Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

Quantitative Risk Assessment for Hydrogen Systems: Model Development, Validation and Case Study

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Train de Charlevoix, North America's first hydrogen-powered train
Quebec City to Baie-Saint-Paul

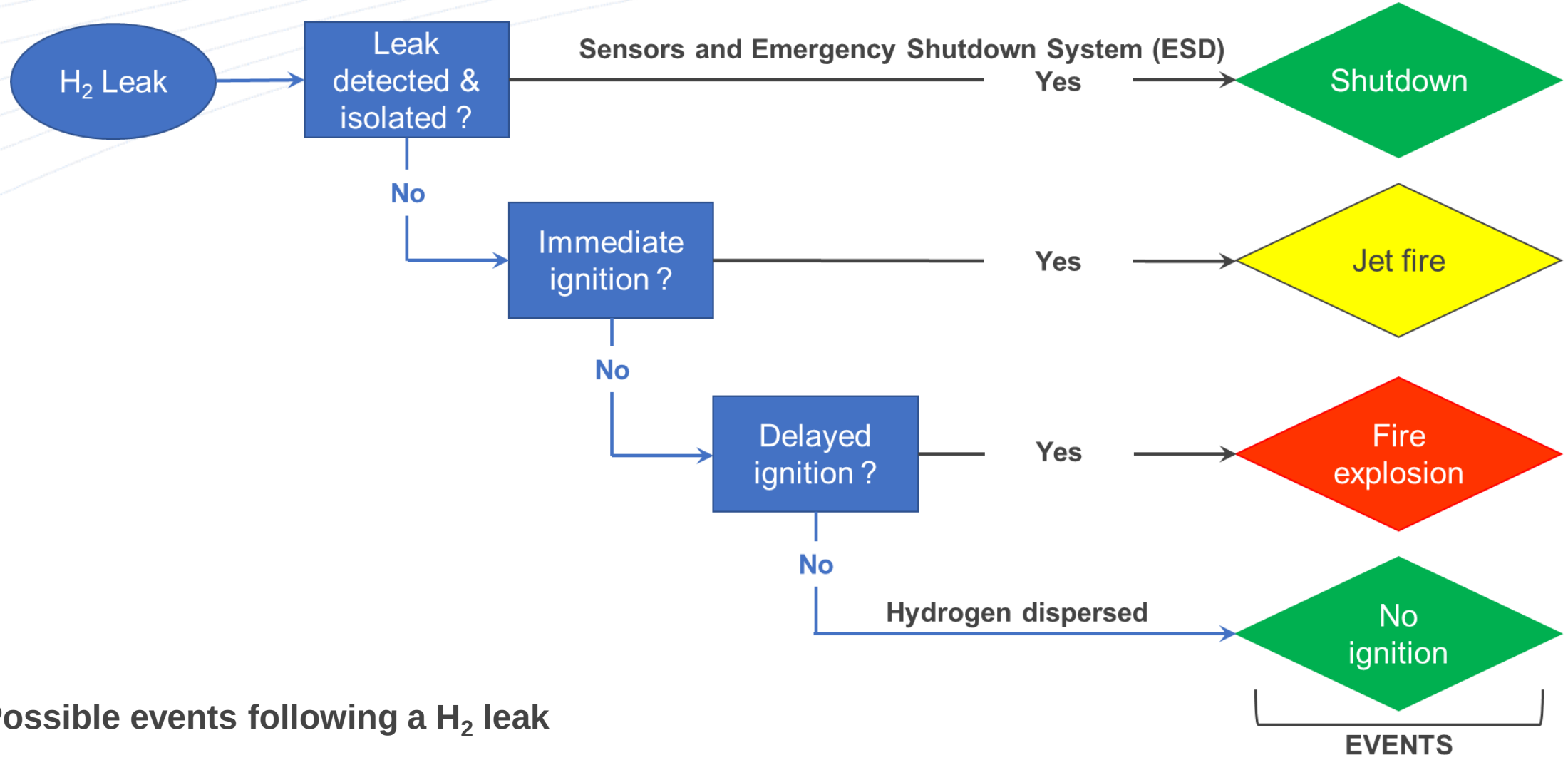
Outline

- **Background of Present Study**
- **Quantitative Risk Assessment (QRA)**
  - ➢ Event Tree Diagram and Risk Assessment Overview
  - ➢ QRA Approach
- **Case Study**: Hydrogen Freight Locomotive
- **Summary**

