Lab-on-a-Chip Device for On-Site Biomonitoring of Workers Exposed to Respirable Silica Aerosol

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Significance and Need

- Respirable crystalline silica (RCS): silicosis, lung cancer, and chronic obstructive pulmonary disease
- Millions of workers are exposed to RCS: significant occupational health hazards, silicosis risk is especially high in some industries.
- Silicosis is disabling, irreversible and sometimes fatal.
- Occupational Safety and Health Administration (OSHA) has announced in 2016 a new occupational exposure limit to RCS (50 µg/m$^3$, 8-hour time-weighted average in all industries).
- Biomonitoring: assess exposures and mitigate risks for silica dust
- New biomonitoring methods needed for successful on-site biomonitoring:
  - Fast and accurate
  - Sensitive and specific
  - Field portable
Objective

- Design, fabricate, and test a miniaturized lab-on-a-chip device for performing immunoassay of a target protein biomarker.
  - Design and fabricate a protein immunoassay-based lab-on-a-chip (LOC) device for early detection of pulmonary responses to inhaled silica aerosol, such as lung inflammation.
  - Demonstrate the utility and capability of a miniaturized LOC for detecting pulmonary responses using commercial assay kits and biosamples from rats exposed to RCS.
New Approach
Detection of Biomarkers using Portable Analyzer with Lab-on-a-Chip

- Develop and characterize a fully **functional polymer lab-on-a-chip**
- Develop and characterize a **field-portable analyzer**
- Develop and **optimize chemiluminescent ELISA to detect biomarkers of early effect to exposure**
- **Perform animal test** to determine the presence of **TNF-α and CC16**

Biomarkers
For crystalline silica exposure

• Extensive database: humans and animals (Gulumian et al., 2006)
  ▪ Biomarkers (in blood or urine) for exposure to crystalline silica
  ▪ Potential biomarkers such as tumor necrosis factor-α (TNF-α), interleukin-6 (IL-6), IL-8, IL-1, neopterin, and Clara cell protein 16 (CC16)

• Two protein biomarkers chosen for silica aerosol exposure in this study (TNF-α and CC16)
  ▪ Evaluated for gold and coal miners exposed to silica dust in South Africa and Germany, respectively.
Lab-on-a-Chip Device
Design and Fabrication

- **Chip Dimensions:**
  60mm X 35mm X 1mm

- **Spiral Reaction Chamber:**
  45.7mm length, 4μL volume & 137.5cm⁻¹ surface-to-volume ratio

- **Detection Antibody Chamber:**
  25μL volume

- **Washing Buffer Chamber:**
  50μL volume

- **Chemiluminescent Chamber:**
  25μL volume

- **On-chip reagent chambers** for minimum user intervention

- **Single-channel assay** for simple microfluidic flow control

- **Air gap** in between each reagent chamber provides sample separation

- **Passive valves** regulate the flow of reagents through the chambers
Lab-on-a-Chip Device
Design and Fabrication

Polymer Lab-on-a-Chip Fabrication Steps

- **Aluminum Master Mold Design & Micromilling** using CNC Milling Machine (5100-S, Microlution, USA)
- **Polymer Chip Replication** at high temperature & pressure using *Injection Molding Machine* (BOY 22A, Procan CT)
- **Polymer Chip Thermal Bonding** of the fabricated lab-on-a-chip with blank polymer chip using Hot-Press (MTP-10, Tetrahedron Associates Inc., USA)
Protein Immunoassay Protocol on Lab-on-a-Chip

**Direction of Reagent Flow**

- **Pump Input**
- **Chemiluminescent Substrate**
- **Washing Buffer**
- **Detection Antibody**
- **Sample Well**
- **Spiral Reaction Chamber**
- **Waste**

1. **Capture Antibody**
   - Blocking
   - Sample with TNF-α is loaded

2. **Sample is loaded into the reaction wells**

3. **HRP Labelled Detection Antibody**

4. **Substrate Incubation & Detection**
   - Light
   - Substrate

5. **Washing Unbounded Detection Antibodies**
Assay Test Results

TNF-α Sandwich ELISA – 96 well plate

- Dynamic Analyte Concentration range of 62.5 pg/mL to 4,000 pg/mL
- Sample and reagent volume = 100µL
• Dynamic Analyte Concentration range of 93.75 pg/mL to 6,000pg/mL
• Sample and reagent volume = 5µL
Plasma sample of rats exposed to silica aerosol was obtained from NIOSH/Health Effects Laboratory Division.

The rats exposed to crystalline silica, 15 mg/m³, 6 hours per day for 5 days.

