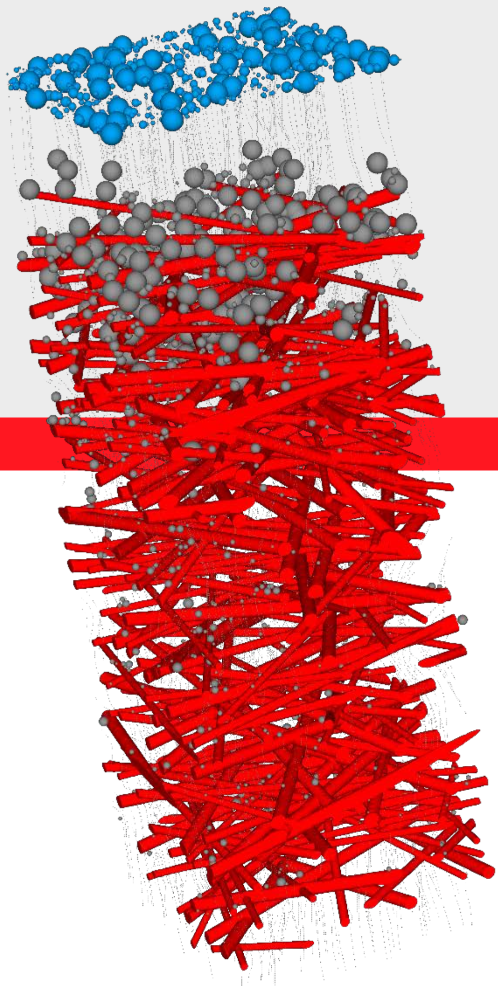
The benefits of designing filter media using pore scale computer modelling

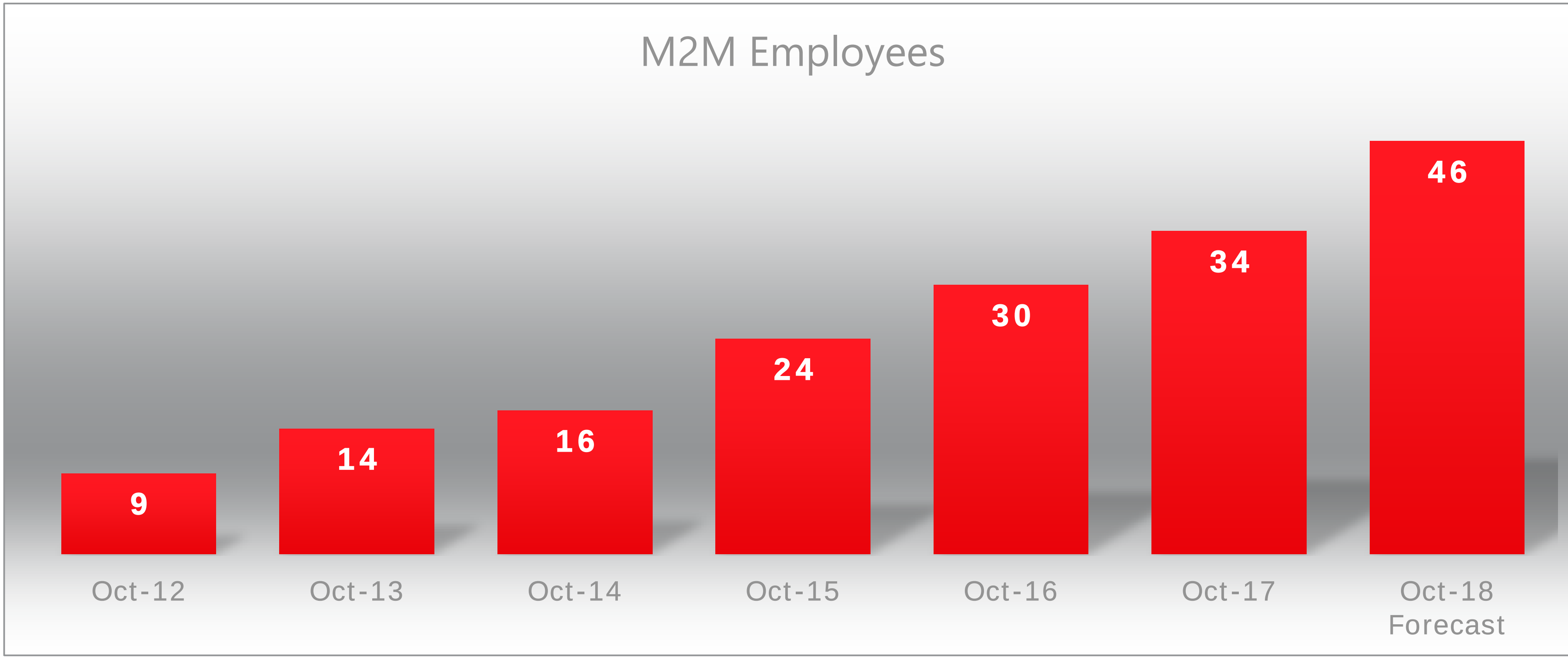


- Andreas Wiegmann
- Christian Wagner
- Mehdi Azimian
- Jürgen Becker
- Liping Cheng
- Sven Linden

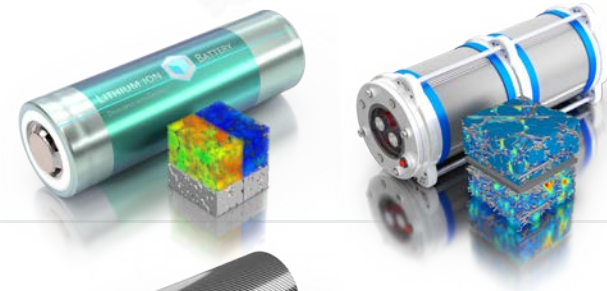
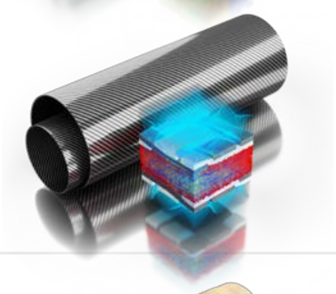
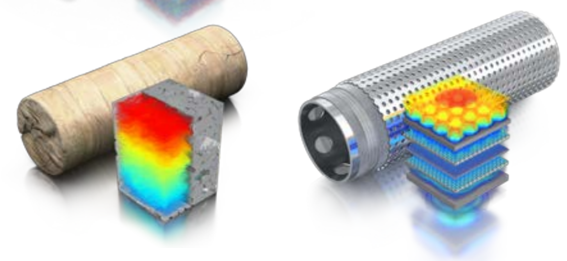
Math2Market …

- was founded in 2011
  - after 11 years of software development at Fraunhofer ITWM
- is based in Kaiserslautern, south west Germany
- has currently 38 employees
- has more than 150 clients worldwide
- has ca. 30% business in “true” filtration applications
- makes & sells FilterDict, a module of the software GeoDict
- provides consulting around the software

Company Growth



GeoDict The Digital Material Laboratory

Filtration	Mostly automotive, filter media & filters for water, sludge, oil, air and fuel	
Electrochemistry	Fuel cell media & battery materials, catalyst materials	
Composites	CFRP, GFRP, mostly automotive, lightweight materials	
Oil and Gas	Digital rock physics, digital sand control	

The 5 steps of GeoDict® - the Digital Material Laboratory

From reality into the computer...

1. Understand your material
2. Compute your materials properties
3. Model your material
4. Design your material
5. Manufacture your material

... and from the computer back to reality

The idea of digital filter media design

1. Represent existing filter media in the computer
   - From images (µCT, FIBSEM), then as model
2. Perform pore size analysis in the computer
   - **Porometry, bubble point, geometric pore size**, etc.
3. Compute flow, get **flow rate & pressure drop** (Delta P)
4. Compute **filter efficiency**, eta or beta
5. Compute **filter life time**, dust holding capacity (DHC)
6. Vary model parameters and repeat 2.-5.
7. Transfer the improved filter media design to production

Use simulation for **technological** *and* **marketing benefits**!

3 examples of this approach

1. Simulation-based development of metal wire mesh media
2. Simulation-based development of soot filter ceramic media
3. Simulation-based determination of filter cake parameters

1. Simulation-based development of metal wire mesh media

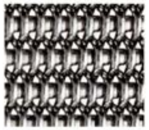
E. Glatt, C. Wagner, M. Azimian, A. Wiegmann

Enlarged models in Showroom – from GKD web site

- Metal Small wire diameters are hard to see in reality
- Enlarged WeaveGeo models can be presented to clients using 3D printing technology

GKD SOLIDWEAVE

TELA mesh



PZ-Microdur mesh

Candle filter in process-specific design

Our filter media are considered especially efficient and economical – regardless of whether they are intended for universally deployable products, components for series manufacturing or complex individual solutions. With our own simulation methods and testing techniques, we integrate these filter media seamlessly into the customer's process.

Our developments are acknowledged across all industries as standards for many industrial applications. Electronics manufacturers use our filters in inkjet printers or as shielding against electromagnetic radiation. The automotive industry uses our meshes for diesel particulate filtration, in exhaust gas aftertreatment and in hydraulic systems. Ship chandlers use them for ballast water filtration. In the aerospace industry, our meshes are used in lightning protection applications or for noise insulation of jet engines.

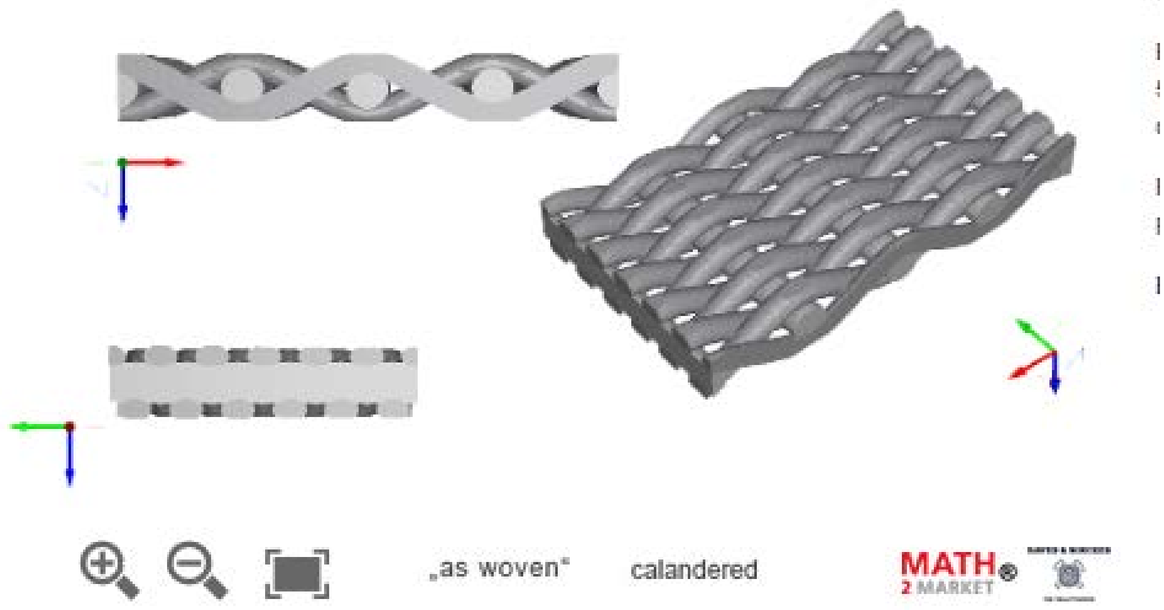
The chemical, pharmaceutical, plastics and foodstuffs industries place their trust in our meshes for demanding filtration tasks. And in the energy and environmental technology sectors, too, they have become successfully established.

