Development of Computational Methods for Evaluating Loose-Fitting Powered Air-Purifying Respirators

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CDC/NIOSH/NPPTL

EXPANDING RESEARCH PARTNERSHIPS: STATE OF THE SCIENCE CONFERENCE

Aurora, Colorado, June 21-23, 2017

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

Background

- Loose-fitting powered air-purifying respirator (PAPR):
  - Battery-operated blower;
  - High efficiency particulate air (HEPA) filter; and
  - Respiratory inlet covering (i.e., hood or helmet).
- Advantages:
  - Comfortable,
  - Does not require fit testing,
  - Covers the wearer's head and neck to reduce contact with an infected person's body.

Photo credit: CDC PHIL

Background

- Disadvantages:
  - Heavy;
  - Noisy; and
  - Battery needs to be charged.

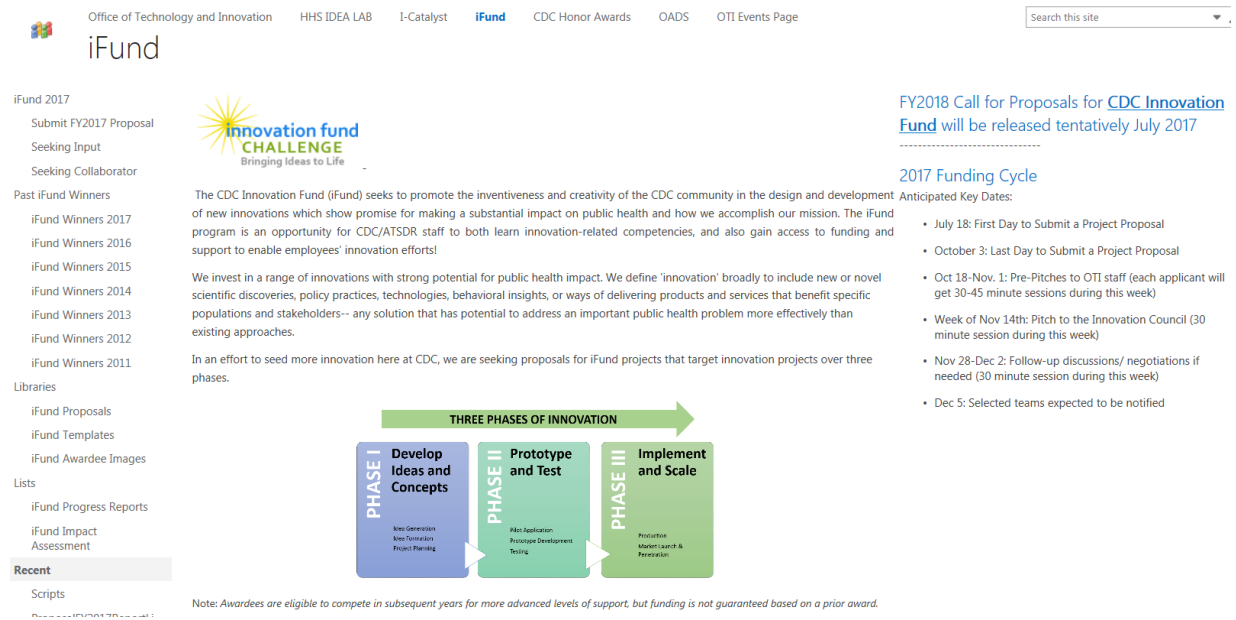
- If supplied-air flow rate can be lower as long as it provides effective protection, this will lead to:
  - Smaller air blower and battery.
  - Quieter and lighter PAPR system.

- There is a need to investigate factors that determine PAPR performance.

Photo credit: NIOSH NPPTL

CDC Innovation Fund (iFund) Project

- Title: Development of Advanced Methods for Evaluating and Designing Loose-fitting Powered Air-purifying Respirators.
- Highlight:
  - Computational Fluid Dynamics (CFD).
  - Python programming for software designing.

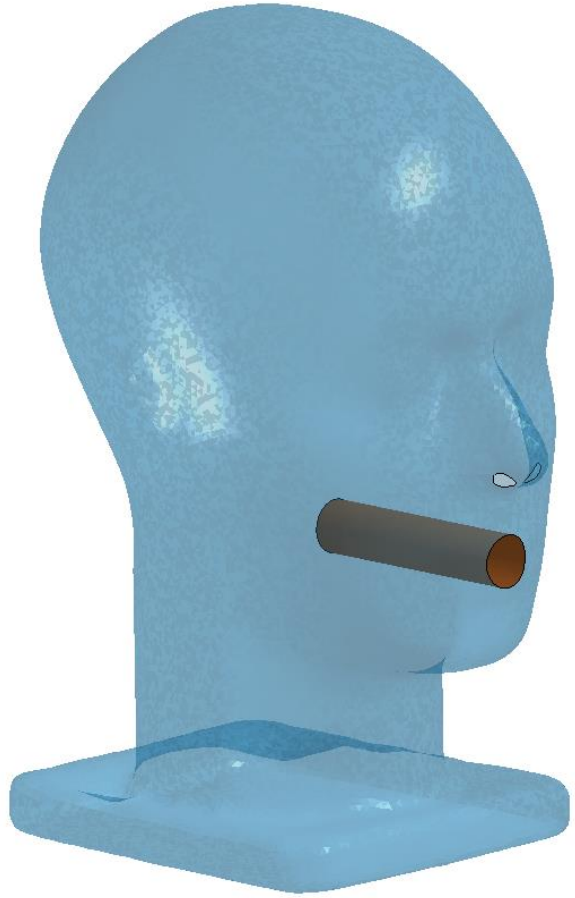


Objectives

- The aim of this study was to develop computational methods for estimating the performance of loose-fitting PAPRs.
  - Develop a digital PAPR model and a digital headform model;
  - Create CFD simulation for airflows and particles inside PAPR; and
  - Explore the effects of breathing and supplied-air on particle leakage.

Headform Model

- Medium-size, representing approximately 50% of the current U.S. workforce.
- One of NIOSH ISO Digital Headforms*.
- Construct a breathing tube for simulating breathing airflows.



Digital headform model having a breathing tube

*** A technical specification standard for ISO TC94 Personal Protective Equipment, SC15 Respiratory Protective Devices, WG1 General, PG5 Human Factors, titled "ISO 16976-2 Respiratory Protective Devices — Human Factors — Part 2: Anthropometrics".**

PAPR Model

- Scan PAPR components;
- Don the PAPR system on the headform; and
- Create PAPR breathing zone by smoothing and trimming surfaces (in next slide).

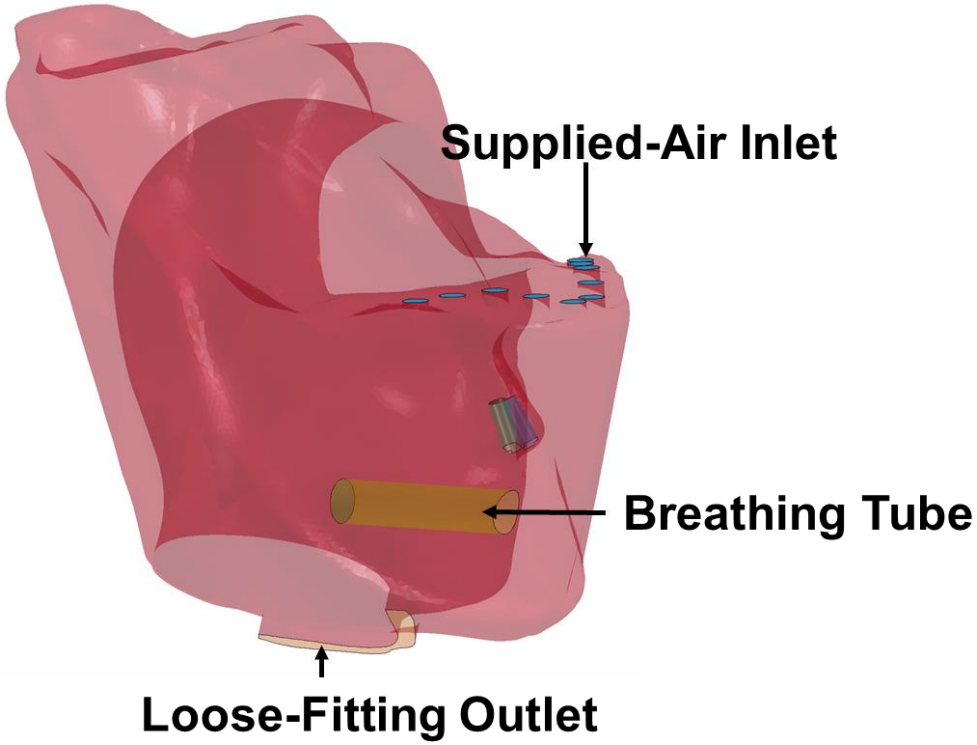
Inlet Covering + Cuff

Filter + Helmet

Photo credit: NIOSH NPPTL

CFD Model

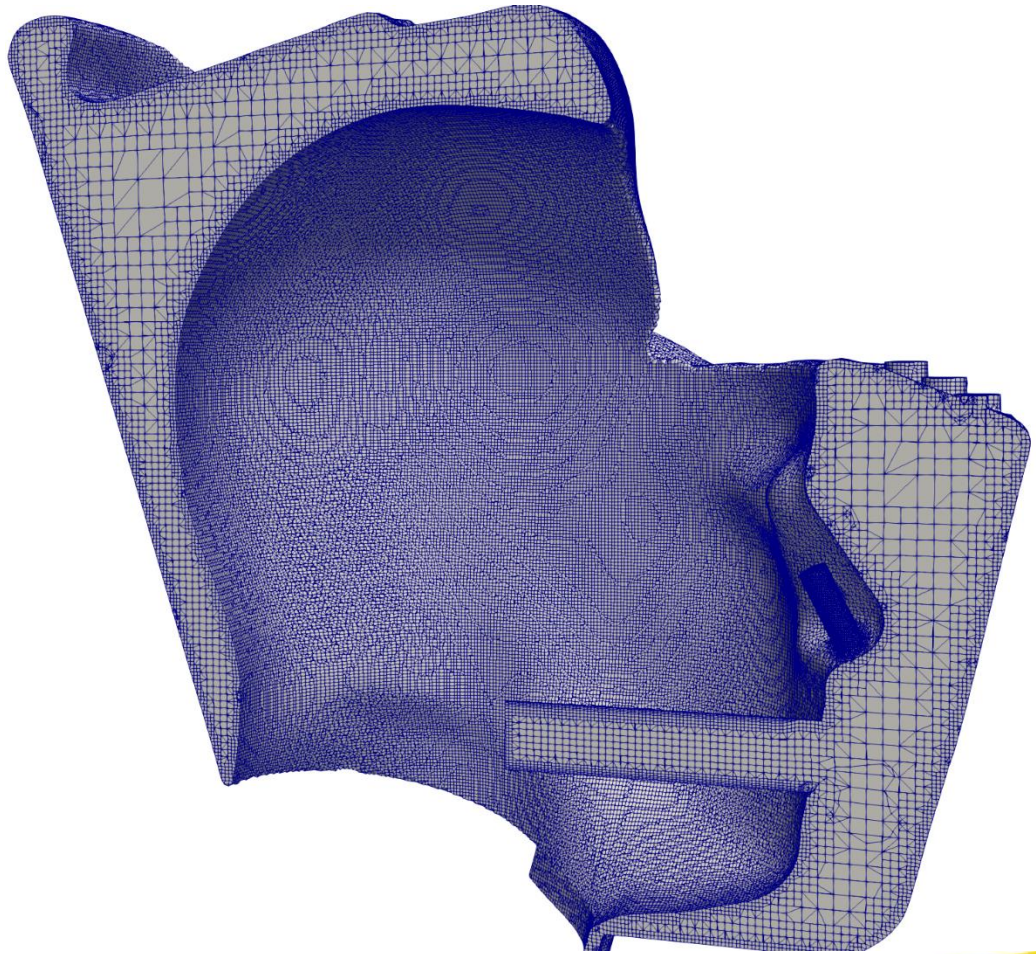
- Boundaries:
  - PAPR surface.
  - Headform surface.
  - Breathing tube.
  - Supplied-air inlet.
  - Loose-fitting outlet.



The CFD model of headform-PAPR.

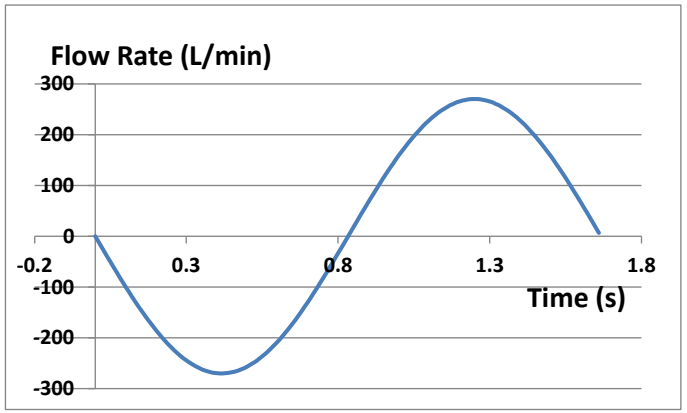
Spatial Discretization

- Used Snappyhexmesh provided by OpenFOAM software;
- Appled Adaptive mesh refinement at the wall, inlet, and outlet; and
- Divided into 913,653 hexahedral cells for the breathing zone.

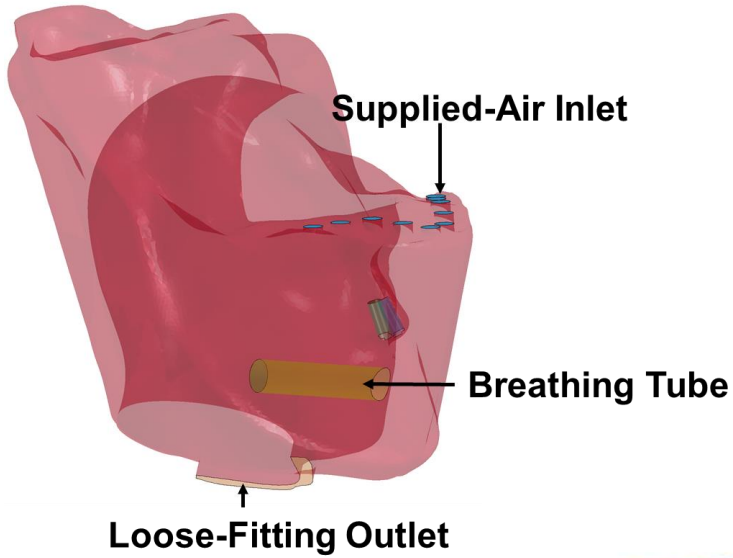


Simulation Setup

- Cyclic breathing
  - A time-dependent flow rate with a sine wave shape.
  - Pass through the venting hole of the breathing tube.
- Supplied-air
  - Constant flow rate with the direction inwards towards the PAPR breathing zone.
- Particles
  - Particle size 0.1μm and concentration 100,000/cm^3.
  - Outside of the PAPR breathing zone.
- Assumption
  - Filter penetration would be negligible.



Profile of breathing flow rate



Simulation Conditions

- Light, moderate, and heavy breathing workloads (minute ventilations of 35, 55, and 85 L/min) *.
- Different PAPR supplied-air flow rates (85, 115, 145, 175, and 195 L/min).
- 15 total simulations (3 workloads × 5 flow rates).

*** Anderson NJ, Casidy PE, Janssen LL, Dengel DR. (2006) Peak Inspiratory Flows of Adults Exercising at Light, Moderate and Heavy Work Loads. Journal of the International Society for Respiratory Protection; Vol. 23.**

Manikin Protection Factors (mPF)

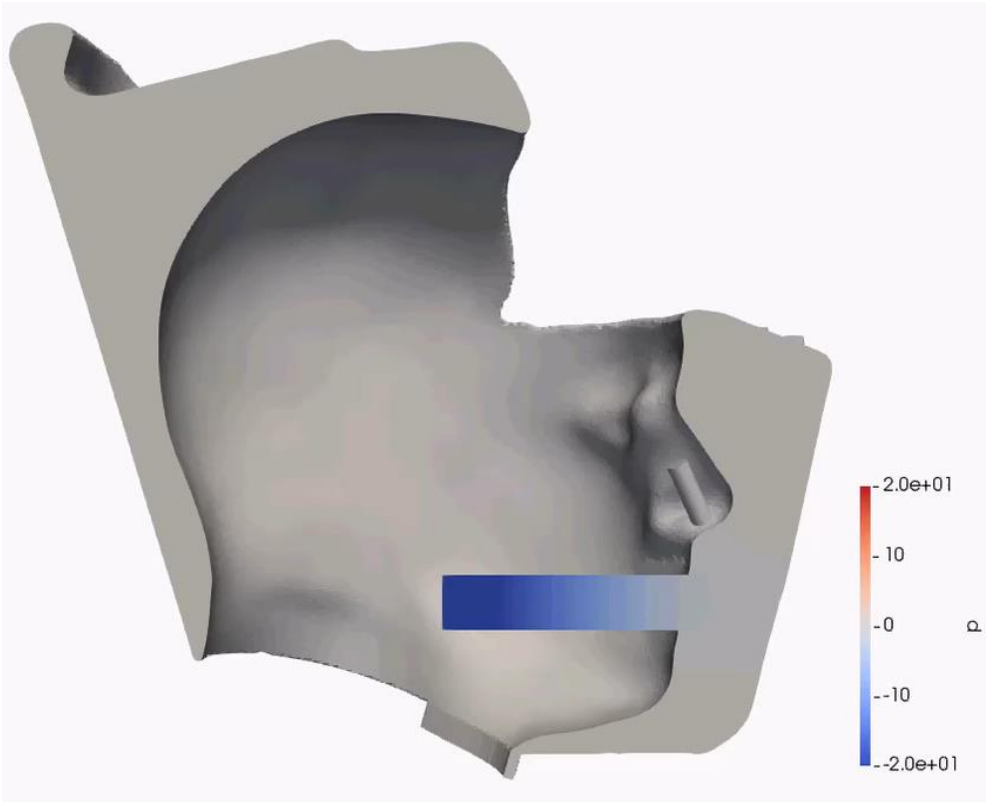
$$mPF = \frac{C_o}{C_i}$$

Where C_o was the challenge particle concentration outside the PAPR and C_i was the particle concentration inside the PAPR breathing zone.