At post-exposure time intervals of 1 month or 12 months, blood was collected from all the rats and plasma was isolated by centrifuging the blood samples.
Components of the portable analyzer

- Piezoelectric micropump (Takasago Fluidics) and the control board (MPD200AUM)
- ARDUINO DUE microcontroller
- Tablet PC (Dell Venue 8 Pro 5855)
Portable Analyzer

- Runs on a LabView based Program
- Variable parameters – ON/OFF sequence, the pump flow speed, the pump run time and the optical detection phase.
- Chip holder and pump input port of the LOC is coupled with the PEEK tubing of the pump of the portable analyzer for automated ELISA testing
Conclusions

• A miniaturized, prototype polymer lab-on-a-chip (LOC) was designed and fabricated to perform immunoassay of target protein biomarker(s) in plasma/serum.

• The fabricated LOC has on-chip reagent chambers for minimum user intervention and single-channel assay for simple microfluidic flow control.

• Assay protocol optimization to achieve optimal assay performance was done using conventional 96-well plate assay and LOC assay.

• The LOC has the ability to detect the biomarker in the dynamic analyte concentration range of 93.75 pg/mL to 6,000 pg/mL.

• Portable analyzer was designed to evaluate the overall performance of the LOC with a similar accuracy and precision as the centralized laboratory testing results.
Future Work

- Evaluating the overall performance of the LOC and a customized portable analyzer.
- Testing with the LOC using other potential biomarkers.
Acknowledgments

- Drs. Jerry Smith and John Snawder at DART/BHAB
- Dr. Dale Porter at HELD
- Dr. Pramod Kulkarni at DART/CEMB
- Dr. Gayle DeBord at DART

Disclaimer—Mention of a company name or product does not constitute endorsement by the Centers for Disease Control and Prevention. The findings and conclusions in this presentation have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination and policy.
Thank you for your attention!
Any questions or comments?

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FrackMap: Building a geo-spatially based nexus of research publications and perceptions related to hydraulic fracking

Ann Backus, MS
Harvard-NIOSH ERC

Nathalie de Marcellis-Warin, PhD
Full Professor, Polytechnique Montréal and President, CIRANO (Montréal)

Thierry Warin, PhD
Associate Professor, HEC Business School (Montréal)

Expanding Research Partnerships: State of the Science
Denver, June 2, 2017
1) The FrackMap as an innovative tool for interactive data visualisation.

2) The potential of FrackMap to enhance our understanding of the scientific evidence related to the risks and impacts of hydraulic fracking.

3) Perceptions embedded in tweets can help us create targeted messages for educational and policy purposes.
Hydraulic Fracking

• In recent years, hydraulic fracturing and unconventional oil/gas developments have **increased exponentially across the US**. Since 2005, **technologies have driven prices down**.

• **Hydraulic fracturing** is a technique used for accessing natural gas and oil in tight geologic formations. The process involves the horizontal directional drilling of wells in addition to the use of water, sand and chemicals at high pressures to fracture rock and release hydrocarbons.

Communities, especially those proximate to hydraulic fracking sites, have raised concerns about the potential environmental and human health issues/impacts associated with hydraulic fracking activities.
Conventional and unconventional oil and gas

95% of new wells drilled are hydraulically fractured

43% of the oil production

67% of the natural gas production

Water, sand and chemical additives are used but the exact formulation varies depending on the well.
## Estimate of Fracking Wells in the US

<table>
<thead>
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<th>State</th>
<th>Fracking Wells since 2005</th>
<th>Fracking Wells Drilled in 2012</th>
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<td>Colorado</td>
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<td>West Virginia*</td>
<td><strong>3,275</strong></td>
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<td>Wyoming</td>
<td>1,126</td>
<td>468</td>
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<td><strong>TOTAL</strong></td>
<td><strong>81,898</strong></td>
<td><strong>22,326</strong></td>
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</table>

* Data for West Virginia is for permitted fracking wells, not wells that have been drilled. Data were not available on drilled wells.

Environment America 2013
Occupational Safety

• 562,000 workers in unconventional oil and gas drilling – mostly well service workers
• Exposures: VOCs, PM$_{2.5}$, diesel exhaust, NBTEX, radon and other NORM, NOx, O$_3$, brines, crystalline silica, etc.

Photo: Flowback technician gauging a flowback tank

REF: Esswein et al., 2014
Lack of Occupational Studies

• Eric Esswein, NIOSH Western States Office, et al. (2014, p. D183.)
  – “…few (if any) systematic studies describing occupational health risks during contemporary land-based unconventional oil and gas extraction have been published in the peer-reviewed literature.”