SOLIDWEAVE AT A GLANCE

- INNOVATIVE RANGE OF MATERIALS
- PRECISION MESH
- COMPLEX FILTER SYSTEMS
- UNIVERSAL PRODUCTS
- STANDARDS ACROSS ALL INDUSTRIES
- CUSTOMER-SPECIFIC SOLUTIONS
- LEADING MANUFACTURING EXPERTISE
- THE LATEST SIMULATION AND TESTING METHODS
- CONTINUOUSLY CERTIFIED QUALITY

Calendering – from Haver & Boecker web site

- Weaves are often modified to smaller pore sizes by calendering
- This can be modelled using ElastoDict



Determination of largest penetrating particle…

- Agrees very well with Whitehouse Scientifics challenge tests…
- … when the meshes are woven with superb quality and all pores are close to the ideal

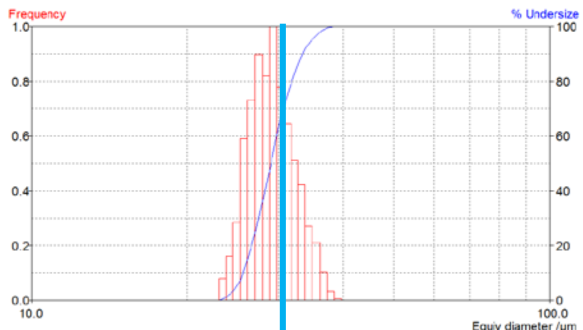
Challenge Test Procedure

30 micron woven stainless steel mesh

Filter standard (24 – 35 microns)

24 - 39um Filter Standard (1251) — **Particle Size Analysis**

% Undersize	3.0	5.0	10.0	25.0	50.0	75.0	90.0	95.0	97.0
Size /µm	24.47	24.91	25.73	27.05	28.94	31.12	33.40	34.81	35.47

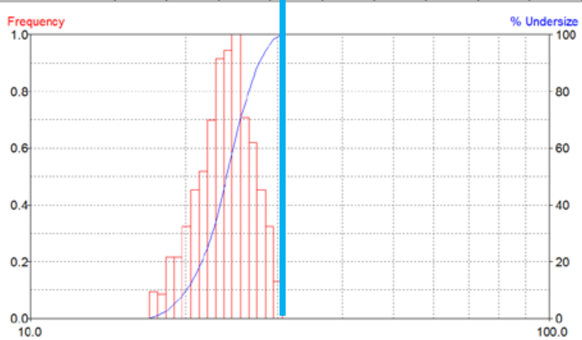


Median: 28.94 µm **Mode:** 29.25 µm **Mean:** 29.23 µm **CV:** 10.1% **D90/D10:** 1.3

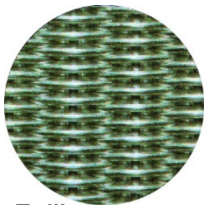
After passing mesh

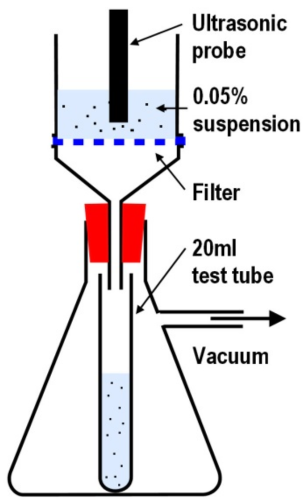
Cut point - dry sonic (1069) — **Challenge Test Filter Cut Point**

% Undersize	3.0	5.0	10.0	25.0	50.0	75.0	90.0	95.0	97.0
Size /µm	18.42	18.91	20.11	21.96	23.95	25.75	27.65	28.64	29.08



Reference standard passing filter - Cut Point (D97): 29.08 µm





Top end of the distribution removed
Cut point (D97) = 29 microns

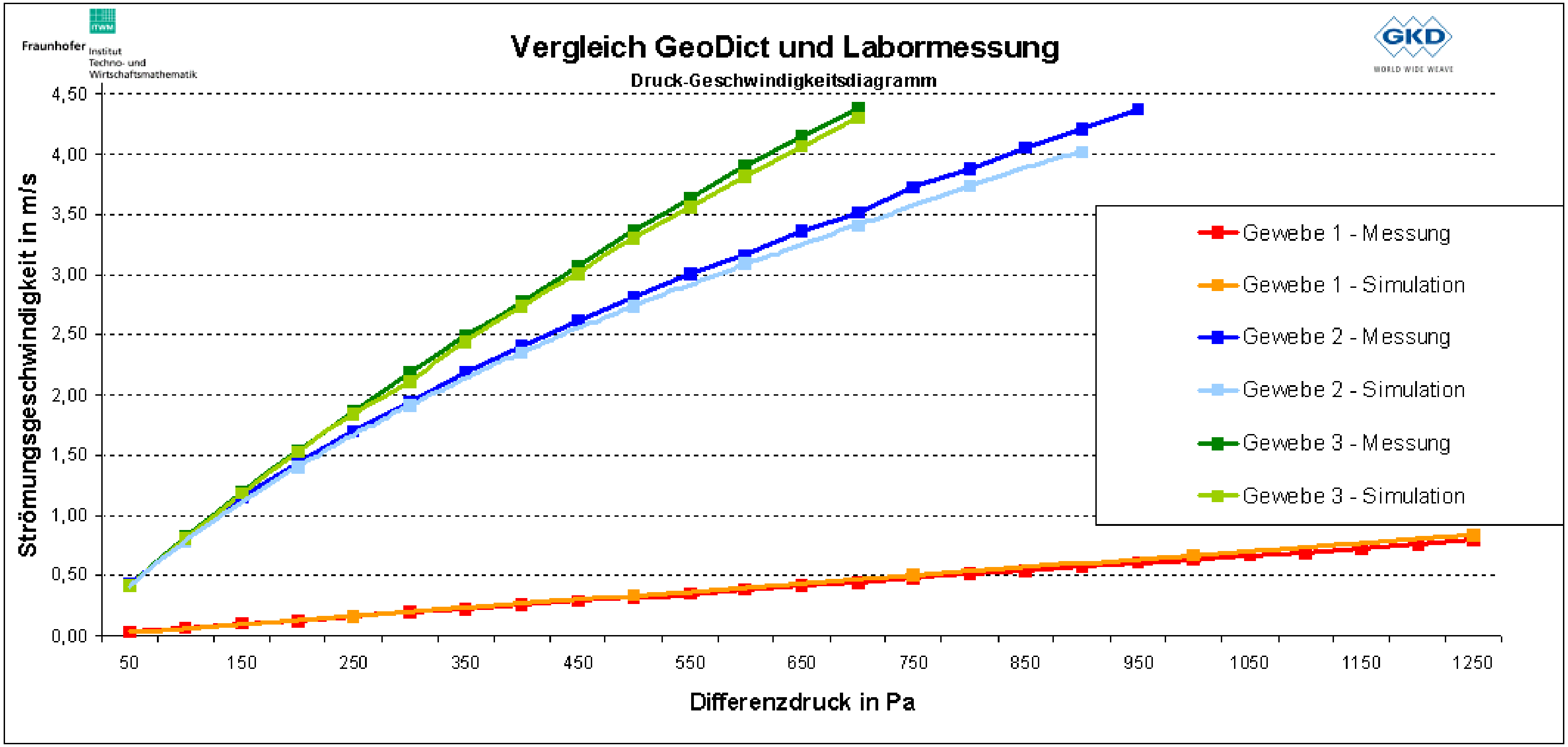
Thankfully permitted by Graham Rideal
Whitehouse Scientific

