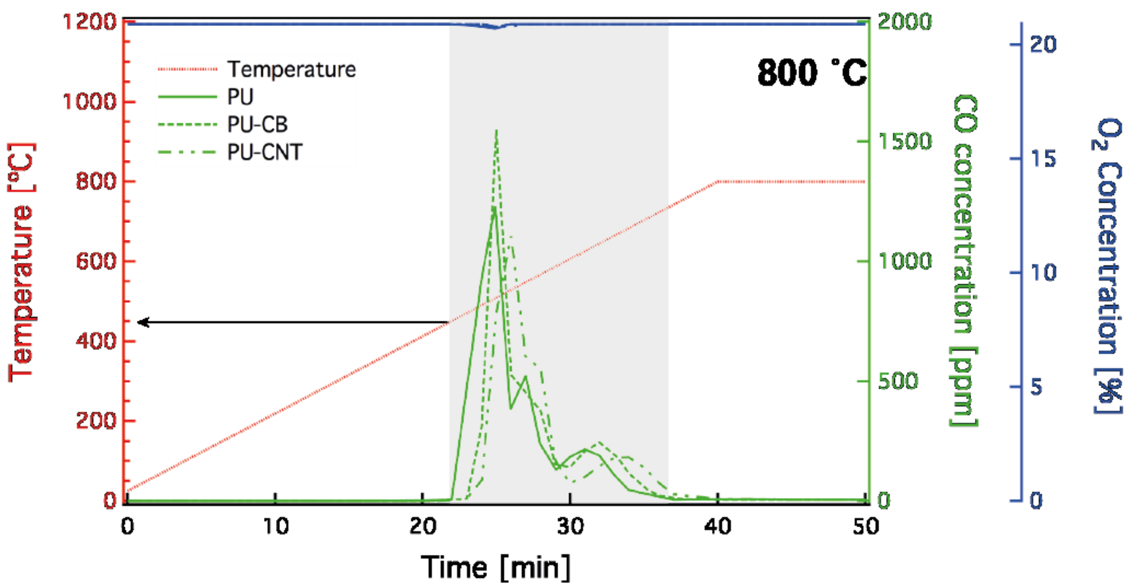






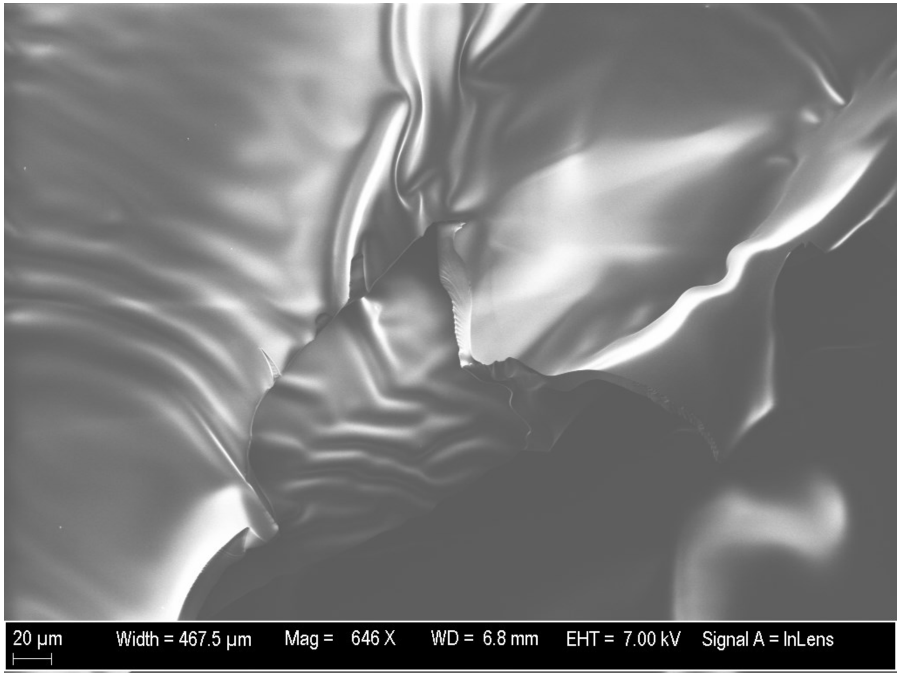
Gas emission during thermal decomposition of PU