• Inspite of
  – A fatality rate 2.5x that of construction industry and 7x more than that of general industry.
  – [Esswein et al., 2013, Witter et al 2014, BLS]
Occupational Fatalities in Hydraulic Fracking


Death rate per 100,000, 1993-2010

Fatalities by length of service, 2003-2009
The FrackMap as an innovative tool for interactive data visualisation

• Brings together a range of fracking related datasets
  shale formations,
  oil and gas permits,
  horizontal legs, etc.

for data visualization and research
Harvard WorldMap a public domain collaborative mapping platform
http://worldmap.harvard.edu/maps/FrackMap
The potential of FrackMap to enhance our understanding of the scientific evidence related to the risks and impacts of hydraulic fracturing: « FrackMapBiblio »
Hydraulic fracking operations can result in a number of potential impacts to the environment including:

- **Stress on surface water and ground water supplies** from the withdrawal of large volumes of water used in drilling and hydraulic fracturing (Gallegos et al., 2015) (Shih et al., 2015);
- **Contamination of underground sources of drinking water and surface waters** resulting from spills, faulty well construction, or by other means (Swistock et al., 1993) (Llewellyn et al., 2015);
- **Adverse impacts from discharges** into surface waters or from disposal into underground injection wells;
- **Air pollution** resulting from the release of volatile organic compounds, hazardous air pollutants, and greenhouse gases (Litovitz et al., 2013) (McKenzie et al., 2012);
- **Fracking-induced earthquakes** (Skoumal et al., 2015) (Atkinson et al., 2015);
- **Workplace safety issues** (Darnell et al., 2016) (Witter et al., 2014) (Esswein et al., 2013 and 2014);
- **Infrastructure degradation**, etc...

[https://www.epa.gov/hydraulicfracturing#improving](https://www.epa.gov/hydraulicfracturing#improving)
FrackMap Biblio

to explore the spatial relationships between hydraulic fracking activities and scientific research on environmental, occupational and human health impacts

INTERACTIVE DATA VISUALISATION
Literature Review

• Keywords:
  ✓ Hydrofracturing; Fracking; Hydraulic fracking; Shale Gas; Wells; Unconventional Gas;
  ✓ Water Impacts; Air Pollution Impacts; Climate Change; Ecological Impacts; Hydrofracturing Chemicals; Human Health Impacts; Community Impacts; Seismicity; Adverse events.

• Scientific studies published from January 2005 to December 2015.

• Databases: PubMed, MEDLINE, ScienceDirect, Scopus, Web of science, Proquest, Google Scholar, etc

• Necessary condition: Data location specified (State, County, City, Shale Play, River, Lake, etc.)

500 peer-reviewed publications with geographical data
Evaluation of impact of shale gas operations in the Barnett Shale region on volatile organic compounds in air and potential human health risks

Added By demaren

Abstract
Shale gas exploration and production (E&P) has experienced substantial growth across the U.S. over the last decade. The Barnett Shale, in north-central Texas, contains one of the largest, most active onshore gas fields in North America, stretching across 3000 square miles and housing an estimated 15,870 producing wells as of 2011. Given that these operations may occur in relatively close proximity to populated/urban areas, concerns have been expressed about potential impacts on human health. In response to these concerns, the Texas Commission on Environmental Quality established an extensive air monitoring network in the region. This network provides a unique data set for evaluating the potential impact of shale gas E&P activities on human health. As such, the objective of this study was to evaluate community-wide exposures to volatile organic compounds (VOCs) in the Barnett Shale region. In this current study, more than 4.6 million data points (representing data from seven monitors at six locations, up to 105 VOCs/monitor, and periods of record dating back to 2006) were evaluated. Measured air concentrations were compared to federal and state health-based air comparison values (HBCVs) to assess potential acute and chronic health effects. None of the measured VOC concentrations exceeded applicable acute HBCVs. Only one chemical (1,2-dibromoethane) exceeded its applicable chronic HBCV, but it is not known to be associated with shale gas production activities. Annual average concentrations were also evaluated in deterministic and probabilistic risk assessments and all risks/hazards were below levels of concern. The analyses demonstrate that, for the extensive number of VOCs measured, shale gas production activities have not resulted in community-wide exposures to those VOCs at levels that would pose a health concern. With the high density of active wells in this region, these findings may be useful for understanding potential health risks in other shale play regions.

Publication Science of The Total Environment
Volume 468-469
Pages 032-042
Date January 15, 2014
Journal Science of The Total Environment
Abbr DOI 10.1016/j.scitotenv.2019.08.000
ISSN 0048-9697
Accessed 2016-01-13 07:10:20
Library Catalog ScienceDirect
Tags Air quality · Barnett Shale · Human health · Natural Gas · Risk Assessment · Shale
Building the FrackMap Biblio with Zotero (open source)
Distribution of Publications by Topic

Distribution of Fracking Research Publication Topics

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- Regulation: 30
Shale Plays and States
Methodology: Algorithm for geo-locating articles within shale plays and states

Get a map of the shale. Is the shale spreading *only* in one state?

