Center for Filtration Research (CFR)
52nd Review Meeting, Oct 5-6, 2017
Donaldson Company, Inc.
Bloomington, Minnesota

David Y. H. Pui
Member of National Academy of Engineering
Distinguished McKnight University Professor
LM Fingerson/TSI Inc Chair in Mechanical Engineering
Director of the Center for Filtration Research
University of Minnesota

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52nd Semi-Annual Review Meeting of the Center for Filtration Research (CFR)

8:00	***Welcoming Remarks, Tom Scalf, SVP of Engine Products, Donaldson Co.*** ***CFR Research Overview, David Pui***
8:30	**Technical Program Session (I): New Initiatives**
10:00	*Refreshment Break*
10:30	**Technical Program Session (II): Filter Loading; Filter Design**
12:00	*Lunch Break; CFR Representatives' Meeting (2 reps each to meeting room)*
1:00	**Technical Program Session (III): Invited Lecture: Zongxuan Sun, Professor; H. Young Chung, Ph.D., Visiting Scientist, Mechanical Engineering, UMN**
2:00	**Technical Program Session (IV): Liquid-borne Particles Filtration; Exposure**
4:00	*Refreshment Break*
4:15	**Technical Program Session (V): Modeling; Instrumentation**
5:30	**Center Planning Meeting**
5:45	*Adjournment*

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UMN Center for Filtration Research (CFR)

Corning

The member companies of CFR have $28 billion annual sales (est.) in filtration industry. Applications include

- Removal of $PM_{2.5}$ pollutants
- Engine emission removal
- Cabin air filter for automobiles/airplanes
- Respirator and personal protection equip

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Objectives

- Foster industry/university collaboration in filtration through
  - graduate education
  - research
  - continuing education and technology transfer
- Help University to become more relevant in its research and education
- Encourage industry to utilize the knowledge and skill base available at the University to make itself more competitive in the global market place.

Technical Objectives

- Perform fundamental filtration research and theoretical modeling
- Develop improved experimental methods useful for filtration research, filter characterization, and filter testing
- Keep abreast of development in fundamental filtration science and new industry and government initiatives
- Seek new application of scientific knowledge to practical filtration problems

Faculty, Senior Staff and Visitors

Name	Title	Affiliation
David Pui*	Professor & CFR Director	UMN Mechanical Engineering
Benjamin Liu	Professor Emeritus & CFR Co-Founder	UMN Mechanical Engineering
David Kittelson*	Professor	UMN Mechanical Engineering
Thomas Kuehn*	Professor	UMN Mechanical Engineering
Peter McMurry	Professor	UMN Mechanical Engineering
Jake Swanson*	Assistant Professor	Minnesota State University, Mankato
Chris Hogan	Associate Professor	UMN Mechanical Engineering
Da-Ren Chen*	Chair Professor	Virginia Commonwealth University
Christoph Asbach	International Collaborator	IUTA, Duisburg, Germany
Rose Amal	International Collaborator	U of New South Wales, Australia
Jing (Jimmy) Wang*	Associate Professor	ETH Zurich, Switzerland
Peter Raynor	Associate Professor	UMN School of Public Health
Seong Chan Kim*	Senior Research Scientist	UMN Mechanical Engineering
Shawn Chen*	Assistant Professor	Virginia Commonwealth University
Qisheng Ou*	Post-doctoral Research Associate	UMN Mechanical Engineering
Min Tang*	Post-doctoral Research Associate	UMN Mechanical Engineering
Doris Segets*	Member of Engineering of Adv Materials	University of Erlangen-Nuremberg
Cheng Chang*	Post-doc (November, 2017)	China University of Petroleum
Yun Liang*	Visiting Professor (December, 2017)	Pulp & Ppaer Key Lab, SCUT
H. Young Chung*	Visiting Scientist	UMN Mechanical Engineering

Current Involvement in Center activities

CFR Graduates

Graduates	Degree	Date	Advisor	Employer
Ming Ouyang	Ph.D.	Jul-95	Liu	Cummins
Seong-Ho Yoo	Ph.D.	Mar-96	Liu	KLA-Tencor
Da-Ren Chen	Ph.D.	Sep-96	Pui	Virginia Commonwealth University
Kim Boelter	M.S.	Sep-96	Davidson	Ellerbe Becket
Wilson Poon	Ph.D.	Jun-97	Liu	WL Gore
Hee-Siew Han	M.S.	Jul-97	Kuehn	TSI
Laura C.F. Lin	M.S.	Jun-97	Vesley	Taiwan
Nicole Hoekstra	M.S.	Dec-97	Davidson	Seattle Community College
Poshin Lee	M.S.	Dec-97	Davidson	Entegris
Suresh Dhaniyala	Ph.D.	Jul-98	Liu	Clarkson University
Bruce Forsyth	Ph.D.	Jul-99	Liu	Boston Scientific
Scott Earnest	Ph.D.	Jul-00	Pui	NIOSH
Huaping Wang	M.S.	Apr-01	Pui	Entegris
Shintaro Sato	Ph.D.	May-01	Pui/Chen	Fujitsu
Poshin Lee	Ph.D.	Jun-02	Pui/Chen	Entegris
Choongkee Seong	M.S.	Jun-02	Kuehn	Korea
Michael Kinsley	Ph.D.	Jul-01	Davidson	State University of New York
Gong Yun	M.S.	Jun-02	Raynor	UMN Hospital
Weijia Sun	M.S.	Sep-03	Chen	JKMU Enterprise, Inc
Soo-hyung Kim	Ph.D	Jun-03	Liu	Post-doc, NIST and U. of Maryland
Edgar Chay	M.S.	Dec-04	Chen	WWT, St. Louis
Sho Takagaki	Ph.D.	Apr-06	Liu/Pui	Post-doc at UMN BioSystems Eng.

