

# **Center for Filtration Research (CFR)**

## **51<sup>st</sup> Review Meeting, May 4-5, 2017**

## **Mechanical Engineering Department**

## **University of Minnesota**

David Y. H. Pui

Member of National Academy of Engineering

Distinguished McKnight University Professor

LM Fingerson/TSI Inc Chair in Mechanical Engineering

Director, Center for Filtration Research

University of Minnesota



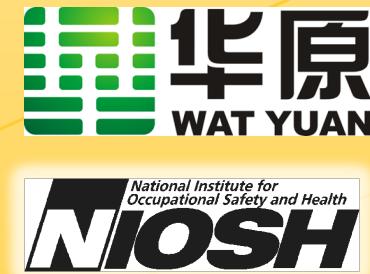
# 51<sup>st</sup> Semi-Annual Review Meeting of the Center for Filtration Research (CFR)

8:00	<i>Welcoming Remarks, Dean Sam Mukasa, College of Science and Engineering</i> <i>CFR Research Overview, David Pui</i>
8:30	<b>Technical Program Session (I): New Initiatives</b>
10:00	<i>Refreshment Break</i>
10:30	<b>Technical Program Session (II): Intake Filters, RH Effect, Dust Dispersion</b>
12:00	<i>Lunch Break; CFR Representatives' Meeting (2 reps each to ME 4125 A,B)</i>
1:00	<b>Technical Program Session (III): Invited Lecture: Dean Kebin HE, Tsinghua University; Prof. Seungki Chae, Sungkyunkwan University (SKKU)</b>
2:00	<b>Technical Program Session (IV): Liquid-borne Particles Filtration; Exposure</b>
3:00	<i>Refreshment Break and Lab Tour</i>
3:45	<b>Technical Program Session (V): Modeling; Instrumentation</b>
5:20	<b>Center Planning Meeting</b>
5:30	<i>Adjournment</i>

# 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<sub>2.5</sub> pollutants
- Engine emission removal
- Cabin air filter for automobiles/airplanes
- Respirator and personal protection equip

# 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
Virgil Marple	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
Yun Liang*	Visiting Professor (December, 2017)	Pulp & Paper Key Lab, SCUT
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 (Fall, 2017)	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

\*Current Involvement in Center activities

# CFR Graduates

<b>Graduates</b>	<b>Degree</b>	<b>Date</b>	<b>Advisor</b>	<b>Employer</b>
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.)

<b>Graduates</b>	<b>Degree</b>	<b>Date</b>	<b>Advisor</b>	<b>Employer</b>
Liming Lo	Ph.D.	Aug-06	Pui/Chen	NIOSH, Cincinnati
Luke Franklin	M.S.	Jun-06	Pui/Kuehn	Optimization of Respirator Filter 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
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
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