Yes → Pinpoint the center of the shale. Association of that state to all such shale missing a state in the database.
E.g.: Eagle Ford (TX); Barnett (TX); Monterey (CA); Fayetteville (AR); Mowry (WY).

No → Pinpoint the center of the portion of the shale within that state.
E.g.: Bakken (MT, ND); Niobrara (CO, NE, WY); Marcellus (NY, OH, PA, WV).

Does the article mention state?

Yes → Pinpoint the center of the whole shale. E.g.: Bakken (MT, ND); Marcellus (NY, OH, PA, WV).

No → Get a map of the shale. Is the shale spreading *only* in one state?
## Geolocalization

### States and shale

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<td>Morton, John; Smith</td>
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<td>Y</td>
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<td>Esswein, Eric J.; Breitenstein</td>
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Harvard WorldMap a public domain collaborative mapping platform

http://worldmap.harvard.edu/maps/FrackMap

FrackMap Biblio
Health Impacts publications

<table>
<thead>
<tr>
<th>Title</th>
<th>Author(s)</th>
<th>Year</th>
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<tbody>
<tr>
<td>Unconventional Gas and Oil Drilling is Associated with Increased</td>
<td>Semmens, Thomas; Garton, George L;</td>
<td>2015</td>
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<tr>
<td>Hospital Utilization Rates</td>
<td>Nodwell, Matthew; Chirrud, Steven;</td>
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<tr>
<td></td>
<td>Yan Beilstein; Stute, Martin; Howarth, Marilyn; Saberi, Pou; Fausti, Nicholas; Penning, Trevor M.; Roy, Jason; Preparat, Kathleer J.; Panettieri, Raymond A.</td>
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<tr>
<td>Spacial analysis of environment and population at risk of natural</td>
<td>Meng, Yiming</td>
<td>2015</td>
</tr>
<tr>
<td>gas fracking in the state of Pennsylvania, USA</td>
<td></td>
<td></td>
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<tr>
<td>Lung Cancer Risk from Radon in Marcellus Shale Gas in Northeast U.S.</td>
<td>Mitchell, Austin L.; Griffith, W. Michael; Casman, Elizabeth A.</td>
<td>2015</td>
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<tr>
<td>Homes</td>
<td></td>
<td></td>
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<tr>
<td>Field Survey of Health Perception and Complaints of Pennsylvania</td>
<td>Saberi, Pou; Probert, Kathleen Jay; Powers, Martha; Emmett, Edward; Green-Mckenzie, Judith</td>
<td>2016</td>
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<tr>
<td>Residents in the Marcellus Shale Region</td>
<td></td>
<td></td>
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<tr>
<td>Exposure pathways related to shale gas development and procedures</td>
<td>Lienkiewicz, P. F.; Quarranta, J. D.; Daniel, A.; Wise, R.</td>
<td>2014</td>
</tr>
<tr>
<td>for reducing environmental and public risk</td>
<td></td>
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</table>

State: Pennsylvania
Shale: Marcellus
Adding the Occupational Safety and Health Category

- Recent increase in number of peer-reviewed articles on OSH now requires 12\textsuperscript{th} category
- Access to HF worksites is improving
- Large number of fatalities is concerning
- Injuries are under-reported
Call for Hydraulic Fracking Research

• Exposure assessment
• Health outcomes studies
  – BTEX, diesel exhaust, HS, fracking chemicals, NORM, heat and cold stress, noise
• Post-intervention assessment studies
• Mitigation evaluation
• Root cause analysis
• Screening and systems – incidence and prevalence
• Occupational Epi collaborations

Witter, 2014; Esswein et al., 2013, 2014; and others
## Occupational Safety and Health

<table>
<thead>
<tr>
<th>Biblio-Category</th>
<th>Publication Title</th>
<th>Content</th>
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<tr>
<td>Waste Water</td>
<td>HF chemical reporting</td>
<td>1,929,128 ingredients</td>
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<td>Waste Water</td>
<td>Malignant human cell transformation ... flowback water</td>
<td>Flow back water</td>
</tr>
<tr>
<td>Waste Water</td>
<td>Organic compounds in produced water</td>
<td>NBTE</td>
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<tr>
<td>Water Quality</td>
<td>Analysis of BTEX groundwater concentrations</td>
<td>BTEX</td>
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<tr>
<td>Air Quality</td>
<td>Air concentrations of volatile compounds</td>
<td>Benzene, formaldehyde, H2S, and 5 others</td>
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<td>Air Quality</td>
<td>Human exposure to unconventional oil and gas drilling</td>
<td>PM 2.5, VOCs</td>
</tr>
<tr>
<td>Regulation</td>
<td>Shale gas operator violations</td>
<td>High rate of spills</td>
</tr>
</tbody>
</table>
FrackMap Bibliography - next steps