CFR Graduates (Cont.1)

Graduates	Degree	Date	Advisor	Employer
Liming Lo	Ph.D.	Aug-06	Pui/Chen	NIOSH, Cincinnati
Luke Franklin	M.S.	Jun-06	Pui/Kuehn	Optimization of Respirator Test System
Chaolong Qi	PostDoc	Oct-08	Pui	NIOSH, Cincinnati
Dain Thul	M.S.	Sep-08	Kittelson	Crankcase Emission Measurement
Wendy Tang	Ph.D.	Sep-08	Kuehn	Intel, Phoenix
Seong Chan Kim	R.Assoc	8/1/10	Pui	Entegris, Chaska; Mechanical Engineering, UMN
Jimmy Jing Wang	ResProf	8/1/10	Pui	Assistant Professor, ETH Zurich and EMPA, Switzerland
Ta-Chih Hsiao	Ph.D.	8/1/10	Chen	Assistant Professor, National Central University, Taiwan
Weon Gyu Shin	Ph.D.	8/1/10	Pui	Assistant Professor, Chungnam National University, Korea
Nick Stanley	Ph.D.	9/1/10	Kuehn/Pui	Donaldson Company, Inc.
Luke Franklin	Ph.D.	4/1/11	Kittelson	Dow Chemical, Minnesota
Jake Swanson	Ph.D.	9/1/10	Kittelson/Pui	Mankato State University, Minnesota
Kyoungtae Kim	PostDoc	9/1/11	Pui	Contamination Engineer, Samsung Electronics, Korea
Zhun Liu	M.S.	12/31/11	Pui	Filter Modeling; Agglomerates Analysis
Jennifer Reinhart	M.S.	5/31/11	Pui	Cummins
Lin Li	Post-doc	6/1/12	Pui	MSP Corporation – a TSI Company
Qisheng Ou	Ph.D.	3/1/13	Chen	Post-doctoral Associate, CFR, UMN
Kai Xiao	M.S.	8/1/13	Kittelson/Pui	Guangdong, China
Tsz Yan Ling	Ph.D.	10/1/13	Pui	Intel, Santa Clara, CA
Gus Lindquist	M.S.	6/14/14	Hogan/Pui	HVAC

CFR Graduates (Cont.2)

Graduates	Degree	Date	Advisor	Employer
Zhili Zuo	Ph.D.	7/15/14	Kuehn/Pui	Applied Materials
Swathi Satish	M.S.	7/15/15	Kittelson/Pui	Cummins
Chang Hyuk Kim	Ph.D.	8/1/16	Pui	Postdoctoral Scholar, California Institute of Technology
Min Tang	Ph.D.	8/15/16	Liang/Pui	South China U of Technology; Post-Doc at UMN
Ningning Zhang	Scholar	9/30/16	Pui	IEECAS: PM2.5 Loading Study and SALSCS Evaluation
Maromu Yamada	Scholar	3/1/17	Pui	JNIOSH: Personal Exposure Assessment using SEM

CFR Current Students/Scholars

Students	Degree	Date	Advisor	Project
Drew Thompson	Ph.D.	9/30/17	Pui	Electret Filter Modeling and Charge Characterization
Nanying (Leo) Cao	Ph.D.	12/30/17	Pui	Agglomerate Charging and Surface Monitor
Sarka Drdova	Ph.D.	10/15/19	Wang	Catalyst Filter for Airborne VOCs Decomposition
Peng Wang	Ph.D.	6/15/20	Chen	Respiratory Filter Media Study
Qingfeng Cao	Ph.D.	6/15/18	Pui/Shen	SALSCS Modeling by CFD and WRF
Seungkoo Kang	Ph.D.	12/15/17	Pui	PIV Measurements of Pleated Filters
Handol Lee	Ph.D.	6/15/18	Pui	Fundamental Study of Liquid Filtration; DDF Recipient
Chenxing Pei	Ph.D.	6/15/19	Pui	HVAC Filter Loading with Salt and Soot Particles
Luying Liu	Ph.D.	6/15/20	Pui	Tsinghua fellowship student
Dong-Bin Kwak	Ph.D.	6/15/21	Pui	ME Fellowship student from Hanyang Univeristy, Korea
Xinjiao Tian	Ph.D.	2/28/19	Pui/Tang	CSC student from China Northeastern University
Lipeng Su	Ph.D.	11/18/18	Pui/Ou	CSC student from Harbin Institute of Technology
Hanchao Gao	Ph.D.	4/19/19	Pui/Kim	CSC student from Donghua University