Mesh Design with GeoDict
Example

- High efficiency
- High flow rates

With permission by Friedrich Edelmeier, Haver & Boecker

Measured & FlowDict pressure drop for metal wire meshes

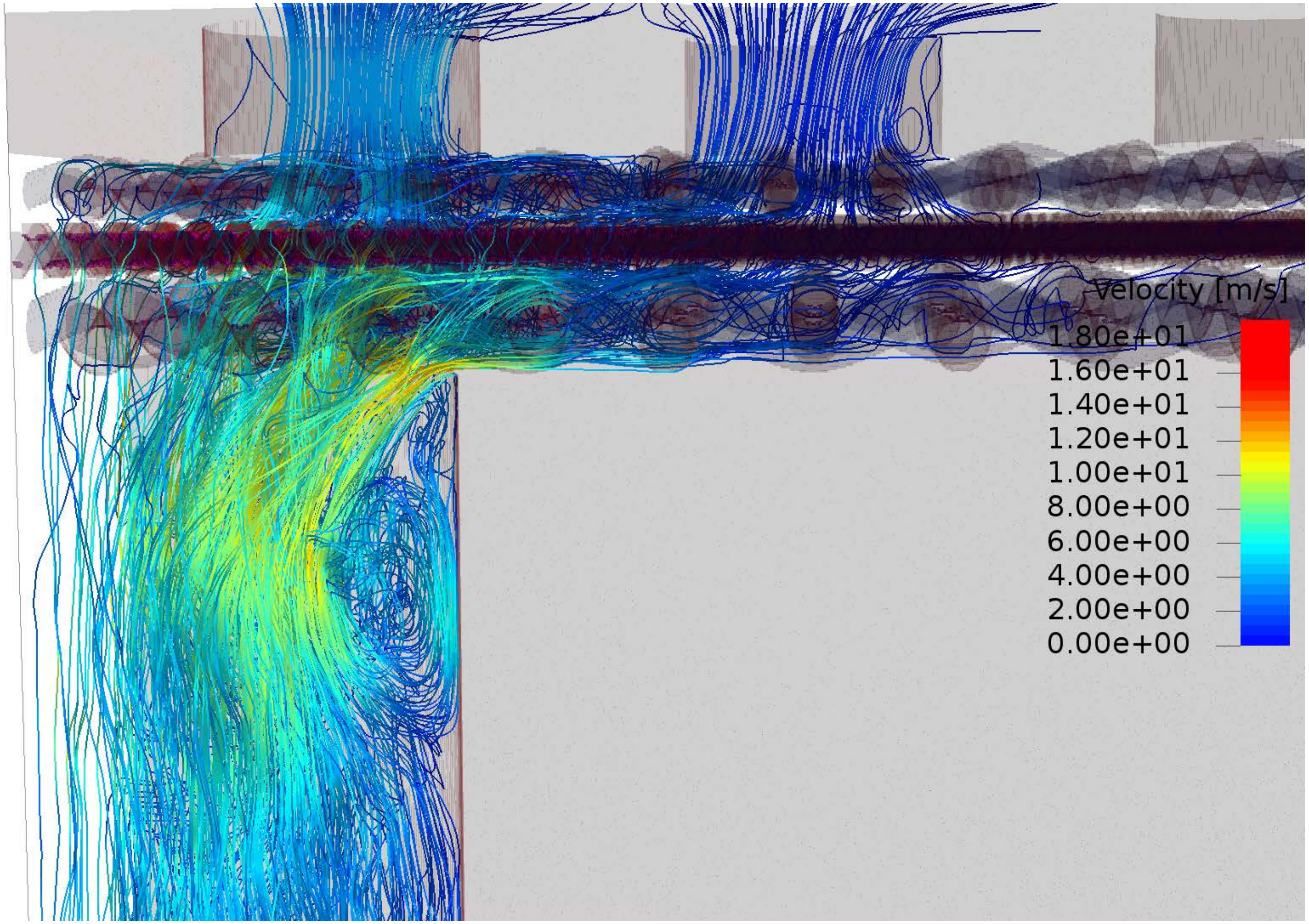


E. Glatt, S. Rief, A. Wiegmann, M. Knefel and E. Wegenke, *Structure and pressure drop of real and virtual metal wire meshes*, Bericht des Fraunhofer ITWM, Nr. 157, 2009.

Deviation of simulation and experiment independently confirmed to lie within 3% over all differential pressures by A. Mantler and M. Theiß of Haver & Boecker, 2017.

Turbulent flows and mesh abrasion is modelled with GeoLab (work by L. Cheng, Math2Market and D. Dreschers, GKD)

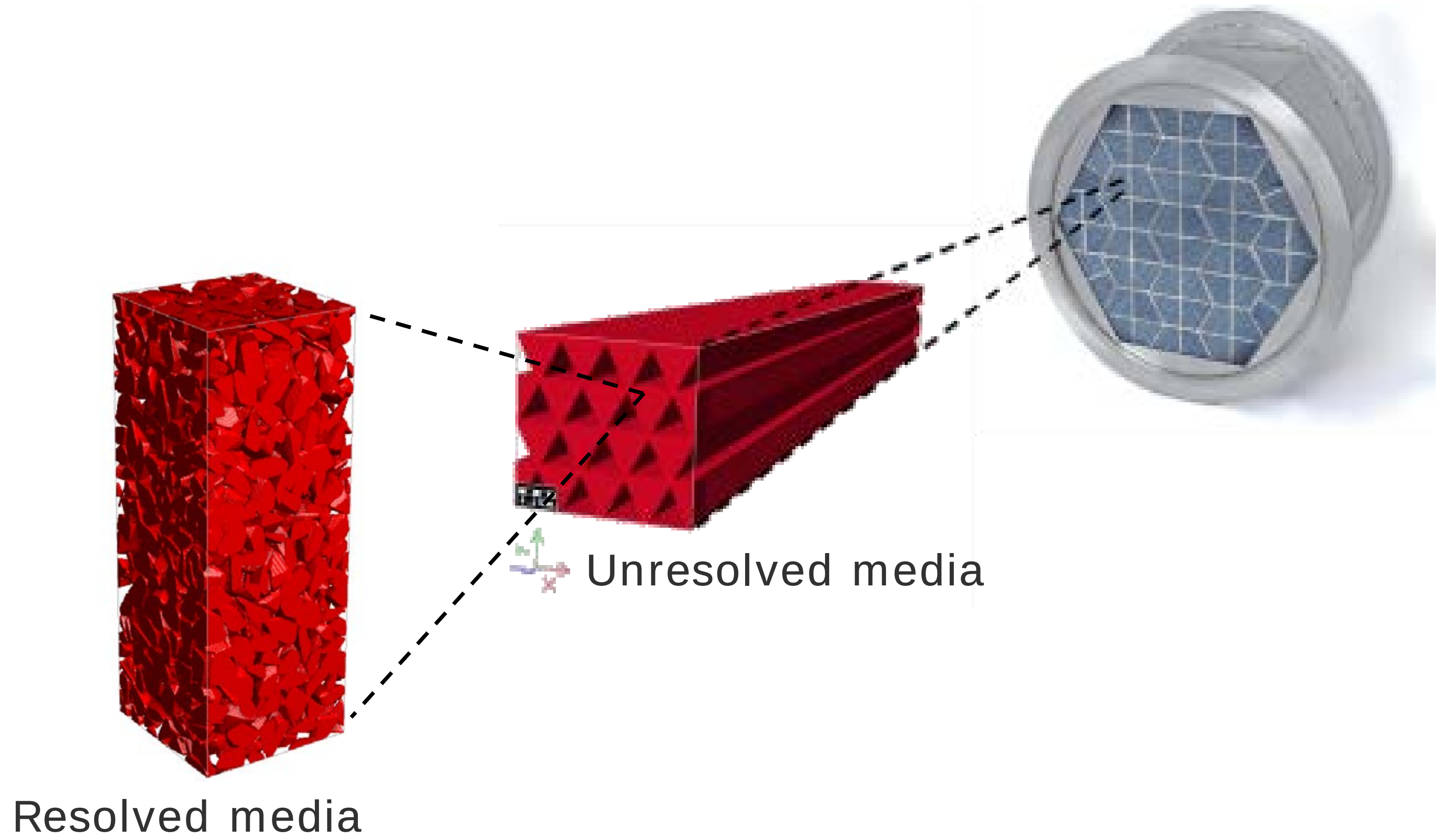
- Sand control screens are complex multilayered structures
- Local pore velocity can be vastly different from the average
- Abrasion by sand particles can lead to hot spots



2. Simulation-based development of soot filter ceramic media

L. Cheng, J. Becker, M. Azimian , A. Wiegmann

Simulate soot filtration at different scales



Introduction to Diesel Particulate Filter (DPF)

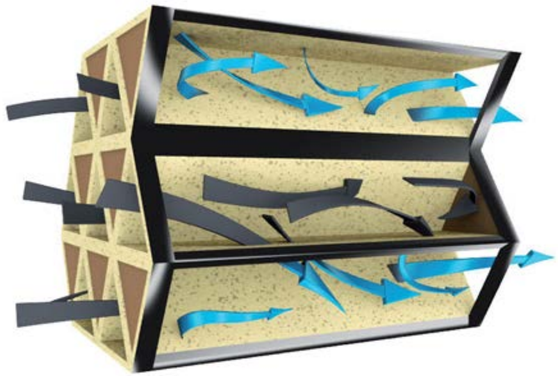
Goal:

Design & improve Diesel/Gasoline Particulate Filters (DPF/GPF) through fast simulations.

- lower pressure drop
- higher filter efficiency
- longer life time

Key element governing the performance of the DPF:

Ceramic filter media



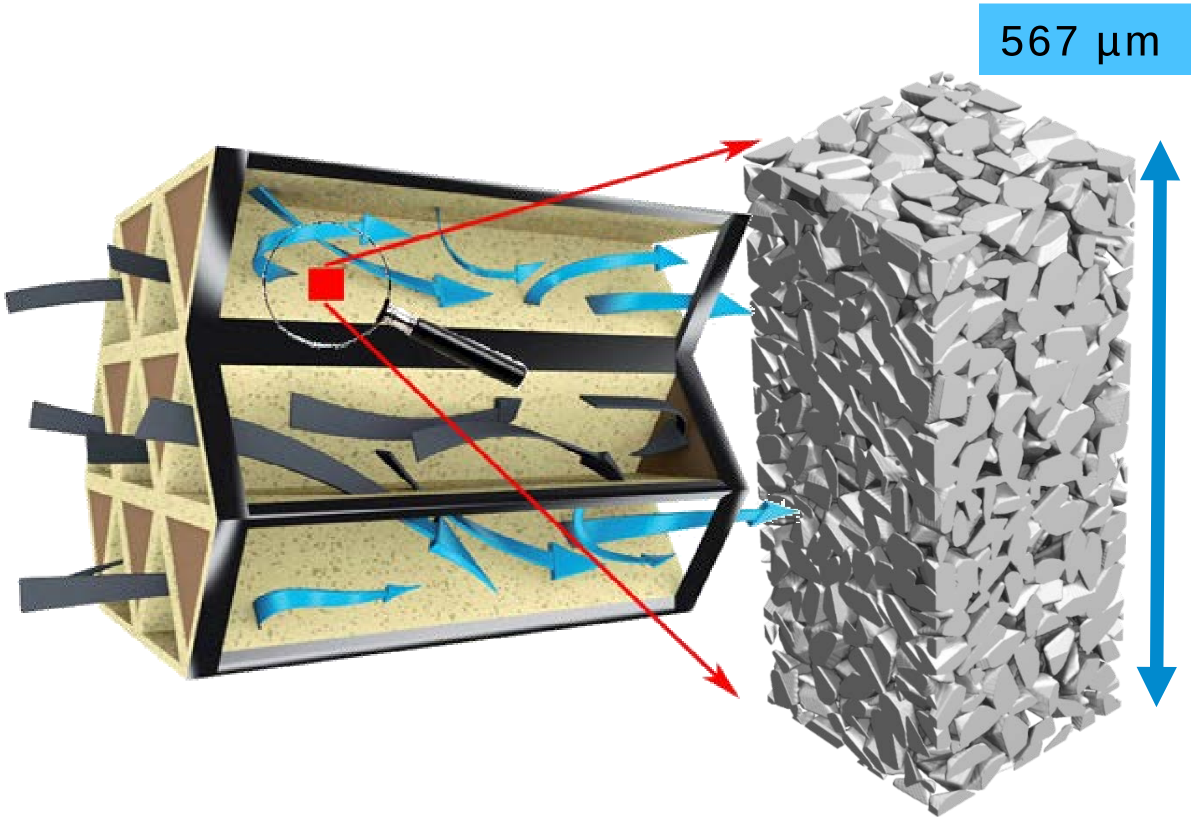
Diesel Particulate Filter (DPF) simulations

Energy use of the DPF:

- Pressure loss across the (loaded) ceramic walls
- Pressure loss along the channels