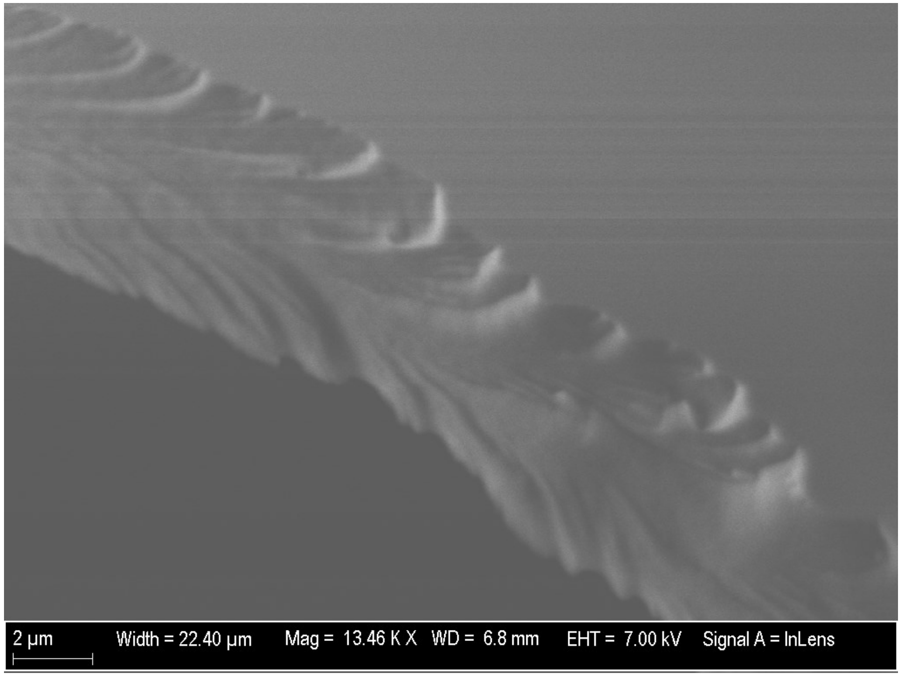




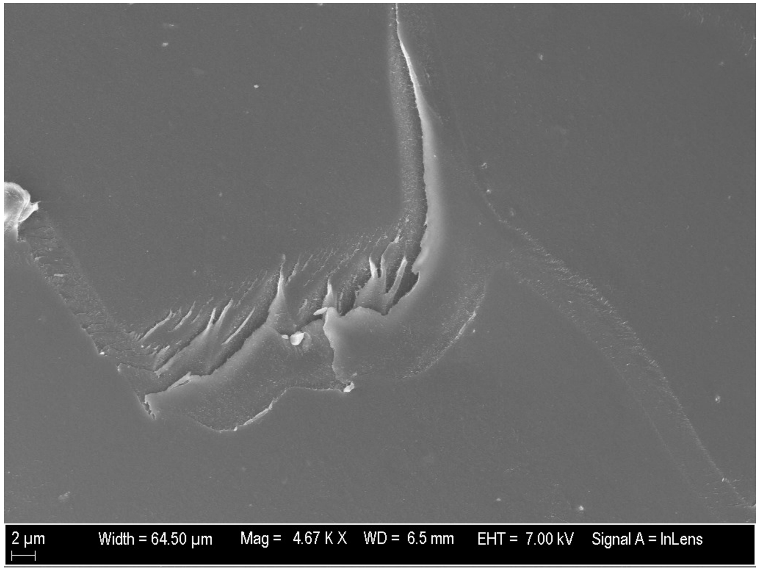
- Sample **(~100 mg)**
- **All** three PU-based polymers
  - Pure
  - PU-CB
  - PU-CNT
- Decomposition starts around 420˚C for both temperature profiles
- Highest CO emission for 800˚C
- O_2 levels slightly affected