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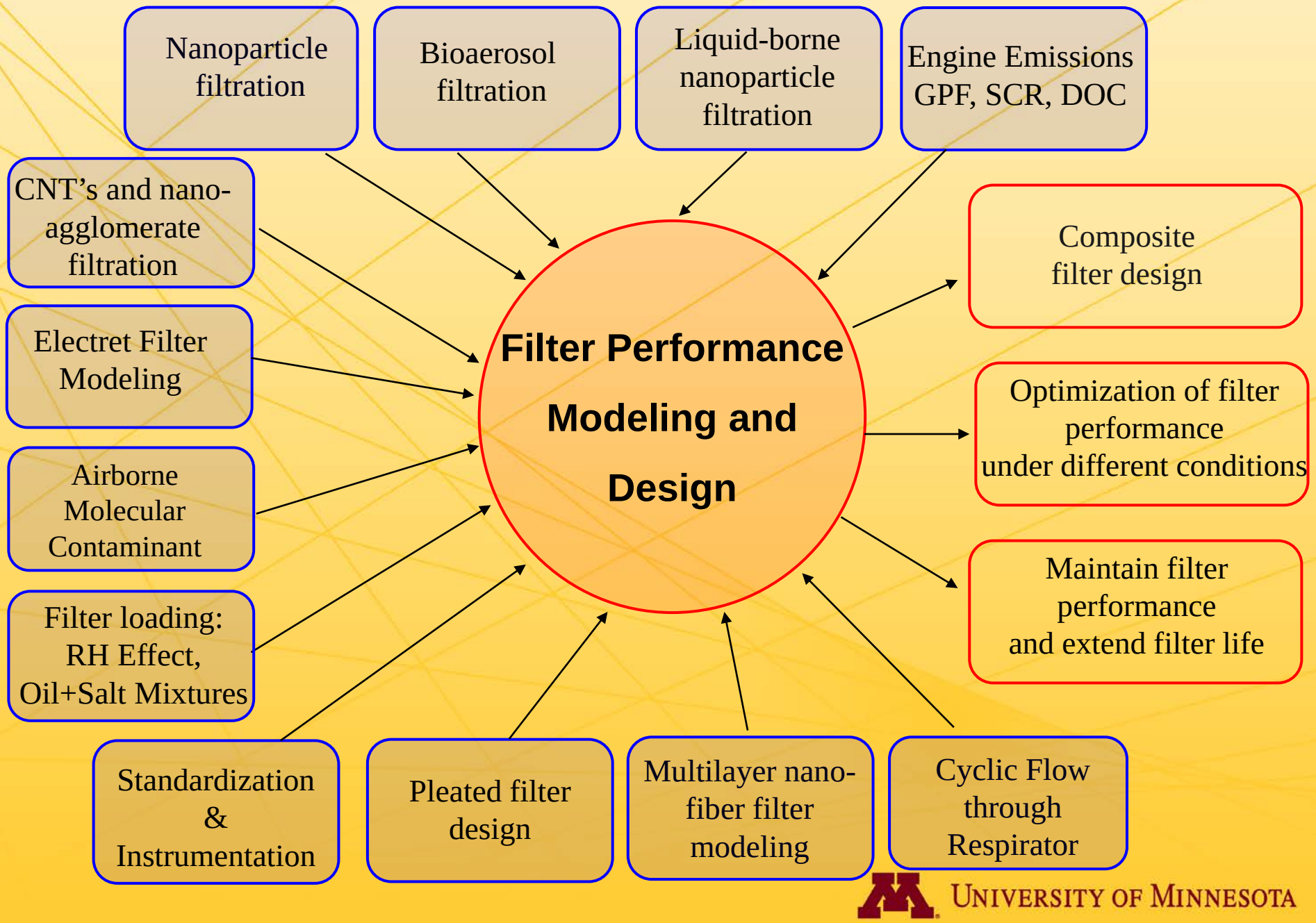
Comprehensive Filter Modeling and Design