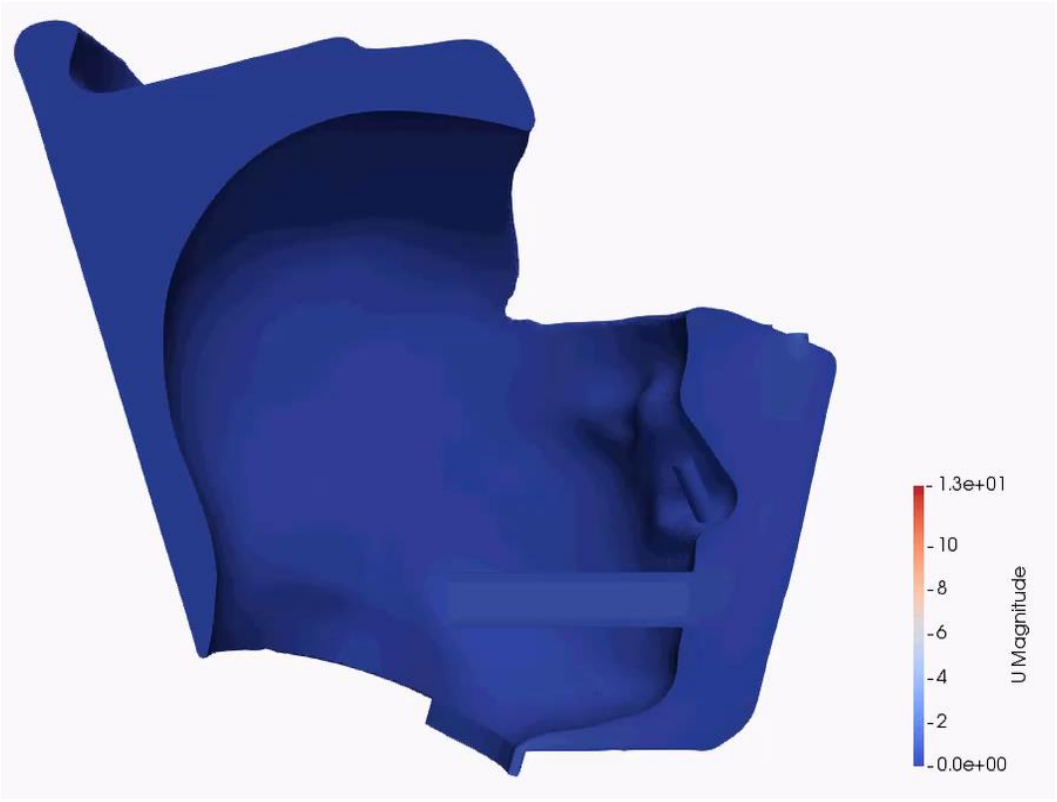
Results

Click to play video

Pressure Contour

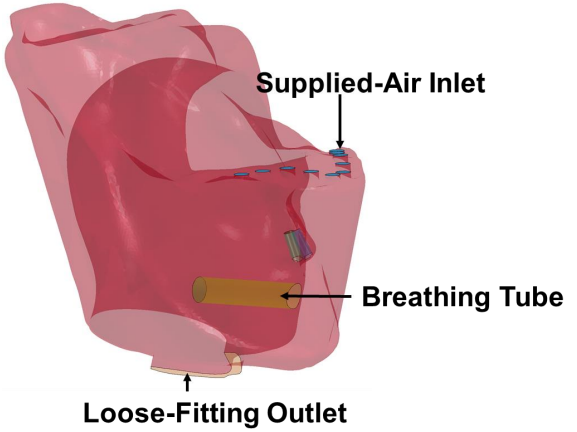


Velocity Contour



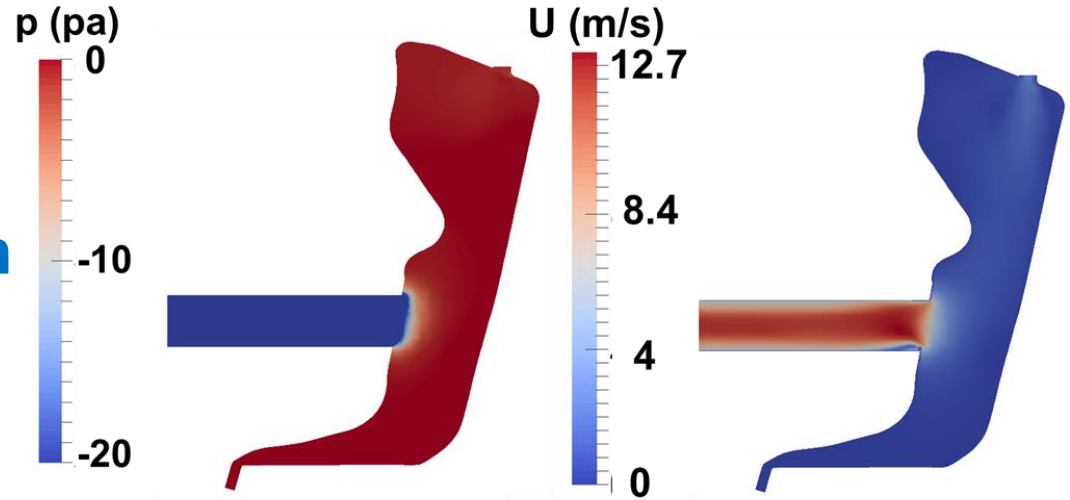
(Heavy workload and 85 L/min supplied-air flow rate)

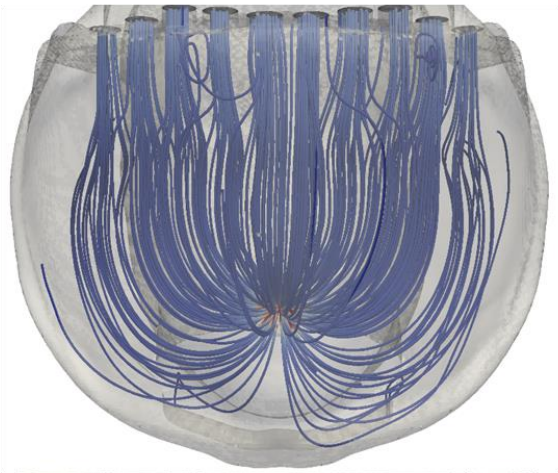
CFD Visualization



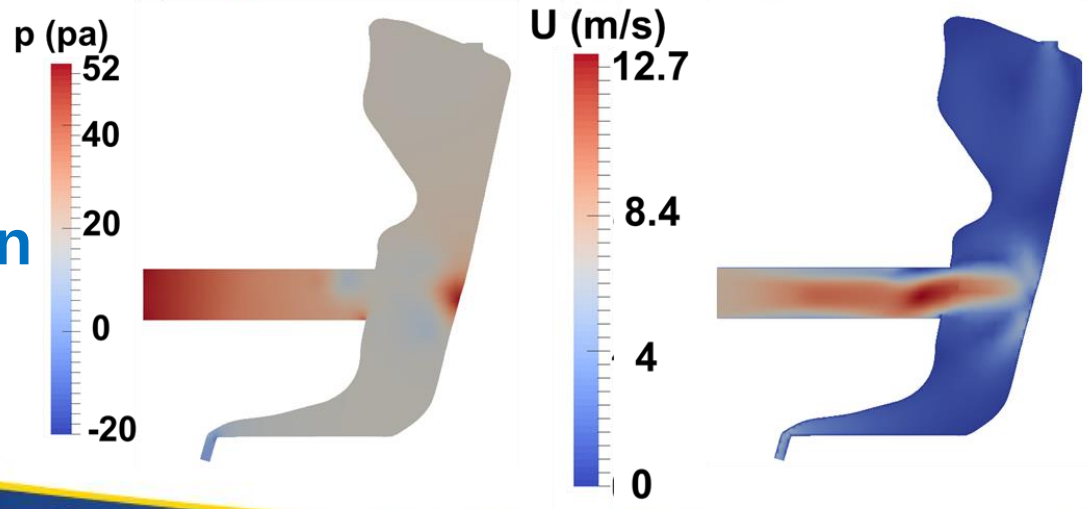
Pressure Contour ***Velocity Contour*** ***Air Streamlines***

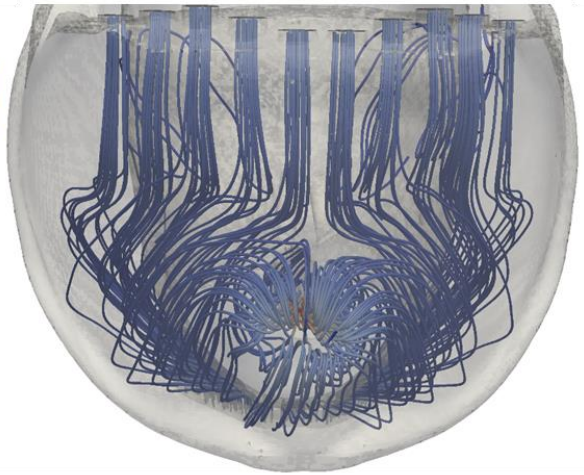
Inhalation





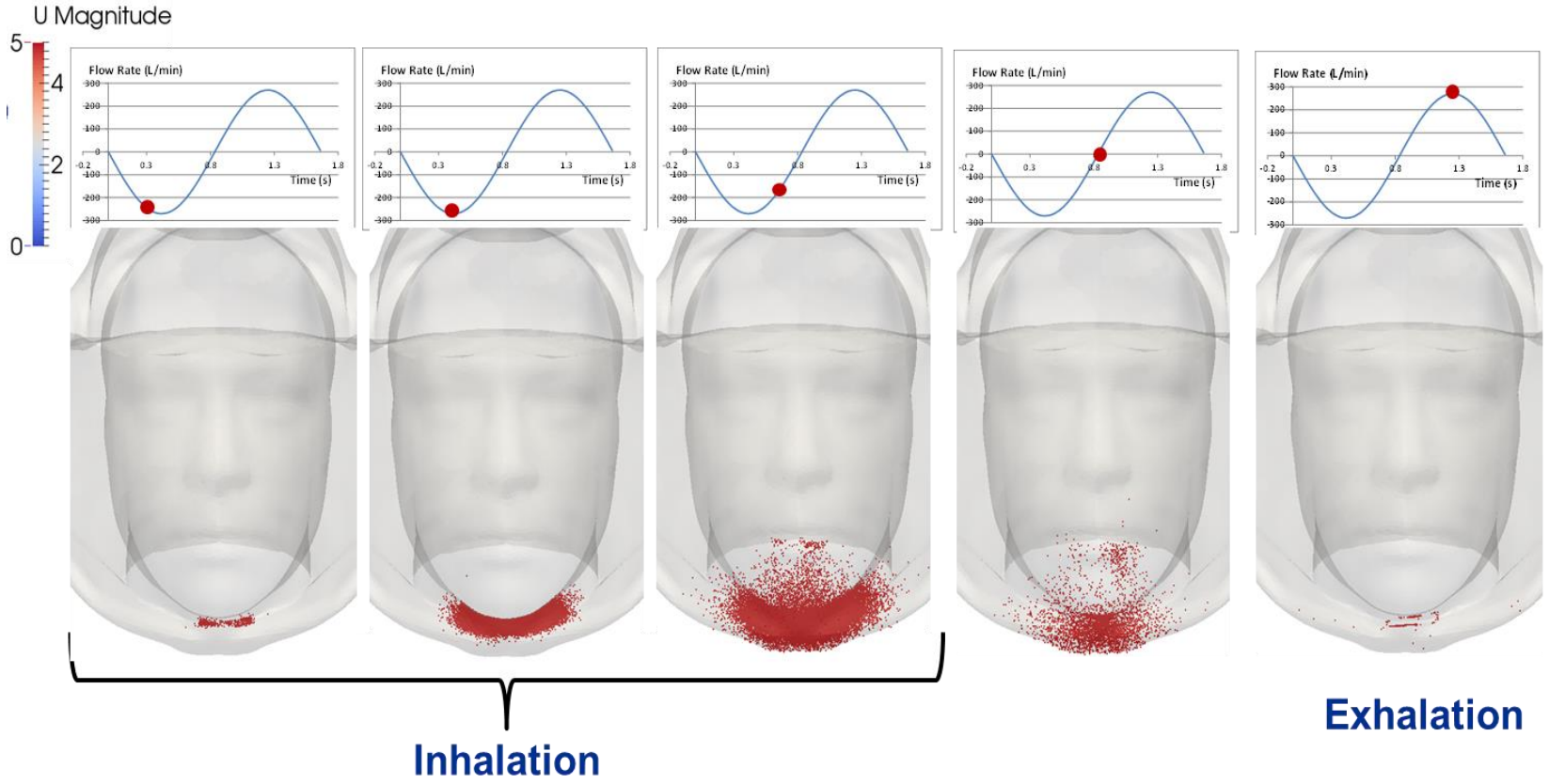
Exhalation





Visualization of flow fields at peak inhalation and exhalation (heavy workload and 85 L/min supplied-air flow rate).

Particle distribution



Particle distribution inside the PAPR inlet covering at different time instances of a breathing cycle (heavy workload and 85 L/min supplied-air flow rate).

Summary of Estimated mPFs

Breathing Workload	Supplied-Air Flow Rate				
	85 L/min	115 L/min	145 L/min	175 L/min	195 L/min
Light (35 L/min)	> 10,000	> 10,000	> 10,000	> 10,000	> 10,000
Moderate (55 L/min)	31.8	> 10,000	> 10,000	> 10,000	> 10,000
Heavy (85 L/min)	6.6	10.6	43.1	> 10,000	> 10,000

- The smaller estimated mPFs were found at heavier workloads and lower supplied-air flow rates.

Discussion

- The CFD method is capable of simulating:
  - Different breathing patterns;
  - Different supplied-air flows of PAPR; and
  - Aerosol particle dynamics.

- The simulation results will be validated by
  - Experiments; and
  - Direct numerical simulation (DNS) using immersed boundary method (IBM).

Experimental setting
Photo credit: NIOSH NPPTL

Next Steps:

- Include additional headforms and PAPRs;
- Explore the effects of particle sizes on leakage;
- Simulate heat stress inside PAPR; and
- Create Python program to help PAPR design.

Conclusions

- Computational methods have potential for assessing PAPR performance and improving PAPR design.
- The smaller estimated mPFs were found at heavier breathing workloads and lower supplied-air flow rates.

Acknowledgments

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Quality Partnerships Enhance Worker Safety and Health

DISCLAIMER: The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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Photos courtesy of NIOSH NPPTL

Questions?