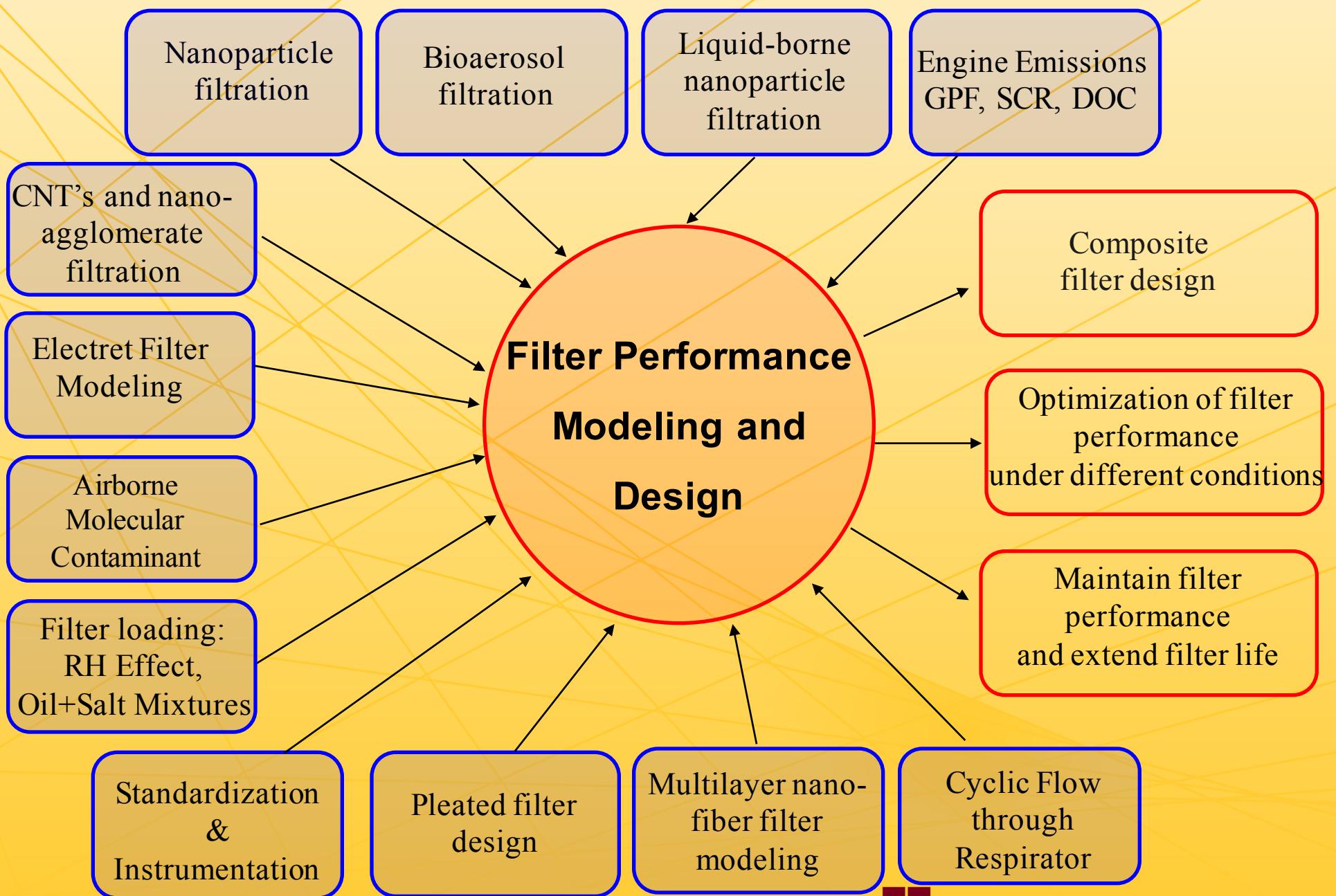
**SOTA**

# CFR Current Students/Scholars

Students	Degree	Date	Advisor	Project
Drew Thompson	Ph.D.	6/30/17	Pui	Electret Filter Modeling and Charge Characterization
Nanying (Leo) Cao	Ph.D.	8/30/17	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
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
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 University, Korea

\*expect to receive two Chinese Scholarship Council students from China.

# Comprehensive Filter Modeling and Design



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# Software Solution for Filter Analysis

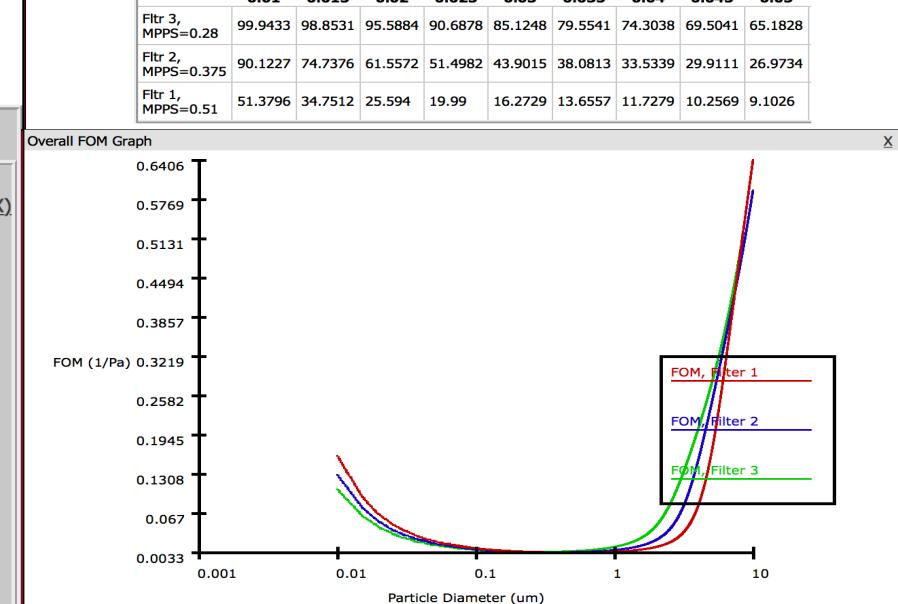
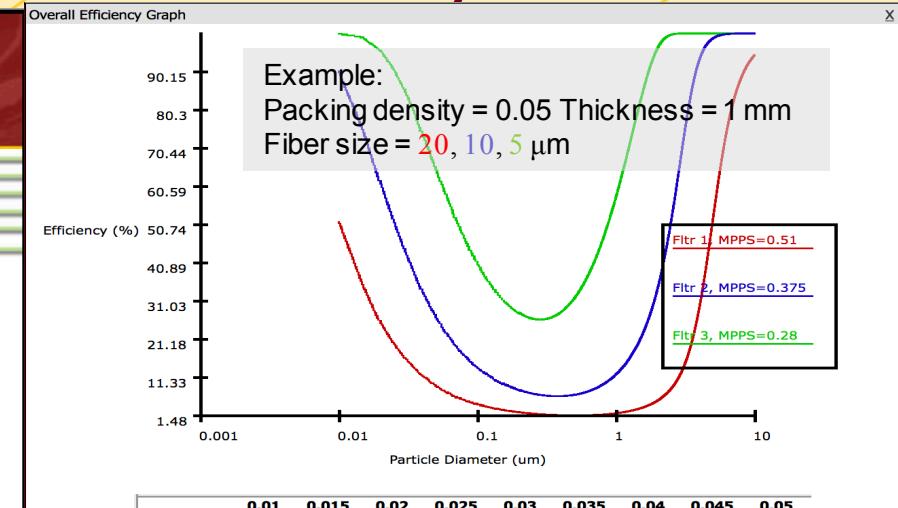
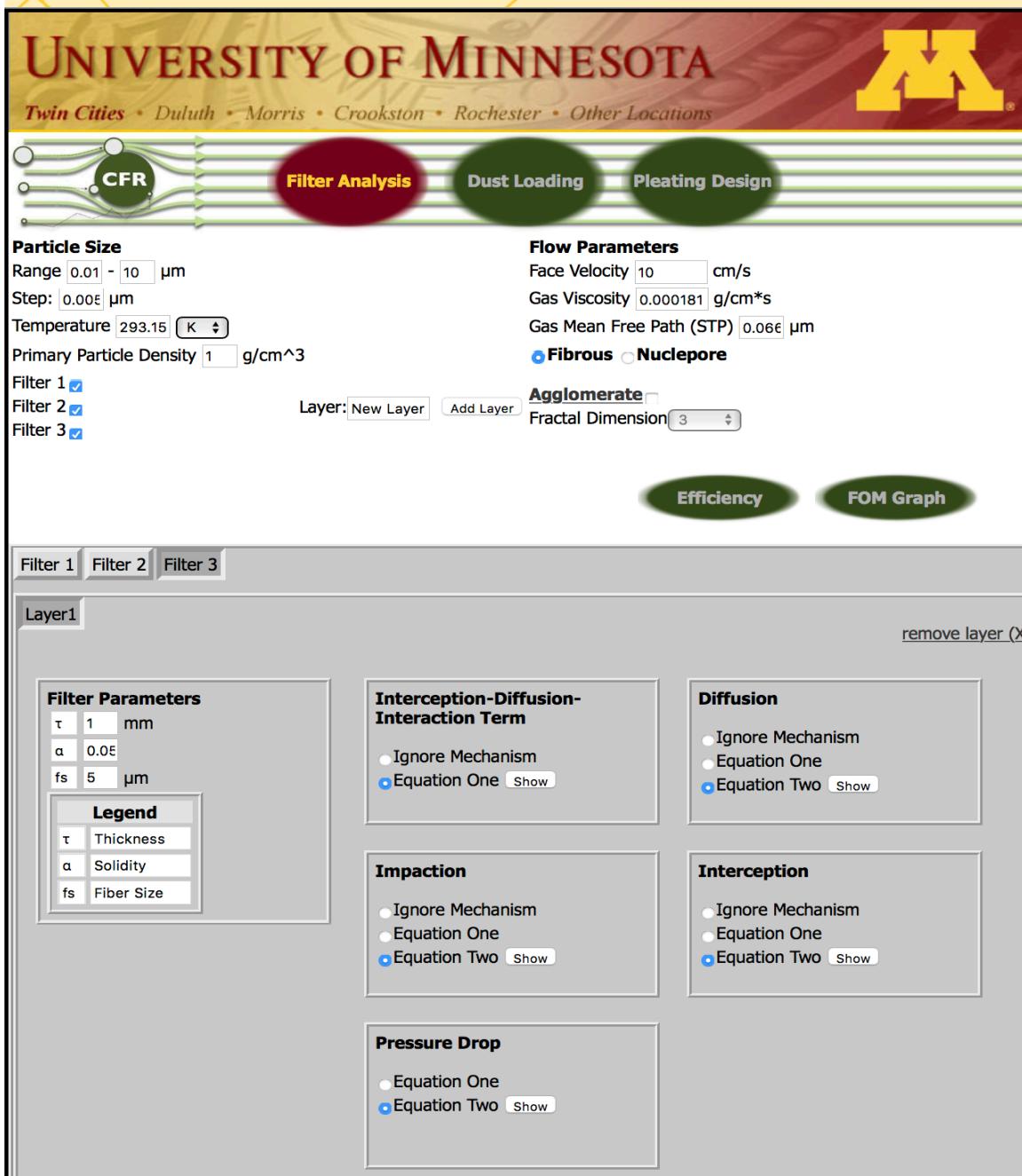