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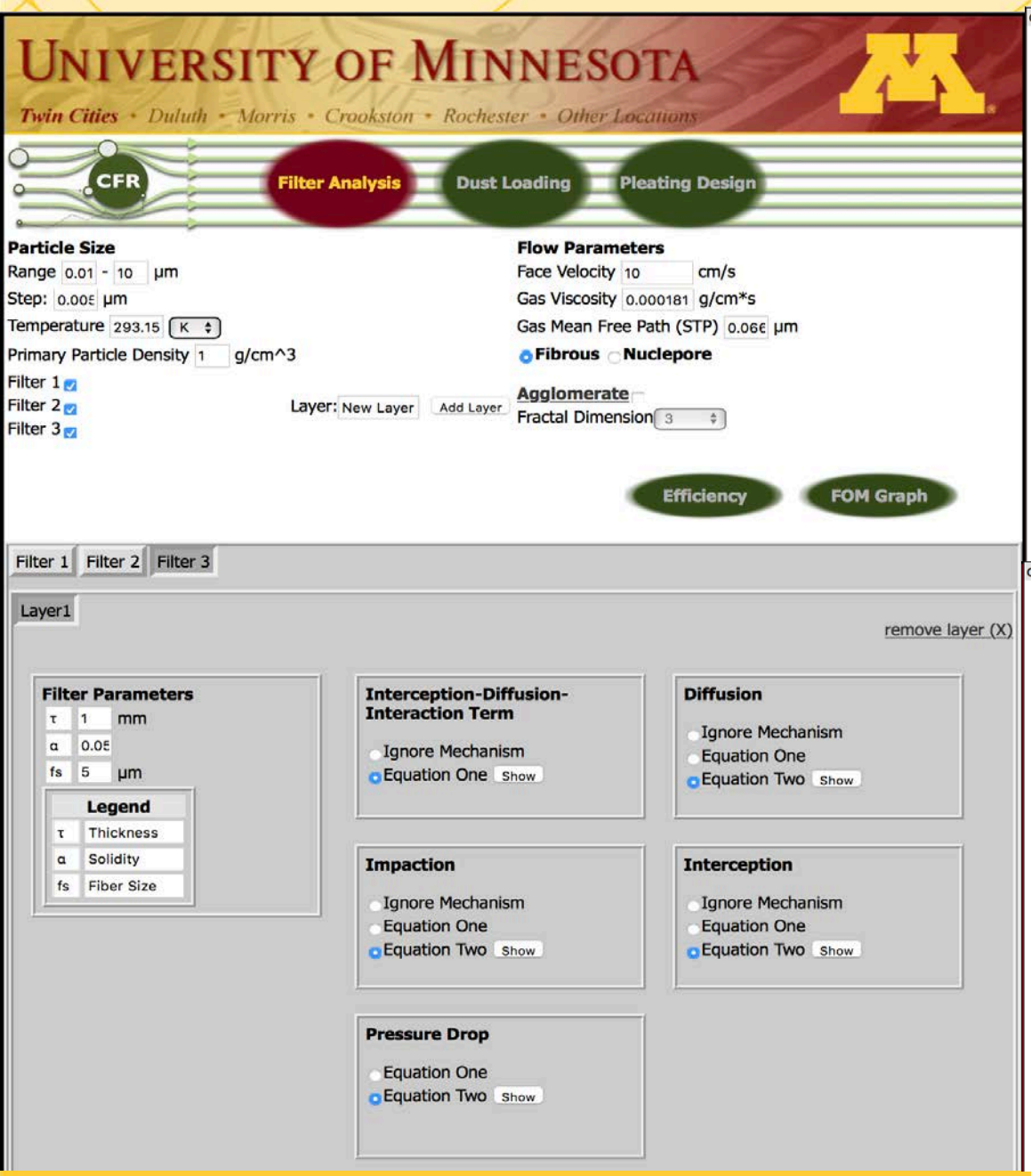
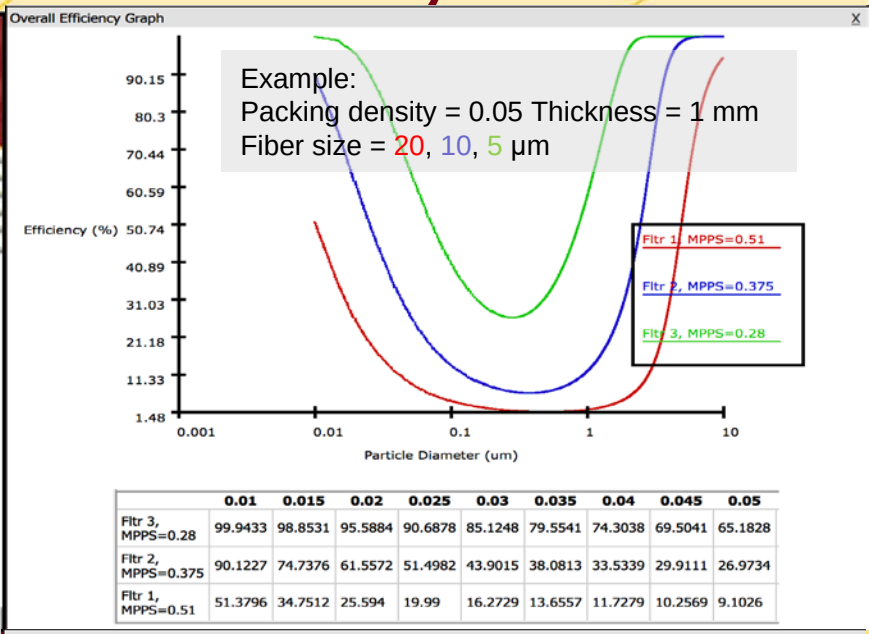
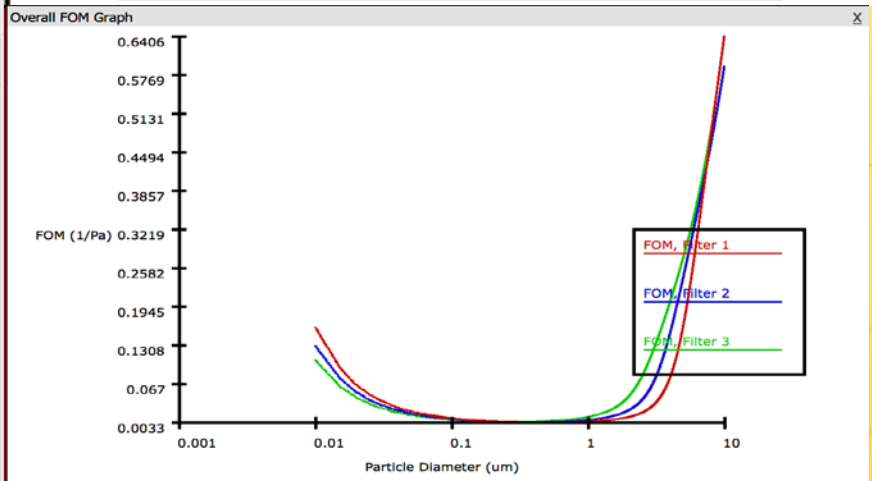
Software Solution for Filter Analysis