• Finish adding the layers (categories) on the FrackMap

• Integrate new publications

• Highlight grey science – e.g., white papers (non-peer reviewed literature)

• Harvest publications from state and federal governments
Perceptions embedded in tweets can help us create targeted messages for educational and policy purposes.
• Millions of people comment in real-time, tweet, retweet, etc.
• Users can optionally choose to provide location information for the tweets they publish.
• This information can be accurate if the tweet is published using a smartphone with GPS capabilities.
Harvard Center for Geographic Analysis

Has an archive of millions of tweets!

Dr. Marcellis-Warin used hashtags and key words to collect 65,000 tweets related to hydraulic fracking
Collecting the tweets (1)

In the following table, we present the hashtags and keywords used to extract the tweets.

<table>
<thead>
<tr>
<th>Hashtags and Keywords</th>
<th>Unconventional gas</th>
<th>#unconventionalgas</th>
<th>unconventional well</th>
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<td>fracking</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic fracturing</td>
<td>#HydraulicFracturing</td>
<td>#unconventionalwell</td>
<td>shaleplay</td>
</tr>
<tr>
<td>shale gas</td>
<td>#shalegas</td>
<td>#gasdrilling</td>
<td></td>
</tr>
<tr>
<td>gas wells</td>
<td>#shalegaswells</td>
<td>frackingwastewater</td>
<td>frackquake</td>
</tr>
<tr>
<td>frackingquakes</td>
<td>frackwaste</td>
<td>fraccidents</td>
<td>frackingpollution</td>
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</table>

Source: Harvard Center for Geographic Analysis Geolocated Tweets Archive

#UNGD : Unconventional Natural Gas Development
# Collecting the tweets (2)

<table>
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<tr>
<th>Hashtags related to shale plays in the US</th>
<th>marcellus</th>
<th>uticashale</th>
<th>Permian</th>
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<td>marcellusshale</td>
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<td>Barnettshale</td>
<td>bakkenshale</td>
<td>devonianshale</td>
<td>eaglefordshale</td>
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<tr>
<td>montereyshale</td>
<td>FayettevilleShale</td>
<td>HaynesvilleShale</td>
<td>NiobraraShale</td>
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<td>WoodfordShale</td>
<td>Muskawa shale</td>
<td>Antrimshale</td>
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</tbody>
</table>

Source: Harvard Center for Geographic Analysis Geolocated Tweets Archive
FrackMapTweets (TBI)
Track public engagement with fracking-related issues by analyzing Twitter conversations (65,000 geolocalized Tweets).

Harvard WorldMap a public domain collaborative mapping platform
http://worldmap.harvard.edu/maps/FrackMap
Opinion Formation: Hashtags

#Fracking
#Utica
#Job, #Jobs, #Kellyjobs,
#Hiring
#Pipeline, #Oil
#Physician, #Nursing,
#Climate, etc.
Opinion formation: "Relevant" words by count for 2015
Outputs of the emotions
Lessons Learned From the Tweet Analyses

• Jobs, Jobs, Jobs,
• Little awareness of the health, safety or environmental impacts of fracking
• Tweets were triggered by local events (such as a spill or earthquake)
• We can learn about opinion formation and the pace and spread of ideas by analyzing tweets
Conclusions

• There is a great need for education of the public about the risks and hazards of hydraulic fracking.

• The opportunity for occupational safety and health research is opening up and there is a great need for a wide variety of research projects.

• The FrackMap, as an innovative tool for communication and interactive data visualization, may help identify research gaps, generate research questions and MAYBE even EXPAND RESEARCH PARTNERSHIPS!
Acknowledgments

– Harvard-NIOSH ERC (T42 OH 008416)
– Harvard Chan NIEHS Center for Environmental Health (P30 ES000002)
– Harvard Center for Geographic Analysis
– Graduate students at Polytechnic, Montreal
– HEC Business School, Montreal
– NIOSH: Expanding Research Partnerships - 2017
Thank you!