Figure of merit for composite filters: Wang, Kim and Pui, *Aerosol Science & Technology*, 42, 722 – 728 (2008).

# Software Solution for Dust Loading

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

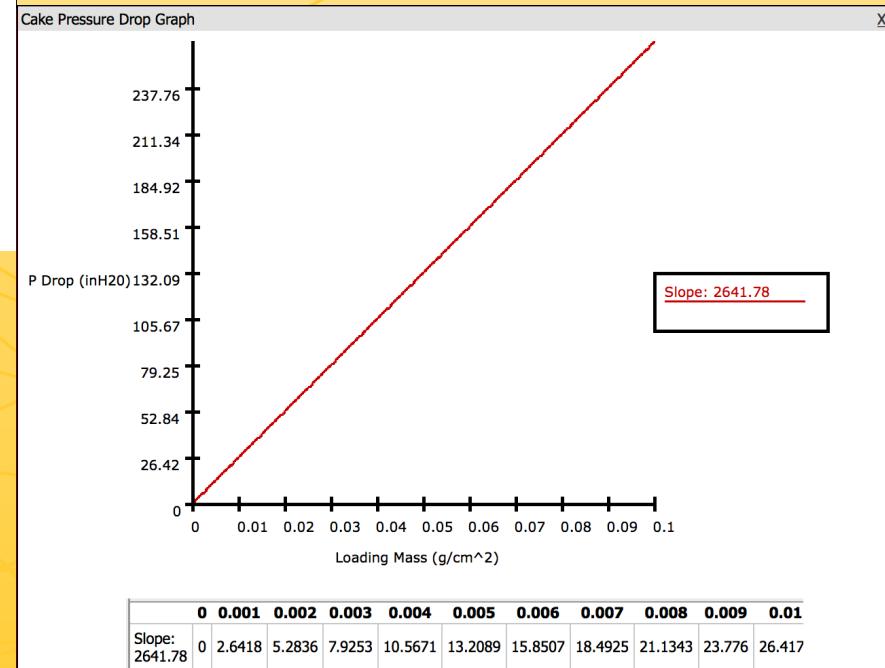
 CFR    Filter Analysis    **Dust Loading**    Pleating Design

**General Parameters**

Gas viscosity  g/cm\*s  
Atmospheric pressure  Pa  
Dust cake porosity   
Estimate cake porosity  What is this?

