IDA

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Downwind Chlorine Hazard Estimates for the 2015-2016 Jack Rabbit II Campaign

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Institute for Defense Analyses

Sponsor: Defense Threat Reduction Agency – Joint Science and Technology Office for Chemical and Biological Defense (DTRA–JSTO/CBD)

IDA | Jack Rabbit Campaign (2010, 2015-16)

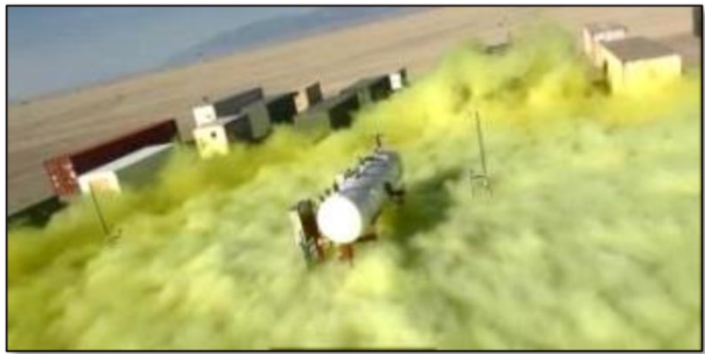
Jack Rabbit I

- 2010: 10 releases of either 1 or 2 tons of chlorine or ammonia into a depression

Jack Rabbit I release

Jack Rabbit II

- Aug-Sept 2015: 5 releases of 5-10 short tons of chlorine
- Aug-Sept 2016: 4 releases of 10-20 short tons of chlorine



Jack Rabbit II release

IDA | Jack Rabbit II FY15/FY16 Details

- Liquefied pressurized chlorine released from a large storage tank
- JRII FY15 focused on how the dense gas would flow through urban areas
  - Shipping containers and vehicles used to create a mock urban area
- JRII FY16 focused on how the dense gas would flow through open terrain
- Release amounts varied between 4.5 and 20 metric tons
- High-resolution samplers were used to detect chlorine concentration levels:
  - Within the vehicles
  - Within some shipping containers (modified to mimic residential and office structures)
  - Within the urban array in FY2015
  - **In arcs up to 11km from the release**

Mock Urban Area

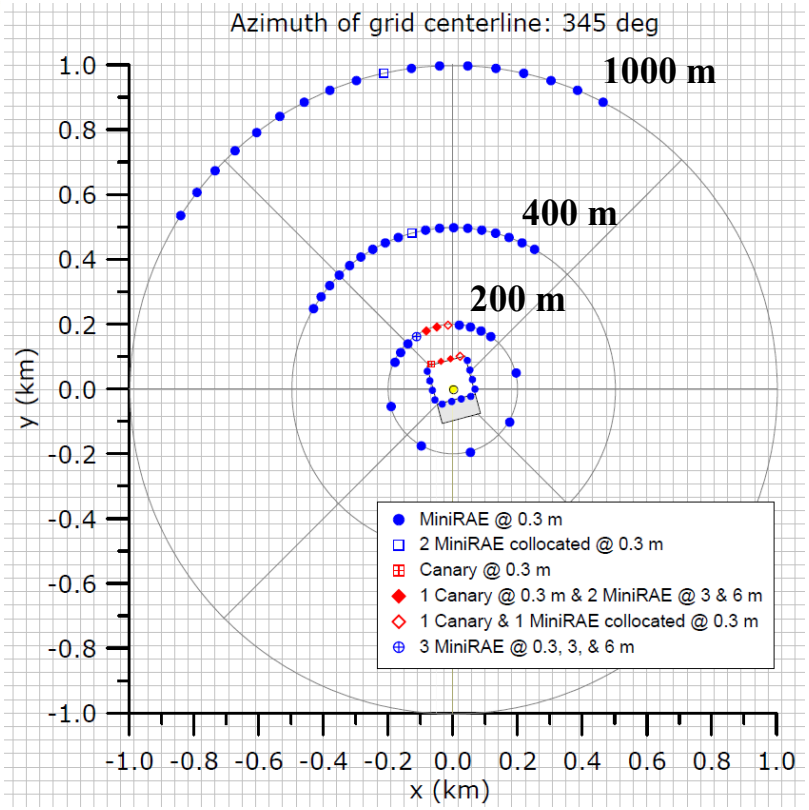
IDA | Brief Summary of JRII Releases

Trial	Release 1 Start		Release 1 Stop		Release 2 Start		Release 2 Stop		Release Chemical	Actual Chlorine Weight (kg)	Release Point Size (inches)	Release Point Orientation From Vertical*
	Date (mm/dd/yy)	UTC Time (hh:mm:ss)	Date (mm/dd/yy)	UTC Time (hh:mm:ss)	Date (mm/dd/yy)	UTC Time (hh:mm:ss)	Date (mm/dd/yy)	UTC Time (hh:mm:ss)				
1	8/24/2015	13:35:45	8/24/2015	13:36:43	NA	NA	NA	NA	Cl2	**4509**	6	180 / NA
2	8/28/2015	15:24:21	8/28/2015	15:25:10	NA	NA	NA	NA	Cl2	**8151**	6	180 / NA
3	8/29/2015	13:56:55	8/29/2015	13:57:31	NA	NA	NA	NA	Cl2	**4512**	6	180 / NA
4	9/1/2015	14:38:50	9/1/2015	14:39:33	NA	NA	NA	NA	Cl2	**6970**	6	180 / NA
5	9/3/2015	13:28:19	9/3/2015	13:29:09	NA	NA	NA	NA	Cl2	**8303**	6	180 / NA
6	08/31/16	14:23:35	08/31/16	14:24:30	NA	NA	NA	NA	Cl2	**8381**	6	180 / NA
7	09/02/16	13:56:00	09/02/16	13:57:20	09/02/16	14:07:08	09/02/16	14:09:20	Cl2	**9075**	6	135 / 180
8	09/11/16	15:01:45	09/11/16	15:04:42	09/11/16	15:17:16	09/11/16	15:26:27	Cl2	**9089**	6	0 / 180
9	09/17/16	14:05:30	09/17/16	14:10:21	NA	NA	NA	NA	Cl2	**17706**	6	180 / NA

Trials 2, 4, 5, 6, 7, and 8 were selected for further analysis to ensure that downwind hazard estimates were derived from comparably-sized releases