	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05
Fltr 3, MPPS=0.28	99.9433	98.8531	95.5884	90.6878	85.1248	79.5541	74.3038	69.5041	65.1828
Fltr 2, MPPS=0.375	90.1227	74.7376	61.5572	51.4982	43.9015	38.0813	33.5339	29.9111	26.9734
Fltr 1, MPPS=0.51	51.3796	34.7512	25.594	19.99	16.2729	13.6557	11.7279	10.2569	9.1026



	0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045
FOM, Filter 3	0.1058063	0.063245	0.0441758	0.033601	0.0269714	0.022469	0.0192338	0.016809
FOM, Filter 2	0.1293088	0.0768532	0.0534007	0.0404175	0.0322896	0.0267757	0.022817	0.019852
FOM, Filter 1	0.1599847	0.0947234	0.0655874	0.0494777	0.0394029	0.0325743	0.0276753	0.024008

Figure of merit for composite filters: Wang, Kim and Pui, *Aerosol Science & Technology,* 42, 722 – 728 (2008).

Software Solution for Pleating Design

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Twin Cities • Duluth • Morris • Crookston • Rochester • Other Locations

CFR | Filter Analysis | Dust Loading | Pleating Design

Filter Medium Selection

Lydall Inc Grade 373

Permeability 6.095e-9 cm^2 Thickness 0.038 cm = 2.181 Frazier

Pleating Parameters rectangular pleat

Pleat height 2.222 cm Panel length 250 cm

Panel width 2.54 cm Flow rate 1935.48 lpm

Pleat density 10 to 90 #/100 mm

High volume flowrate mode (triangular pleat)

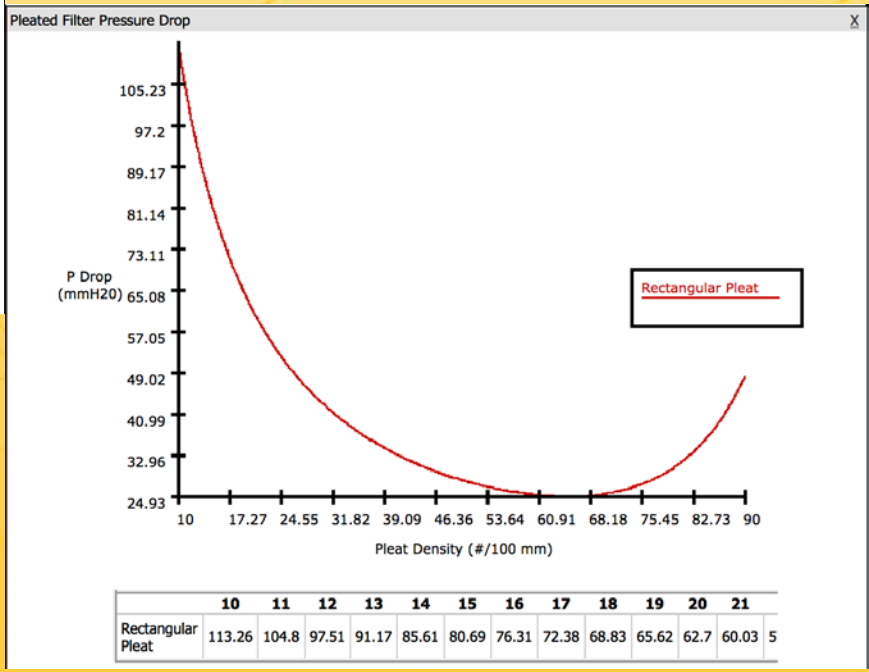
Medium pressure drop non-Darcy effect

c1 0.024 c2 0.000335

Channel flow turbulence effect References

m1_k 0.00000782 m1_p 2 m2_k 8.96e-10 m2_p 3.2

Pressure Drop mm H20



	10	11	12	13	14	15	16	17	18	19	20	21
Rectangular Pleat	113.26	104.8	97.51	91.17	85.61	80.69	76.31	72.38	68.83	65.62	62.7	60.03

Chen, Liu and Pui, *Aerosol Sci. Technol*. 23:579-590 (1995).

Software Solution for Dust Loading

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Twin Cities • Duluth • Morris • Crookston • Rochester • Other Locations

CFR | Filter Analysis | Dust Loading | Pleating Design

General Parameters

Gas viscosity 0.000181 g/cm*s

Face velocity 10 cm/s

Atmospheric pressure 101325 Pa

Temperature 293.15 K

Dust cake porosity 0.8464

Estimate cake porosity ☑ What is this?