**Aerosol 1**  
% of number concentration:   
Geometric mean of volume equivalent diameter   $\mu\text{m}$   
Geometric standard deviation   
Particle density  g/cm<sup>3</sup>  
Dynamic shape factor   
[Show Pressure Drop Eqn.](#)

**Aerosol 2**  
50 % of number concentration:  
Geometric mean of volume equivalent diameter   $\mu\text{m}$   
Geometric standard deviation   
Particle density  g/cm<sup>3</sup>  
Dynamic shape factor   
**Pressure Drop**  



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# Software Solution for Pleating Design

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

**CFR** Filter Analysis Dust Loading Pleating Design

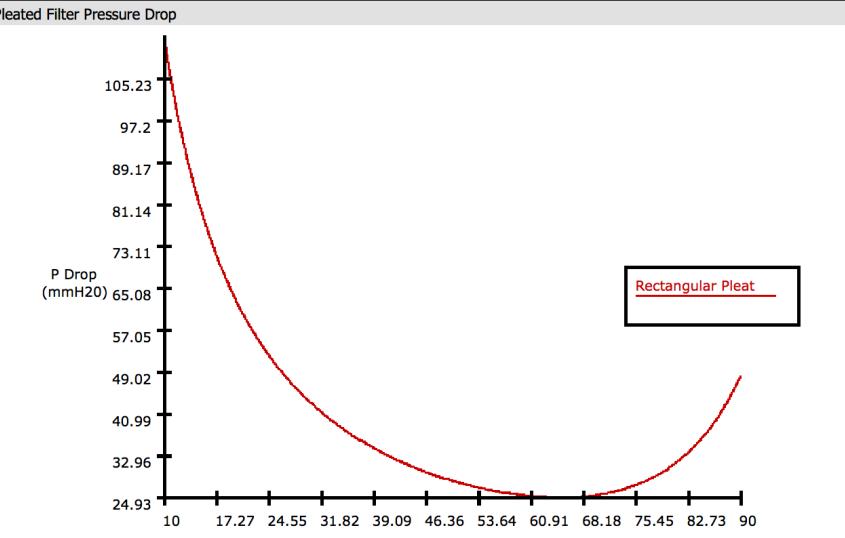
**Filter Medium Selection**  
Lydall Inc Grade 373  
Permeability  $6.095 \times 10^{-9}$  cm<sup>2</sup> Thickness 0.038 cm = 2.181 Frazier

**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  
m1\_k 0.00000782 m1\_p 2 m2\_k 8.96e-10 m2\_p 3.2 

**Pressure Drop** mm H<sub>2</sub>O

Pleated Filter Pressure Drop



Pleat Density (#/100 mm)	P Drop (mmH <sub>2</sub> O)
10	105.23
11	97.2
12	89.17
13	81.14
14	73.11
15	65.08
16	57.05
17	49.02
18	40.99
19	32.96
20	24.93

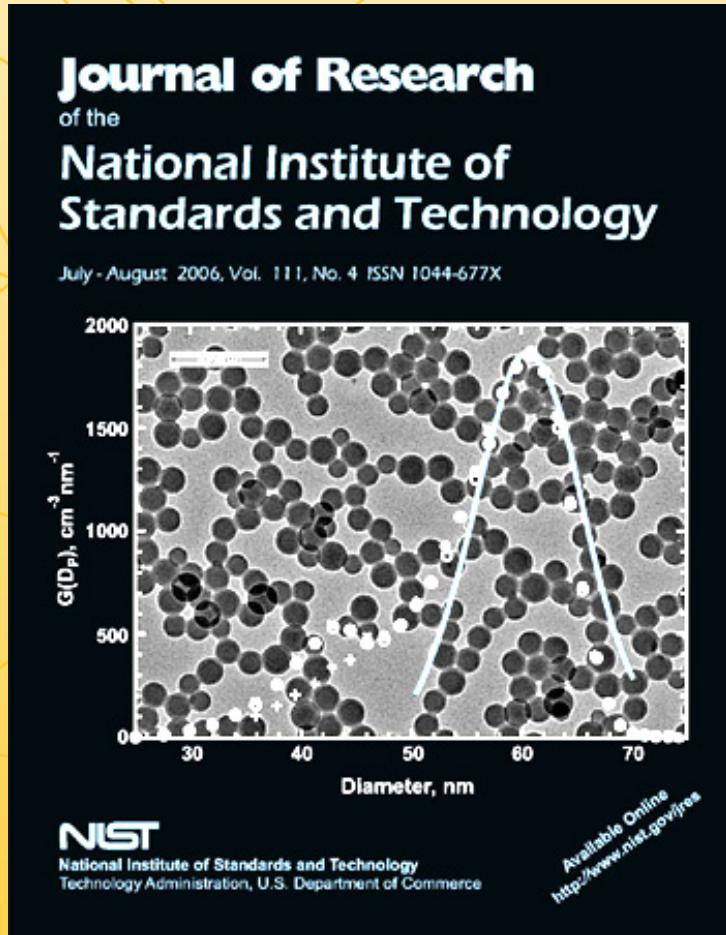
Rectangular Pleat

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



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# 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