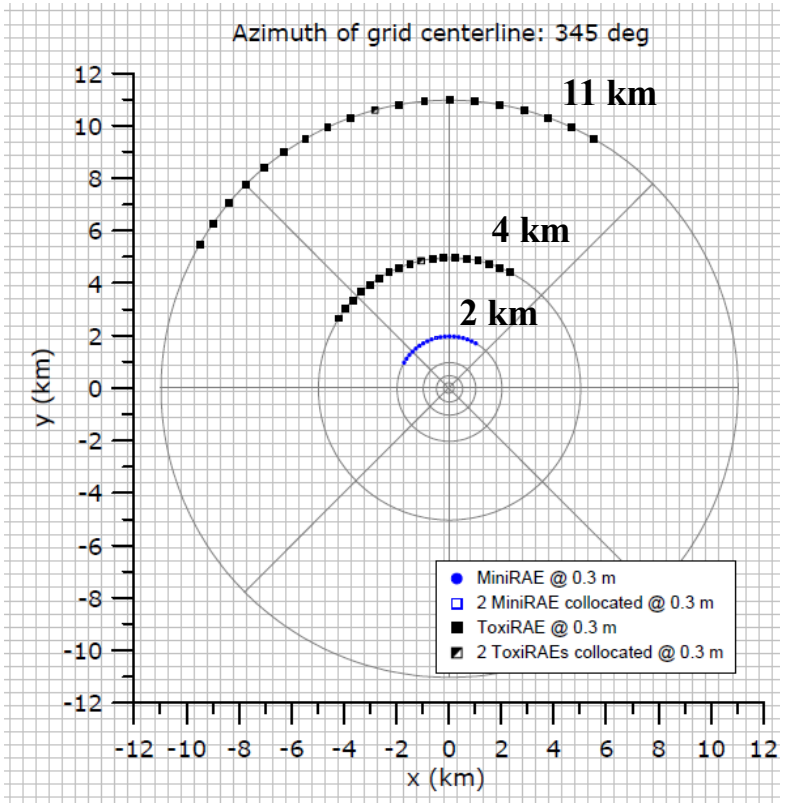
IDA | Chlorine Samplers in the Jack Rabbit II Campaign

Close-in Chlorine Samplers



Sampler Arcs at 200, 500, and 1 km @ 0.3 m AGL

Outer Arc Chlorine Samplers



Sampler Arcs at 2, 5, and 11 km @ 0.3 m AGL

IDA | How far does the downwind hazard from JRII extend?

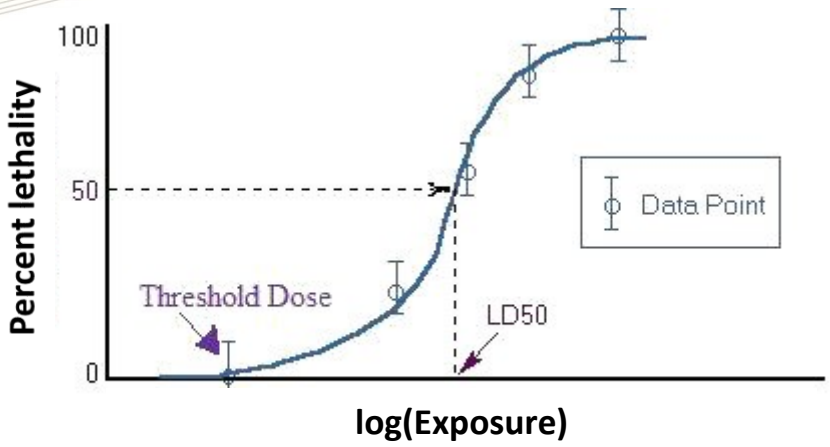
- Examine chlorine concentration time series measured at each sampler
  - 6 releases varying between 6.9 and 9.1 metric tons
  - Sampler arcs at 0.2, 0.5, 1, 2, 5, and 11 km @ 0.3 m above ground level

- Predict human health effects at each sampler location
  - Lethal effects calculations are based on the toxic load model with parameters obtained from *Review and assessment of chlorine mammalian lethality data and the development of a human estimate* by D.R. Sommerville et al., Military Operations Research, V15 N3 2010
    - Includes toxicity parameters for both the U.S. military population and the general U.S. population
  - Severe and mild effects calculations are based on the toxic load model with parameters obtained from *Development of Exposure Guidelines for Acute, Non-Lethal Health Effects Following Exposures to TICs/TIMs – Chlorine*, D. Winkel, July 25, 2014
  - Acute Exposure Guideline Levels (AEGLs) from the U.S. EPA

- Result: Estimates of the downwind extent of the chlorine hazard for the JRII comparably-sized releases

IDA | Overview of Time-Dependent Inhalation Toxicology

Exposure-response relationship

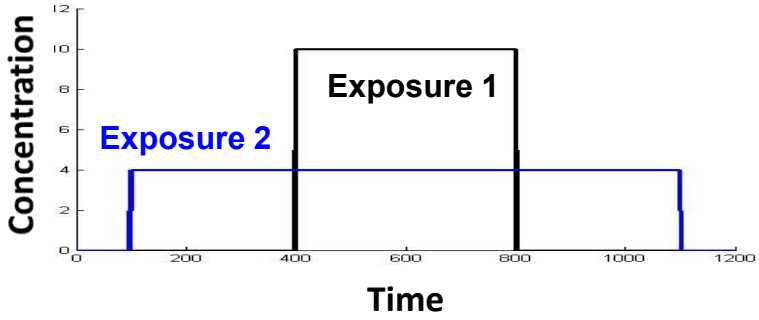


For some toxic agents, the population response depends on the time history of the exposure

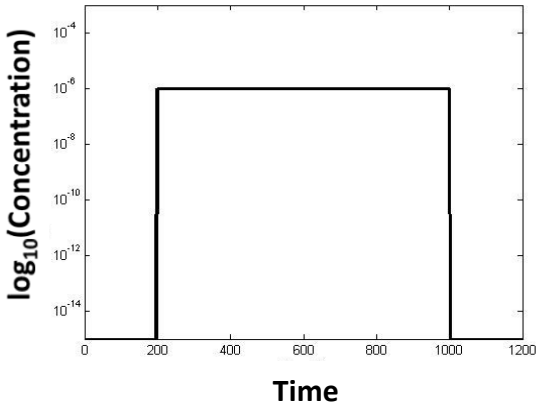
Common phenomenological measures of exposure:

Dosage = $C \times T$ (~total amount of agent delivered)

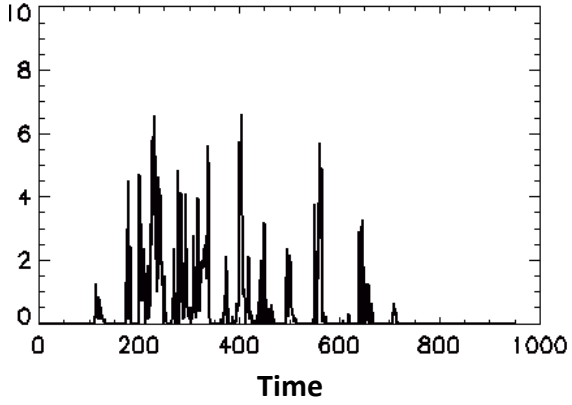
Toxic Load = $C^n \times T$ (depends on time history)



Laboratory Testing Profile



Possible Real-World Profile



Until recently, laboratory toxicology experiments were designed to test the effects of time-dependent exposures using idealized square-pulse profiles.