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Evaluating a novel respirator seal integrity monitor for controlling inhalation exposure of firefighters

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Center for Health-Related Aerosol Studies
University of Cincinnati

University of Cincinnati
Education and Research Center

University of CINCINNATI

Outline

- Background: Firefighter Exposure
- Concept: Real-time Respirator Seal Integrity Monitor (ReSIM)
- Methodology: Laboratory Evaluation
- Results
- Conclusions

Background

Respirator performance

N95, N99,
P100,…
Filter certification

Fit testing
(29 CFR 1910.134)

Workplace usage

Fire overhaul

- High concentration of toxic particles from burning
  - Plastics
  - Roofing
  - Household chemicals
- Exposure associated with adverse health outcomes
- Elastomeric respirators instead of SCBA for overhaul

Combustion particles

- Combustion particles (Baxter et al., 2010)
  - Ultrafine (< 0.1 μm): > 70% by count
  - Submicron (< 1 μm): > 99%
- Large particles ($\gtrsim$ 0.5 μm) are present in these environments at low, but measureable, concentration levels

Particle penetration into a respirator

- $P_{Leakage} >> P_{Filter}$
  - Half-mask equipped with two P-100 filters challenged with combustion particles (He et al., 2013)

Partially sealed	Fully sealed
$P_{Leakage} + P_{Filter} = 6 – 8\ \%$	$P_{Filter} = 0.001 – 0.011\ \%$

Concept

Concept

- A new sensor should be able to measure aerosol inside respirator
- It should be capable of detecting relatively large particles ($\gtrsim 0.5\ \mu m$)
- Penetration of these large particles indicates a performance failure (the respirator seal integrity is compromised)

Respirator Seal Integrity Monitor (ReSIM) prototype

- Particle detection
  - PPD60PV-T2 (Shinyei, Kobe, Japan) Particle Sensor Unit
  - Utilizes the light scattering method
  - Detects particles sizes $\gtrsim 0.5$ µm
  - Low particle concentration detection threshold
  - Inexpensive
- Data acquisition and recording module
- Pump, battery and circuitry

Objective

To evaluate the newly-developed ReSIM that can rapidly detect the respirator performance failure in real time and alert the wearer

Methodology

Laboratory evaluation of ReSIM

- Sensitivity and accuracy
  - Calibration against a reference optical particle spectrometer (flow-through set-up)
- Capability to detect respirator failure
  - Testing the capability of ReSIM to detect a faceseal leakage (manikin-based set-up)

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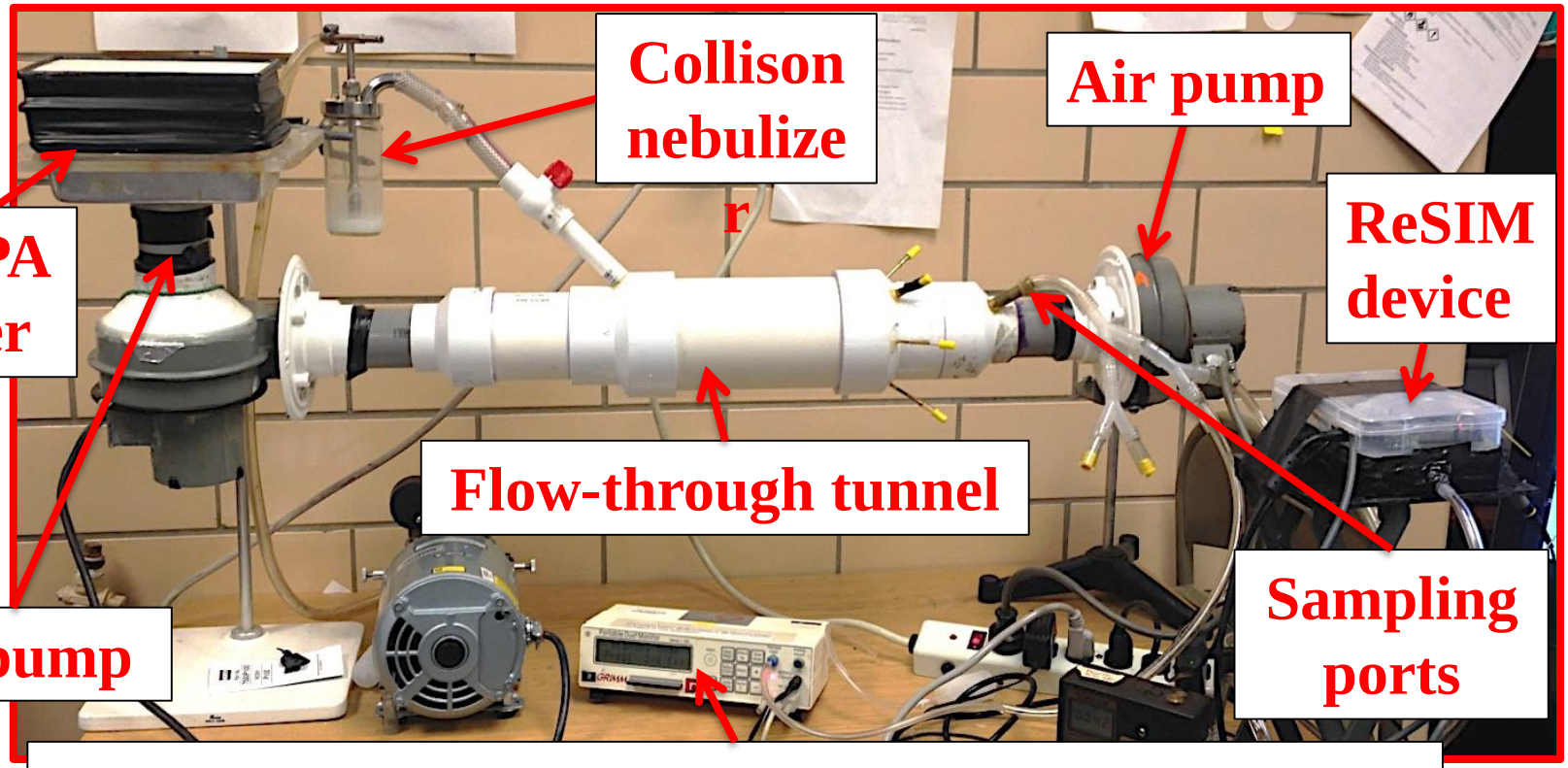
Experimental set-up: flow-through design



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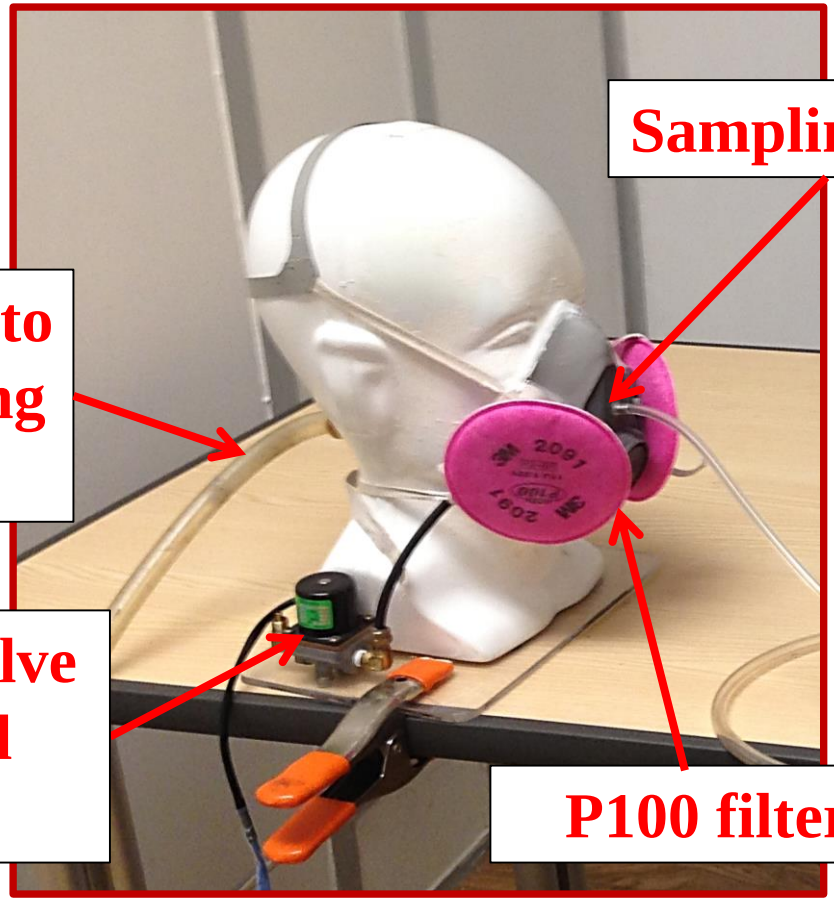
Experimental set-up: manikin-based design



Experimental design (leak detection)

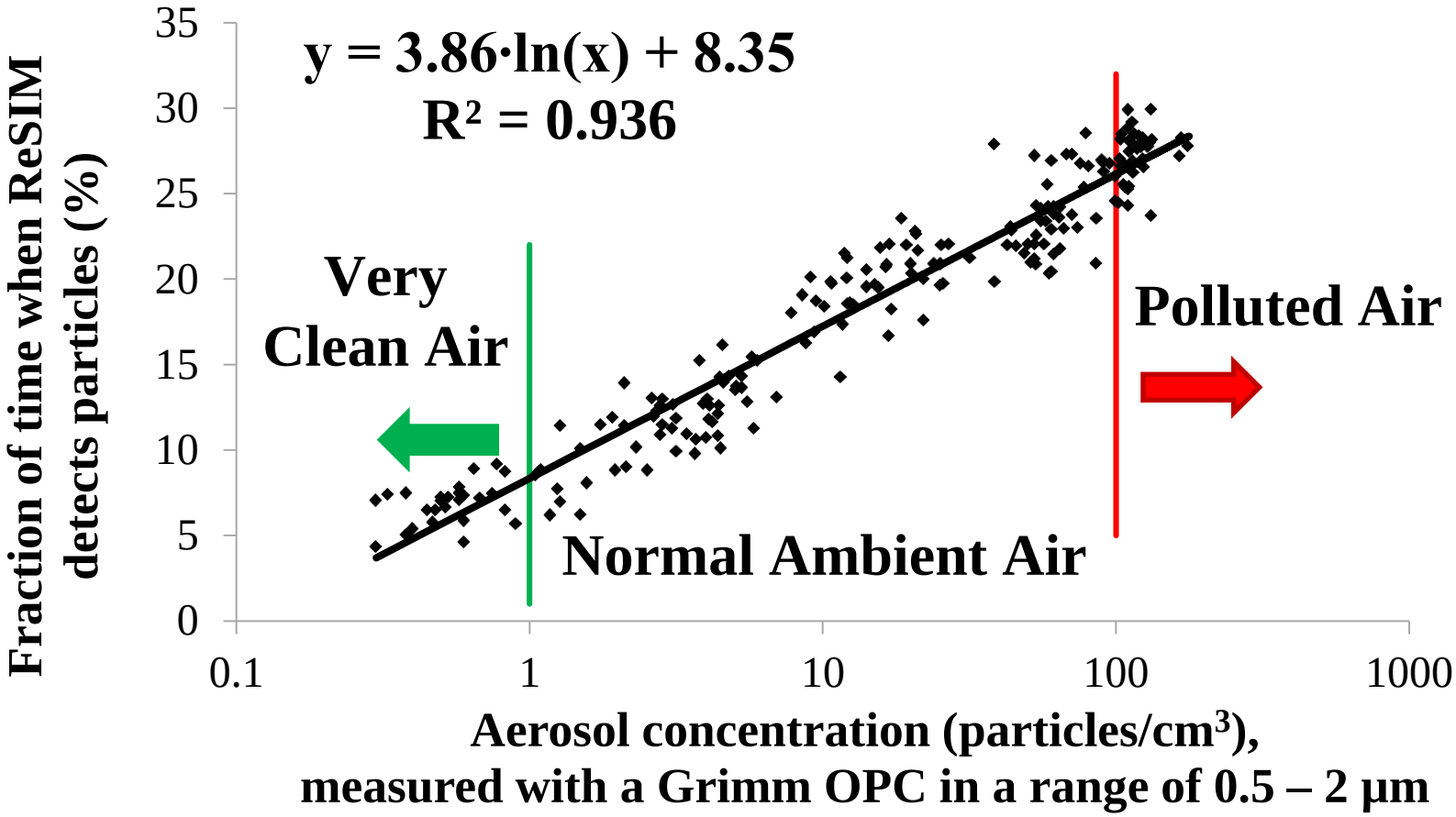
- Test chamber (24.3 m^3)
- Challenge aerosols
  - Combustion
  - NaCl
- Respirator seal failure simulation
  - An orifice (dia = 5 mm) in the faceseal to simulate a leak
  - Controlled by a solenoid valve (leak vs. fully sealed mask)
  - Leak openings for 5 s, 10 s, 15 s, and 20 s
- Respirator tested under cyclic breathing conditions
  - Mean inspiratory flow (MIF) rate = 30, 60 and 85 L/min

Results

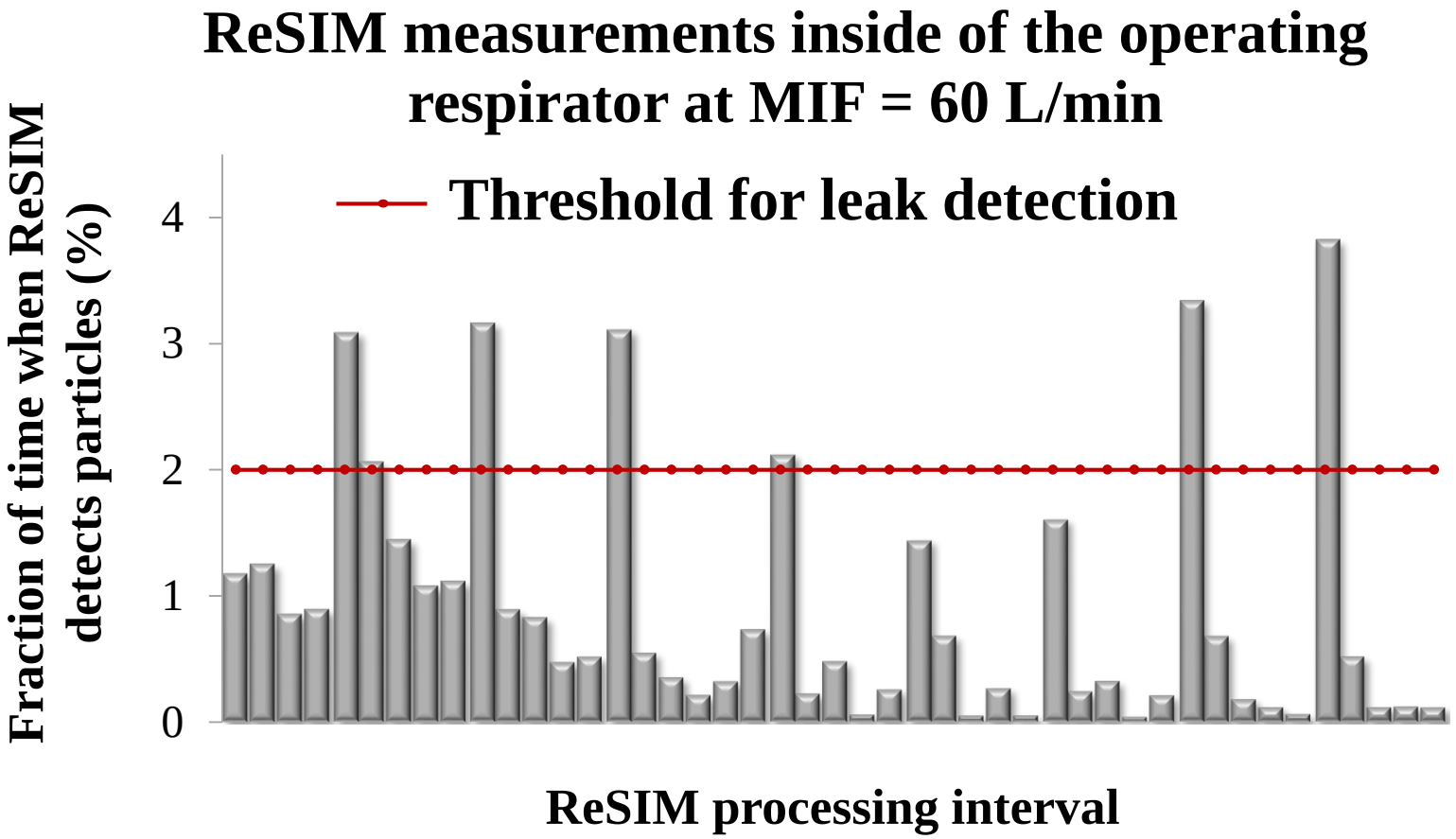
Data processing of ReSIM

- ReSIM outputs
  - Fraction of time (%) during which ReSIM detects particles
  - Output is recorded at 30-s intervals
- 3-step leak detection algorithm
  - Background level (non-leak): concentration inside a fully sealed operating respirator
  - Threshold: based on the rolling average of previous 5 consequtive intervals with no leaks created
  - Leak: aerosol concentration > threshold