Void Function Vanni-Happel

Aerosol 1

% of number concentration: 50

Geometric mean of volume equivalent diameter 1 µm

Geometric standard deviation 1.5

Particle density 1 g/cm^3

Dynamic shape factor 1.2

Aerosol 2

50 % of number concentration:

Geometric mean of volume equivalent diameter 0.01 µm

Geometric standard deviation 1.5

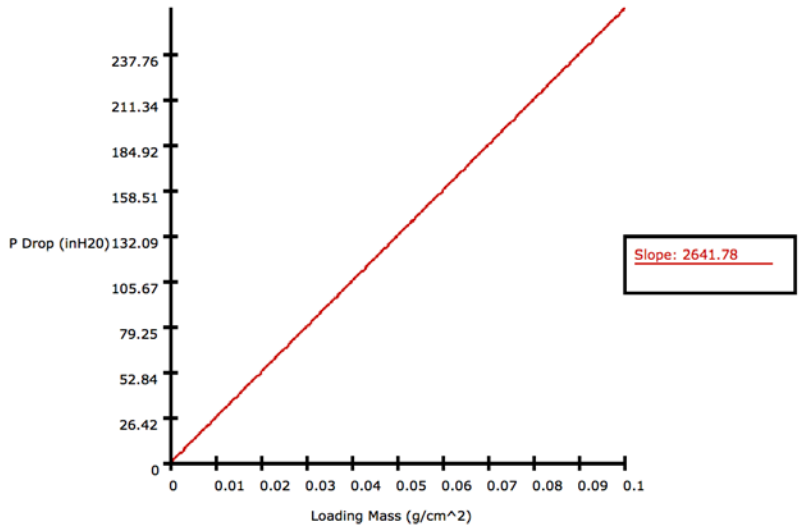
Particle density 2 g/cm^3

Dynamic shape factor 2

Show Pressure Drop Eqn.

Pressure Drop | inches H20

Cake Pressure Drop Graph X



	0	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.01
Slope: 2641.78	0	2.6418	5.2836	7.9253	10.5671	13.2089	15.8507	18.4925	21.1343	23.776	26.417

ISO, NIST-SRM, and NFPA Standards

Mulholland, Pui et al., *J. Research NIST* 111:257-312 (2006)

ISO/FDIS 15900
Determination of particle size distribution – Differential electrical mobility analysis

ISO/WD 27891
Calibration of aerosol particle number concentration measuring instruments

NFPA 96
Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations – reduce air velocity through any duct to 500 ft/min from 1500 ft/min (Note: 42% Bldg, 28% Transport, 30% manufacturing)

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Innovative Development of Environmental Protection Industry – From U.S. Perspectives

David Y. H. Pui 裴有康

Member of US National Academy of Engineering (NAE)

Einstein Professor of Chinese Academy of Sciences (CAS)

Distinguished McKnight University Professor

Director of the Center for Filtration Research (CFR)

University of Minnesota

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2017·盐城
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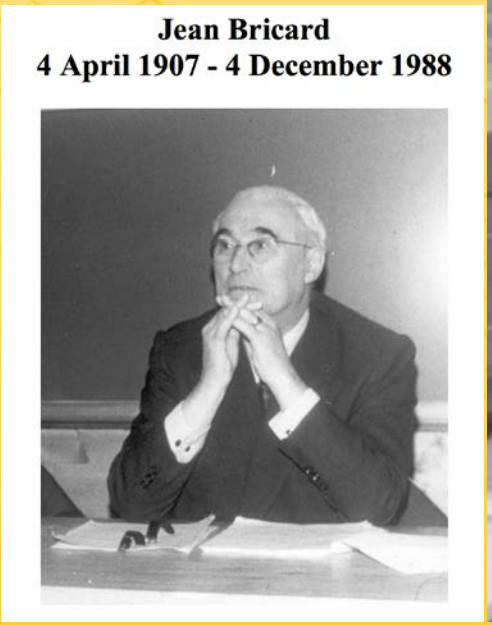
盐城欢迎您
Welcome to Yancheng
ion

Condensation Particle Counter (CPC)

- Professor Bricard and his students, Pourprix, Reiss, Madelaine developed the CPC in Paris around 1972
- Bricard and Pourprix came to University of Minnesota to calibrate the CPC using DMA-electrometer method developed by Liu and Pui
- Based on good calibration results, TSI decided to license the CPC patent from French Atomic Energy Commission (CEA).
- The CPC becomes the most widely used aerosol counters in the world, estimated at over 100,000 units sold.
- CPCs are used for respirator fit-testing, atmospheric and cleanroom particle counting, and Euro 6 vehicle emission standard.



TSI CPC Condensation Particle Counters

CONDENSATION PARTICLE COUNTER 3750

The most referenced CPC. Counts from 7nm up to 1L/min.

CONDENSATION PARTICLE COUNTER 3007

Handheld CPC for measuring particles 0.01-1.0 µm, concentrations 0-100,000 particles/cm3.

CONDENSATION PARTICLE COUNTER 3772

Counts airborne particles down to 10 nr at an aerosol flow rate of 1.0 L/min, over a concentration range from 0 to 104

ENVIRONMENTAL PARTICLE COUNTER 3783

Boasts over 20 new product features ideal for long term, 24/7 monitoring in both pristine and heavily polluted environments.