• abackus@hsph.harvard.edu
• www.worldmap.harvard.edu/maps/FrackMap
• References


Esswein, Eric J.; Snawder, John; King, Bradley; Breitenstein, Michael; Alexander-Scott, Marissa; Kiefer, Max. 2014 Evaluation of Some Potential Chemical Exposure Risks During Flowback Operations in Unconventional Oil and Gas Extraction: Preliminary Results. J Occ Env Hyg. 11:10, D174-D183.

Witter, Roxana Z.; Tenney, Liliana; Clark, Suzanne; Newman, Lee S. 2014 Occupational exposures in the oil and gas extraction industry: State of the science and research recommendations. AJIM. 57: 847-856,
Affiliations

- **Ann Backus, MS**
  - Director of Outreach, Harvard-NIOSH ERC
  - Harvard T.H. Chan School of Public Health

- **Nathalie de Marcellis-Warin, PhD** @n_demarcellis
  - Visiting Scientist, Harvard T.H. Chan School of Public Health
  - Full Professor, Polytechnique Montréal and President, CIRANO (Montréal)

- **Thierry Warin, PhD**
  - Visiting Scholar Harvard University
  - Associate Professor, HEC Business School (Montréal)

- Thanks to **Christophe Mondin**, M.A.Sc.
  - Research Assistant at CIRANO, Polytechnique Montreal and IMT Lille Douai
Marcellus Shale
@MarcellusGas

Founded in 2008, the Marcellus Shale Coalition (MSC) is committed to the responsible development of clean—.

Suivi par centrehc et 13 autres

Shale Gas Europe
@ShaleGasEurope

Shale Gas Europe, the European resource centre for shale gas, tight gas & coal bed methane. #ShaleGas #EU ...

Suivi par JL Schilansky et 3 autres

Duke of Chalfont @ChrisDarroch2 · 3 déc.
@Jonny_Nabb @HeartScotland They let it fall because Saudi decided to flood the market to break shale gas producers in the US.

Marco Leofrigio @marcoleofrigio · 3 déc.
@SissiBellomo scrive di arrivo prima volta shale gas Usa da noi
@GermanoDottori @GianandreaGaian @nicklocatelli @alessandracatsi @LucaSusic
# US Active Oil and Gas Wells (2014)

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<td>Wyoming</td>
<td>7,349</td>
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<tr>
<td>Totals</td>
<td>15,257</td>
<td>20,785</td>
<td>23,879</td>
</tr>
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</table>

* - While the FracTracker Alliance was able to get totals for MD, NC, and TX, well data is not available for these states. While TX data is technically available for purchase, it cannot be redistributed.
States requiring disclosure of hydraulic fracturing chemicals (January 2015)

Source: Ground Water Protection Council, http://fracfocus.org/welcome
Mapping the tweets [2015]
The Continuous Personal Dust Monitor: A Partnership Success Story

Steven Mischler
Senior Mining Engineer, Pittsburgh Mining Research Division

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Mining Research Establishment in UK develops first sampler for mining

- Used gravity to size the aerosol
- Used filter to weigh the sized dust
- MRE 113A horizontal elutriator
- Extensive health effects data collected
U. S. develops “personal sampler” for mining use in mid 1960’s

- Centrifugal force used to size aerosol
  - Small and light weight
  - Less sensitive to orientation
  - Portable use

- Filter mass determination

- Portable pump

- Incorporated into 1969 law
Continued concern reflected in continuing lung disease in miners

- 1969 H&S Act sets 2 mg/m³
- Almost 30 years after the act CWP was still occurring
- In 1996, Sec. of Labor urges better monitoring
- NIOSH “…more accurate and reliable measures of worker exposures…” needed
Compliance sampling unchanged

Little changed in the almost 40 years
Continuous Monitoring

• Under recommendation of Secretary of Labor and the 1996 “Federal Advisory Committee on the Elimination of Pneumoconiosis among Coal Mine Workers”, NIOSH mandated to improve personal dust monitoring instruments to provide timely data output to miners
Partnership development of PDM

• Purpose of partnership – To implement parts of the Asst. Secretary of Labors 1996 recommendations to eliminate Black Lung

• Members
  • Coal Mining company representatives
  • BCOA
  • UMWA
  • NMA
  • R&P/Thermo
  • Government -- MSHA/NIOSH

• History – formed late 90’s to guide development of personal dust monitor. Continue to meet regularly
Mass based sensor

• Mid 1970’s Bureau of Mines began development of short term dust monitors
  • Beta-attenuation mass monitor GCA-301
  • SRI Light scattering photometer
  • Real Time Aerosol Monitor (RAM-1)
  • Personal Data Ram

• BOM/NIOSH concludes that direct aerosol mass sensing instrument eliminates need for estimates/assumptions thus reducing potential for error
Development of mass based sensor

During the 1990’s BOM and MSHA worked jointly on developing a short-term dust monitor for underground mines based on the R&P Environmental TEOM monitor.