Real-world exposure profiles, however, can be highly fluctuating and intermittent.

Toxic Load Model for Time-Varying Exposures

Different models have been proposed to extend the toxic load model to the general case of time-varying exposures.

All the proposed extensions reduce to the standard toxic load, $TL = C^n \times T$, in the case of square-pulse exposures.

We investigated three different proposed extensions that in general bracket potential toxic load exposures and got similar results for the downwind hazard distance, so we will present results for only one proposed extension.

Integrated Concentration (or ten Berge) extension of the toxic load model:

$$TL(x) = \int [c(x,\tau)]^n \, d\tau$$

x = location of exposure
τ = time

Note: We bin-averaged $c(x,\tau)$ in 0.1 min increments to account for the approximate duration of a single breath.

IDA | Toxic Load Parameters for Lethal Effects

General Population

- ***n* (toxic load exponent) = 2.75**
- LD_{50} (median lethal dose) = 9500 mg-min/m^3
- Probit slope based on concentration = 6
- TL_{50} (median lethal toxic load): $$TLGeneral_{50} = 2 \times \left(\frac{9500}{2} \right)^{2.75} = 2.5818881 \times 10^{10}$$

- Lethality Fraction (or probability of death):
$$FractionLethalEffects\_General = \Phi\left(\frac{6}{2.75} \times \log_{10}\left(\frac{TL}{2.5818881 \times 10^{10}} \right) \right)$$

Military Population

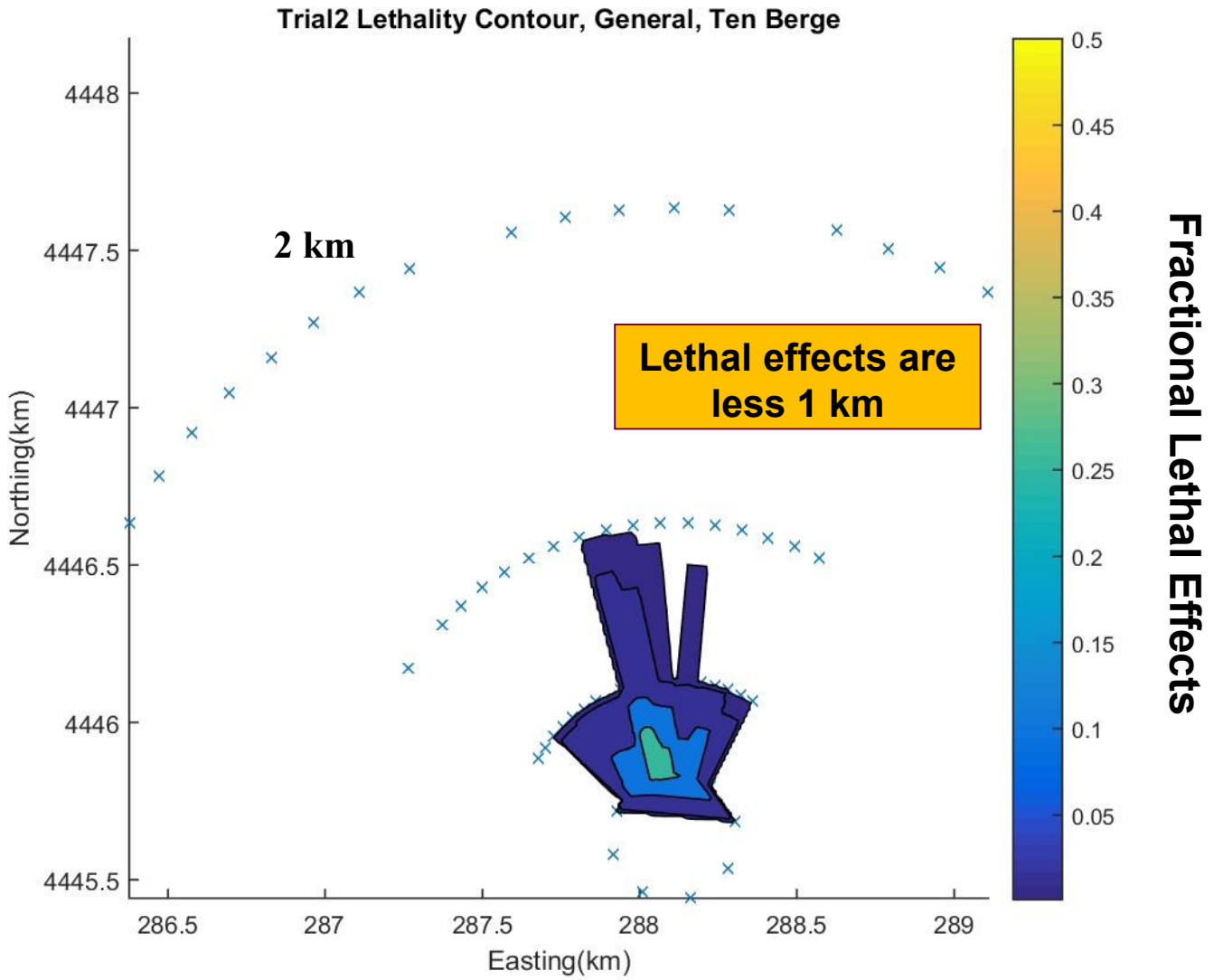
- ***n* (toxic load exponent) = 2.75**
- LD_{50} (median lethal dose) = 13500 mg-min/m^3
- Probit slope based on concentration = 8
- TL_{50} (median lethal toxic load): $$TLMilitary_{50} = 2 \times \left(\frac{13500}{2} \right)^{2.75} = 6.7860237 \times 10^{10}$$