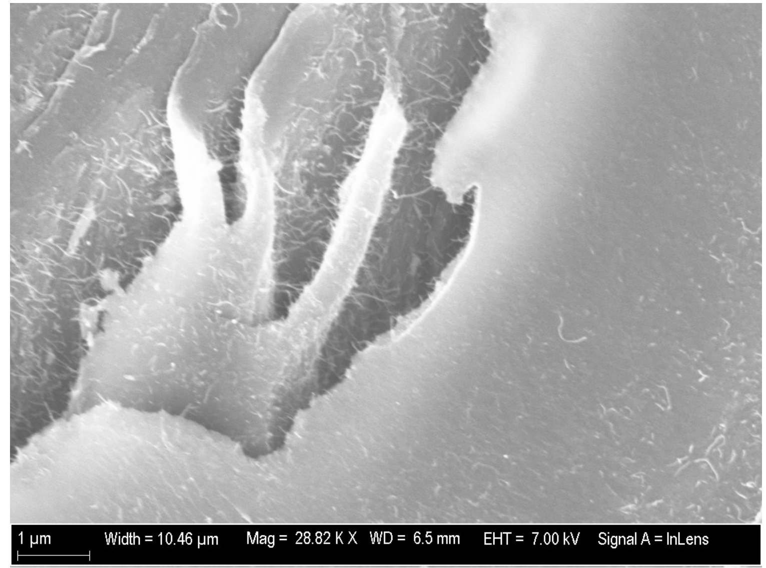
Residual ash @500˚C of pure PU: SEM

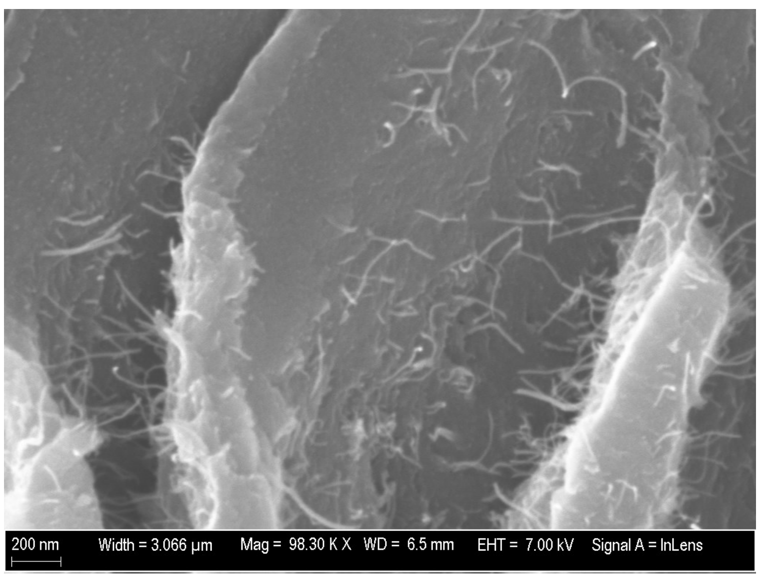


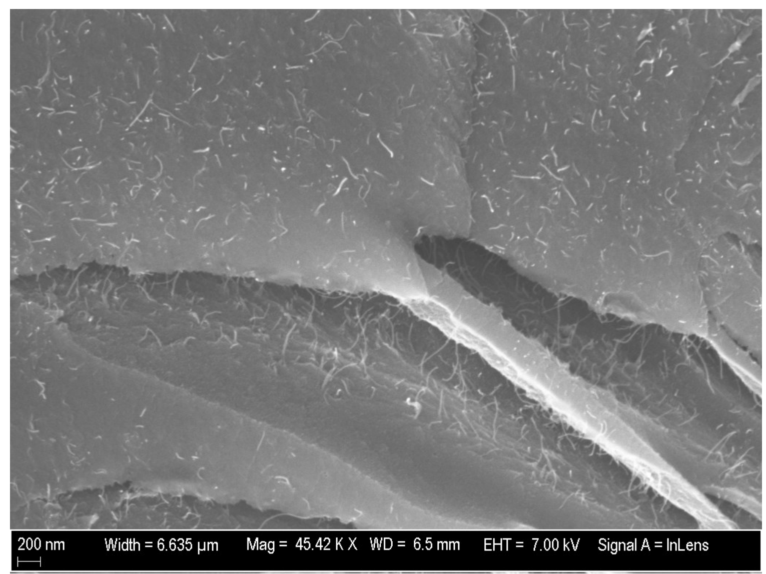


Residual ash @500˚C of PU-CNT: SEM

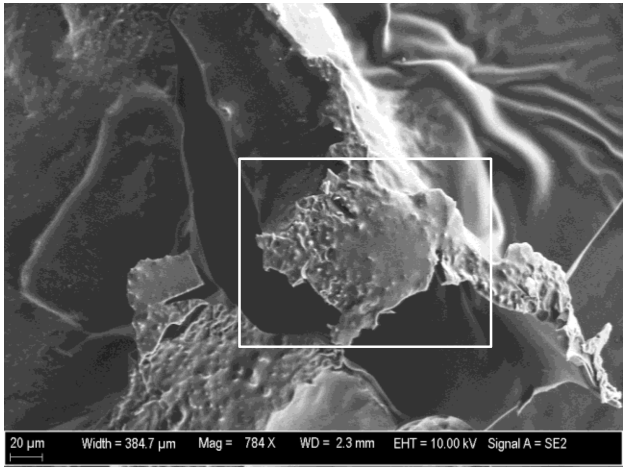


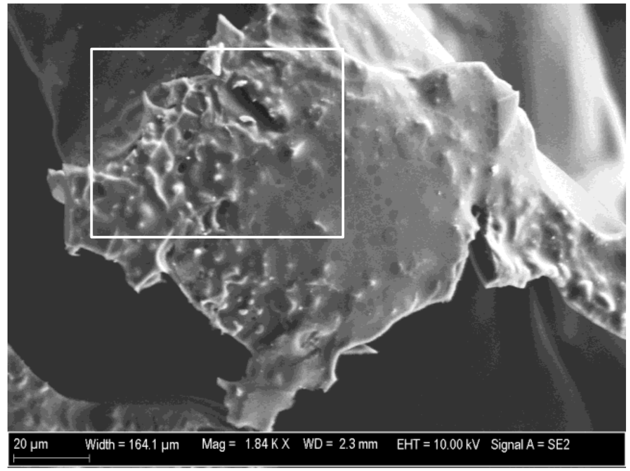