### Approach 1
- Machine-mounted continuous respirable dust monitor (MMCRDM).
- 4 cu ft. box weighing 160 lbs.
- Relied on area measurements, no data on personal exposure and not reliable
- Failed to meet NIOSH accuracy criteria and found to not be mine-worthy
- Research discontinued in 1999

### Approach 2
- Personal End-of-Shift/Continuous Respirable Dust Monitor (PESCRDM)
- Person-wearable, tamper resistant,
- Capable of 1) providing full shift time-weighted average respirable dust mass concentration and, 2) Display continuously-measured respirable dust exposure information
- Start of PDM research
Evolution of PDM Technology

Prototype bench unit

PDM-2

PDM-1

PDM 3700

PDM 3600
Equivalency of PDM to CMDPSU measured in underground coal mines

- Data from 119 MMU’s selected using a random proportional allocation strategy

- MRE/ISO impactor based comparison influenced by loading

- Direct comparison to CMDPSU requires a multiplier of 1.05

- Published in peer reviewed*
Interaction between rock dust and respirable dust rules

• In 2010 MSHA instituted an Emergency Temporary Standard that increased rock dusting requirements so that 80% incombustible content (IC) is maintained in all areas including within 40 feet of the face and the intake. Final rule enacted in 2011.
• Rock dust contains significant amounts of respirable-sized dust (2012 NIOSH study showed 88% of 260 rock dust samples > 20% respirable and nearly 30% > 30% respirable)
• Bimonthly compliance sampling on 5 consecutive days provides off-sampling time to complete rock dusting
• Quarterly sampling of 15 consecutive shifts (30-45 shifts with ODO sampling) does not provide off-sampling time to apply rock dust
• Workers potentially exposed when initially applying rock dust and also, if applied rock dust is re-entrained into airstream by equipment/personnel movement
Development of new inlet

• Partnership decided to incorporate PDM with cap lamp to make it invisible to the miner, since miner was already accustomed to wearing a cap lamp, lead acid battery and cord.

• In recent years lighting technology has improved, allowing for the battery and cap lamp to be incorporated into one unit affixed to the miners helmet.

• In response, NIOSH removed the cap lamp and cord from the PDM and redesigned the inlet to be worn on the miners lapel.

• Currently writing a paper showing the equivalency of the old and new inlet.
MSHA’s Final respirable dust rule

• Provides comprehensive, integrated approach to reduce miners’ exposure to respirable coal mine dust and prevent and end black lung disease
• Improves respirable dust sampling program to better reflect working conditions
• Implemented in 3 phases: August 1, 2014,
  • February 1, 2016, and August 1, 2016
• Since rule went in effect on August 1, 2014, there has been over 99 percent compliance with sampling requirements
## Significant changes in respirable dust regulations

<table>
<thead>
<tr>
<th><strong>1969 Act</strong></th>
<th><strong>2014 Rule</strong></th>
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</thead>
<tbody>
<tr>
<td>• 5 valid samples each bimonthly period on DO – consecutive days or shifts</td>
<td>• 15 valid samples each quarter on DO on consecutive shifts</td>
</tr>
<tr>
<td>• Citation on average concentration</td>
<td>• Citation on single MSHA sample – Excessive concentration value (ECV)</td>
</tr>
<tr>
<td>• 50% of production from previous sampling period for valid sample</td>
<td>• 80% of production from previous 30 shifts</td>
</tr>
<tr>
<td>• 8 hour sampling period</td>
<td>• Full-shift sampling regardless of length</td>
</tr>
<tr>
<td>• Gravimetric sampler provides average concentration (one number)</td>
<td>• PDM provides end-of-shift concentration and running concentration</td>
</tr>
<tr>
<td>• 7 to 10 days for compliance results</td>
<td>• In-shift feedback and projection of compliance</td>
</tr>
<tr>
<td>• Reduced dust standard for quartz &gt; 5% (10 ÷ % silica)</td>
<td>• Establish 100 µg/m³ quartz standard</td>
</tr>
<tr>
<td>• 2.0 mg/m³ dust standard</td>
<td>• 1.5 mg/m³ dust standard (August 1, 2016)</td>
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Continuous Personal Dust Monitor (CPDM)

- As of February 1, 2016, MSHA requires the underground coal industry to utilize a CPDM for compliance dust monitoring.
- Thermo Fisher Scientific PDM 3700 is the only certified CPDM sampler.
- Over 2,300 units have been sold.
- Sampler weighs 2 kgs (4.4 lbs).
Worker empowerment - increasing the capacity of individuals to make choices and to transform those choices into desired actions
Impact of CPDM use under new MSHA dust rule

CPDM is designed to provide workers and management with exposure information during the work shift, which enables them to make adjustments in an effort to avoid overexposures.