- Lethality Fraction (or probability of death):
$$FractionLethalEffects\_Military = \Phi\left(\frac{8}{2.75} \times \log_{10}\left(\frac{TL}{6.7860237 \times 10^{10}} \right) \right)$$

where $\Phi(\cdot)$ denotes the Standard Normal CDF

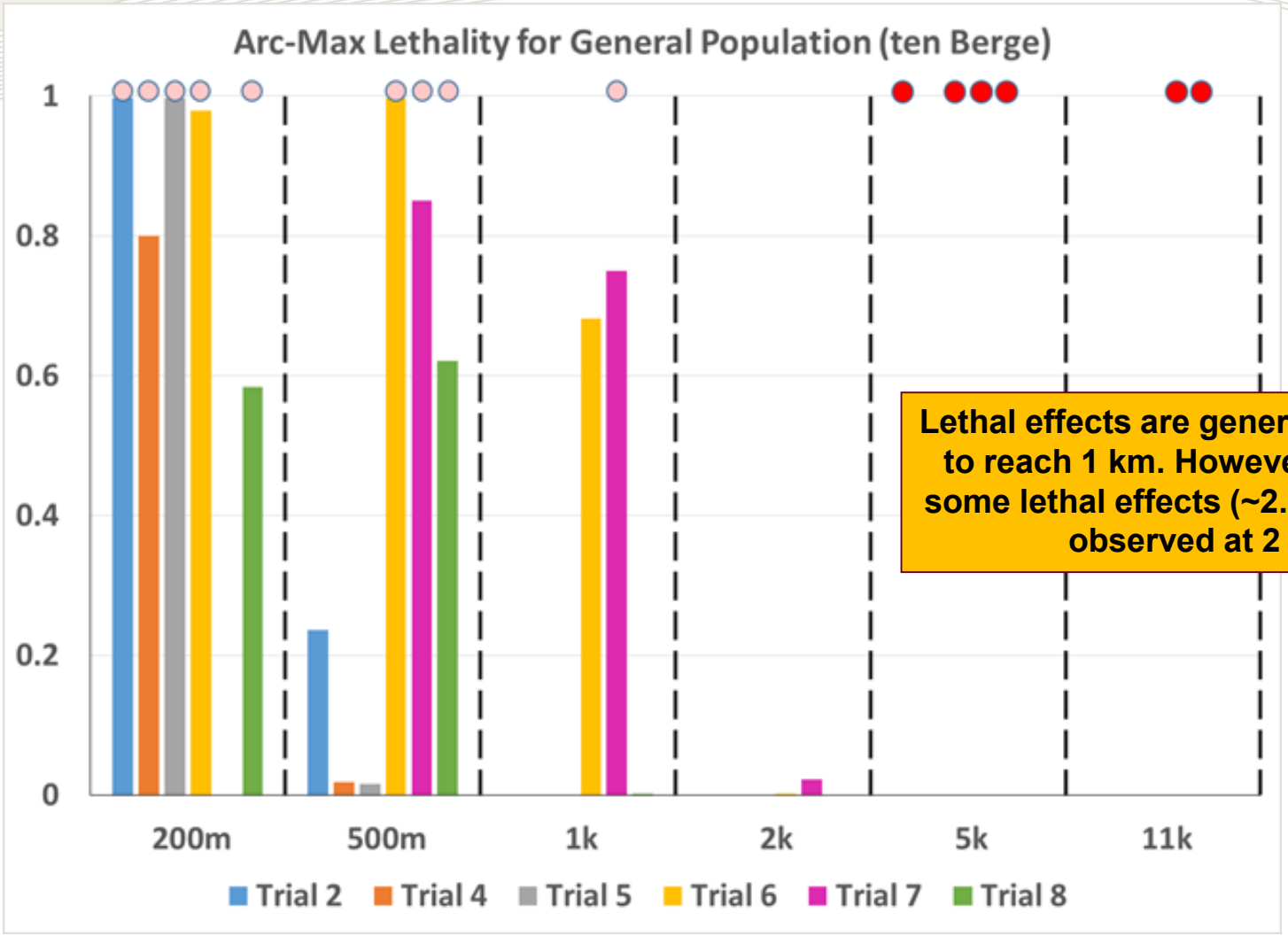
Calculations presented on this slide are only applicable to *n* = 2.75

IDA Lethality Contours (General Population) – JRII FY15 Trial 2



Contours are interpolated from single-sampler fractional lethality estimates

IDA | JRII Lethality Distances for the General Population

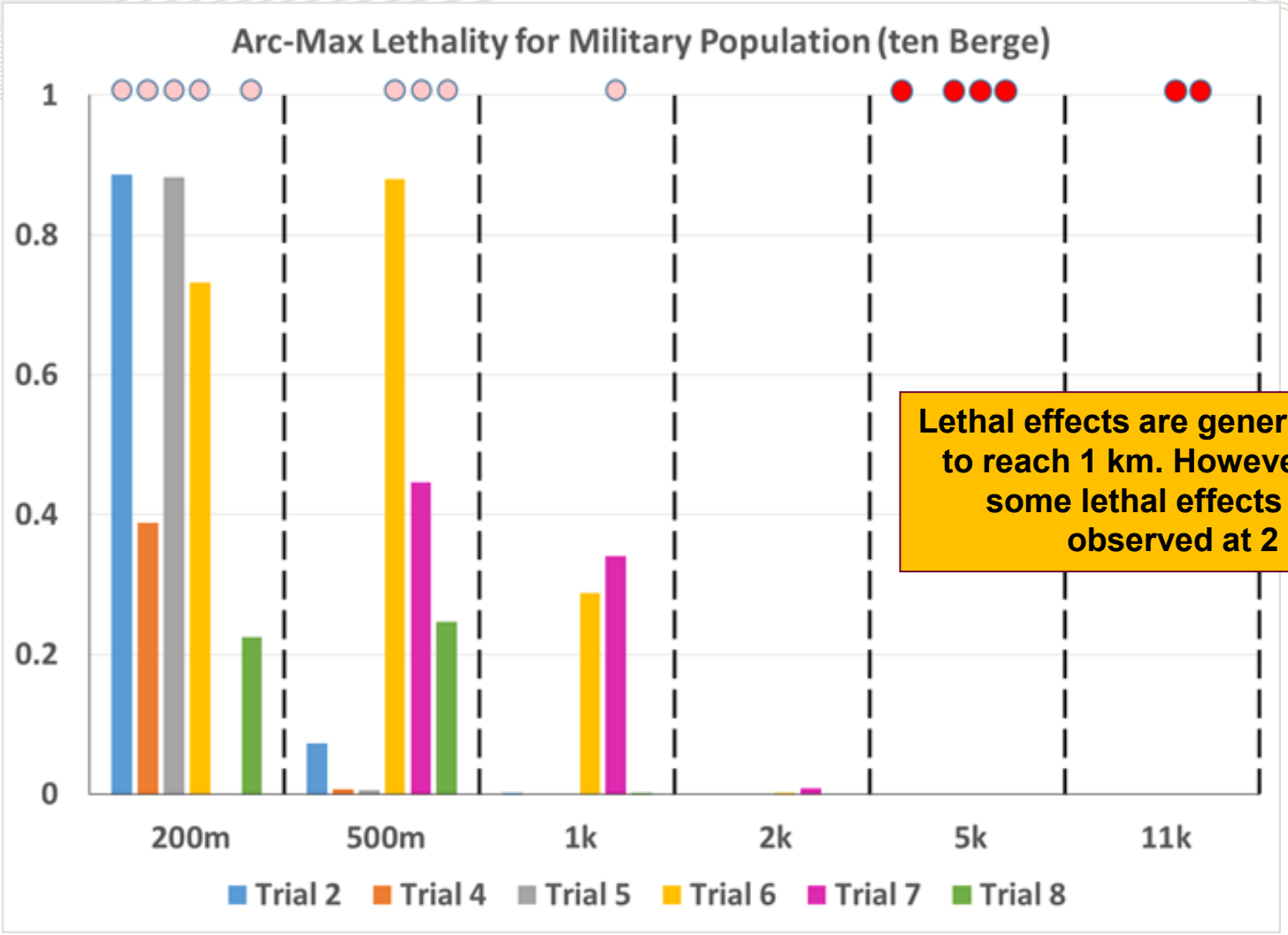


Lethal effects are generally expected to reach 1 km. However, for trial 7 some lethal effects (~2.3%) could be observed at 2 km.