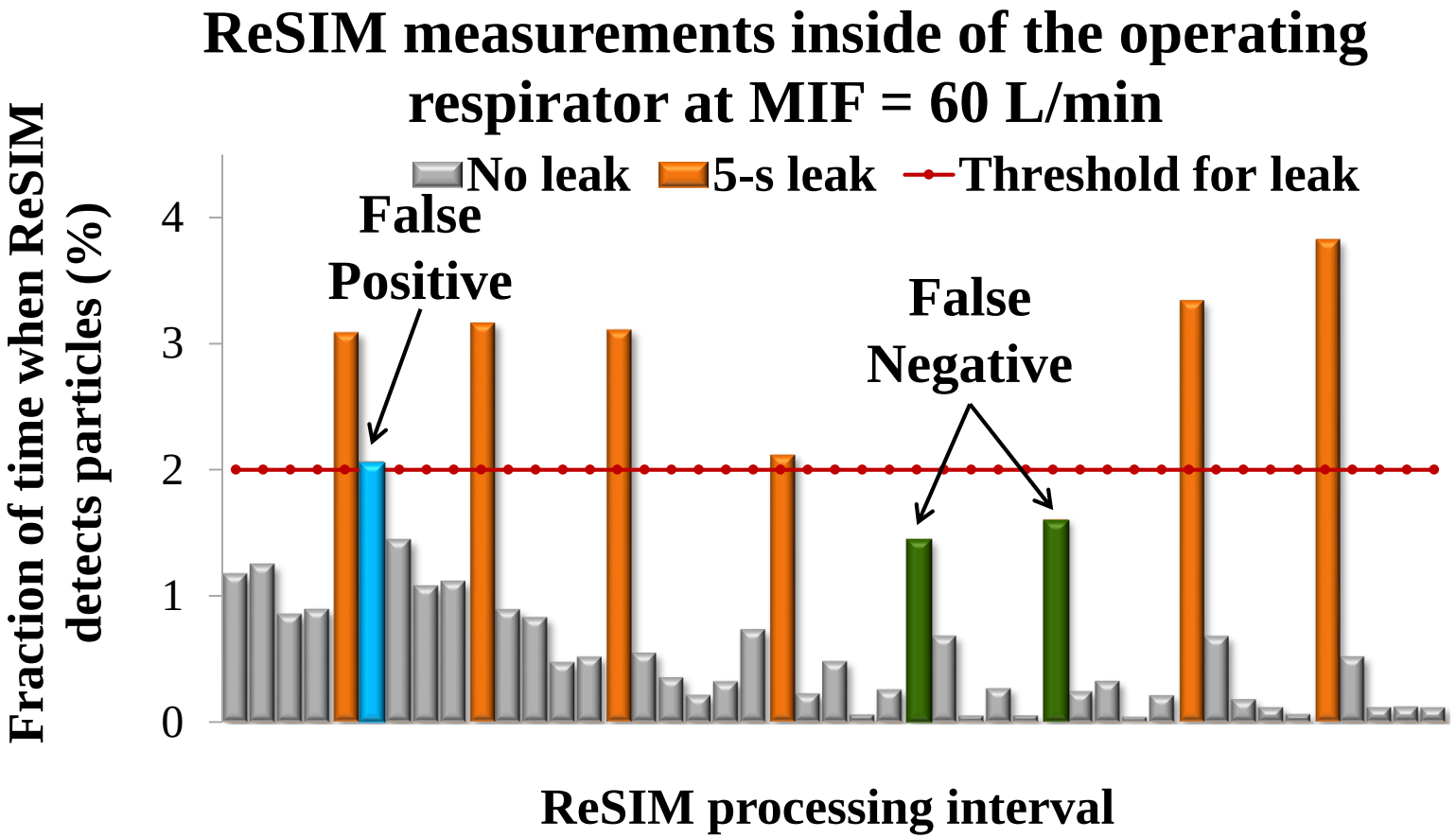
ReSIM calibration against a Grimm OPC with NaCl aerosol



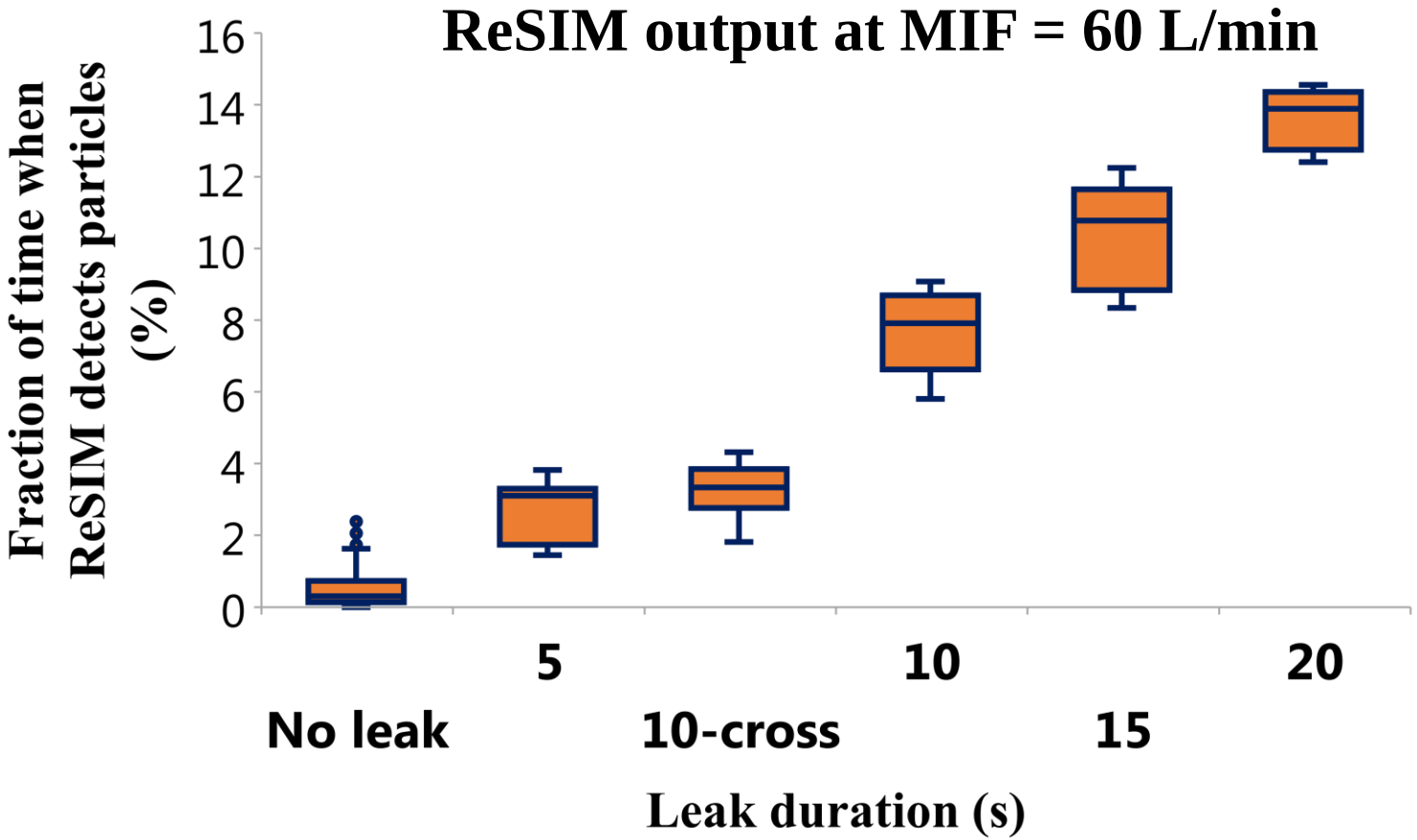
Leak detection (combustion aerosol)



Leak detection (combustion aerosol)



Leak detection (combustion aerosol)



10-cross: a 10-s leak intentionally timed to split the leak time across two ReSIM processing intervals.

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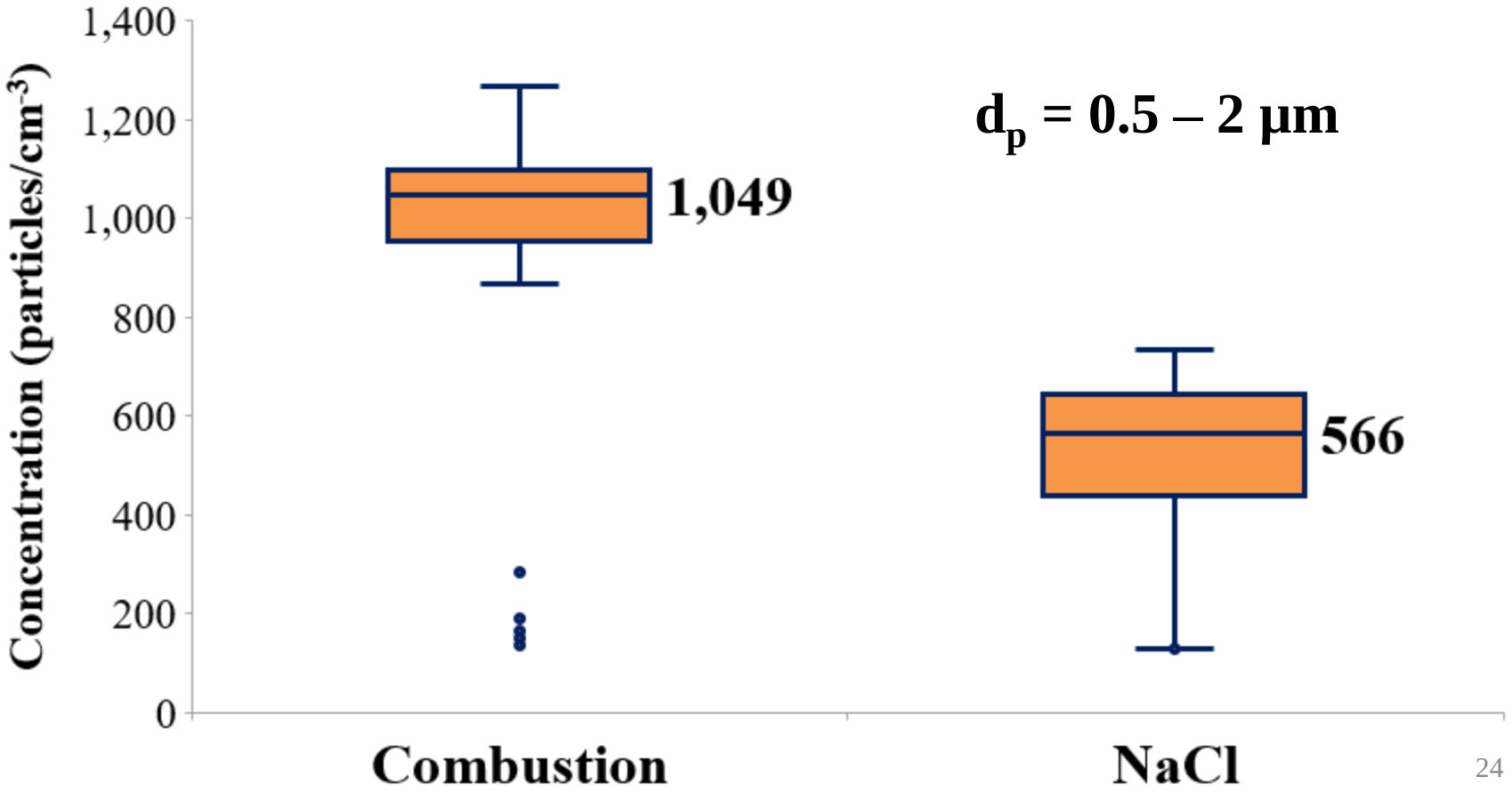
Leak detection vs. false negatives (combustion aerosol)

Flow rate MIF (L/min)	Leak duration (s)	Number of intervals with		True leaks correctly identified
		true leaks	false negatives	
30	5	11	0	100%
	10-cross	14	0	100%
	10	8	0	100%
	15	6	0	100%
	20	6	0	100%
60	5	8	2	75%
	10	6	0	100%
	15	6	0	100%
	20	6	0	100%
85	5	9	0	100%
	10-cross	14	0	100%
	10	8	0	100%
	15	6	0	100%
	20	6	0	100%
All Tests	**Overall**	**126**	**2**	**98.4%**

Particle concentration measured with a Grimm OPC in the test chamber



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Leak detection vs. false negatives (NaCl aerosol)

Flow rate MIF (L/min)	Leak duration (s)	Number of intervals with		True leaks correctly identified
		true leaks	false negatives	
30	5	8	0	100%
	10-cross	14	0	100%
	10	8	0	100%
	15	5	0	100%
	20	6	0	100%
60	5	9	9	0%
	10-cross	12	8	33.3%
85	5	8	8	0%
	10-cross	12	10	16.7%
All Tests	**Overall**	**124**	**35**	**71.8%**

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Leak detection vs. false positives

Particle type	Flow rate MIF (L/min)	Number of intervals with				Correctly identified
		no leak	false positives			
Combustion	30	200	6			97.0%
	60	124	5			96.0%
	85	187	5			97.3%
	All Tests	**511**	**16**			**96.9%**
NaCl	30	183	14			92.3%
	60	142	1			99.3%
	85	196	1			99.5%
	All tests	**521**	**16**			**96.9%**

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Leak detection vs. false positives

Particle type	Flow rate MIF (L/min)	Number of intervals with				Adjusted correctly identified
		no leak	false positives	persistent false positives	adjusted false positives	
Combustion	30	200	6	6	0	100%
	60	124	5	5	0	100%
	85	187	5	4	1	99.5%
	All Tests	**511**	**16**	**15**	**1**	**99.8%**
NaCl	30	183	14	14	0	100%
	60	142	1	1	0	100%
	85	196	1	0	1	99.5%
	All tests	**521**	**16**	**15**	**1**	**99.8%**

Conclusions

- High sensitivity and specificity
- Capable of rapidly detecting respirator performance failure in real time and enact alarm for a firefighter
- With modifications, can be applied to other particulate filter respirators

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Future field study

- Evaluation with firefighters engaged in routine operational activities (fire overhaul)
- Inspiratory flow rate measurement
- Performance evaluation of ReSIM installed in respirators of different types

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  - Dr. Sergey A. Grinshpun
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  - Dr. Jonathan Corey
  - Yan Liu, PhD Student
  - Bingbing Wu, PhD Student
- This work was supported by the Ohio Bureau of Workers' Compensation

Thank you!

QUESTIONS

BINGBING WU
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A Test for Liquid Penetration through Protective Fabric

2017 Expanding Research Partnerships:
State of the Science Conference

June 22, 2017

Lee Portnoff, Health Scientist
National Institute for Occupational Safety and Health (NIOSH)
National Personal Protective Technology Laboratory (NPPTL)

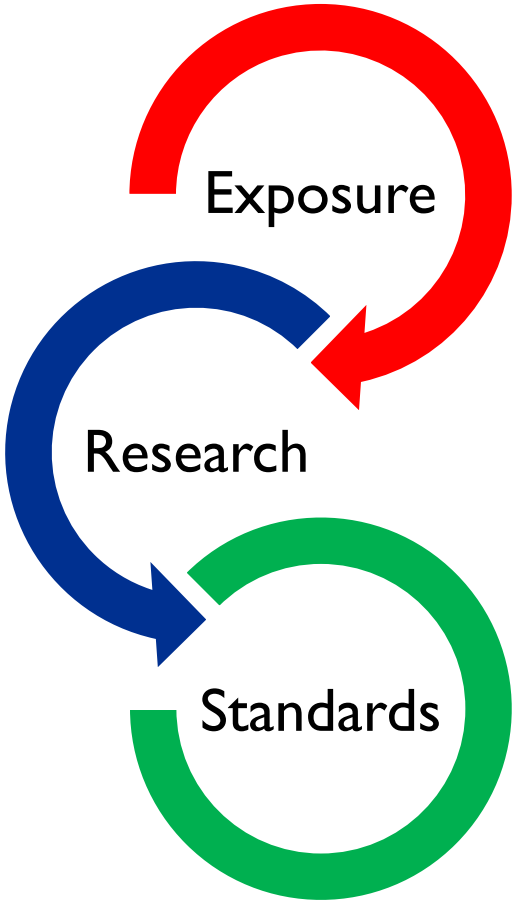
Courtesy of NIOSH NPPTL

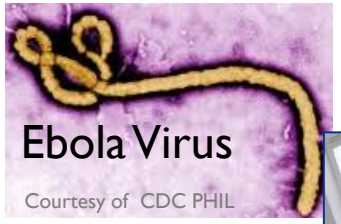
National Personal Protective Technology Laboratory (NPPTL) Research Branch (Pittsburgh, PA)

NPPTL prevents work-related injury, illness and death by advancing the knowledge and application of personal protective technologies (PPT).