Step 1: Simulate pressure loss & solid loading across the wall

Step 2: Simulate pressure loss & solid loading along the channels



Micro-structure

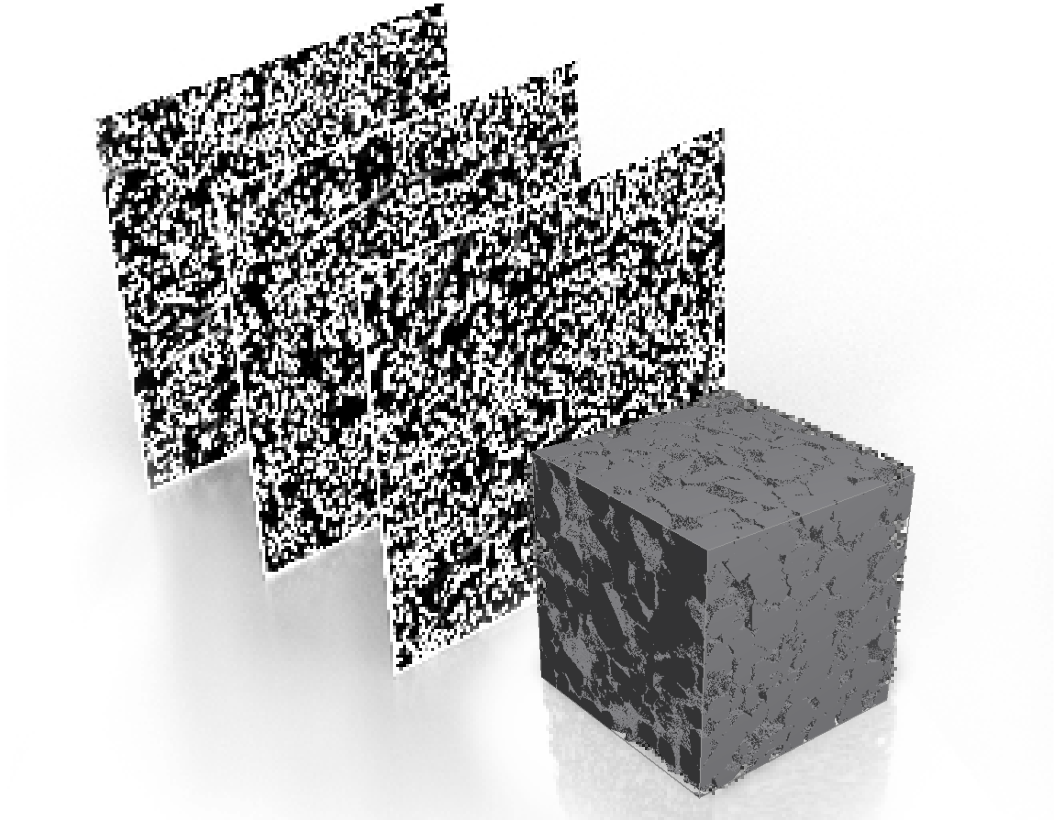
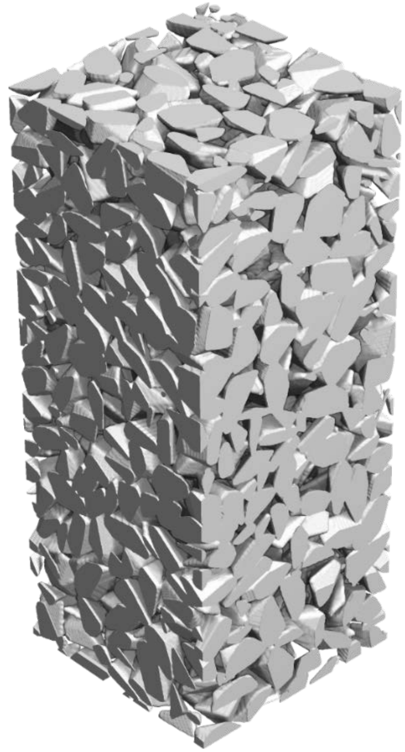


Image acquisition: µ-CT

(+) Allows simulations on real filter structures

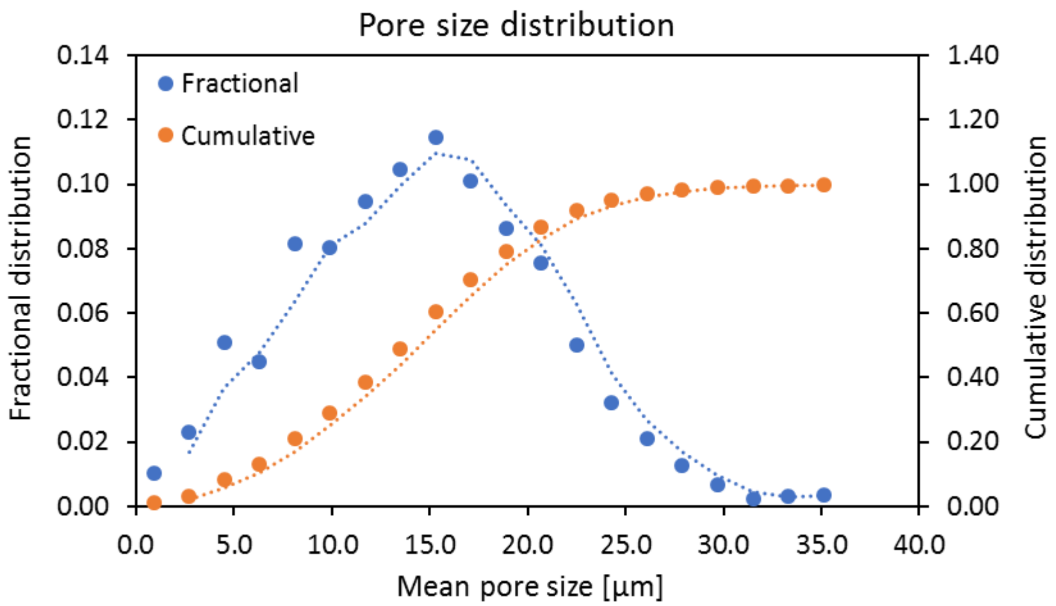
(-) Modification of the filter structure is not possible only through µ-CT images

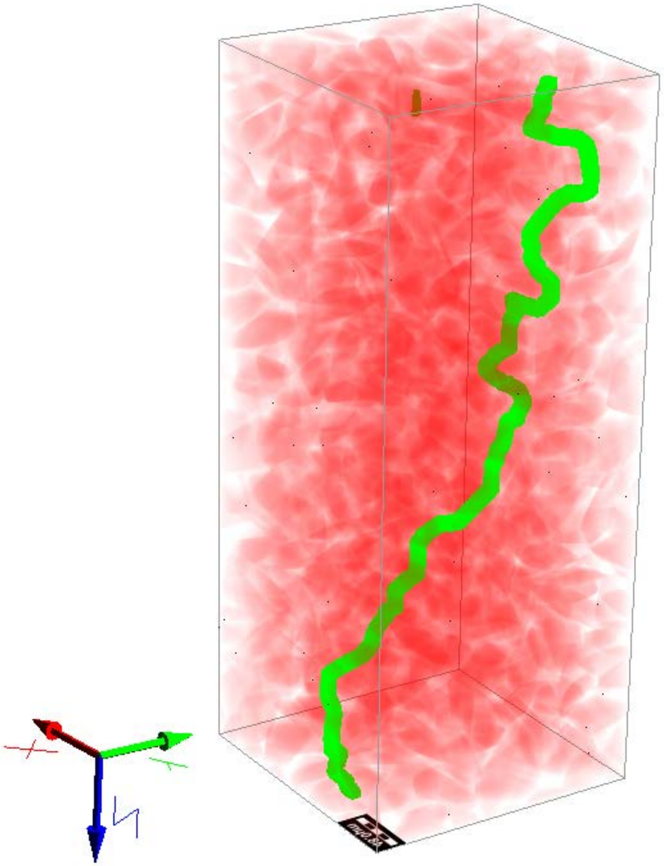


Modelling with GeoDict structure generator modules

Characterizing the ceramic

Evaluation of the pore size distribution & percolation path



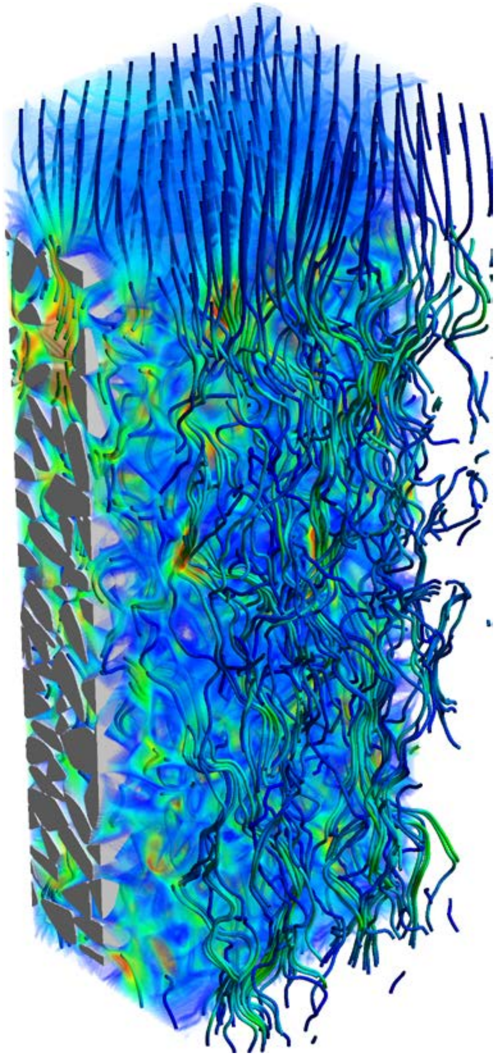


Maximum particle diameter [µm]	Path length [µm]
9.94	929.1

Ceramic model characterization

Characterizing the ceramic

- Domain size: 256x256x630 Voxels
- Voxel length: 0.9 µm
- Ceramic porosity: 48.7 %
- Pressure drop is 252.8 Pa at mean air flow velocity of 0.04 m/s
- Flow resistivity: 1.115e+07 kg/(m^3s)
- Permeability: 1.63e-12 m^2