Notes:

- The plume for trial 5 went off grid
- Pink/Red dots indicate that some samplers on the arc reached saturation limit:
  - 200 m – 2 km arcs saturation limit > 2000 ppm
  - 5 km – 11 km arcs saturation limit is 50 ppm

IDA | JRII Lethality Distances for the Military Population



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IDA | Toxic Load Parameters for Mild and Severe Effects

Mild

- ***n* (toxic load exponent) = 2.75**
- TL_{50} = 7500 $((mg/m^3)^{2.75})$-min)
- Probit slope based on toxic load = 0.95
- Mild Effects Fraction:

$$FractionMildEffects = \Phi\left(0.95 \times \log_{10}\left(\frac{TL}{7500}\right)\right)$$

Severe

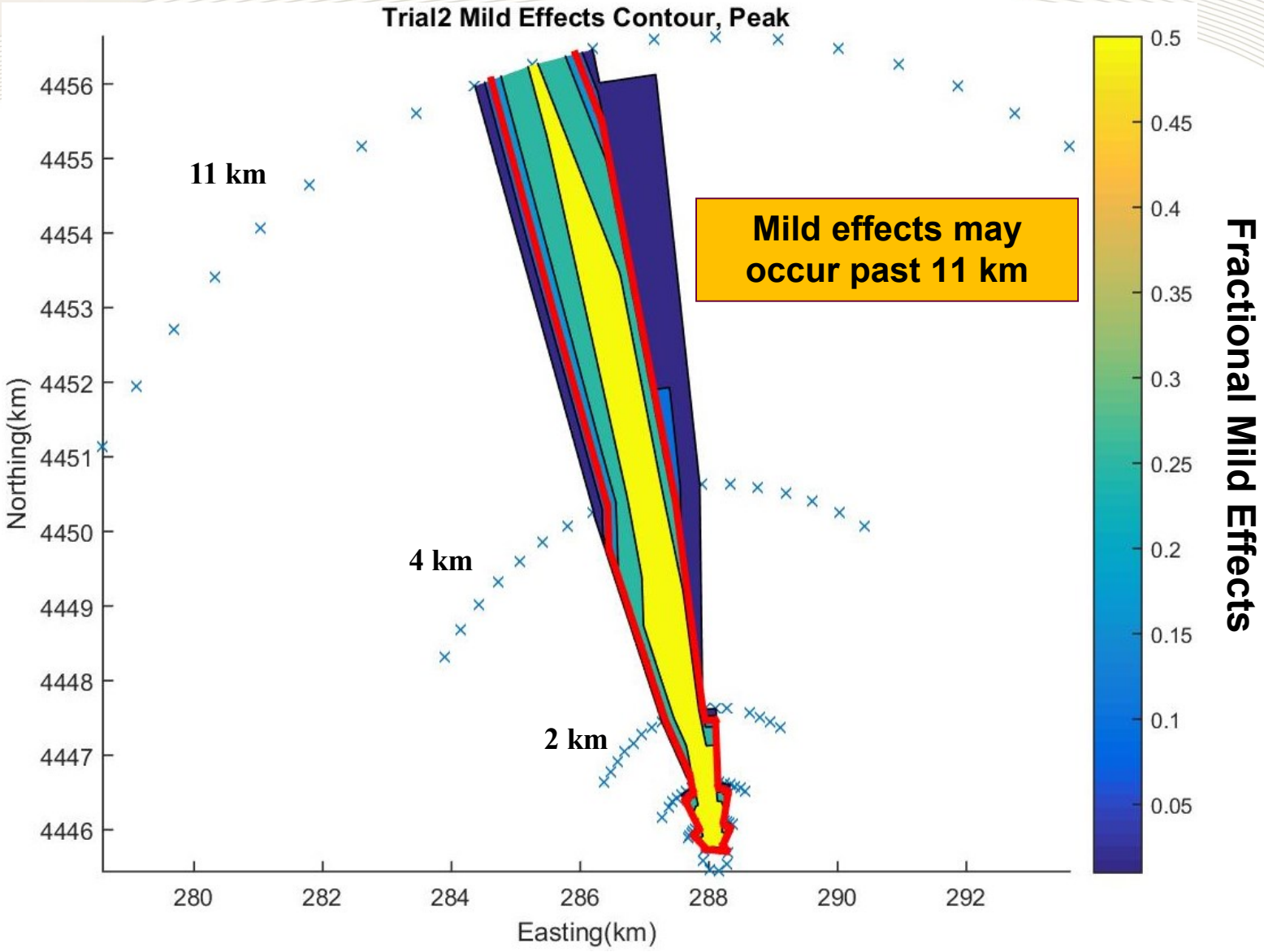
- ***n* (toxic load exponent) = 2.75**
- TL_{50} = 1.2e8 $((mg/m^3)^{2.75})$-min)
- Probit slope based on toxic load = 2.9
- Severe Effects Fraction:

$$FractionSevereEffects = \Phi\left(2.9 \times \log_{10}\left(\frac{TL}{1.2 \times 10^8}\right)\right)$$