Courtesy of MSA and CDC PHIL

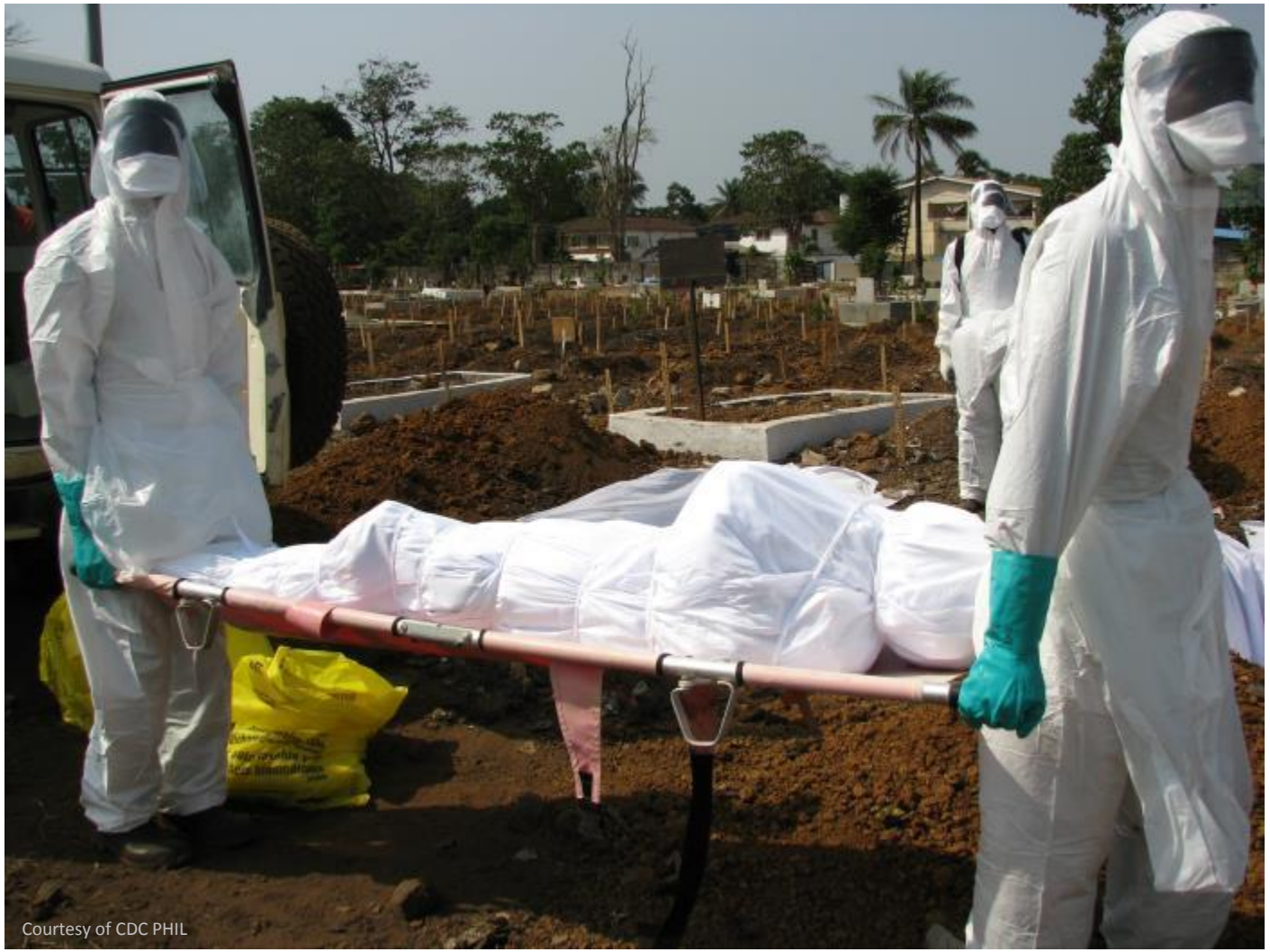
Improving Standard Test Methods





Personal Protective Equipment (PPE)

- Eye Protection
- Respiratory Protection
- Protective Clothing
- Gloves
- Foot Coverings


Courtesy of CDC PHIL

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A manufacturer may ask

What quality of garment is needed?


Creative Commons

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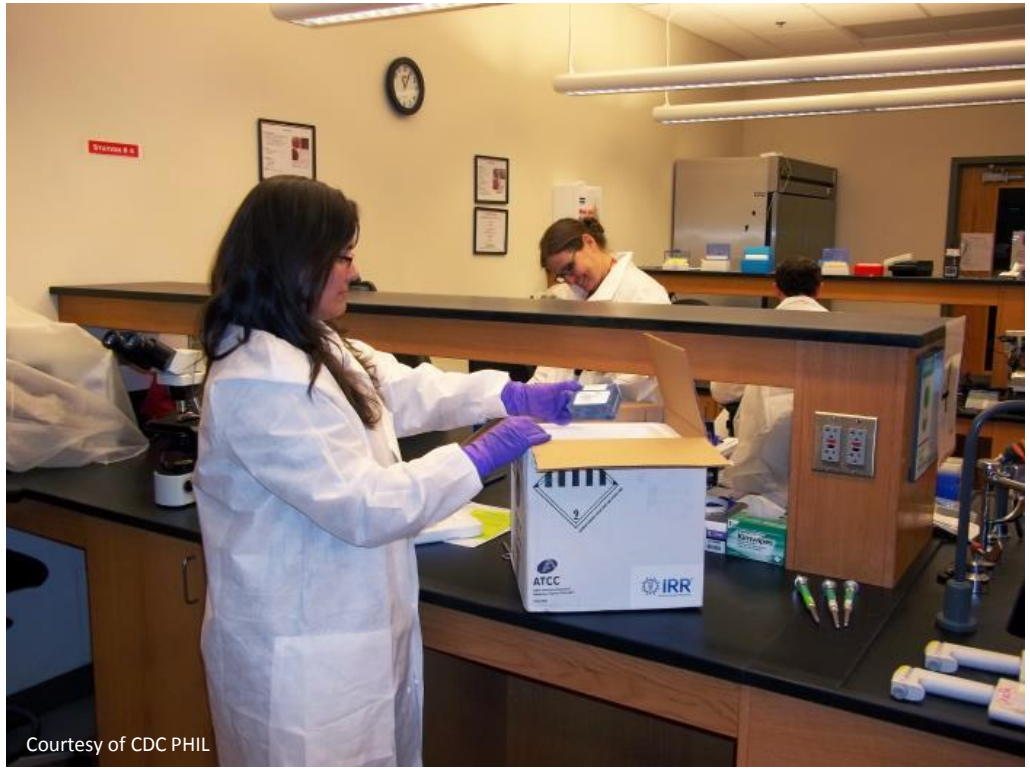
A consumer may ask

Will virus pass through my garment?

For the most protective garment (Level 4),
A failure rate of one in 25 is acceptable

4% Acceptable Quality Level (AQL)



Courtesy of CDC PHIL

An agency may ask

Do state, county, city, and hospital stockpiles provide viral protection?

Courtesy of CDC PHIL

Standard Tests to Evaluate Protective Clothing

	Test	Criteria	Est.
Level 1	AATCC 42	<=4.5 g	1945
Level 2	AATCC 42	<=1.0 g	
	AATCC 127	<=20 cm	1968
Level 3	AATCC 42	<=1.0 g	
	AATCC 127	<=50 cm	
Level 4	ASTM F1671	PASS	1997

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Standard	Description
AATCC 42	Water Resistance: Impact Penetration Test
AATCC 127	Water Resistance: Hydrostatic Pressure Test
ASTM F1670	Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Synthetic Blood
ASTM F1671	Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Bloodborne Pathogens Phi-X174 Bacteriophage Penetration as a Test System
ANSI/AAMI PB70	Liquid barrier performance and classification of protective apparel and drapes intended for use in healthcare facilities
ASTM F903	Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Liquids
ASTM F1819	Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Synthetic Blood Using a Mechanical Pressure Technique
ISO 16603	Clothing for Protection Against Contact with Blood and Body Fluids—Determination of the Resistance of Protective Clothing Materials to Penetration by Blood and Body Fluids — Test Methods Using Synthetic Blood
ISO 16604	Clothing for Protection Against Contact with Blood and Body Fluids—Determination of the Resistance of Protective Clothing Materials to Penetration by Bloodborne Pathogens — Test methods using Phi X-174 Bacteriophage
NFPA 1999	Standard on Protective Clothing for Emergency Medical Operations

http://www.cdc.gov/niosh/npptl/topics/protectiveclothing/default.html

Designation: F1671/F1671M – 13

Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Blood-Borne Pathogens Using Phi-X174 Bacteriophage Penetration as a Test System[1]

This standard is issued under the fixed designation F1671/F1671M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

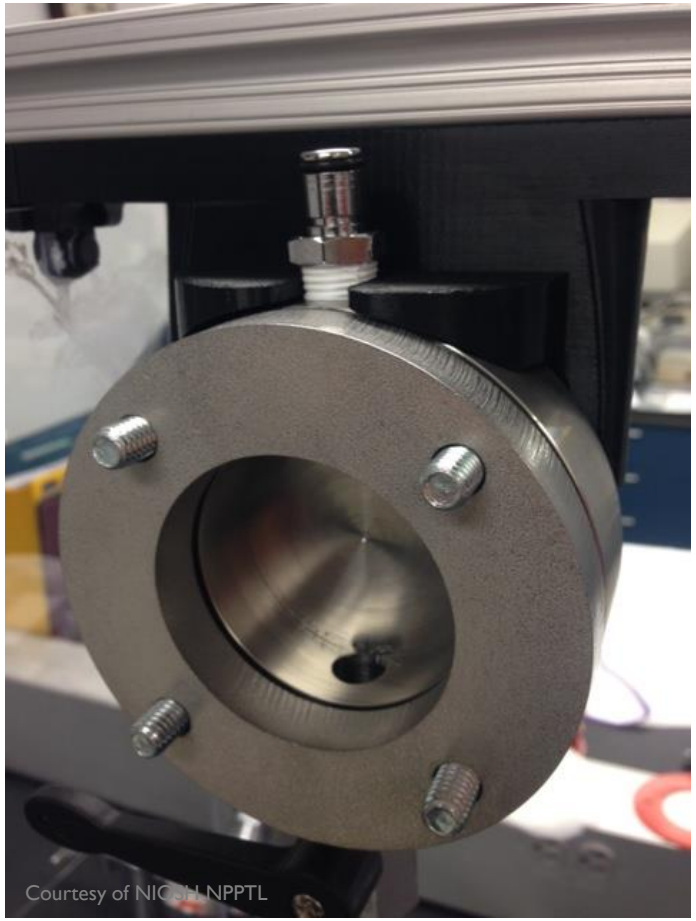
INTRODUCTION

Workers, primarily those in the health care profession, involved in treating and caring for individuals injured or sick, can be exposed to biological liquids capable of transmitting disease. These diseases, which may be caused by a variety of microorganisms, can pose significant risks to life and health. This is especially true of blood-borne viruses which cause Hepatitis (Hepatitis B Virus (HBV) and Hepatitis C Virus (HCV)) and Acquired Immune Deficiency Syndrome (AIDS) (Human Immunodeficiency Virus (HIV)). Since engineering controls can not eliminate all possible exposures, attention is placed on reducing the potential of direct skin contact through the use of protective clothing that resists penetration (29 CFR Part 1910.1030). This test method was developed to assess the effectiveness of materials used in protective clothing for protecting the wearer against contact with blood-borne pathogens using a surrogate microbe suspended in a body fluid simulant under conditions of continuous contact.

1. Scope

1.1 This test method is used to measure the resistance of materials used in protective clothing to penetration by blood-borne pathogens using a surrogate microbe under conditions of

1.4 This test method addresses only the performance of materials or certain material constructions (for example, seams) used in protective clothing and determined to be viral resistant. This test method does not address the design, overall