<table>
<thead>
<tr>
<th>Dust sampler</th>
<th>Sampling period</th>
<th>Dust standard</th>
<th>Number of samples</th>
<th>Percent greater than standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric</td>
<td>August 1, 2014 to March 31, 2016</td>
<td>2.0 mg/m³</td>
<td>28,101</td>
<td>1.9%</td>
</tr>
<tr>
<td>CPDM</td>
<td>April 1, 2016 to July 31, 2016</td>
<td>2.0 mg/m³</td>
<td>13,176</td>
<td>0.1%</td>
</tr>
<tr>
<td>CPDM</td>
<td>August 1, 2016 to December 31, 2016</td>
<td>1.5 mg/m³</td>
<td>9,372</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

CPDM dropped overexposures for the designated occupation (high risk) samples by over 94% under the 2.0 standard and over 78% with the reduced standard.
The PDM reduces overexposures of underground Miners regardless of occupation.
The PDM reduces overexposures of underground Miners regardless of mine size.
Significant guidance provided by PDM Partnership

- Technology for continuous measurement
- Machine-mounted vs personal sample
- Recommended 1 piece unit combined with cap light
- Reviewed Phase 1 testing protocol
- Suggested many changes between prototype and pre-commercial
- Guided phase 2 test protocol. Provided mine sites for testing.
- Expanded test protocol to add low coal and extended unattended mine testing
- Helped secure funding for pre-commercial development
- Changes to 30 CFR part 74 – define requirements of a continuous personal dust monitor
- Equivalency of PDM to CMDPSU
- Certification of PDM 3600
- Development and testing of new inlet for revised PDM
- Certification of PDM 3700
- Implementation of the new dust rule requiring use of the PDM
- Interaction between rock dust and respirable dust rule
- PDM partnership received R&D 100 award for PDM in 2004
Future Partnership interaction

• Miniaturization of the PDM.
• Open competition for mass based measurement technology
• Testing and certification of ergonomically based PDM
Thank You and Questions
PDM development timeline

- 1970 – 1990 – BOM researches different technologies for use as a short-term dust monitor in underground mines (beta attenuation, light scattering, mass) Concludes that direct mass measurement is most feasible and accurate for underground mining environment.
- 1990 – 1998 – BOM and MSHA research use of TEOM (direct mass measurement) for both machine-mounted continuous respirable dust monitor (MMCRDM) and personal end-of-shift/continuous respirable dust monitor (PESCRDM). Before 1998 PESCRDM was only in the development stages. Most work was on the MMCRDM which was heavily favored by MSHA management (Davit Mcateer)
- 1995 – Secretary of Labor advisory committee recommends improved monitors for coal mine dust
- 1998 – NIOSH signs contract with R&P to develop and deliver personal end-of-shift/continuous respirable dust monitor (PESCRDM). This was a 2 year contract
- 1999 - NIOSH ends work on the MMCRDM finding it failed to meet NIOSH accuracy criteria and found to not be mine-worthy.
- 2000 – 2004 – NIOSH laboratory and field testing several iterations of the PDM
- 2004 – 25 pre-commercial TEOM 3600 PDM units were purchased and testing at 20% of US mines was initiated (evaluating accuracy, precision, durability, wearability and equivalency to the MRE/CMDPSU)
- 2004 – publication of RI9663 reporting lab results and field testing of initial PDM.
- 2004 – PDM partnership received R&D 100 award for PDM
- 2006 – publication of RI 9669 reporting lab and field testing of PDM compared to CMDPSU
- 2007 – R&P purchased by Thermo Fischer Scientific
- 2008 - Peer review equivalency paper published reporting the underground full shift performance of the PDM compared to the CMDPSU. Page, et.al. 2008.
- 2009 - Commercial version of PDM made available for purchase
- 2010 - Changes in Part 74 of CFR finalized to define requirements of a continuous personal dust monitor for use as a certified dust sampler
- 2011 – PDM 3600 certified by MSHA and NIOSH for use in underground coal mines
- 2012 – NIOSH releases RFP for development of PDM without a cap lamp. Thermo is awarded the contract.
- 2013 – NIOSH develops and tests new inlet for revised PDM
- DEC 2014 - PDM 3700 certified by MSHA and NIOSH for use in underground coal mines
- 2016 – Publication reporting testing results for the new lapel inlet for the PDM 3700
- 2016 – Publication reporting certification testing results for the PDM 3700.