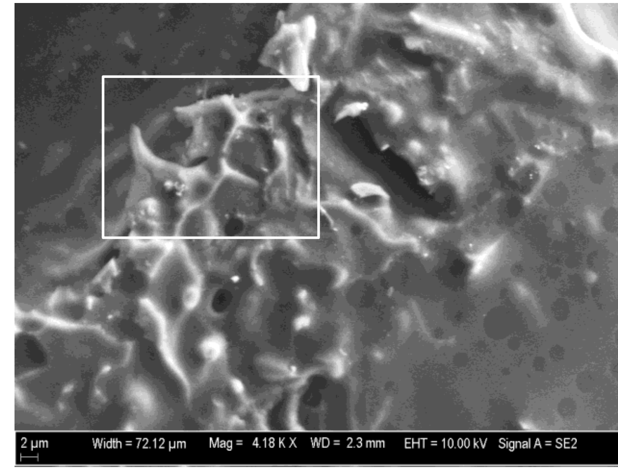


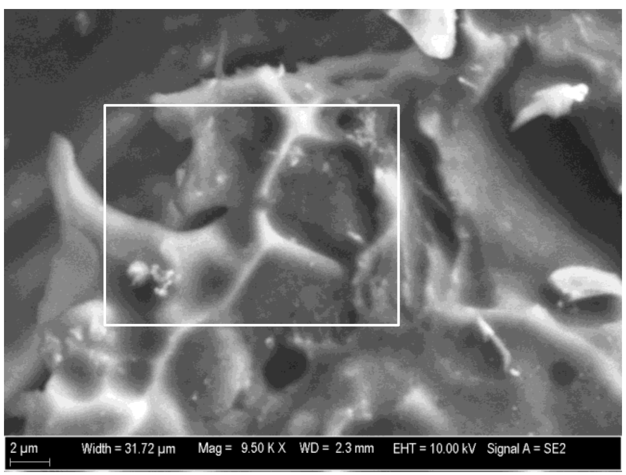


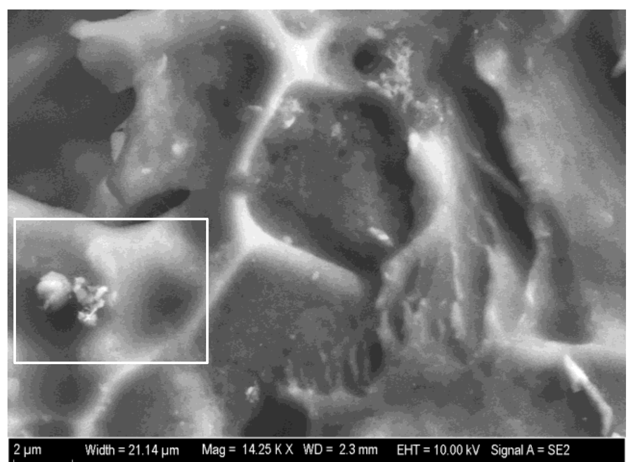
Residual ash @500˚C of PU-CNT: SEM



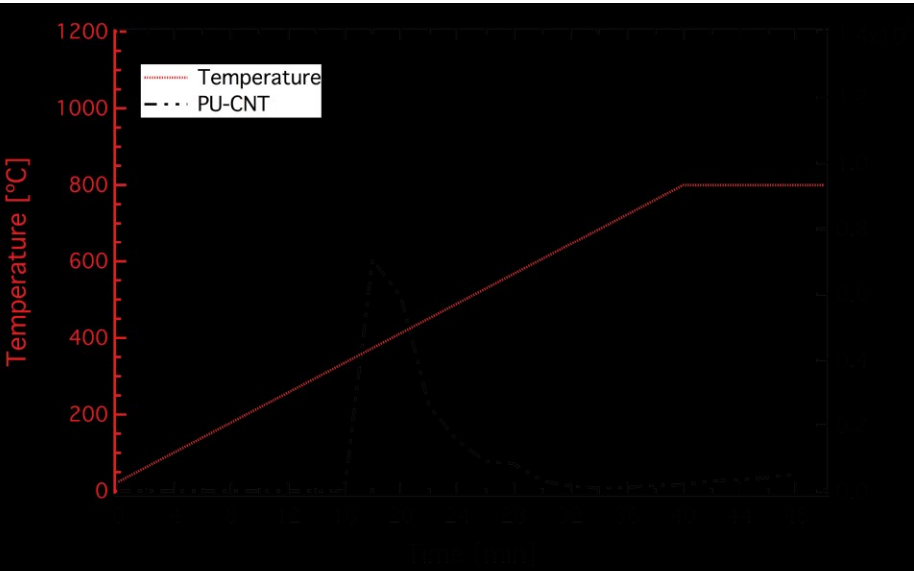


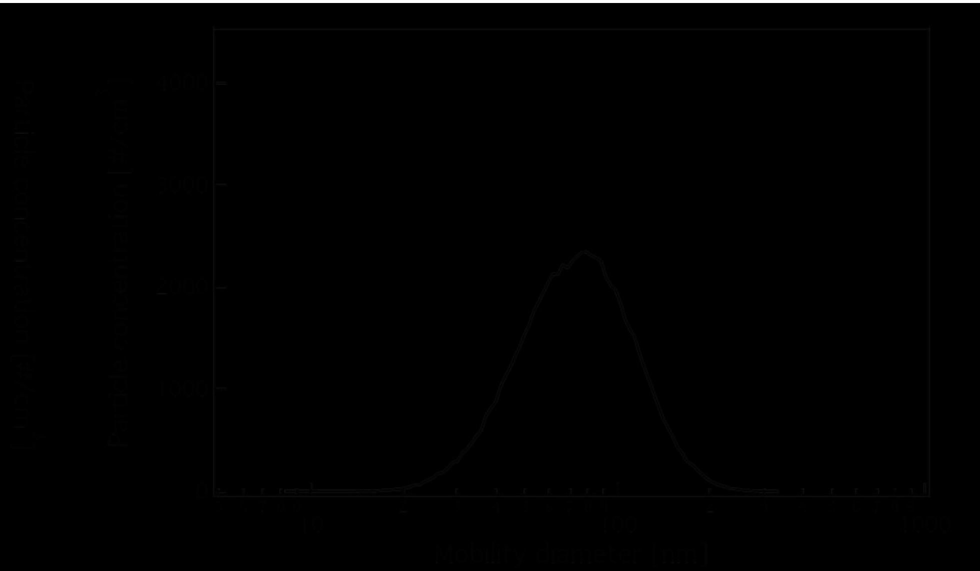


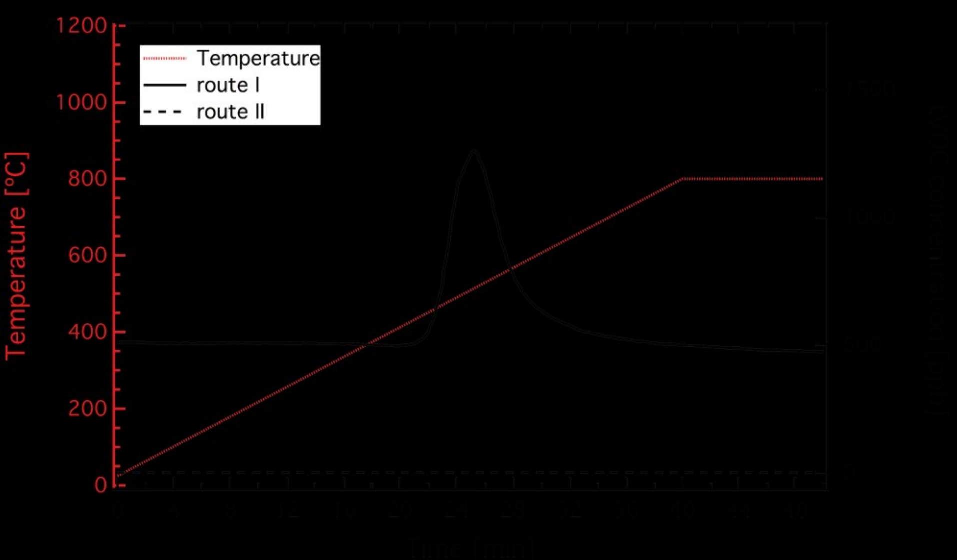