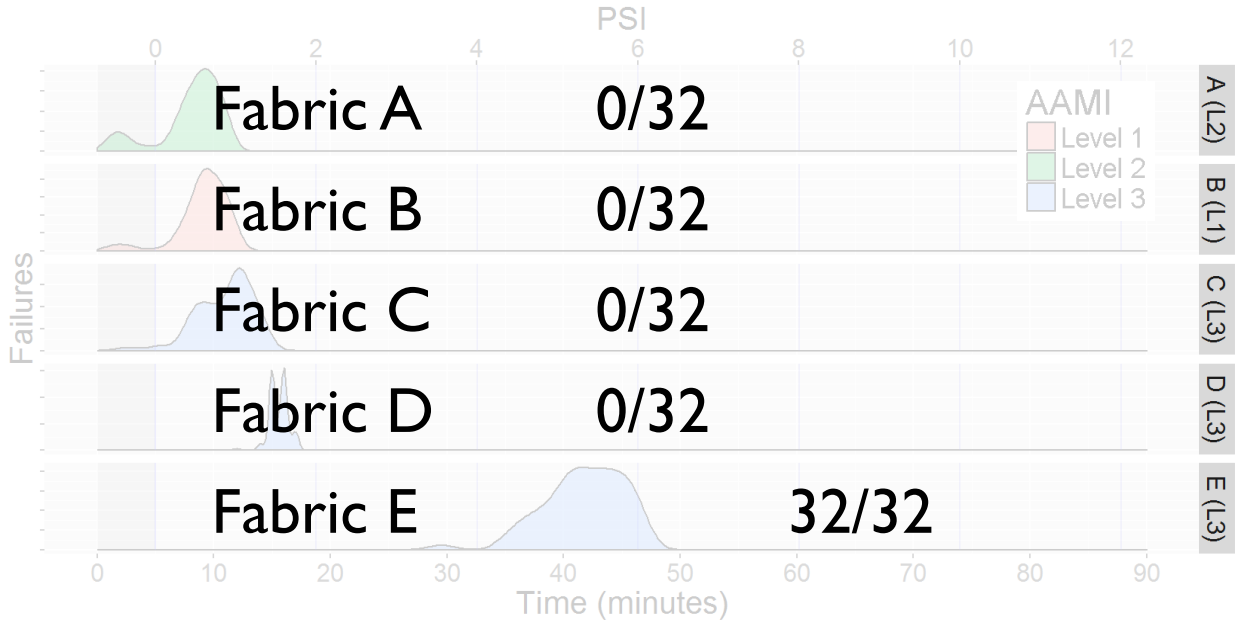

Courtesy of NIOSH NPPTL

Non-parametric vs. parametric data

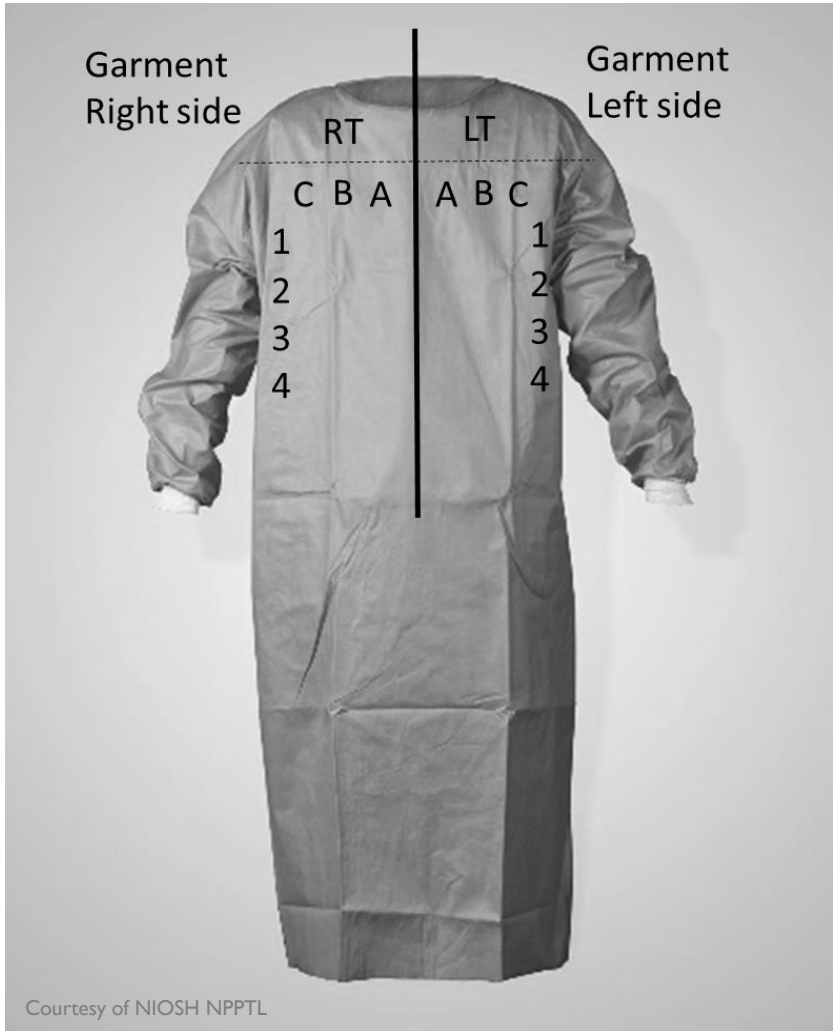
Courtesy of NIOSH NPPTL

ASTM F1671

Costs $12,800 for 160 tests



Consider the location of the fabric swatch



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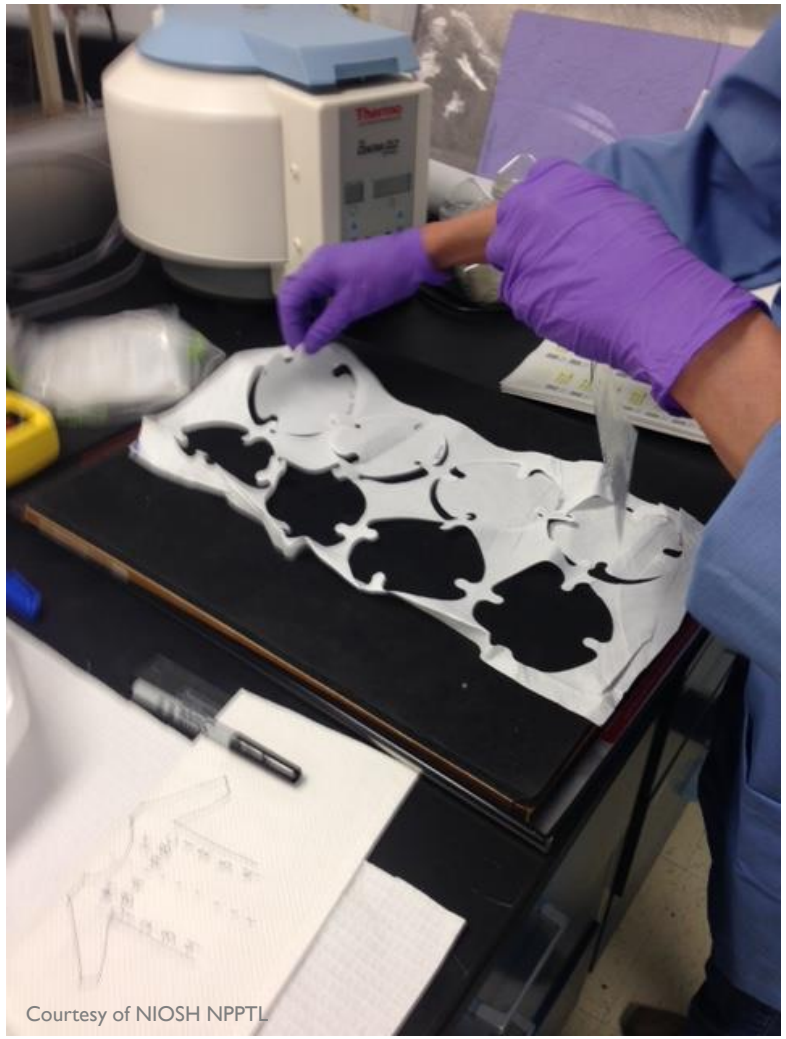
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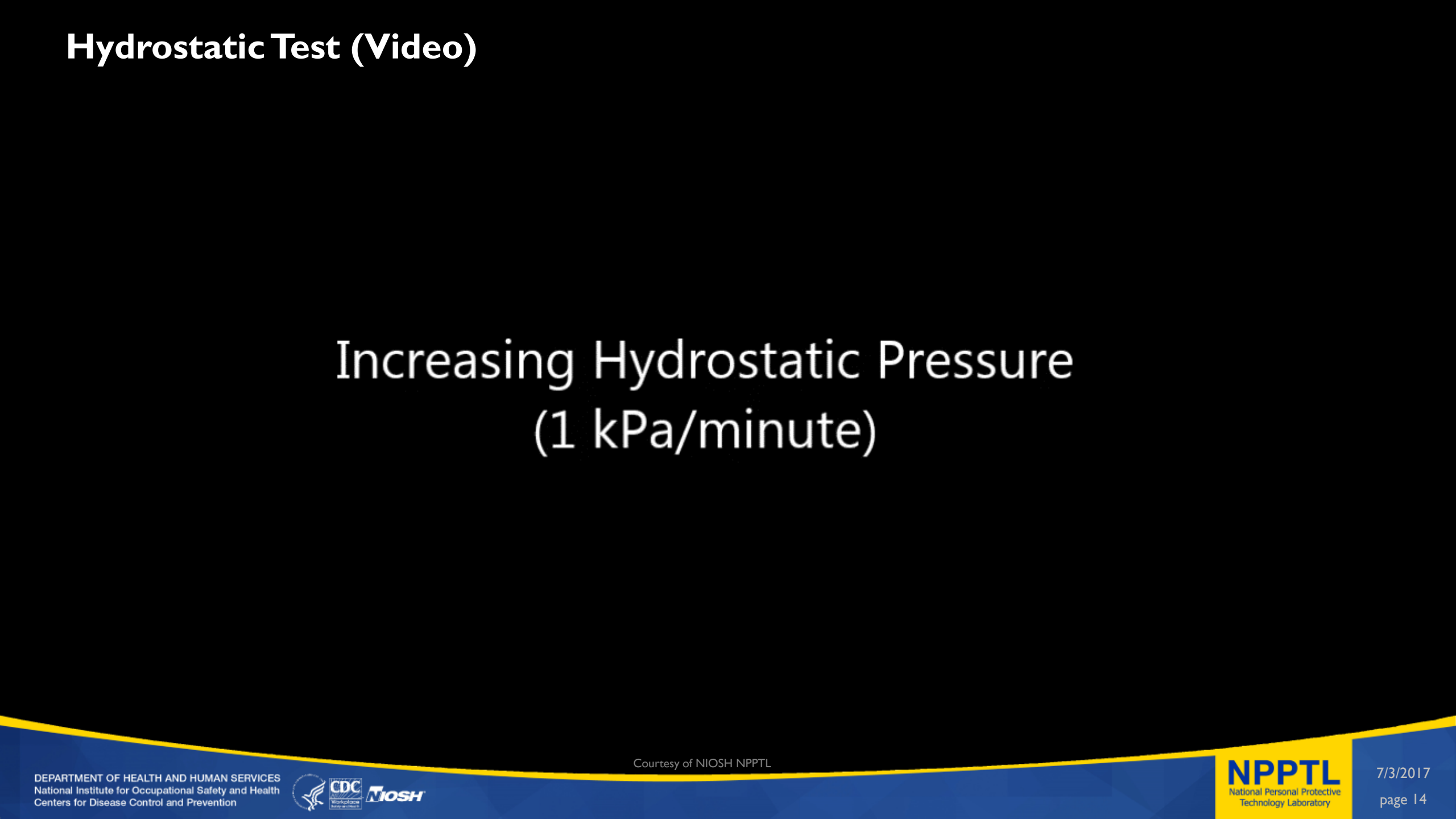
Hydrostatic Test (Video)



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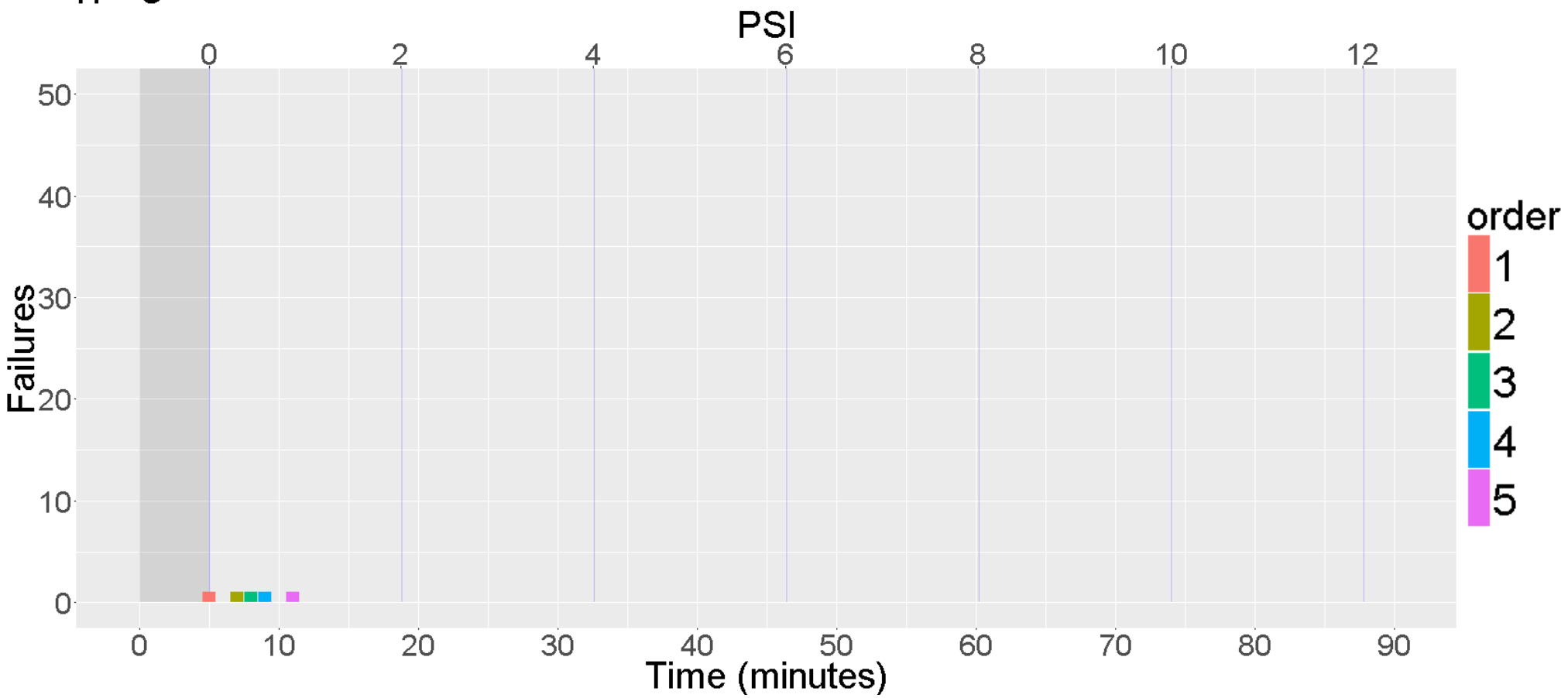
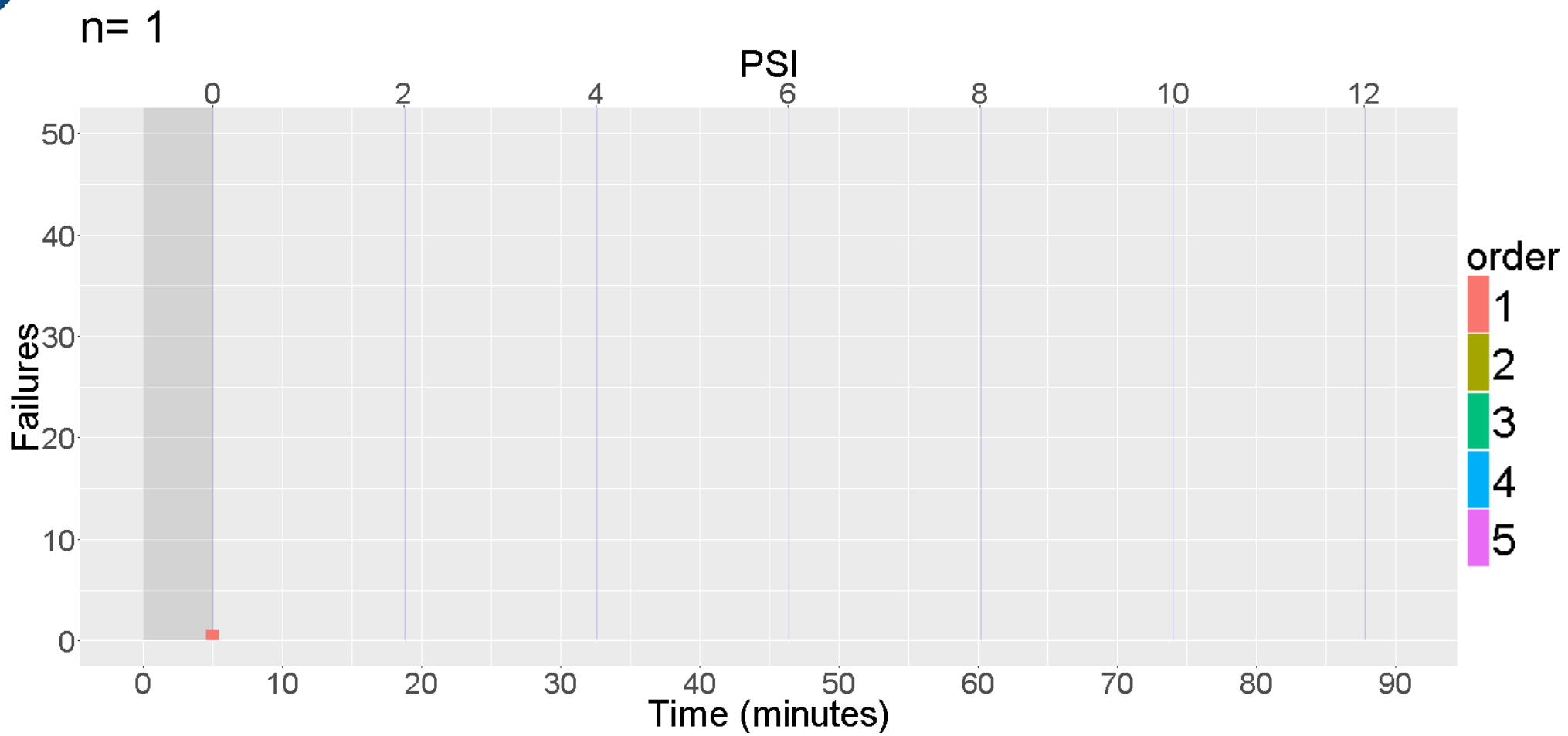
n= 5