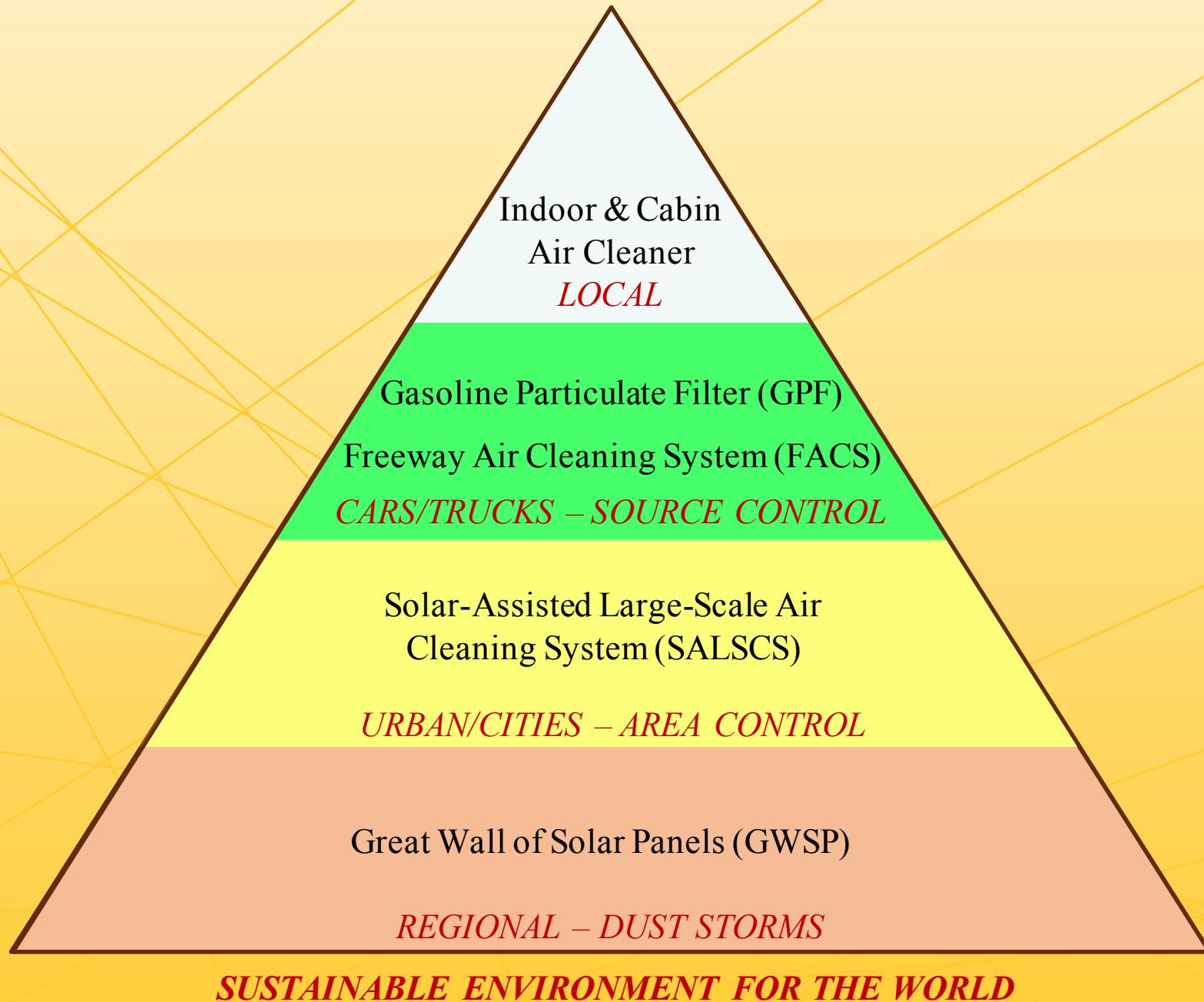
Calibration of aerosol particle number concentration measuring instruments

## NFPA 96

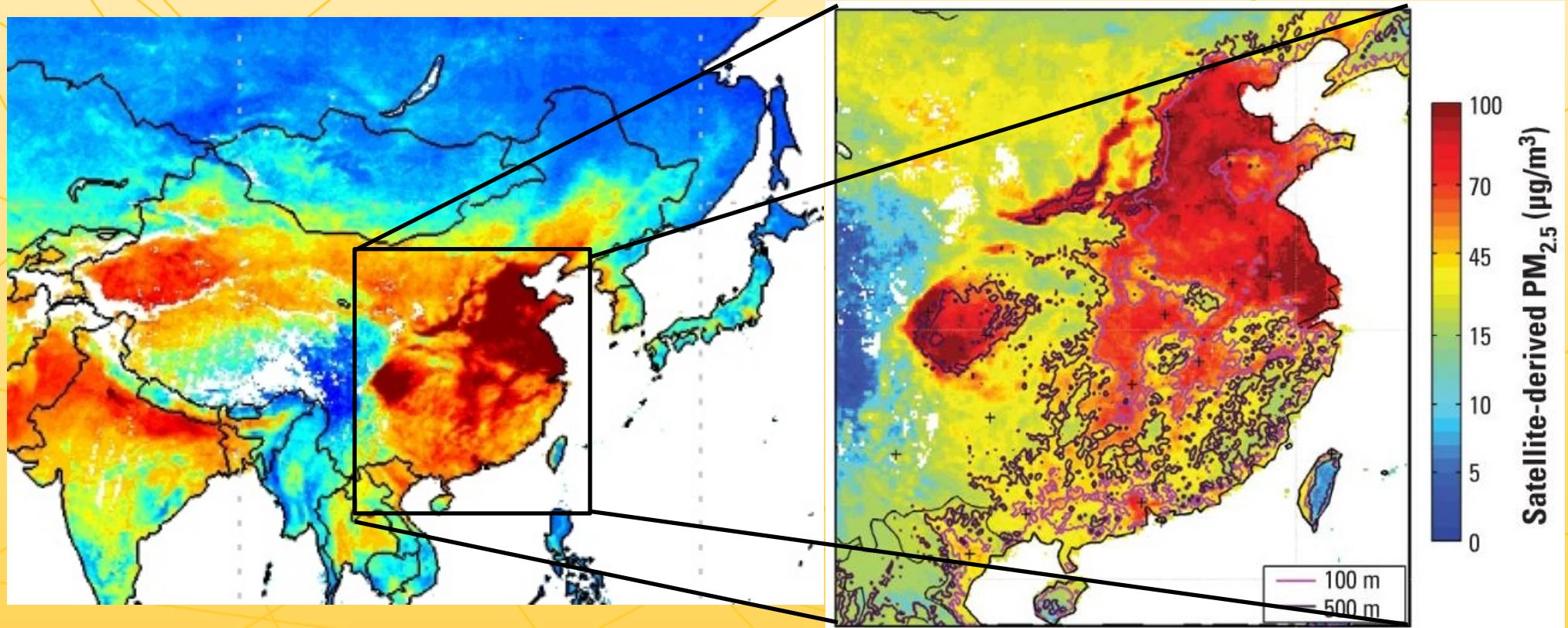
Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations – reduce air velocity through any duct to 500 ft/min from 1500 ft/min  
(Note: 42% Bldg, 28% Transport, 30% manufacturing)