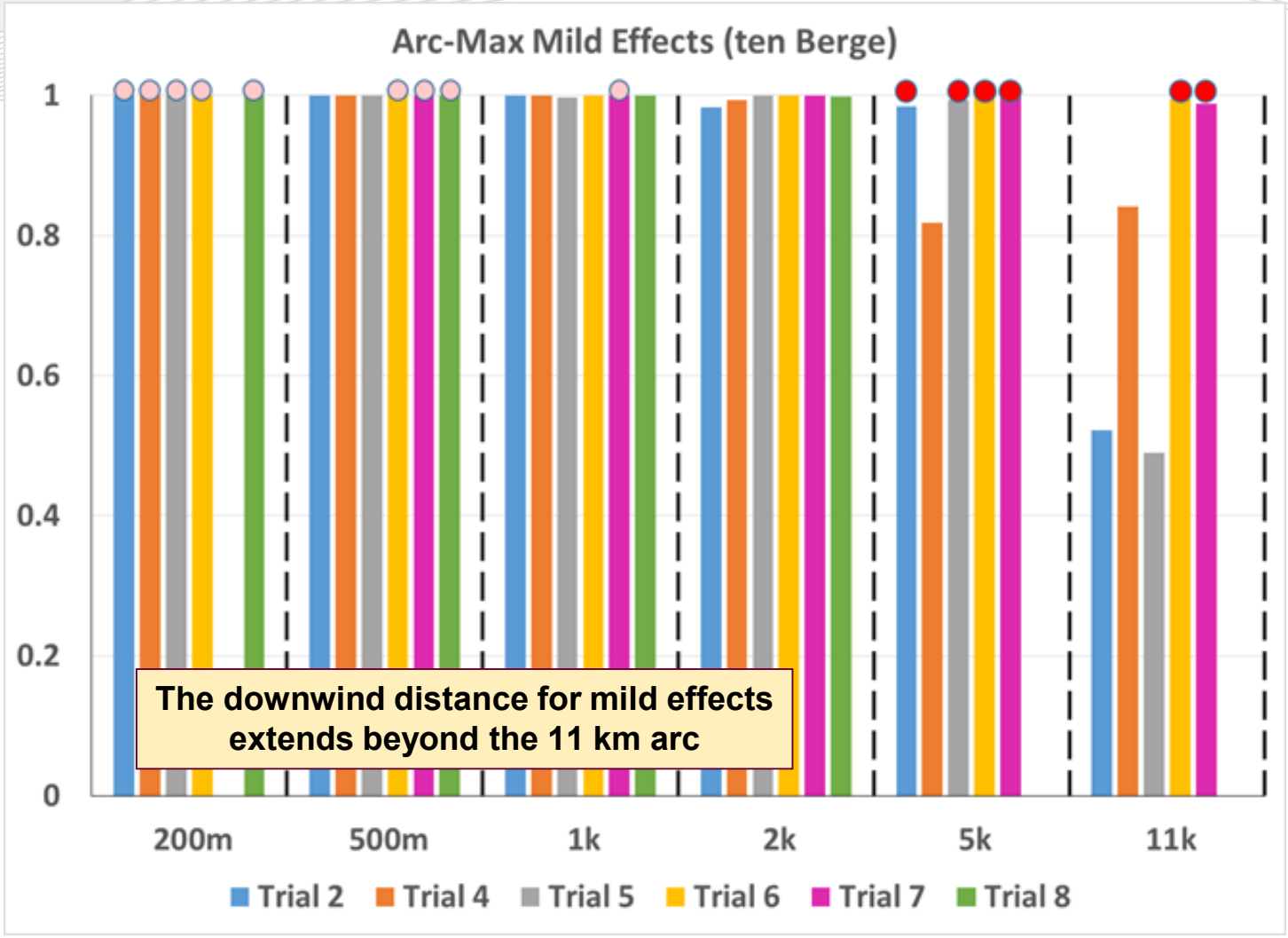
Where $\Phi(\cdot)$ denotes the Standard Normal CDF

Calculations presented on this slide are only applicable to *n* = 2.75

IDA | Mild Effects Contours – JRII FY15 Trial 2



IDA | JRII Mild Effects Downwind Distances



Notes:

- The plume for Trial 5 went off grid
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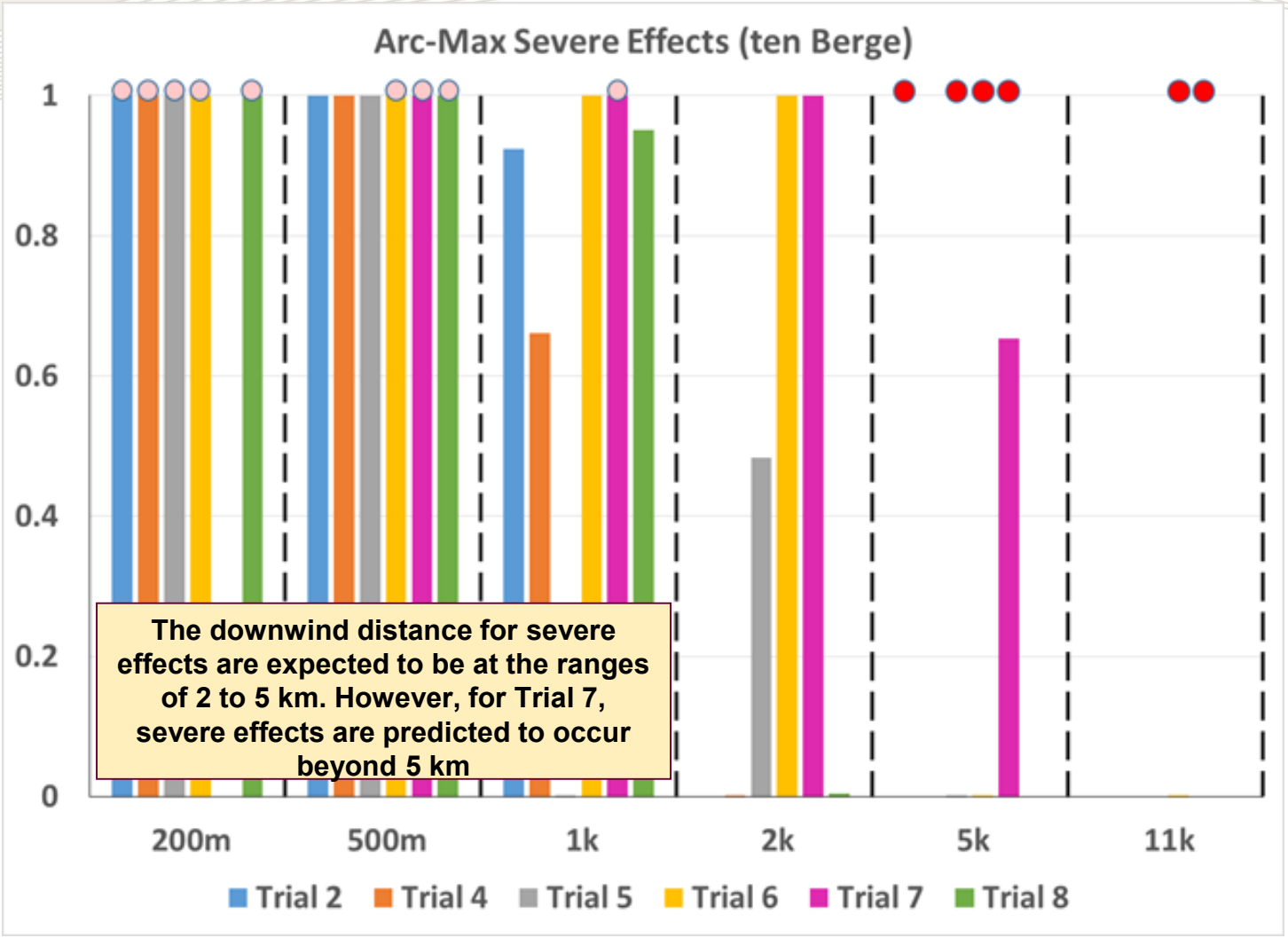
  - 5 km – 11 km arcs saturation limit is 50 ppm

IDA | JRII Severe Effects Downwind Distances



Notes:

- The plume for Trial 5 went off grid
- Pink/Red dots indicate that some samplers on the arc reached saturation limit:
  - 200 m – 2 km arcs saturation limit > 2000 ppm
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IDA | Acute Exposure Guideline Levels (AEGLs)

AEGLs are conservative guidelines on human exposures due to toxic airborne hazards. Each AEGL has an airborne concentration and associated exposure time: the concentration is not to be exceeded for exposures of that duration in order to ensure a low probability of experiencing certain health effects.