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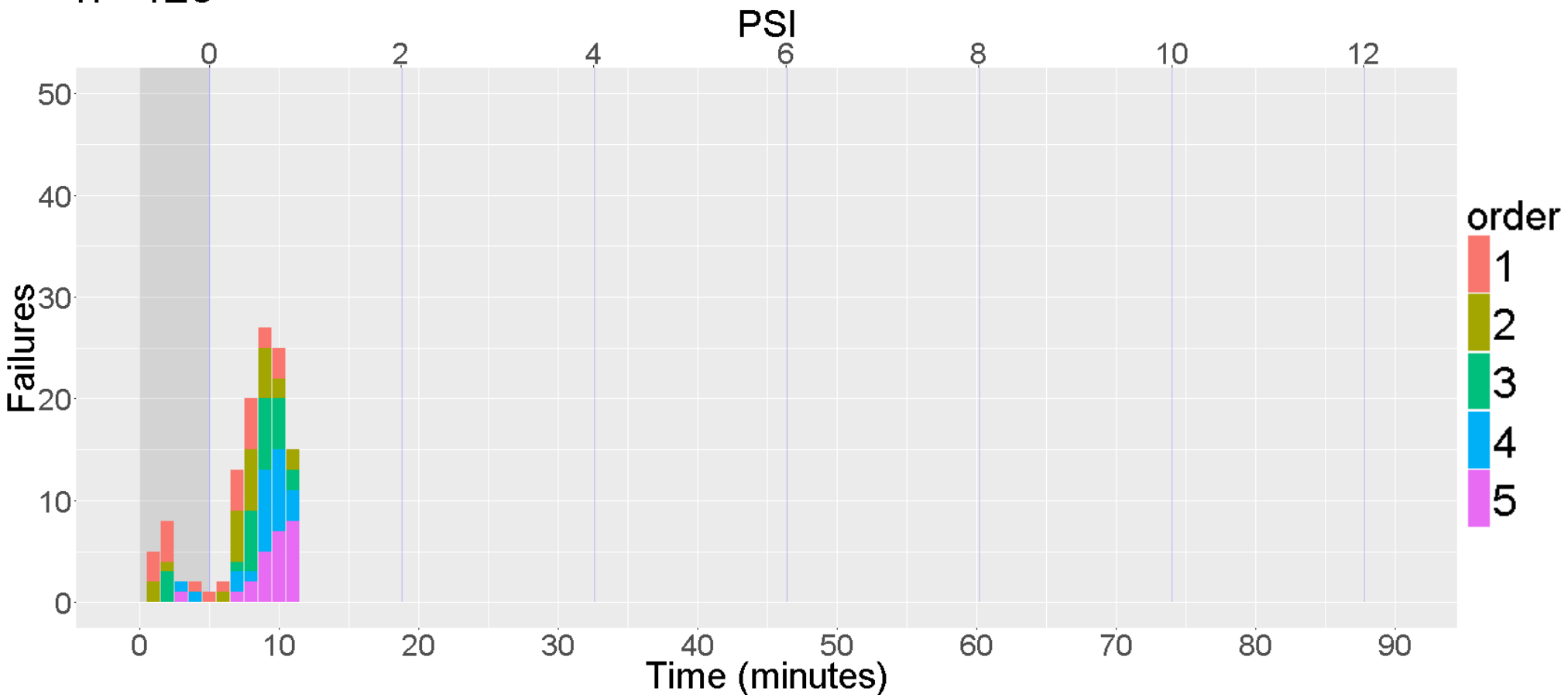
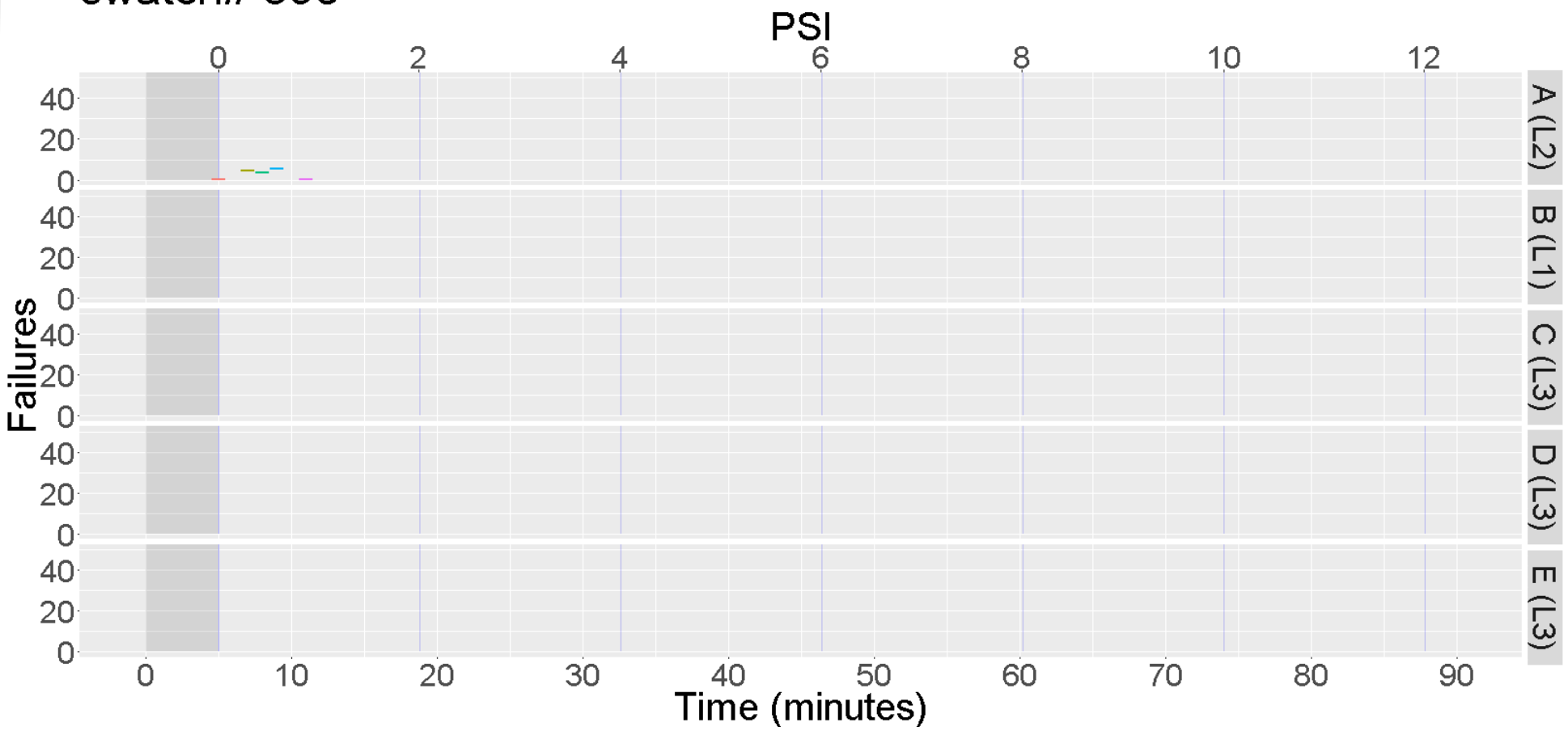
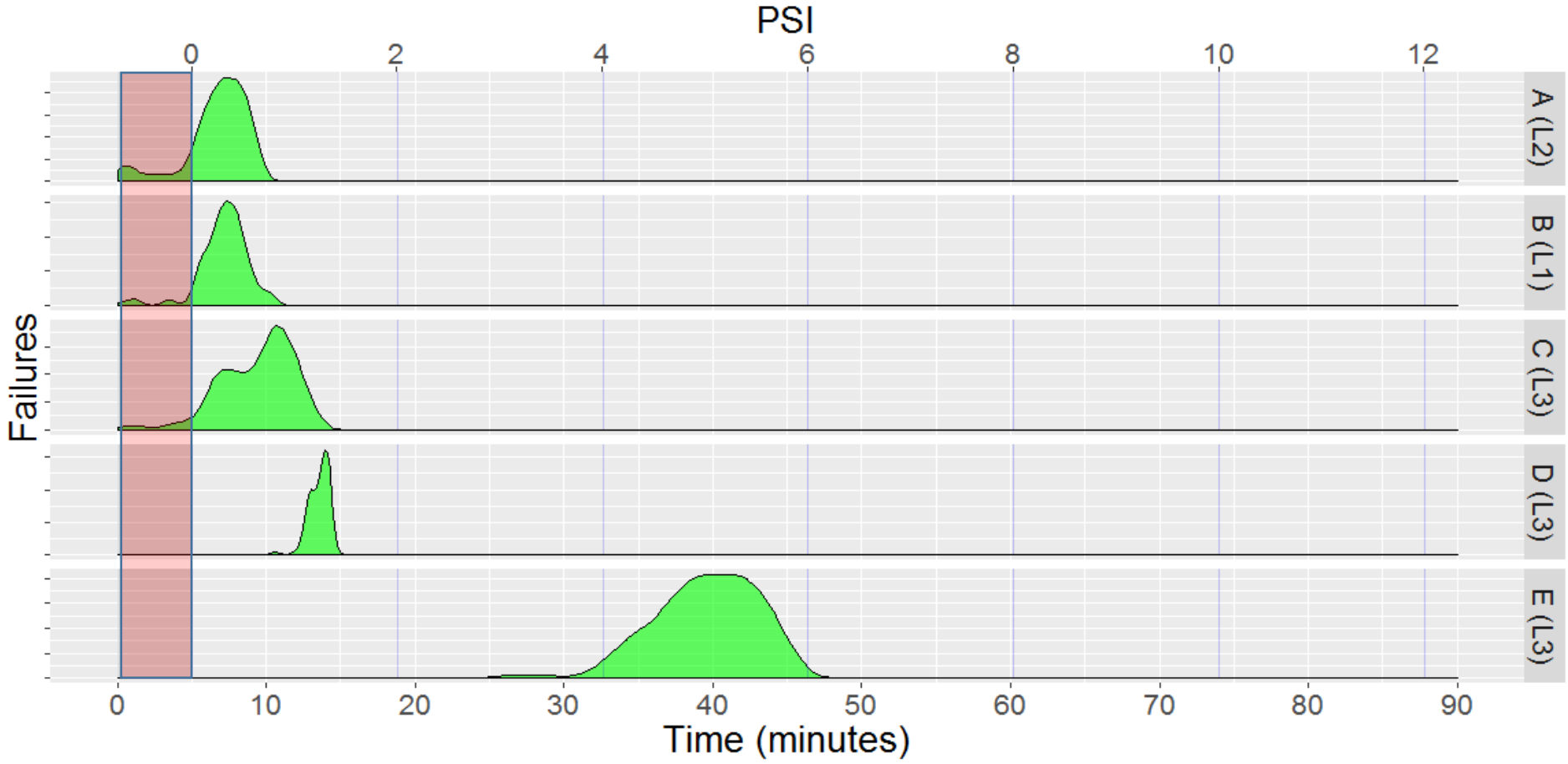
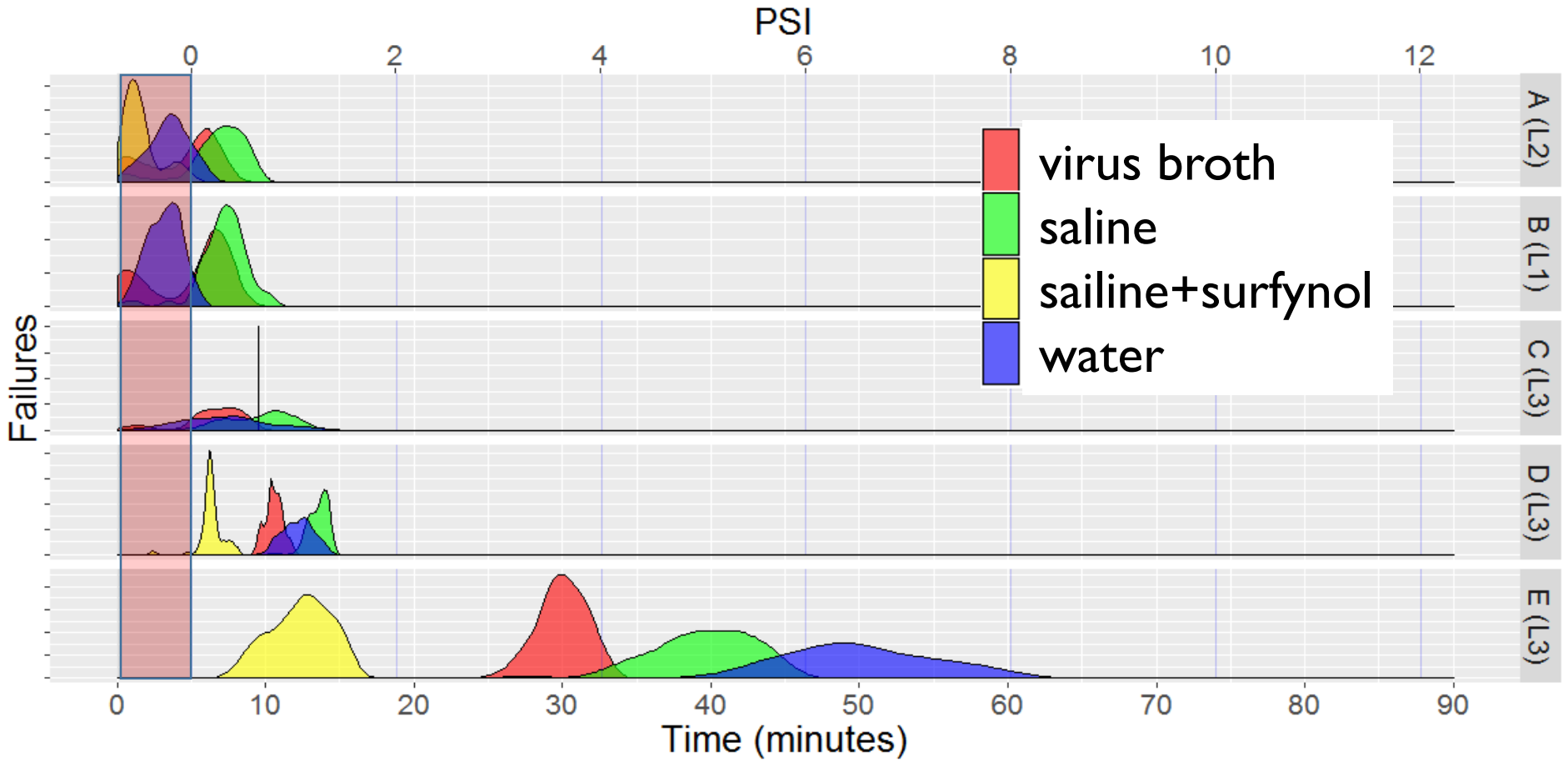
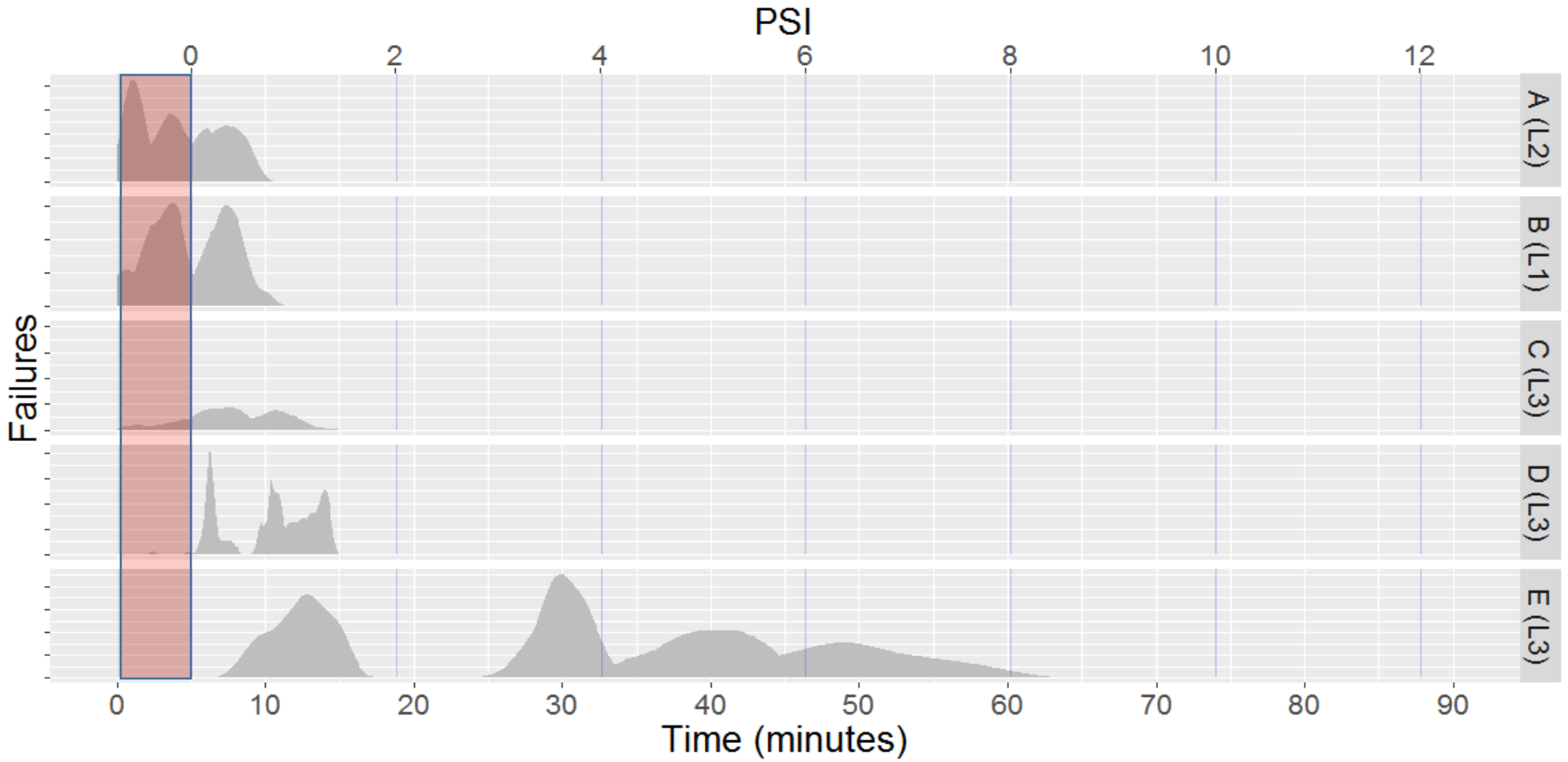