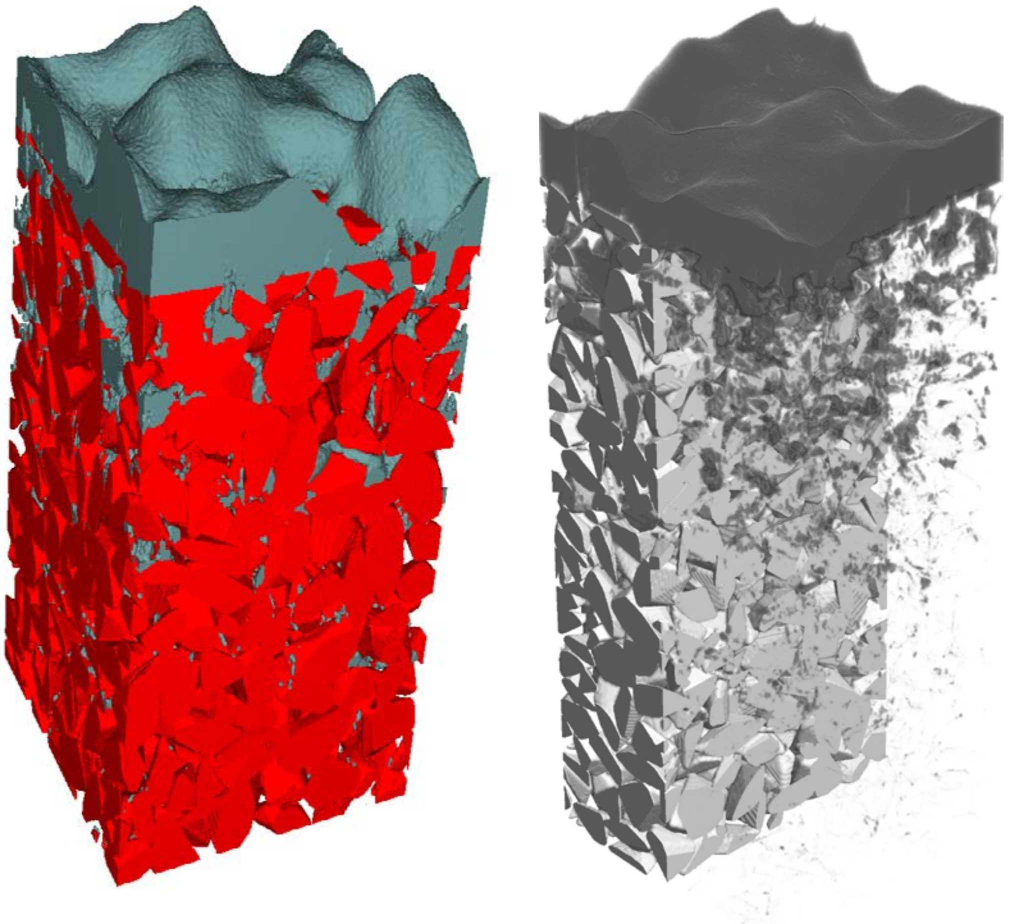
Analysis of cermaic filter performance

Analysis of the filtration performance with

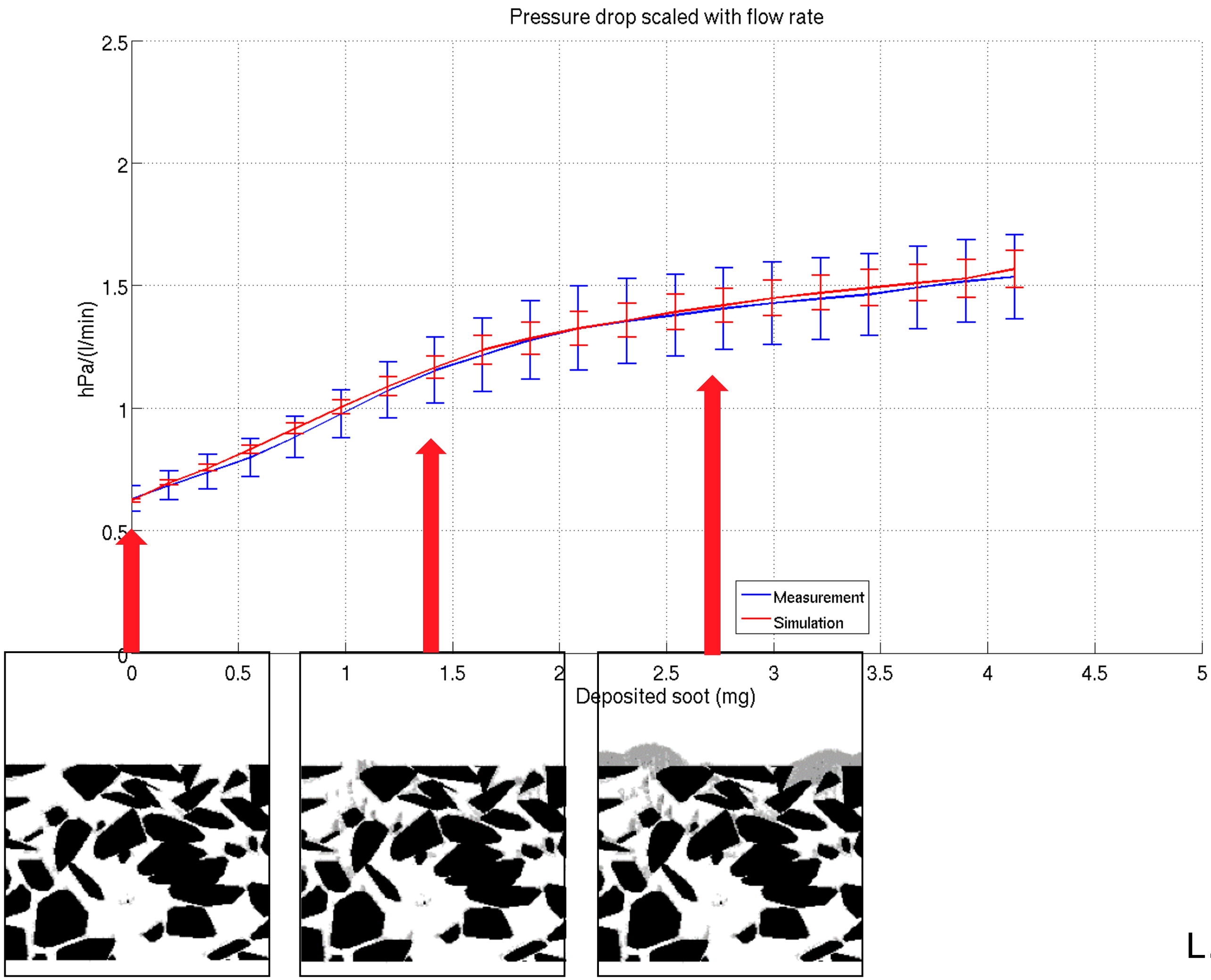
Simulation of soot particles deposition.

Evaluation of fractional filter efficiency.

Evaluation of pressure drop in depth filtration & cake filtration regimes.



Experimental and simulated pressure drop evolution



- Error bars induced by 5 measurements and 5 different realizations of the digital structure.

- Match achieved by introducing different parameters f_{max} & $\sigma(f)$ for depth & cake filtration.

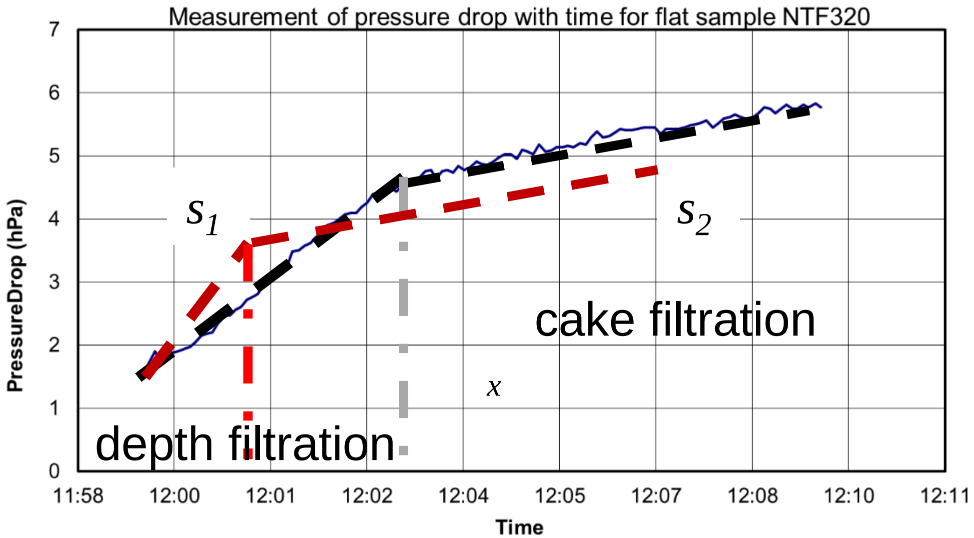
L. Cheng et al., WFC 11, 2012.

Spatial particles deposition over depth and time

Reduced pressure drop over time

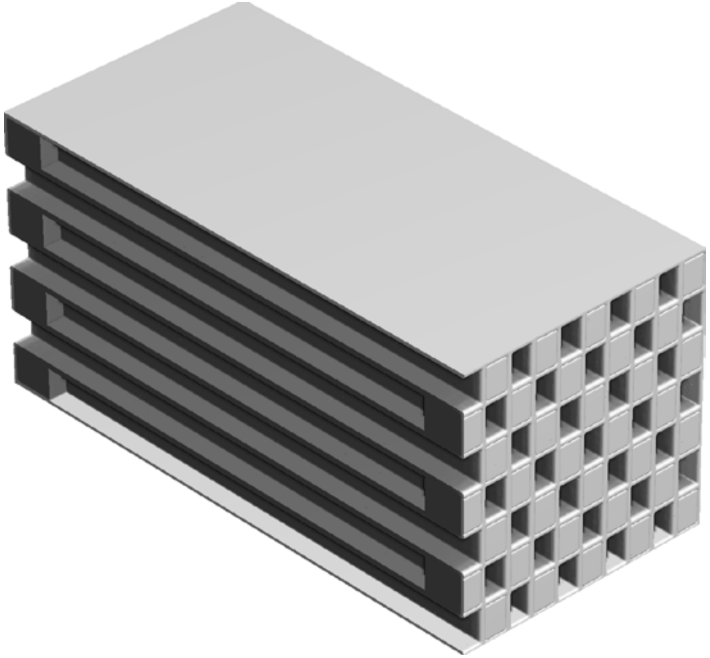
After fast initial pressure drop increase (slope s_1, depth filtration phase)
follows long slower pressure drop increase (slope s_2, cake filtration phase)

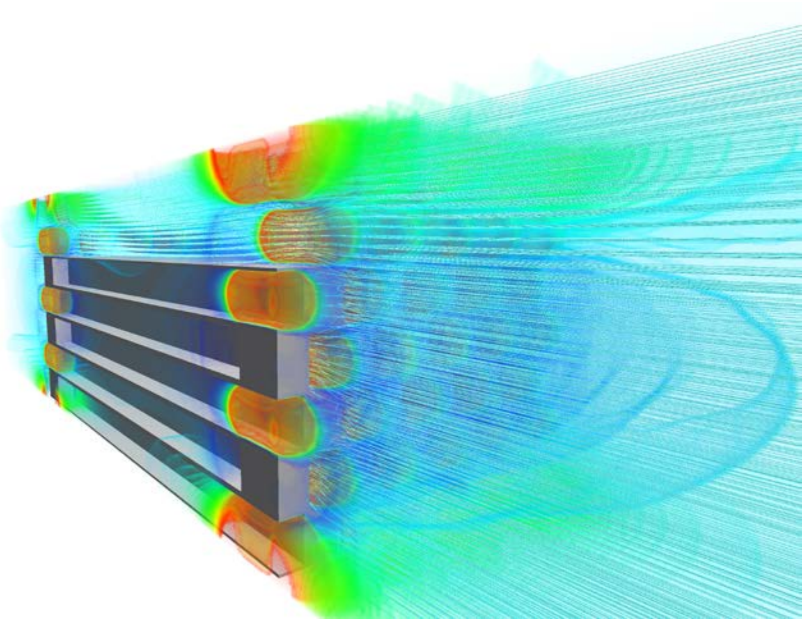
- Matched experiment with simulations
- Shortened depth phase to lower pressure drop during cake phase
- Fraunhofer IKTS manufactured ceramic, experiment matched simulations, and patent was granted: *Particulate filter, No. DE102012220181 A1*