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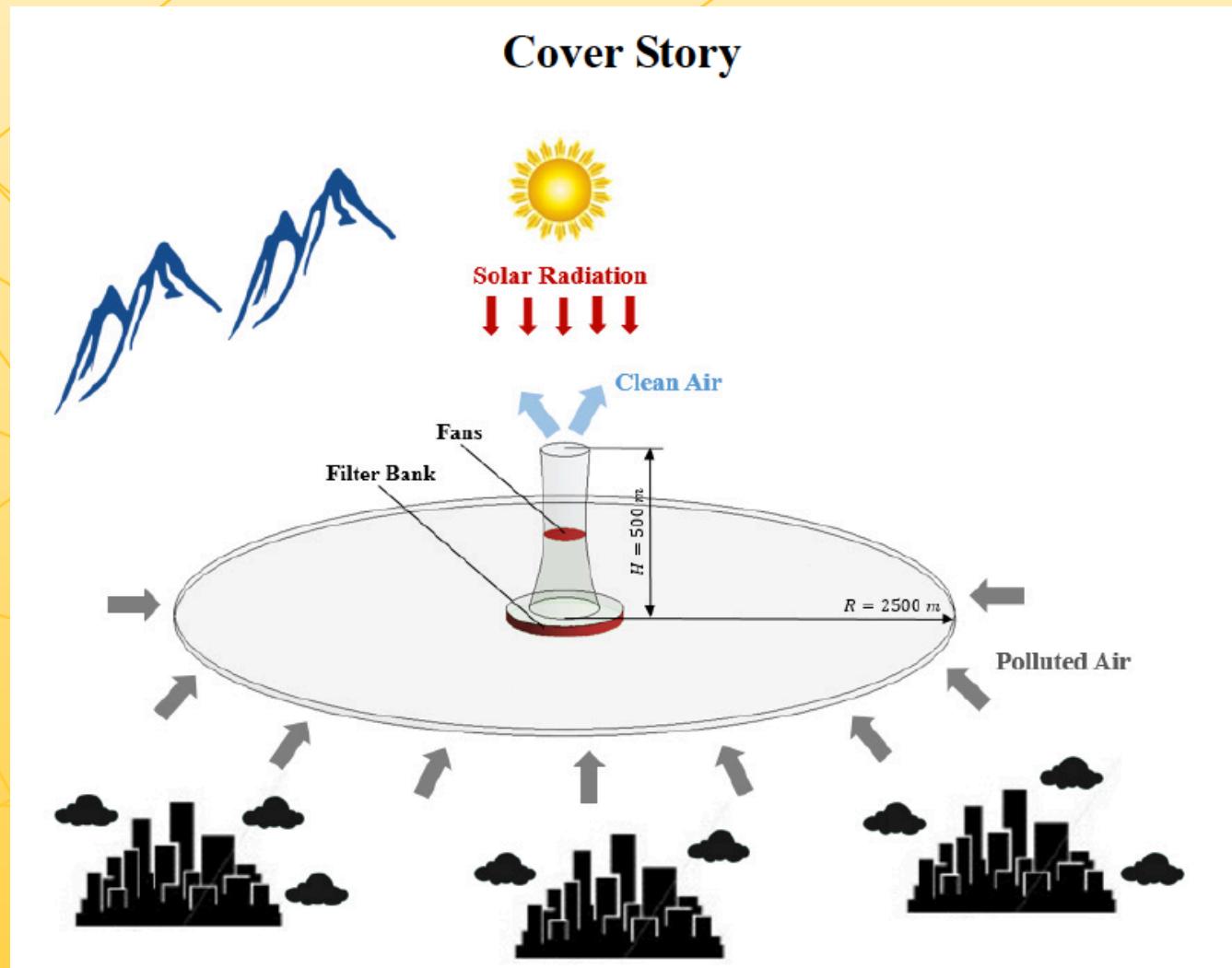


# PM<sub>2.5</sub> Pollution and Haze Formation in China



- 600 million Chinese (50% of the population) and 25 provinces (25% of the land area) are being affected
- WHO Global Burden of Disease (GBD) estimated the outdoor air pollution has resulted in 1.2 million premature deaths each year in China.