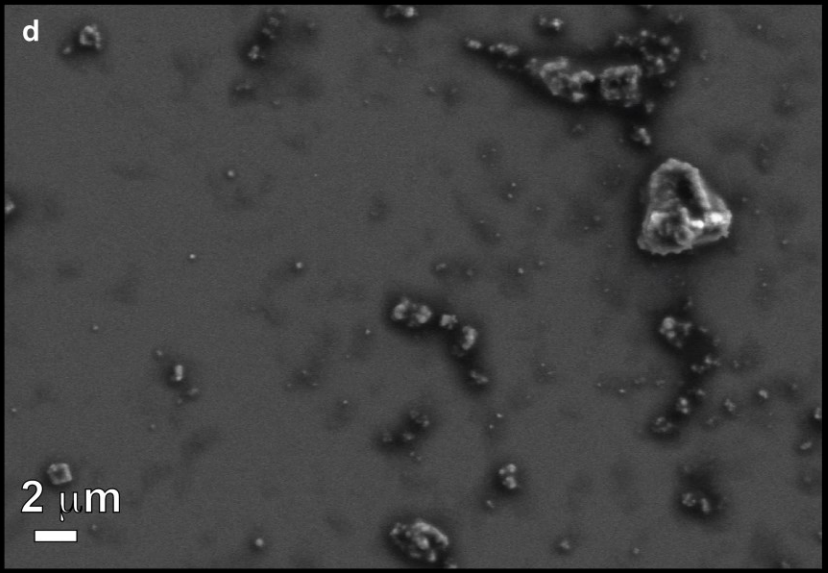


Effect of denuder

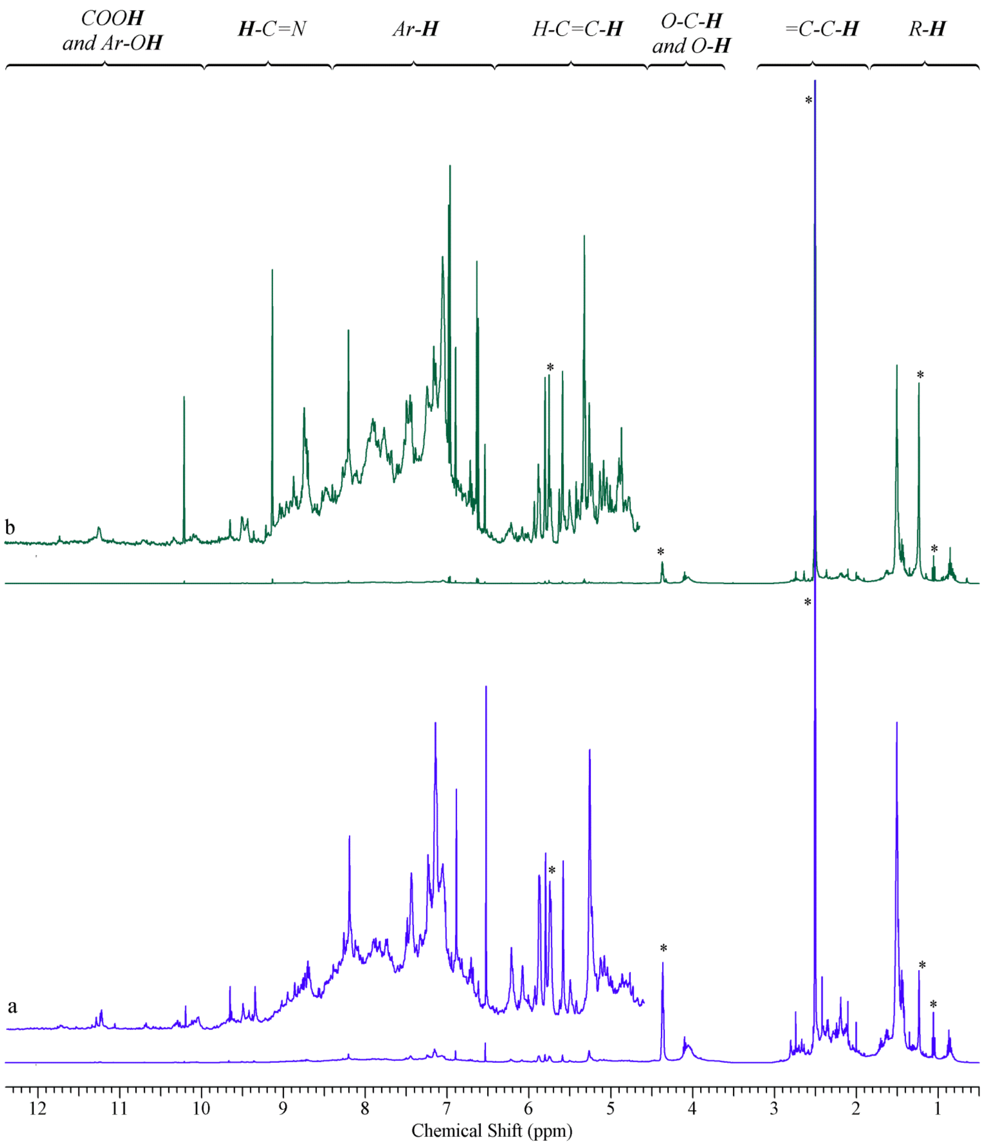






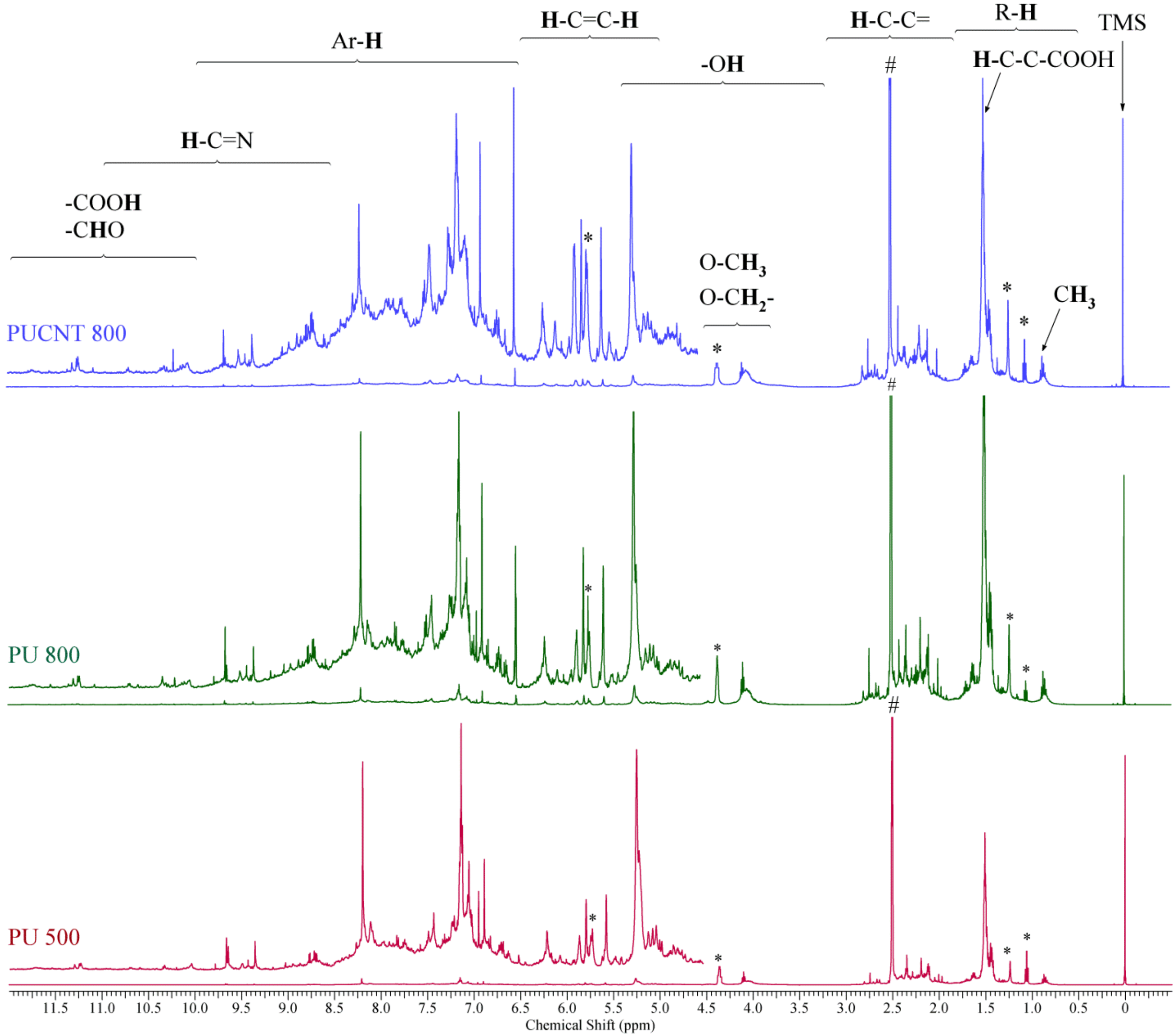


NMR



	Route I	Route II
Total H content (μmol/m³)	223.8	84.4
% (*R-**H***) (0.5-1.8 ppm)	42.7	62.7
% *(=C-C-**H**) (1.8-3.1 ppm)*	26.1	17.5
% *(O-C-**H** and O-**H**) (3.5-4.6 ppm)*	7.7	5.4
% *(H-C=C-**H**) (4.6-6.5 ppm)*	7.1	3.0
% *(Ar-**H**) (6.5-8.5 ppm)*	13.7	9.6
% (***H**-C=N*) *(8.5-10.9 ppm)*	2.5	1.8
% *(COO**H** and Ar-O**H**) (10.9-12.4 ppm)*	0.3	0.1
WSOC (μmol/m³)	96.7	36.3
H/C molar ratio	2.31	2.38