Step 2

Simulate pressure loss along the channels





3. Multi-scale modeling and simulation of pleated filter

M. Azimian, C. Kühnle, A. Wiegmann

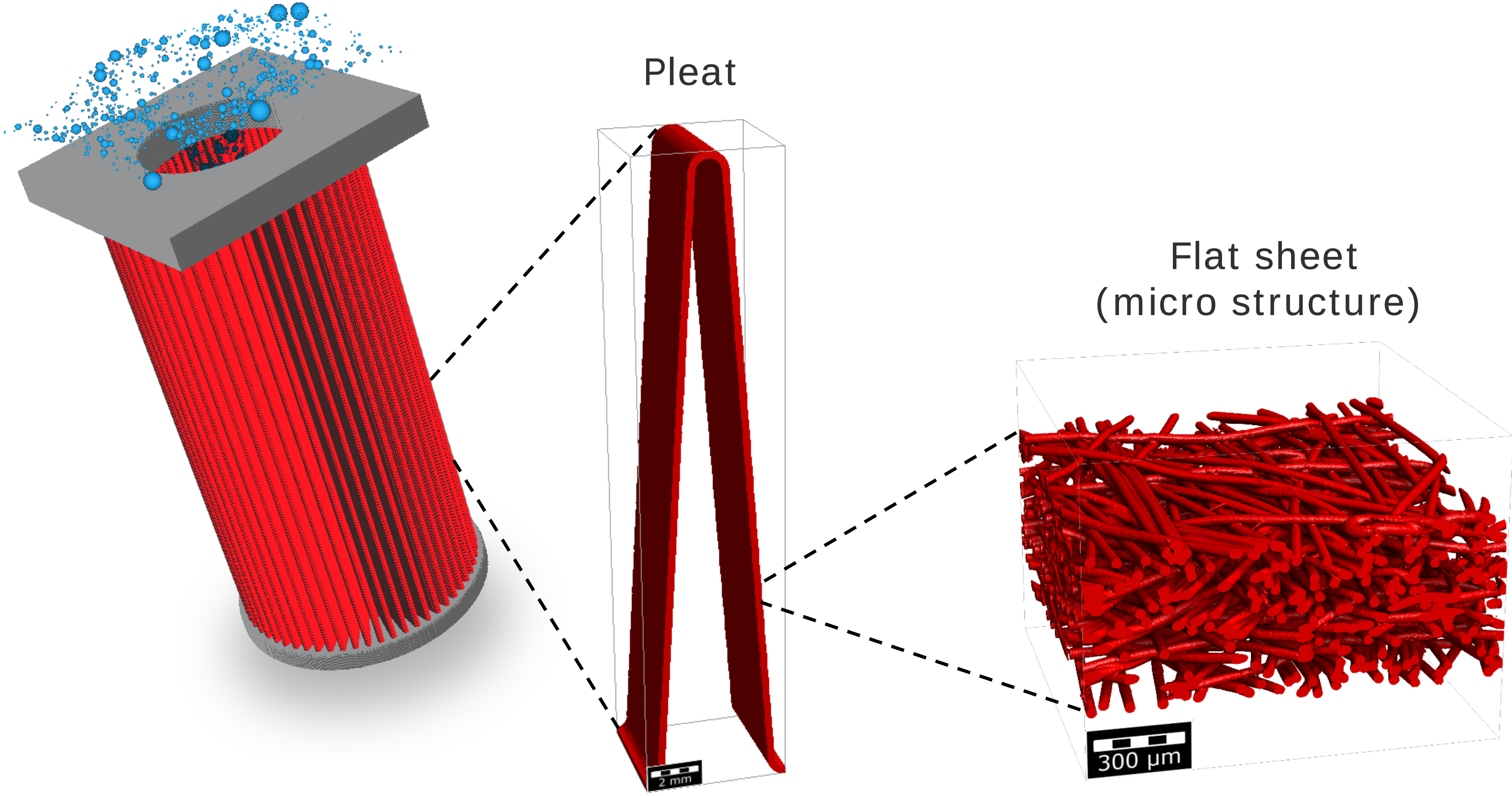
Introduction

- Want to calculate filtration in a pleat
- Design pleat by choice of filter media and choice of pleat shape
- Determine flat sheet properties via simulation

Main steps:

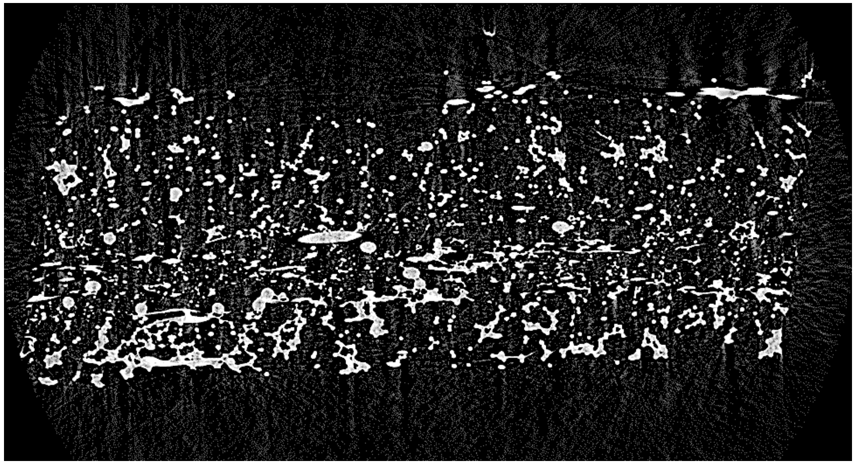
- Start with µ-CT scan of filter media
- Compute permeability via Stokes equation
- Model pleat shape and again solve for flow using stokes equation
- To get clogging, repeat
  - tracking and capturing of particles and
  - flow simulations

Simulate filtration at different scales

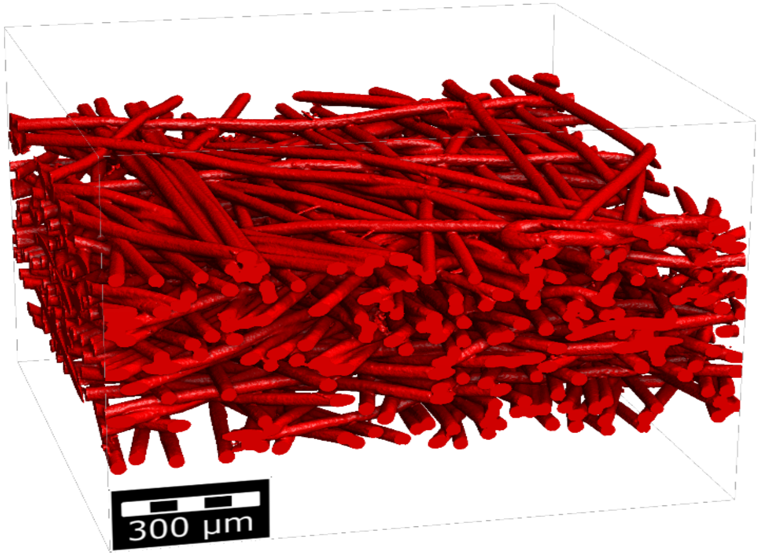


Analysis of the filter media from μ-CT scan

- Analysis of the flat sheet material (filter media) by μ-CT scan

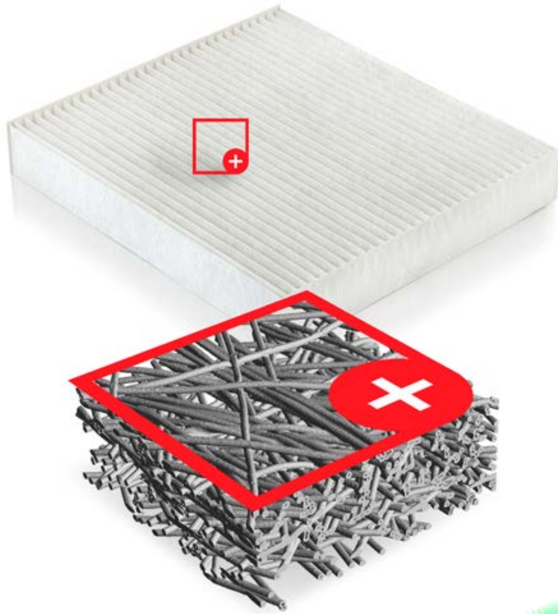


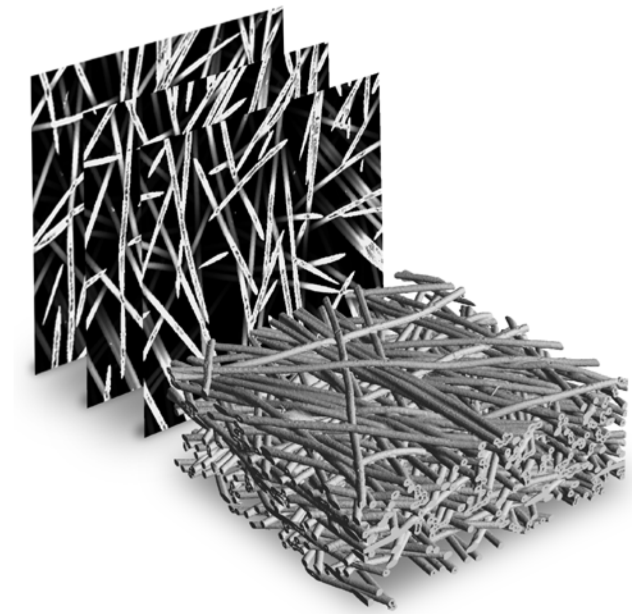
A single 2D image of the μ-CT scan

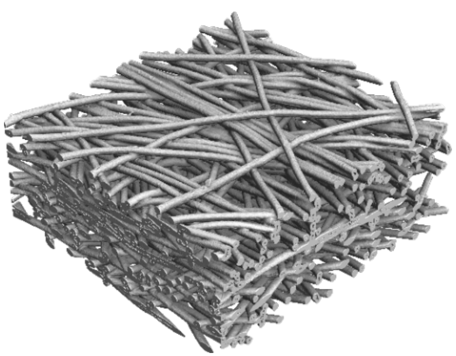


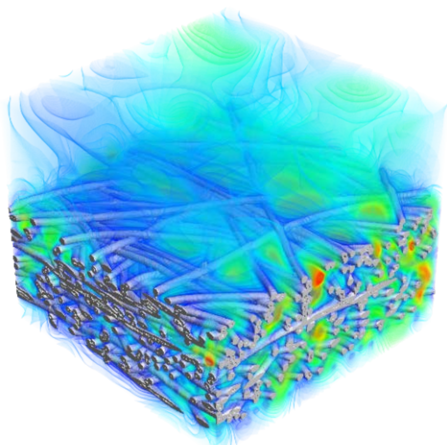
Resulting 3D micro-structure of a sample after image filter processing, segmentation & cropping