PSI
0
2
4
6
8
10
12
A (L2)
B (L1)
C (L3)
D (L3)
E (L3)
Failures
virus broth
saline
sailine+surfynol
water
0
10
20
30
40
50
60
70
80
90
Time (minutes)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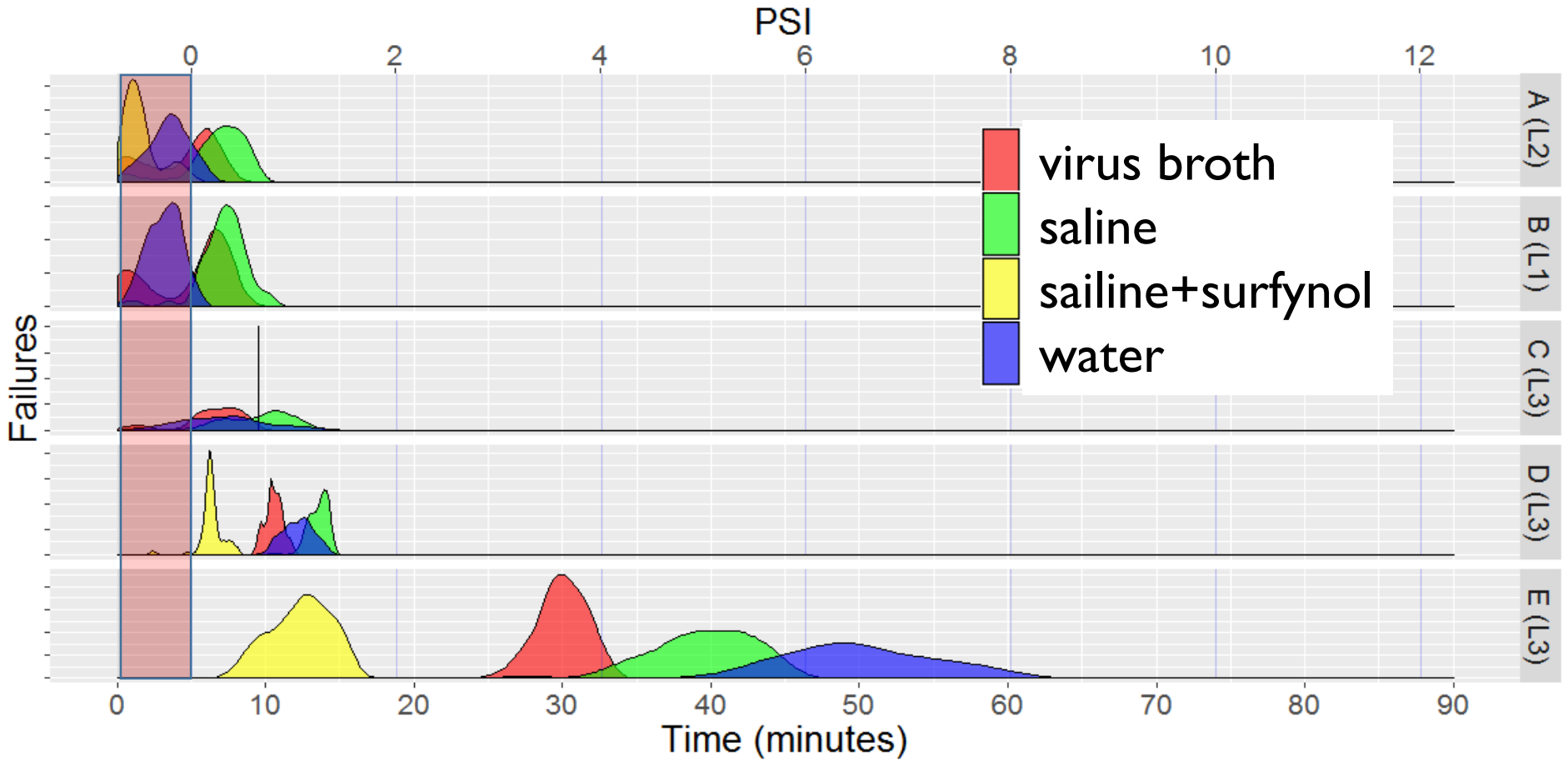
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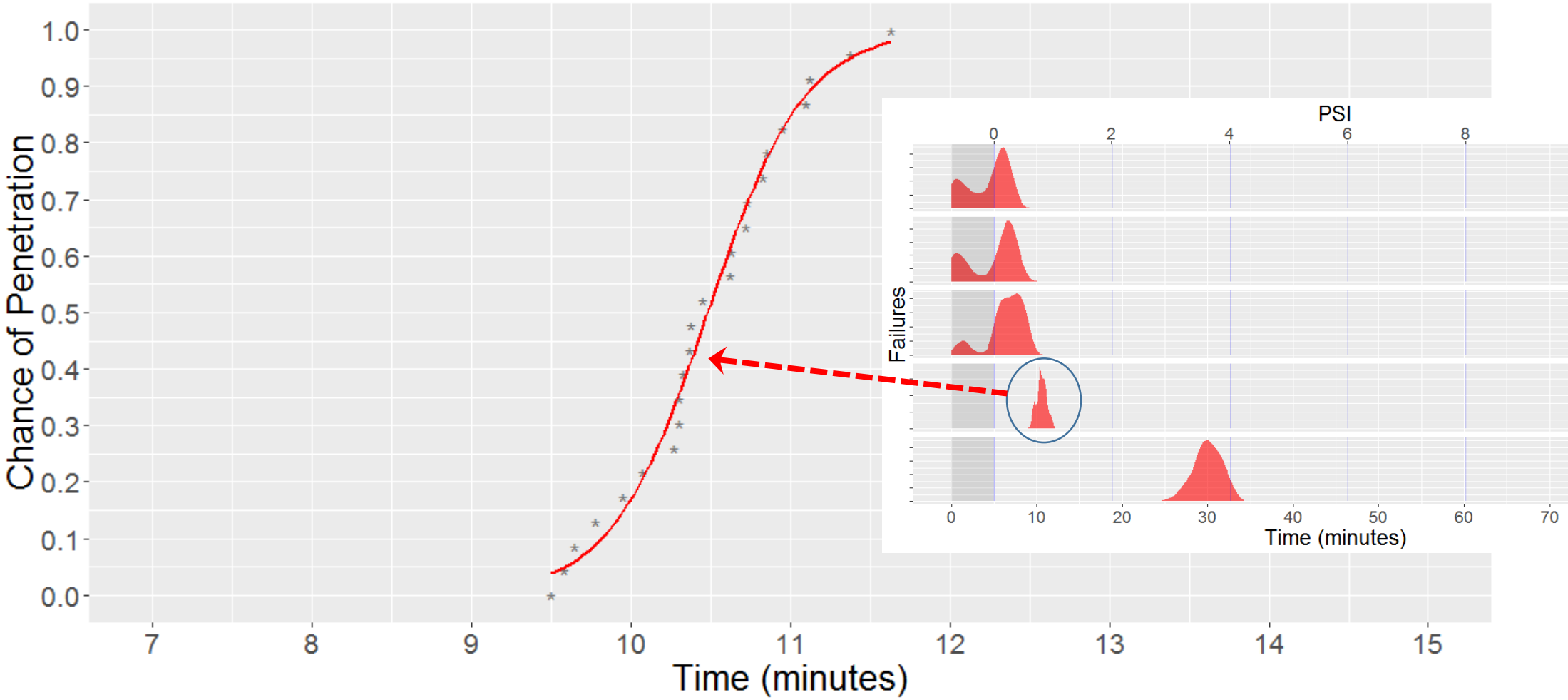
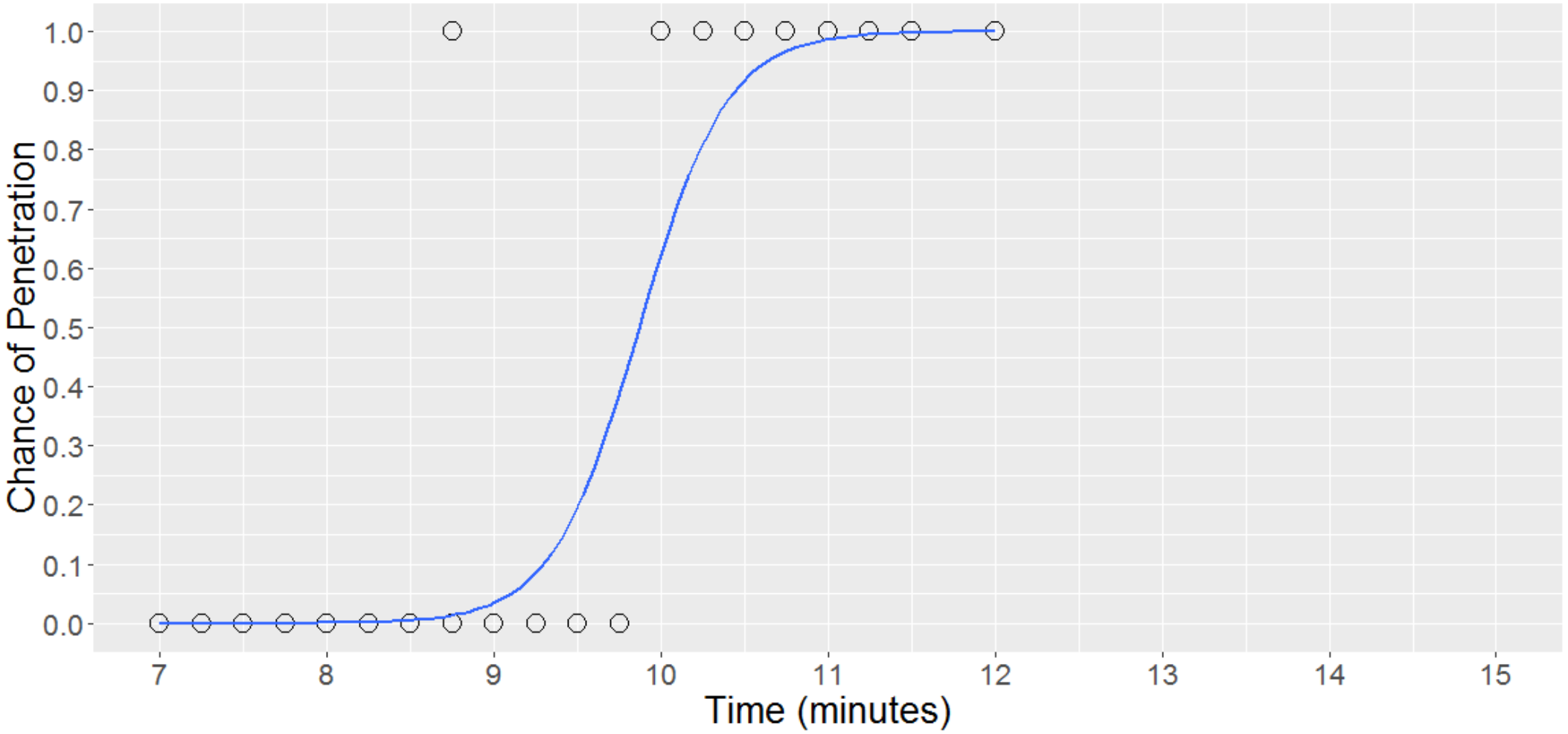
Time (minutes)

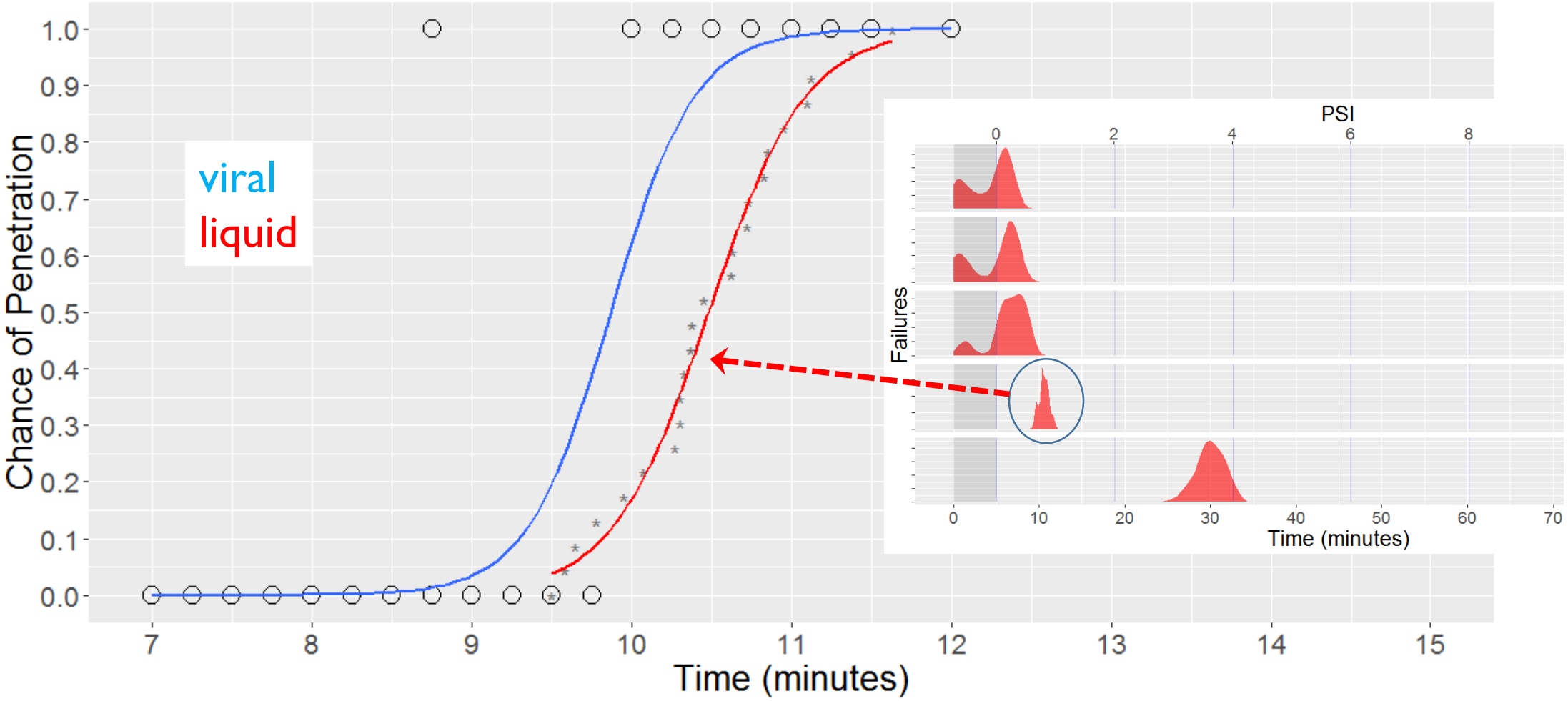
Time of first liquid penetration (n=24)

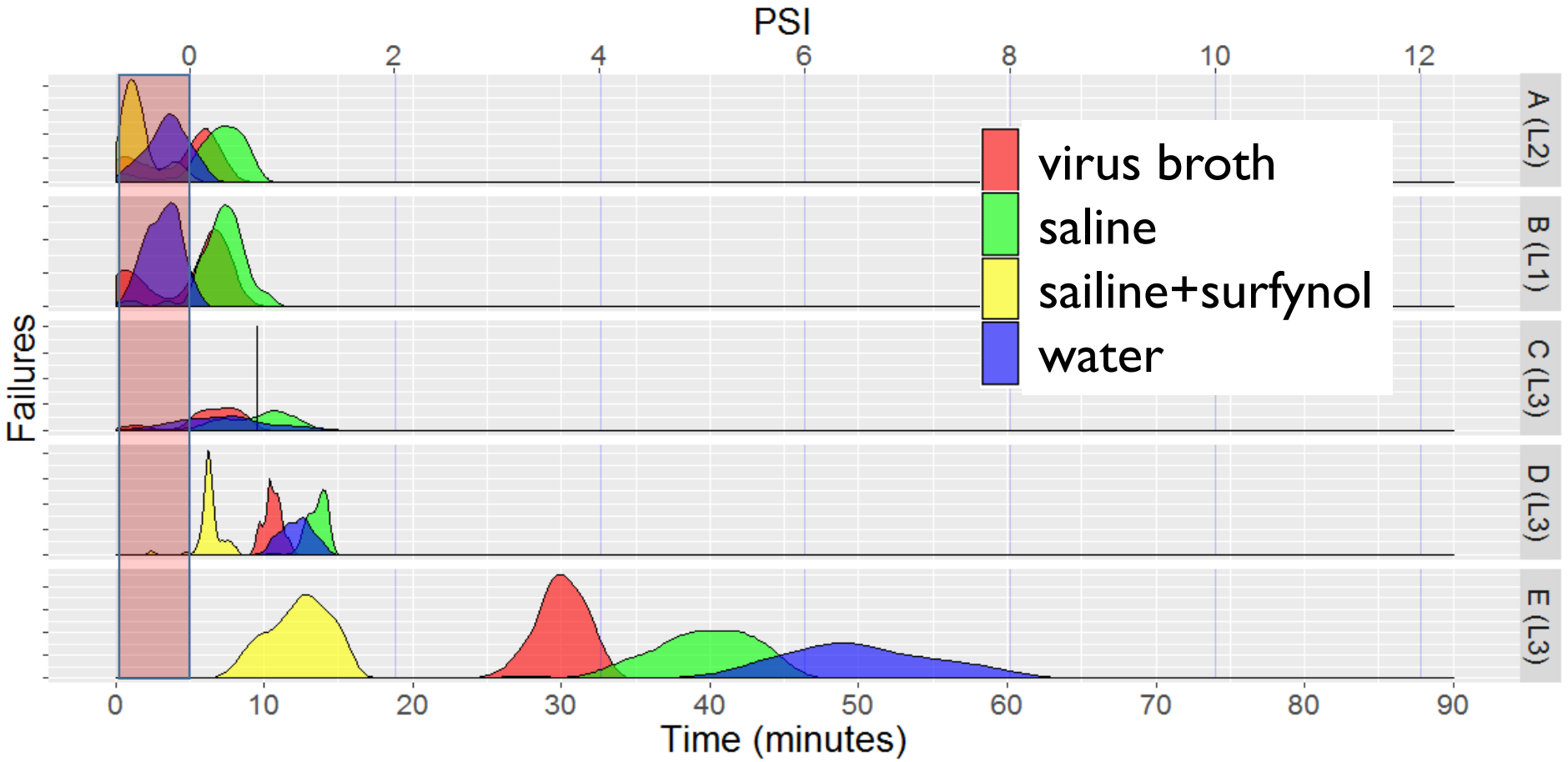


Time of first viral penetration (n=36)



Time of penetration: viral vs. liquid

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Time (minutes)

Current Work

- Evaluating factors contributing to penetration (time, pressure, carrier fluid, virus type, screen/no-screen, pre-wetting, elevated temperature and RH
- Writing manuscripts
  - ranking factors contributing to penetration
  - dynamic hydrostatic test protocol
  - comparing viral to liquid penetration

Next Steps

- To develop multi-modal models of liquid and viral penetration
- To increase magnification/resolution of camera
- To develop AI (Tensorflow open-source library) to record time and location of penetration events
- To conduct experiments in dark with UV light
- To propose as new ASTM test method

DISCLAIMERS: The findings and conclusions in this presentation are those of the author(s) and do not necessarily represent the views of the National institute for Occupational Safety and Health. Mention of a product or use of a photo does not constitute NIOSH endorsement.

THANK YOU

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