- The levels are:
  - **AEGL-1** – Discomfort, irritation, non-disabling/reversible effects
  - **AEGL-2** – Impaired ability to escape, long-lasting/serious/irreversible effects
  - **AEGL-3** – Life threatening effects, death

- The conditions corresponding to each level for a given hazard were determined through a worldwide private- and public-sector effort, now led by the U.S. EPA with assistance from the National Academies

- AEGLs are given as an average concentration for specific exposure times:
  - 10 min, 30 min, 1 hour, 4 hours, 8 hours

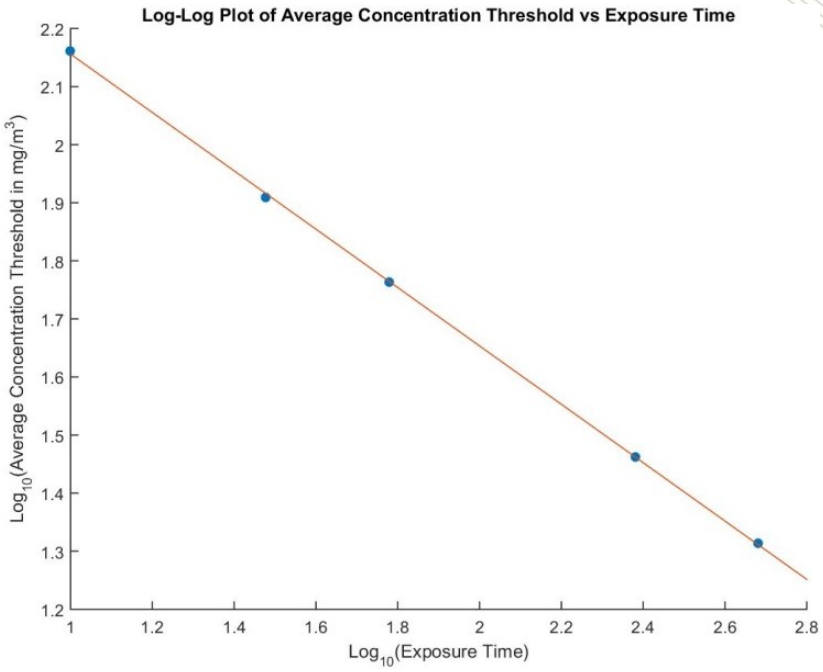
AEGL for Airborne Chlorine Exposure in ppm

	Exposure Duration				
	10 min	30 min	60 min	4 hr	8 hr
AEGL 1	0.50	0.50	0.50	0.50	0.50
AEGL 2	2.80	2.80	2.00	1.00	0.71
AEGL 3	50.00	28.00	20.00	10.00	7.10

AEGL 1 are constant value for different exposure levels
AEGL 2 are constant value up to 30 minute exposure;
utilize toxic load model for longer exposures
AEGL 3 utilize toxic load model

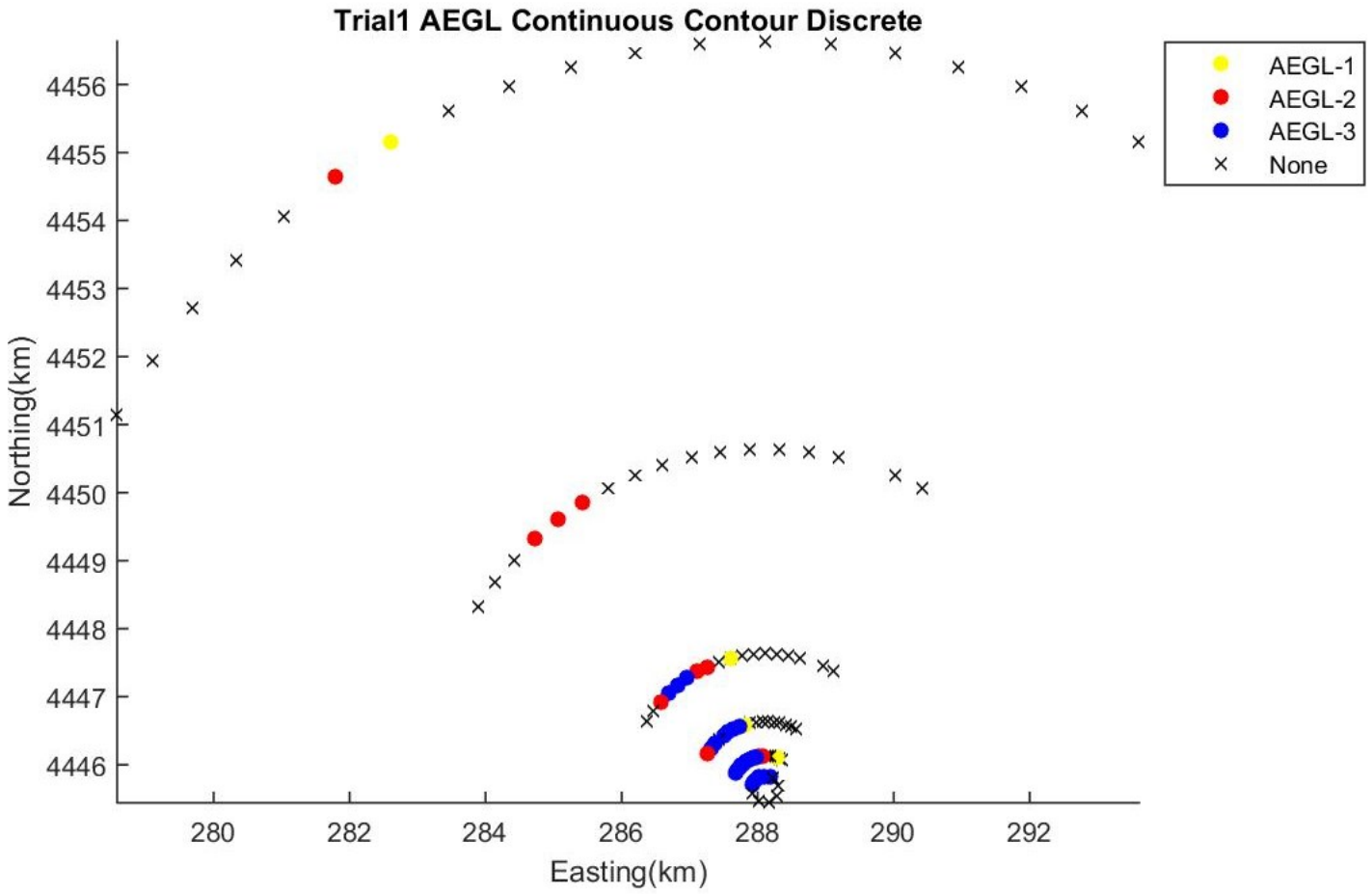
Determining AEGL-3 Values Based on Variable Exposure Time