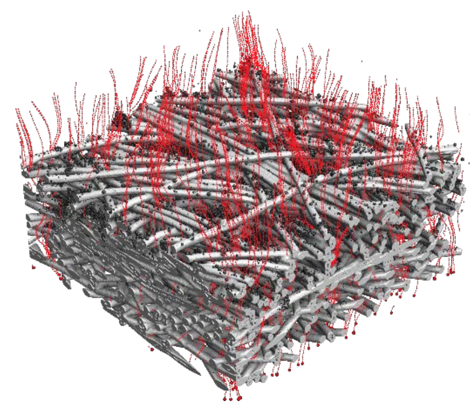
Simulation on the micro-structure of the filter media

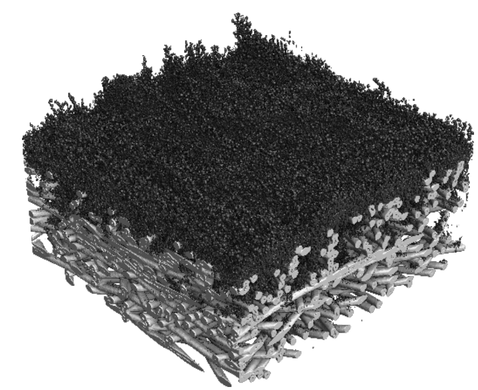




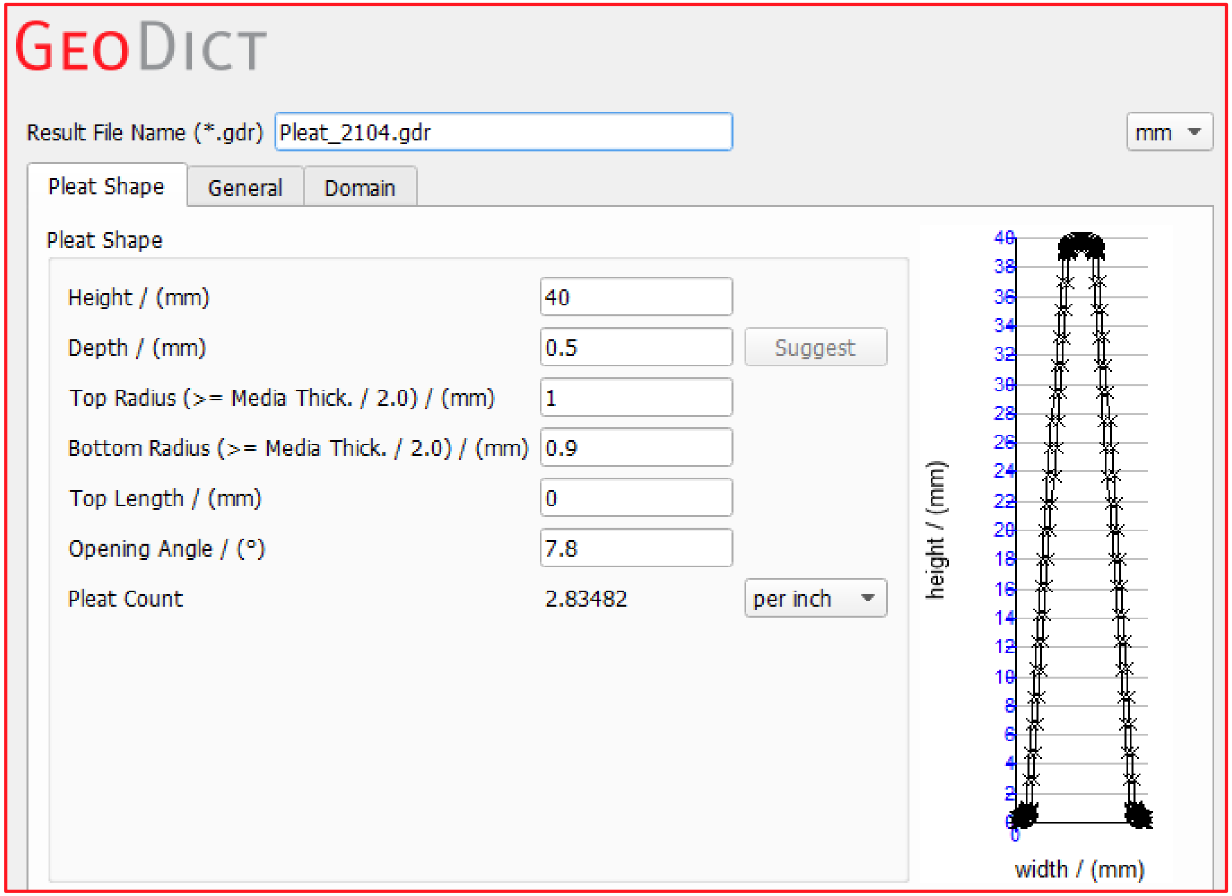


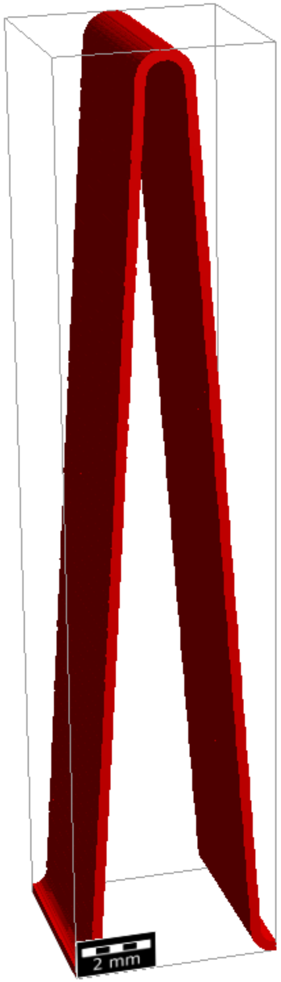




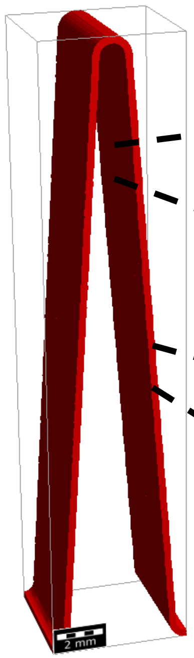


Geometric model of the pleat filter with PleatGeo





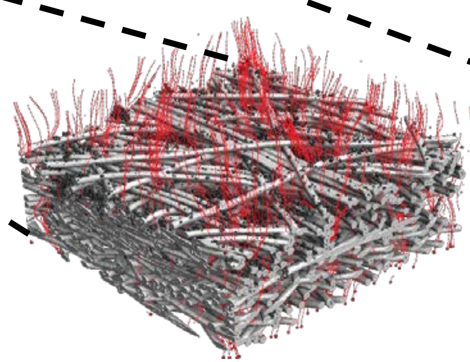
Parameter identification:
Estimate packing density and flow resistivity



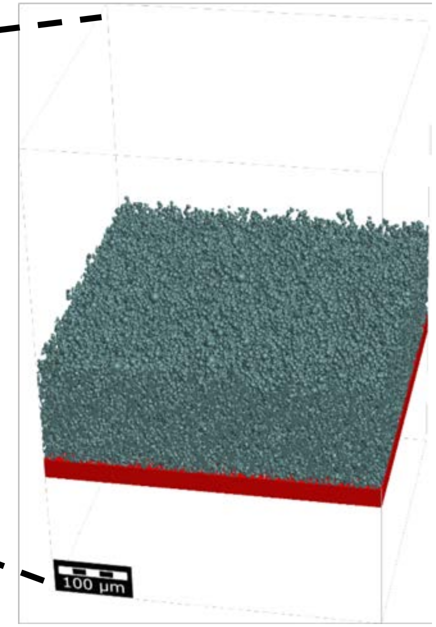
Deposited particles on pleat

Simulation requires

f_{max} maximum packing density
σ_{max} corresponding flow resistivity



Deposited particles in media
micro scale simulation to find
f_{max} & σ_{max} for <u>depth filtration</u>



Deposited particles on membrane

micro scale simulation to find
f_{max} & σ_{max} for <u>cake filtration</u>

Particles:
ISO A1 Ultrafine test dust

	Diameter / (m)	Volume Percentage	Restitution (in [0,1])	Adhesion / (J)	Restitution (in [0,1])	Adhesion / (J)	Media Thickness / (m)	Efficiency / (1)
1	1e-06	2.00385	0.5	1e-18	0.5	1e-18	0.000395	0.307604
2	2e-06	9.01738	0.5	1e-18	0.5	1e-18	0.000395	0.539795
3	3e-06	13.0254	0.5	1e-18	0.5	1e-18	0.000395	0.770146
4	4e-06	16.0318	0.5	1e-18	0.5	1e-18	0.000395	0.92041
5	5e-06	20.037	0.5	1e-18	0.5	1e-18	0.000395	0.975494
6	6e-06	15.0333	0.5	1e-18	0.5	1e-18	0.000395	0.99266
7	7e-06	11.0333	0.5	1e-18	0.5	1e-18	0.000395	0.99698
8	8e-06	7.02501	0.5	1e-18	0.5	1e-18	0.000395	0.9991
9	1e-05	4.97428	0.5	1e-18	0.5	1e-18	0.000395	0.9997
10	1.5e-05	1.81872	0.5	1e-18	0.5	1e-18	0.000395	0.99996