# Solar-Assisted Large-Scale Cleaning System (SALSCS)

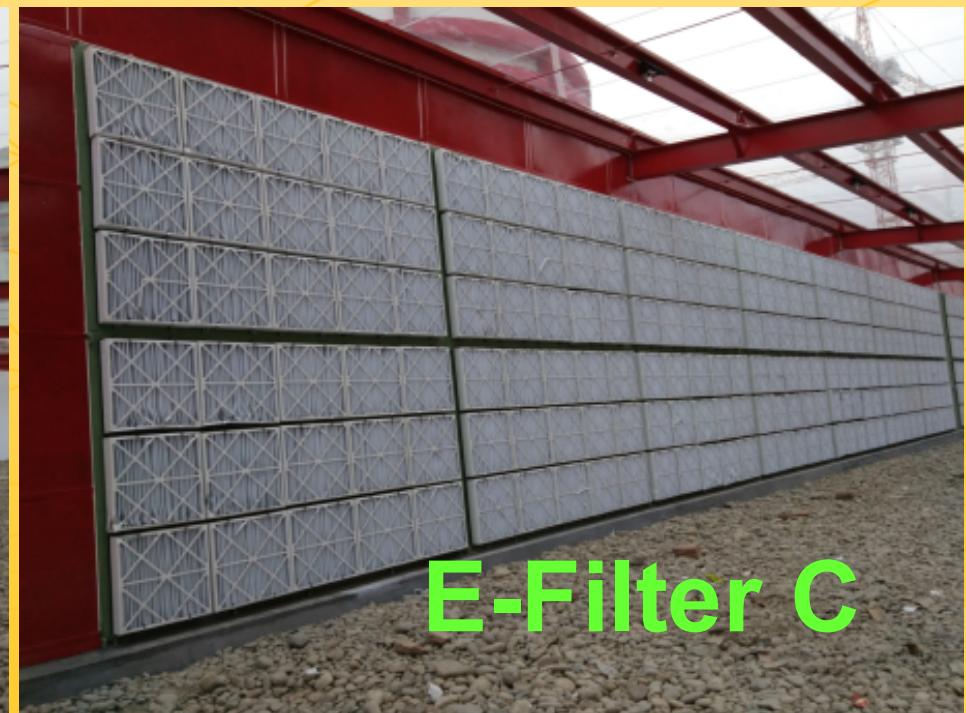


(Cao, Q.F., Pui, D.Y.H. and Lipiński, W. (2015). A Concept of a Novel Solar-Assisted Large-Scale Cleaning System (SALSCS) for Urban Air Remediation. *Aerosol Air Qual. Res.* 15: 1–10)



SALSCS Construction Completed: July 22, 2016

## **Photos of the three filtration systems**





**2<sup>nd</sup> Generation SALSCS in City**

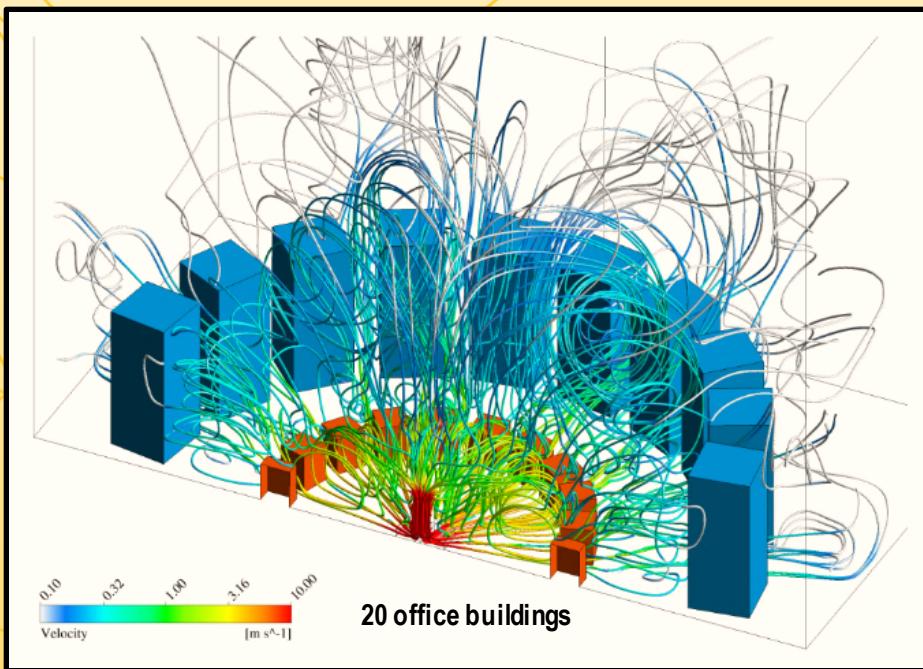
# AMSA Green Community

- There are 10 office buildings, each has 5 stories (20 m tall) and only 1 unit on a floor.
  - Air exchange rate:
 
$$= \frac{\text{control volume}}{\text{clean air flow rate}}$$

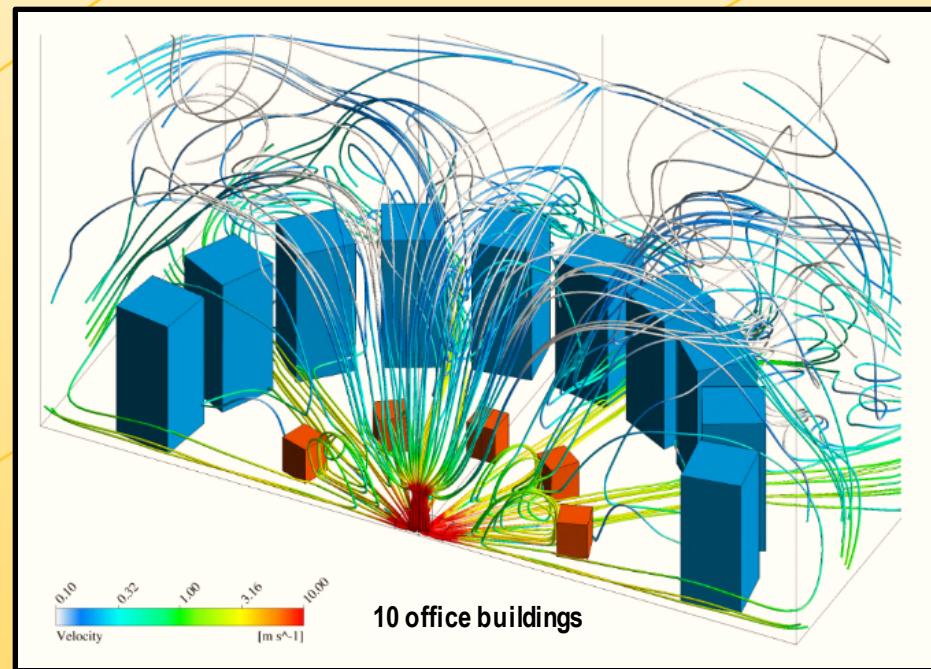
$$= \frac{75 \text{ m} \times 300 \text{ m} \times 300 \text{ m} \times \pi / 4}{2000 \text{ m}^3 / \text{sec}}$$