GENERAL PURPOSE WATER-BASED CONDENSATION PARTICLE COUNTER 3787

Detects particles down to 5 nm utilizing state-of-the art WCPC technology.

ULTRAFINE CONDENSATION PARTICLE COUNTER 3776

Designed primarily for researchers interested in airborne particles smaller than 20 nm.

CONDENSATION PARTICLE COUNTER 3772-CEN

For the monitoring of ultrafine particles in atmospheric aerosol compliant to CEN/TS 16976

CONDENSATION PARTICLE COUNTER 3775

A general-purpose counter for detecting particles down to 4 nm over a concentration range of 0-107 particles/cm3.

ENGINE EXHAUST CONDENSATION PARTICLE COUNTER 3790A

Fully meets all proposed PMP requirements for Euro and 6 regulations.

NANO ENHANCER 3777

Capable of sizing from 1 nm to 50 nm, when integrated with an SMPS spectrometer.

NANO WATER-BASED CONDENSATION PARTICLE COUNTER 3788

Detection of particles as small as 2.5nm with 1/10th second data reporting.

Commercialization and Patent Protection

To companies commercializing the inventions:
1. Companies are happy to pay for the patent royalty, because they can insure no competition from other companies. They will have extra time to develop a bigger market and better product.

To academic researchers:
1. The patent acknowledges the researcher to be the first person who develops the idea, similar to a journal paper.
2. Researchers do not worry about other people competing on the same technology, and can continue to develop a better product.

The Role of Government in Promoting Technology Innovation

1. In U.S., the environmental protection industry is largely driven by laws and regulations, e.g., catalytic converters in early 1980's.
2. It is advisable for the government to get input from academic researchers on feasible technology that can be developed.
3. For environmental protection industry to thrive, enforcement of environmental laws and regulations will be the key.
4. Enforcement of IP rights will allow the researchers and the industry to invest and produce truly innovative IPs.

Ref: http://equitablegrowth.org/report/environmental-regulation-technological-development-u-s-auto-industry/

Vice Minister Wang of China Environmental Ministry review the SALSCS on September 25, 2017

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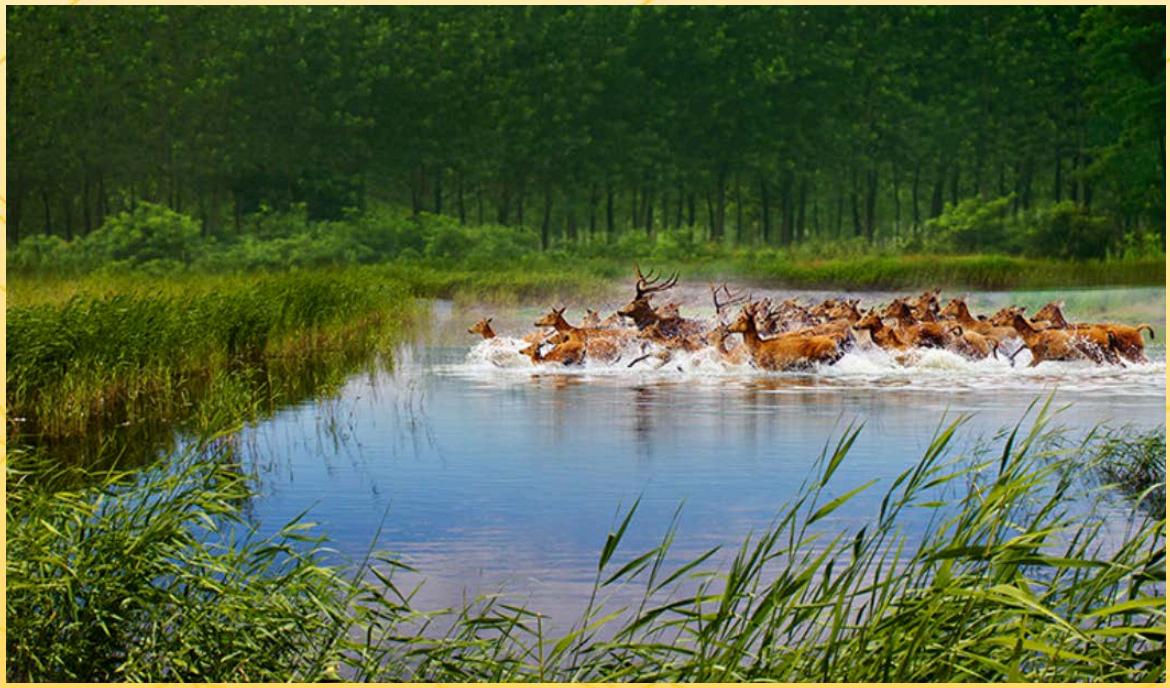
CFR Companies Visits

- Visited Corning Headquarter (5/12/17) in Corning Valley, hosted by Dr. Liming Wang and Huiqing Wu. SVP Gary Calabreze spent half-day with me and offered to host the CFR Meeting next Fall at Corning Valley.
- Visited Wat Yuan (7/26/17). Chairman Zhang was very busy expanding Wat Yuan business and asked CTO Yu Tian to host my visit and tour.
- Gave a lead-off speech at a Workshop (8/14/17) at Applied Materials Headquarter. CTO Om Nalamasu, also President of Applied Venture, and colleagues expressed great interest in CFR research.
- Gave Plenary talk at Yancheng EXPO (9/25/17). Director Dahai Zhao offered to host the next CFR Meeting after the Corning meeting, and offered to pay for the hotel expenses of all delegates.
- Dr. Nalamasu will be inducted to National Academy of Engineering this Sunday (10/8/17) at NAE Headquarter in DC. Fellow NAE members David Pui and Gary Calabreze will be there to congratulate him.