Volume %

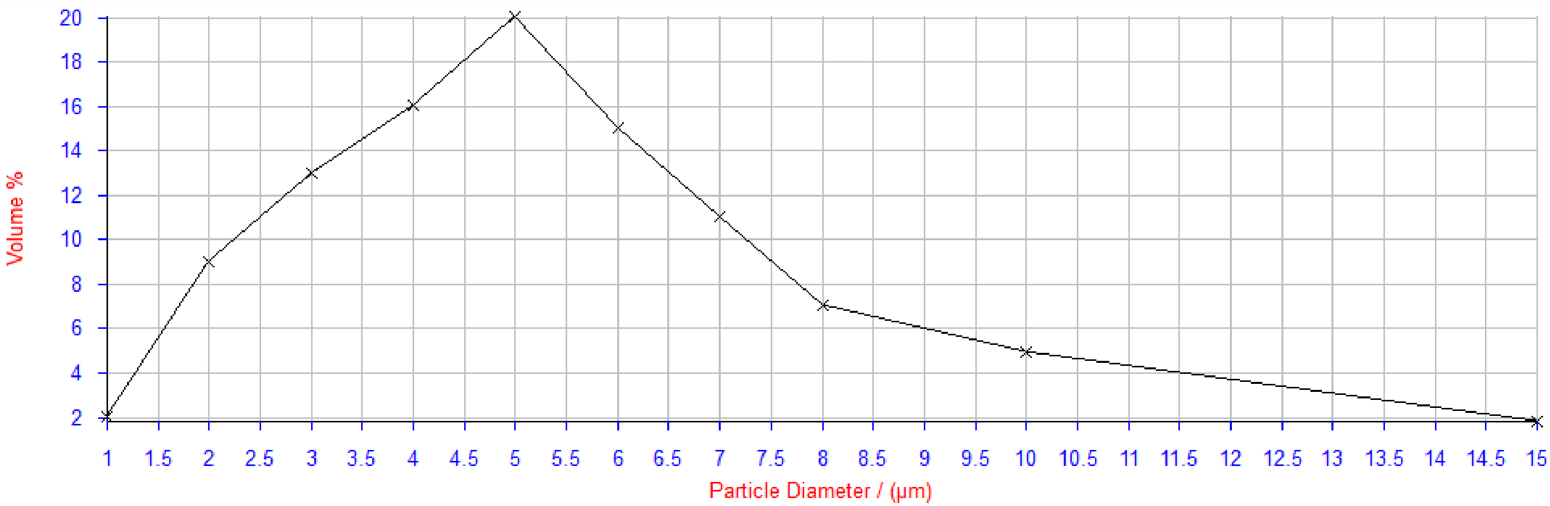
Delete Row

Insert Row

Import ...

Collision model: Hamaker

Filtration efficiency of each particle size class



Particle density: 2650 kg/m^3

Test dust concentration: 2 g/m^3

Determination of filter cake parameters

Determine f_{ma}

the filter cake

simulation on

The $f_{max,c}$ is ca

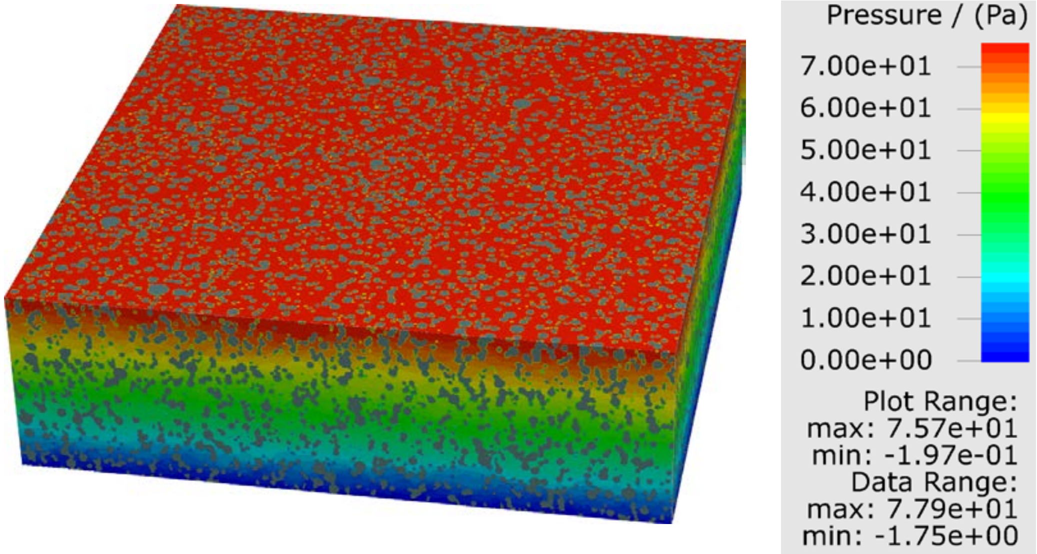
(1-Porosity$_{Cake}$

$\sigma_{max,c}$ (flow res

the flow simul

1.002e+07 kg

Flow simulation on the filter cake



Pressure drop is 77.2 Pa at mean flow velocity: 0.05 m/s

Flow resistivity :1.002e+07 kg/(m^3s)

Permeability: 1.82e-12 m^2

Determination of depth filtration parameters

Currently there are 2 ways to find $f_{max,d}$ and $\sigma_{max,d}$.

1. Run a FilterDict-Element simulation on the pleat & compare the results with the experiments & fit those parameters. (not possible when no exp. data is available!)

2. Run a FilterDict-Media simulation on the µ-CT scan data.

After the depth filtration is completely occurred & a filter cake started to form above the media structure, stop the simulation and remove/cut the generated filter cake.

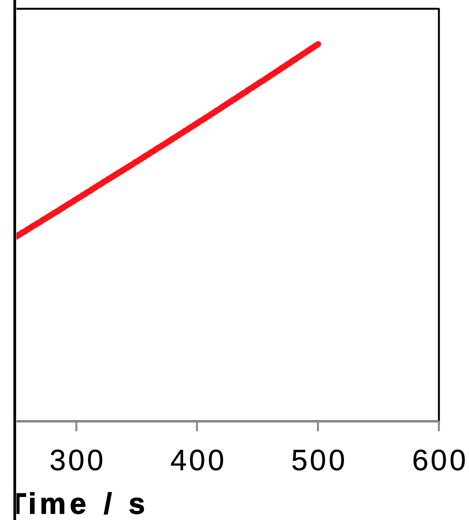
$f_{max,d\,|\,homogeneous\ media}$: (porosity of the clean filter media) - (porosity of the clogged filter media)

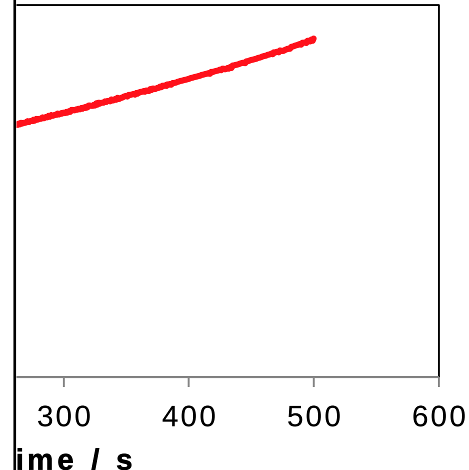
→ 0.0138

$\sigma_{max,d}$: (flow resistivity of the clogged filter media) - (flow resistivity of the clean filter media) → 489415 kg/(m^3s)

Determination of depth filter parameters

Simulation of the pleat filter clogging

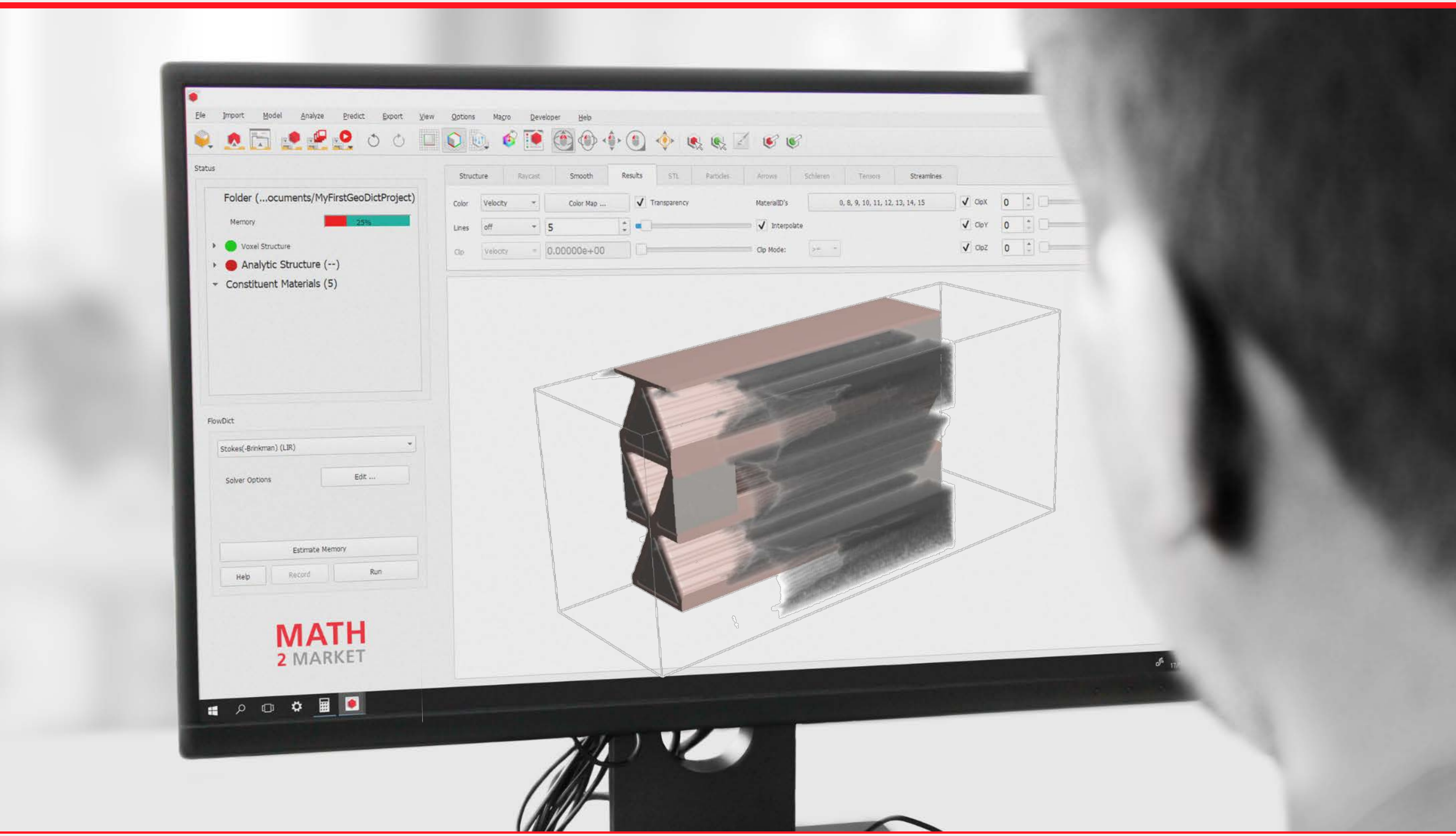




Conclusions about filtration simulations

- ✓ They apply to many filter media, e.g. woven ceramic and fibrous materials.
- ✓ They provide benefits to users both on the technological side and on the marketing side
- ✓ They can usefully be combined for example with mechanical deformation simulations
- ✓ They can provide real world insights can lead to patents
- ✓ They can also provide parameters for further filtration simulations on larger scale

Thank you for your attention.



GeoDict

MATH
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