$$= 2650 \text{ sec} = 45 \text{ min}$$
  - There are 20 apartment buildings, each has 25 stories (75 m tall) and 4 units on a floor.
  - Each unit has  $225 \text{ m}^2$  area including public utilities.
- 
- Diagram details:
- Apartment Building:** 75 m tall, 30 m wide, 30 m deep.
  - Office Building:** 20 m tall, 15 m wide, 15 m deep.
  - AMSA Tower:** 25 m tall, 15 m wide, 15 m deep.
  - Fish Pond Garden:** Radius 17 m, width 8.5 m.
  - Central Plan:** A 3x4 grid of apartment units labeled 1 through 4. Each unit is 30 m wide and 30 m deep.

# Modeling Results

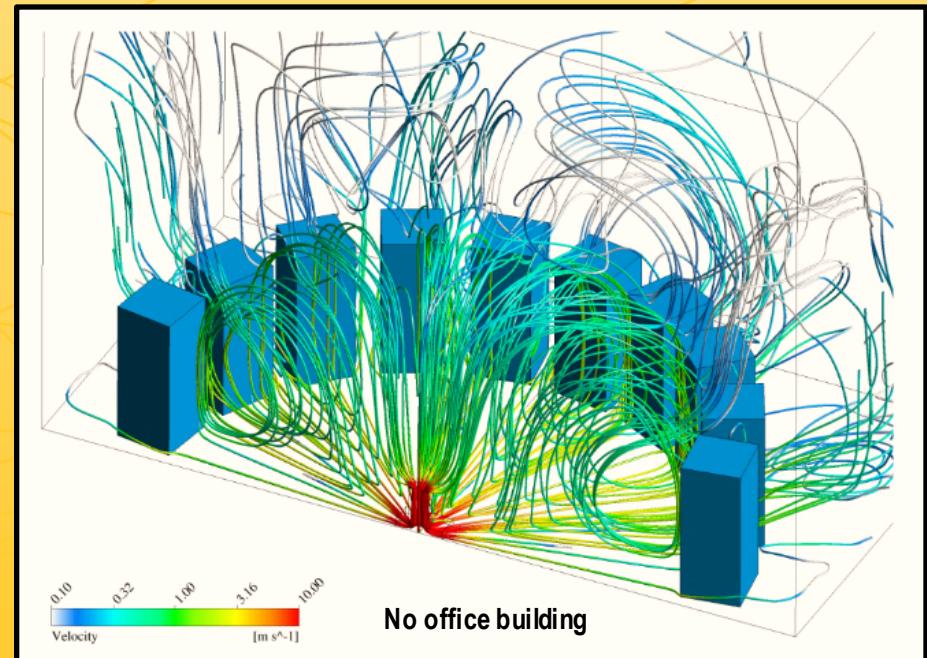


20 office buildings



10 office buildings

- The 3 figures show the streamline patterns colored by velocity magnitude for 3 different cases with having 20, 10 or 0 office buildings, respectively.
- Airflow mainly circulates inside the first ring of office building for the case with 20 office buildings.
- After the office buildings are removed, airflow circulates inside the ring of apartment buildings.



No office building

# CFR Member Requests (2016)

- PM<sub>2.5</sub> Loading of Electret HVAC and Engine In-take Filters
- Effect of Particle Properties and RH on Filter Loading
- PM<sub>2.5</sub> Outgassing from Loaded Filters used as Pre-filter of Cleanroom
- Ultrafiltration of Liquid-borne Nanoparticles and Quantum Dots
- Measurement Geometric Surface Area of Airborne Nanoparticles
- Evaluating the Loading Performance and Holding Capacity for Engine Intake Filter by ISO 12103-1 A2 Dusts under Different RH
- Measurement of Size Distribution of ISO Standard Dusts from Different Dust Dispersers by Shadowgraphy Method
- Characterization of the Charge on Electret Filter Media
- Respirator Filtration Efficiency under Realistic Cyclic Flow Condition
- Effect of the Filtered Particles on Changing Gas Filtration Efficiency of Granular Activated Carbons (GACs); VOCs Decomposition by Catalyst
- HVAC Filter Loading by Ammonium Sulfate and Ammonium Nitrate Submicron Particles and the Effect of Mixing with Combustion Soot
- Measurement of the Porous Coefficients of Pleated Filter Media
- Utilizing the WRF Modeling System to Simulate Atmospheric Flow over Beijing for SALSCS Evaluation
- Three-Way-Catalyst for Engine After-treatment
- Aerosol Generation and CMP Measurement



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# 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: 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) VP Gunter Leugering led a delegation of 12 faculty members to conduct a joint-workshop at UMN, August 16-19, 2016. UMN delegation, led by Dean Sam Mukasa, will go to Erlangen-Nuremberg for a return visit, June 5-8, 2017.
- 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, 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
- 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
  - First offered in 1978
  - 40 offerings with more than 2,300 attendees
  - 42<sup>nd</sup> offering, August 21-23, 2017
  - [www.cce.umn.edu/aerosol](http://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