- The AEGL-3 concentration thresholds are nearly linear on a log-log plot vs. exposure time
- We performed a linear regression that allowed us to estimate the AEGL-3 concentration thresholds for arbitrary exposure times

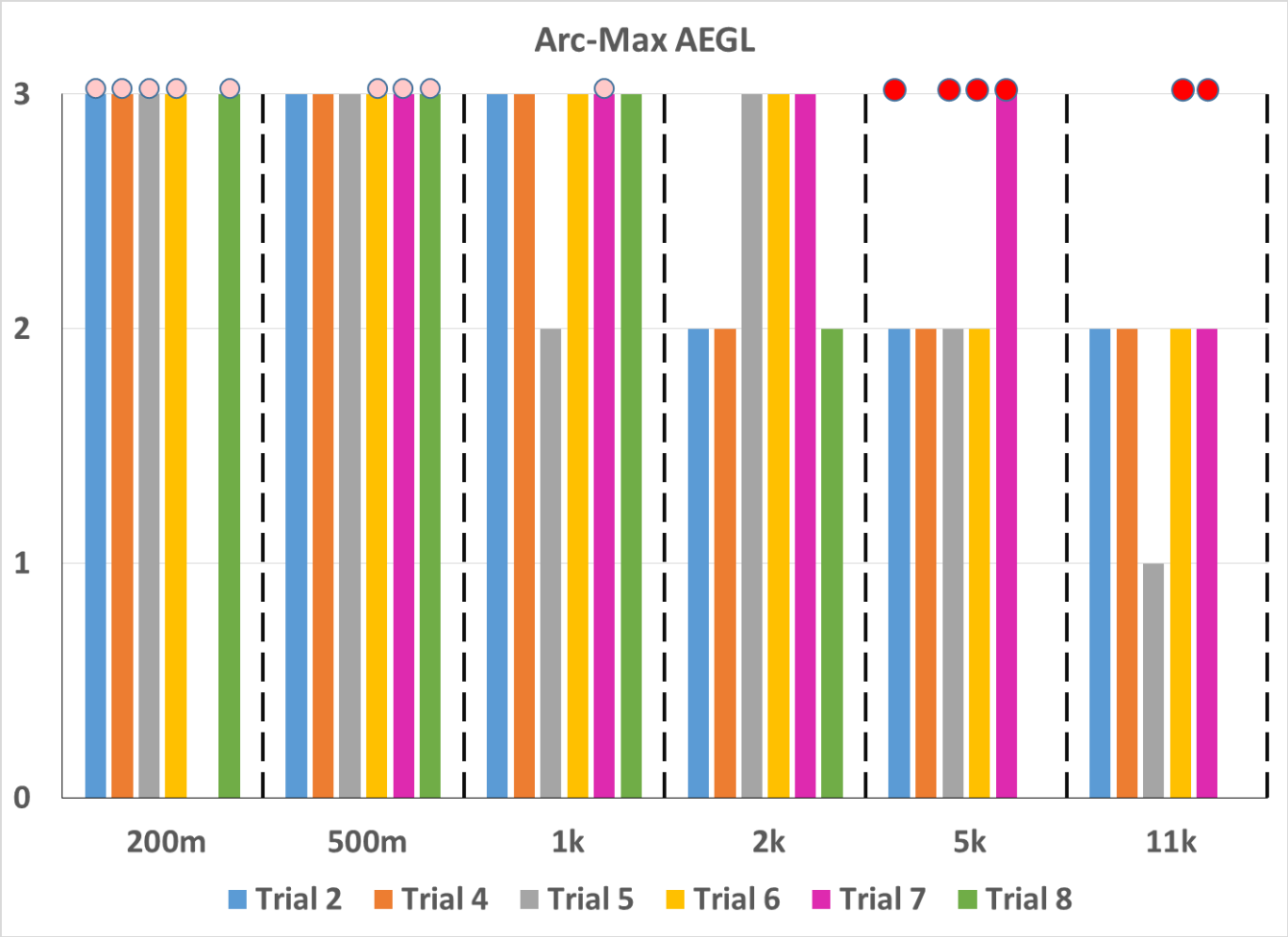


Log-log plot of AEGL-3 exposure time and concentration threshold

AEGLs Exceeded at Each Sampler (JRII FY15 Trial 1)



IDA | Maximum AEGL Reached at Each Downwind Distance



- **AEGL-3: > 2 km, but likely < 5 km**
  Trial 7 extends past 5 km
- **AEGL-2: Up to at least 11 km**
- **AEGL-1: Beyond 11 km**

Notes:
- The plume for Trial 5 went off grid
- Pink/Red dots indicate that some samplers on the arc reached saturation limit:
  - 200 m – 2 km arcs saturation limit > 2000 ppm
  - 5 km – 11 km arcs saturation limit is 50 ppm

IDA | Summary

- We used data from the Jack Rabbi II FY15/FY16 campaign (sampler measurements of the chlorine time series) to estimate downwind hazard distances for comparably-released amount releases based on human effects consequence assessment models
  - **Releases involved between 6.9 and 9.1 metric tons of chlorine**

Estimated downwind hazard distances:

- Lethal effects: Expected up to 1 km; Trial 7 predicts > 2% lethality at 2 km
- Severe effects: Expected between 2 km and 5 km; Trial 7 predicts severe effects beyond 5 km
- Mild effects: Beyond 11 km (the farthest downwind observations in JRII)

Estimated downwind AEGL extent:

- AEGL-3: 2 to 5 km with some possibility extending past 5 km (Trial 7)
- AEGL-2: Up to at least 11 km (the farthest downwind observations in JRII)
- AEGL-1: Beyond 11 km (the farthest downwind observations in JRII)

We note that since our hazard distance estimates are produced from chlorine concentrations that were directly measured (i.e., not modelled), the accuracy of these estimates depends only on the quality of the health effects models we applied, and not on the quality of any atmospheric transport and dispersion model or container release (chemical source term) model.