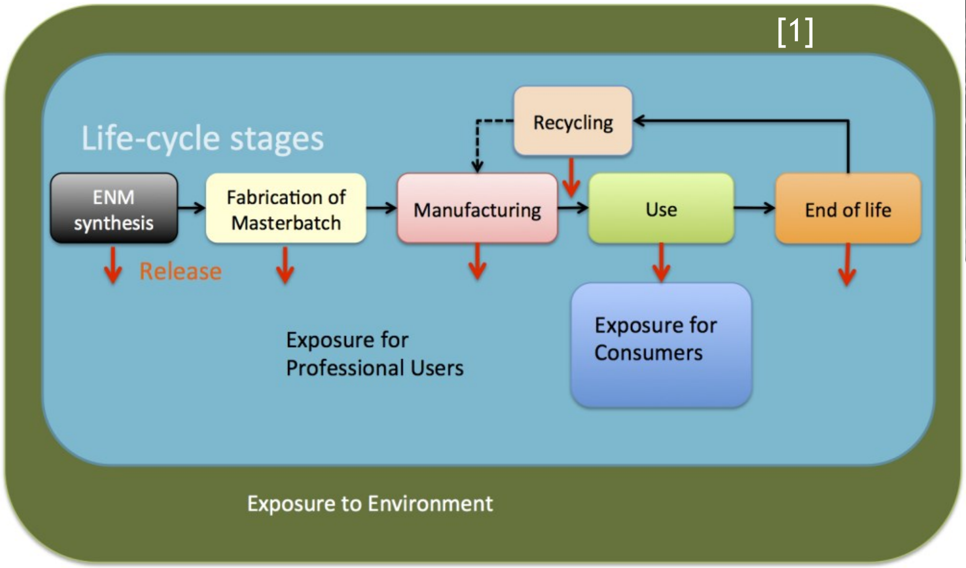
NMR

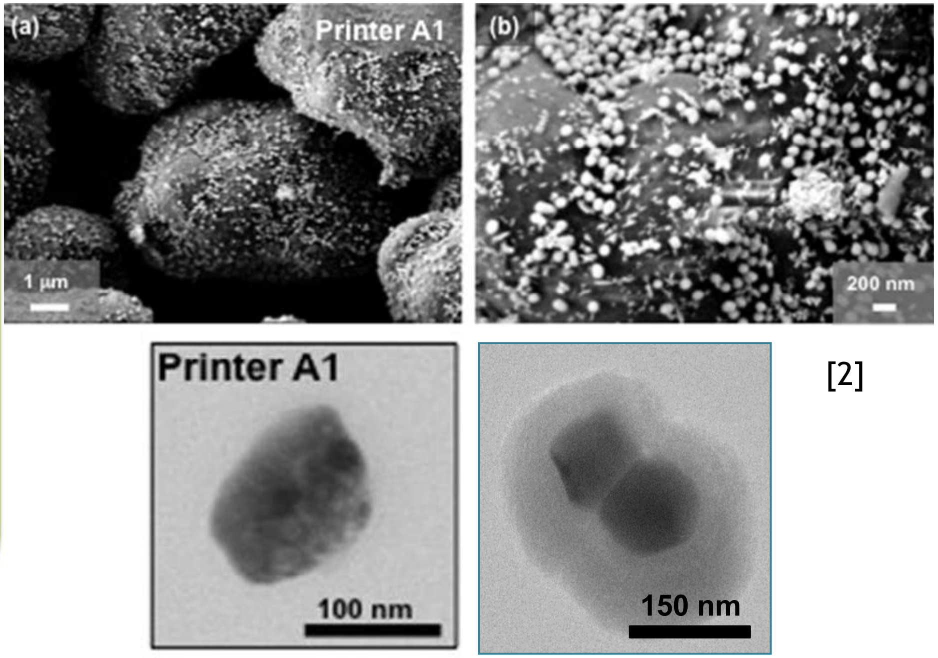


Ar-H
H-C=C-H
H-C-C=
R-H
TMS
H-C-C-COOH
-OH
#
H-C=N
-COOH
-CHO
*
O-CH3
O-CH2-
CH3
PUCNT 800
PU 800
PU 500
11.5 11.0 10.5 10.0 9.5 9.0 8.5 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0
Chemical Shift (ppm)

Nanotoxicity: Realistic exposure scenarios?

- **So far**: Nanotoxicity evaluation of "raw" nanomaterials
  - Mechanistic understanding
  - Occupational exposures
- Realistic exposures?
- Transformations of nanomaterials during their life-cycle[1]





[2]

[1] Nowack, David, Fissan, Morris, Shatkin, Stintz, Zepp, Brouwer. *Environ. Int.* **59**, 1 (2013).
[2] Pirela, Sotiriou, Bello, Shafer, Bunker, Castranova, Thomas, Demokritou. *Nanotoxicology* **in press** (2014).

- **Focuses on Applications and Implications of engineered nanomaterials and nanotechnology**
  - **Mission:** Integrate material & exposure science and nanotoxicology risk assessment to facilitate science-based decision-making regarding nanosafety.
  - State of the art exposure systems and **in-vitro and in-vivo toxicological platforms** coupled with cutting edge **particle synthesis and characterization systems (CNS)**
  - **Strategy:** Bring together ALL stakeholders: industry, academia, policy makers and the general public to address nano-EHS
  - **Industrial Partners:** BASF, Panasonic, Nanoterra, etc
  - **International in nature:** Current collaborations with Federal Agencies, and Universities around the world (ETH, MIT, SUNY, UMass, Northeastern Univ., UCLA, NIOSH, CPSC, US EPA, etc)