Many National Parks at Yancheng



CFR Member Requests (2017)

- Ultrafiltration of Liquid-borne Nanoparticles and Quantum Dots
- Measurement Geometric Surface Area of Airborne Nanoparticles
- Charge Neutralization of Electret Filter Media
- Respirator Filtration Efficiency under Realistic Cyclic Flow Condition
- Efficiency of Granular Activated Carbons; VOCs Decomposition by Catalyst
- Measurement of the Porous Coefficients of Pleated Filter Media
- HVAC Filter Loading by Ammonium Sulfate and Ammonium Nitrate Submicron Particles and the Effect of Mixing with Combustion Soot
- Air Intake Filter Loading by Mixture of Solid and Oil Particles
- Real-life Filter Loading Test Rig Development
- Modeling of ISO Dust Dispersers and Measurement of Size Distribution of ISO Standard Dusts by Shadowgraphy Method
- Utilizing the WRF Modeling System to Simulate Atmospheric Flow over Beijing for SALSCS Evaluation
- Effect of Wash Coatings on Wall Flow Filter Performance
- Characterization of CMP Particles using Aerosolization Method
- Electrospun Transparent Filter Media and High Loading Media
- Modeling of Liquid Filtration and of Polydisperse Fibers
- Microbial Growth on Filter and Insulating Materials
- Ultra-high Efficiency Filter Tests

Research Projects Leveraged with CFR Support

- MIT led National Initiative ($317 million), Advanced Functional Fibers of America (AFFOA) to develop smart fibers and fabrics. (UMN PIs: David Y.H. Pui and Julianna Abel), with UMN matching commitments of up to $5 million over the first five years.
- European Committee for Standardization (CEN/TC195/ M/461), “Methodology to Determine Effectiveness of Filtration Media against Nanoparticles in the Size Range of 3 to 500 Nanometer,” (Project Leader and Reference Lab PI: J. Wang; Support Lab PI: D.Y.H. Pui), $400,000 total for both labs (2013-19)
- Chinese Academy of Sciences (CAS) International Collaboration with Prof. Junji Cao of Institute of Earth Environment (Xi’an) and with Prof. Jing Sun of Shanghai Institute of Ceramics (PI: D.Y.H. Pui), (2014-2017)

International Collaborations

- University of Erlangen (FAU): Prof. Wolfgang Peukert, Director of German Cluster of Excellence – Engineering of Advanced Materials (Euro 200 million Center); ongoing collaboration on Quantum Dots Filtration. David Pui is a Scientific Advisory Board member of the Center. U Erlangen (#1 ranked Chemistry and Chemical Eng in Germany). Two Joint Workshops were held between UMN-FAU August 16-19, 2016, and June 5-8, 2017 led by FAU VP and UMN Dean.
- ETH Zurich-Empa: Jing Wang, Associate Professor, Institute of Environmental Engineering. Jing is the PI of a new project funded by Swiss Federal Office of Civil Aviation (FOCA), "Particulate Matter and Gas Phase Emission Measurement of Aircraft Engine Exhaust," which will contribute significantly to the setup of a certification requirement for non-volatile PM measurement and of standard at an international level.
- Virginia Commonwealth University (VCU): Da-Ren Chen, Chair Professor, and Shawn Chen, Assistant Professor, Mechanical and Nuclear Engineering Department; continue collaboration on filtration research.
- Shanghai Institute of Ceramics, Prof. Jing Sun, on photocatalysis of nano-coatings.
- China Northeastern University, Prof. Jingxian Liu and Dr. Deqiang Chang; new CSC Ph.D. student Xinjiao Tian
- Institute of Earth Environment, Chinese Academy of Sciences (IEECAS), Prof. Junji Cao, Key Lab for Aerosol Chemistry and Physics. David Pui is a co-Director of the Scientific Advisory Board of the CAS Key Lab of Aerosol Chemistry & Physics.
- Washington University in St. Louis, Department of Energy, Environmental & Chemical Engineering (EECE). David Pui is an Advisory Board member of EECE.

Short Course Offerings

- Aerosol and Particle Measurement
- (**25% discount** for CFR Companies)
  - First offered in 1978
  - 42 offerings with more than 2,500 attendees
  - 43rd offering, August 20-22, 2018
  - www.cce.umn.edu/aerosol
- Air and Gas Filtration
  - Developed under NSF support; first offered in 1995
  - 11th offerings, 1995-2008
  - Combined with Aerosol Measurement as a Special Topic
- Two courses started by Tom Kuehn are now part of professional societies' certification training and exams:
  - Health Care Facility Construction Management: Indoor Air Quality
  - Mold Management in Health Care Facilities