Website: http://hsph.harvard.edu/nano

Funding Sources

NIOSH
National Institute for Occupational Safety and Health

NIEHS
National Institute of Environmental Health Sciences

USDA

NSF
National Science Foundation
WHERE DISCOVERIES BEGIN

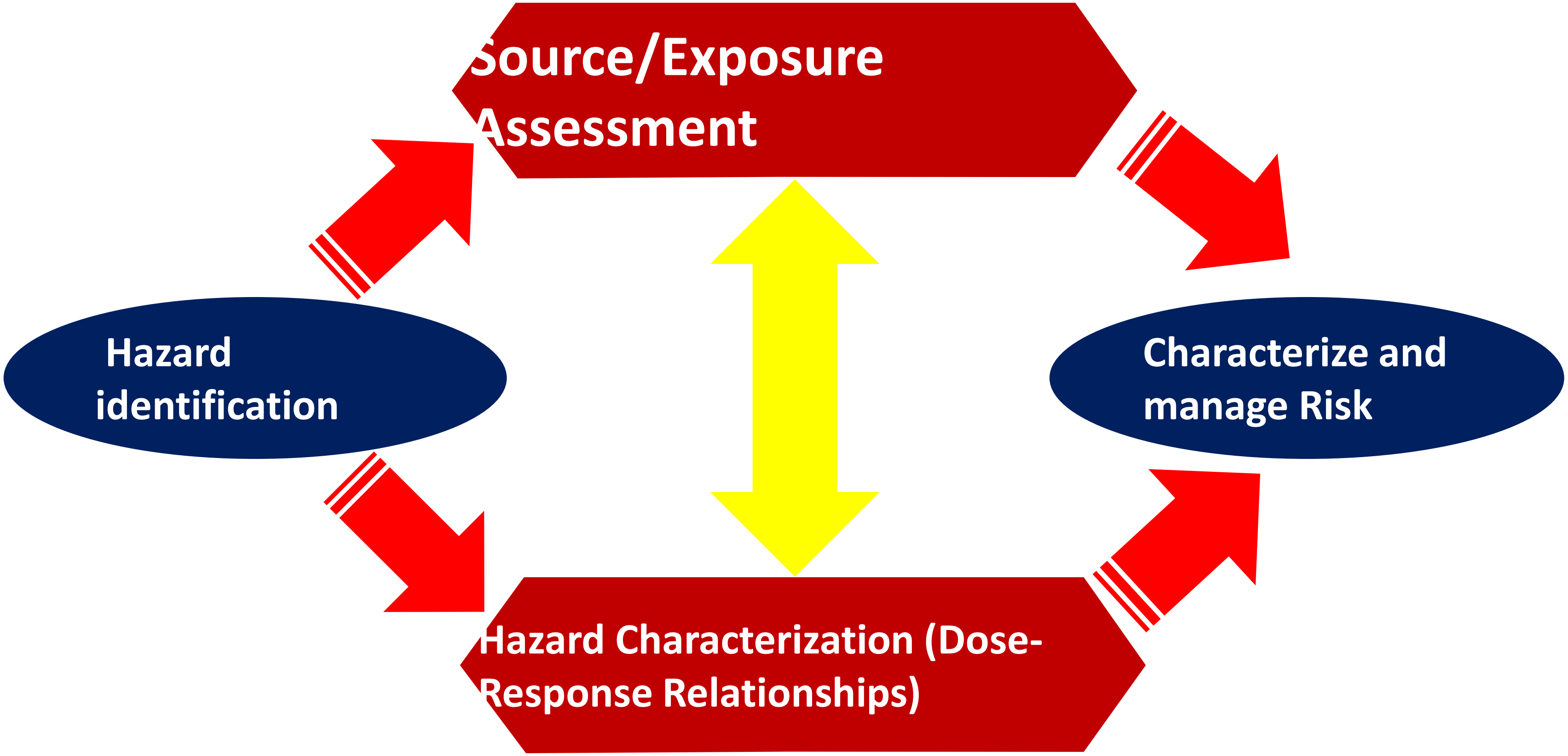
UNITED STATES OF AMERICA
CONSUMER PRODUCT SAFETY COMMISSION

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

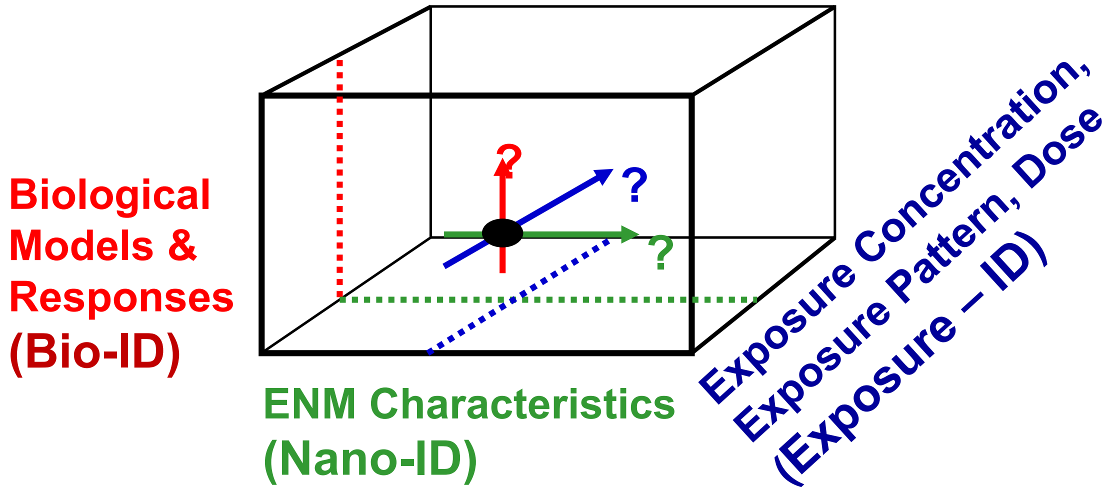
BASF
The Chemical Company

Panasonic

Current Risk Assessment Paradigm for ENMs



The nano Risk space is 3 dimensional:
3 - IDs are needed to assess RISK



INFORMATION ON Nano-RISK HAS EXPANDED SINCE 2005

…

… BUT HAVE THE ISSUES EVOLVED SUBSTANTIALLY?

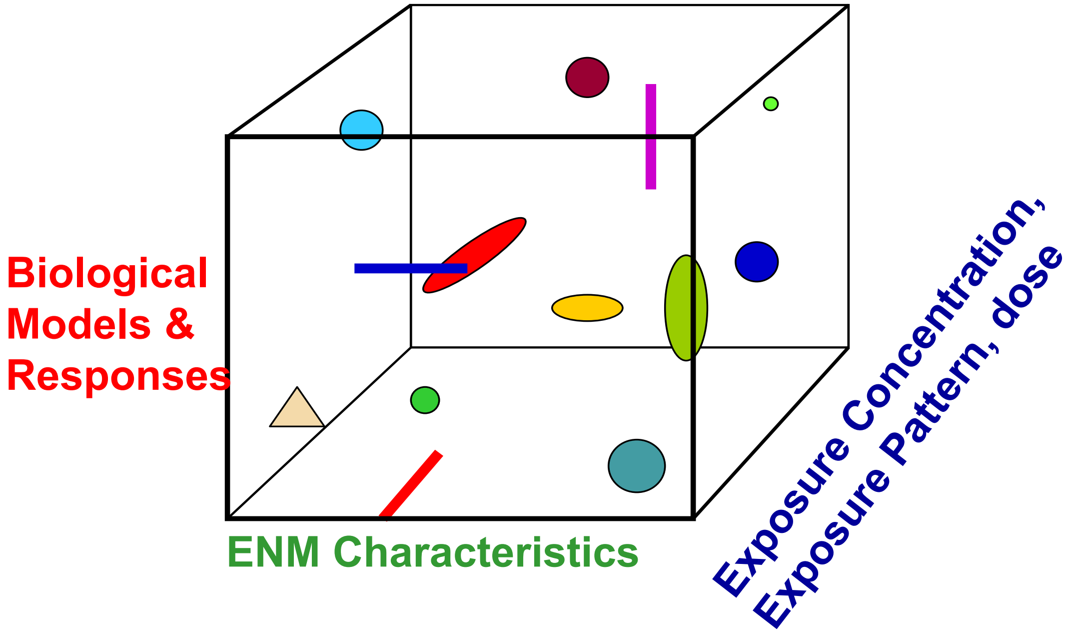
Current Risk Assessment Paradigm:
Important Questions to be answered (2/2)

at plausible doses and exposure conditions,

- "HAZARD IDENTIFICATION" : Can the material cause an adverse effect?
- "HAZARD CHARACTERIZATION: What effects? Under what exposure concentration, deposited doses, and time?
- "RISK: We need EXPOSURE data to determine RISK.
- We need to assess risks across LC and not based of exposures/properties of raw ENMs

Nano- RISK 3D model

DO WE HAVE A SYSTEMATIC UNDERSTANDING? OR WE JUST GENERATED POINTS OF INFORMATION



- Progress has been made in understanding key toxicity pathways at molecular and cellular level
- Major knowledge gaps exist preventing us from a systematic understanding
- There is still a **huge uncertainty** surrounding nano-safety