Background of Present Study

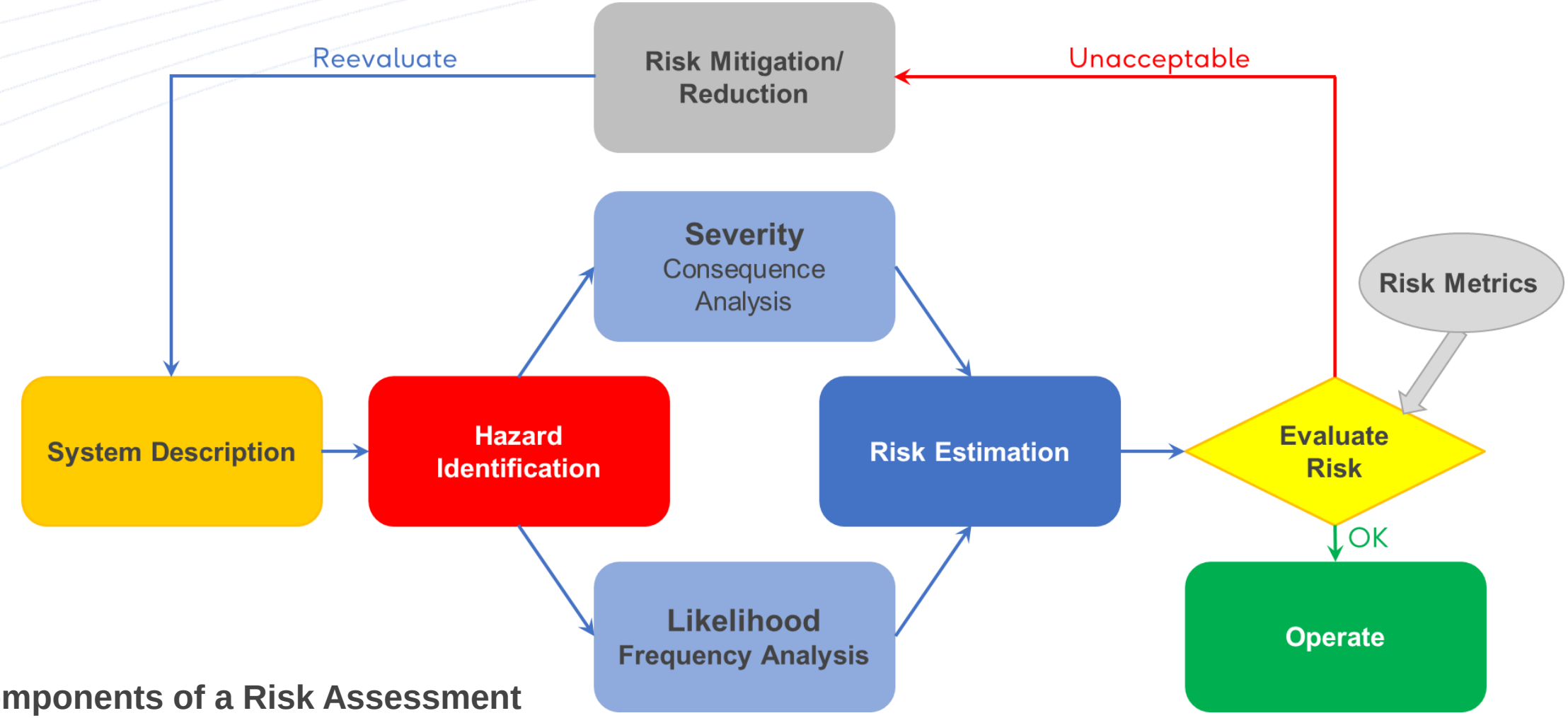
- **2014 HySafe Priority Workshop**
  - Integrated Computational Toolset for risk assessment ranked the highest
  - Translate fundamental scientific findings to a suite of engineering probabilistic and physical effects models for quantitative risk assessment (QRA)
- **2015 Hydrogen Risk Assessment Tool: HyRAM** by Sandia National Laboratories
  - Integrates deterministic and probabilistic models for quantifying accident scenarios
  - Predicts physical effects, characterizes impact on people and structures
- **In-house QRA toolkit by CNL**, adopted approach of HyRAM
  - Ability to couple in-house CFD model and experimental results to the toolkit
  - Ability to conduct transient analysis and adjust for specific applications
  - Include gases and blends that could be of CNL's interests, e.g., syngas

Event Tree Diagram



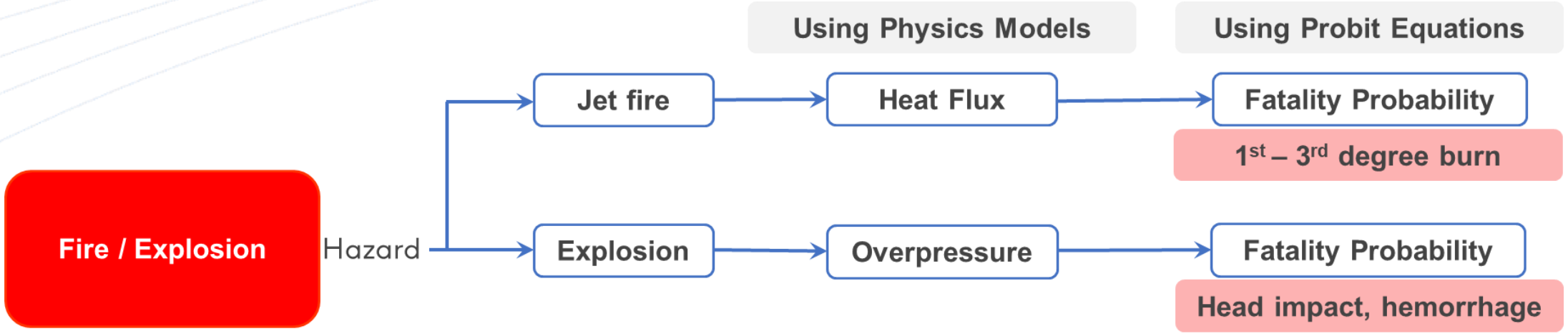
Possible events following a H_2 leak

Risk Assessment Overview



Components of a Risk Assessment

Quantitative Risk Assessment: Severity



For this study

Parameter	Threshold	Consequences
Heat Flux	≤ 2.0 kW/m^2	No harm over long exposures
Overpressure	≤ 10 kPa	Threshold for window glass shattering

Quantitative Risk Assessment: Likelihood

Incident

H_2 Leak

Component leak frequency
f_c

Frequency Historical data:
Very small leak
Minor leak
Medium leak
Major
Rupture

Components: *Pipes, Valves*
Vessels

Events

Shutdown

Jet fire

Fire explosion

No ignition

Event Frequency = $f_c \times$ probability $(\boldsymbol{P})$

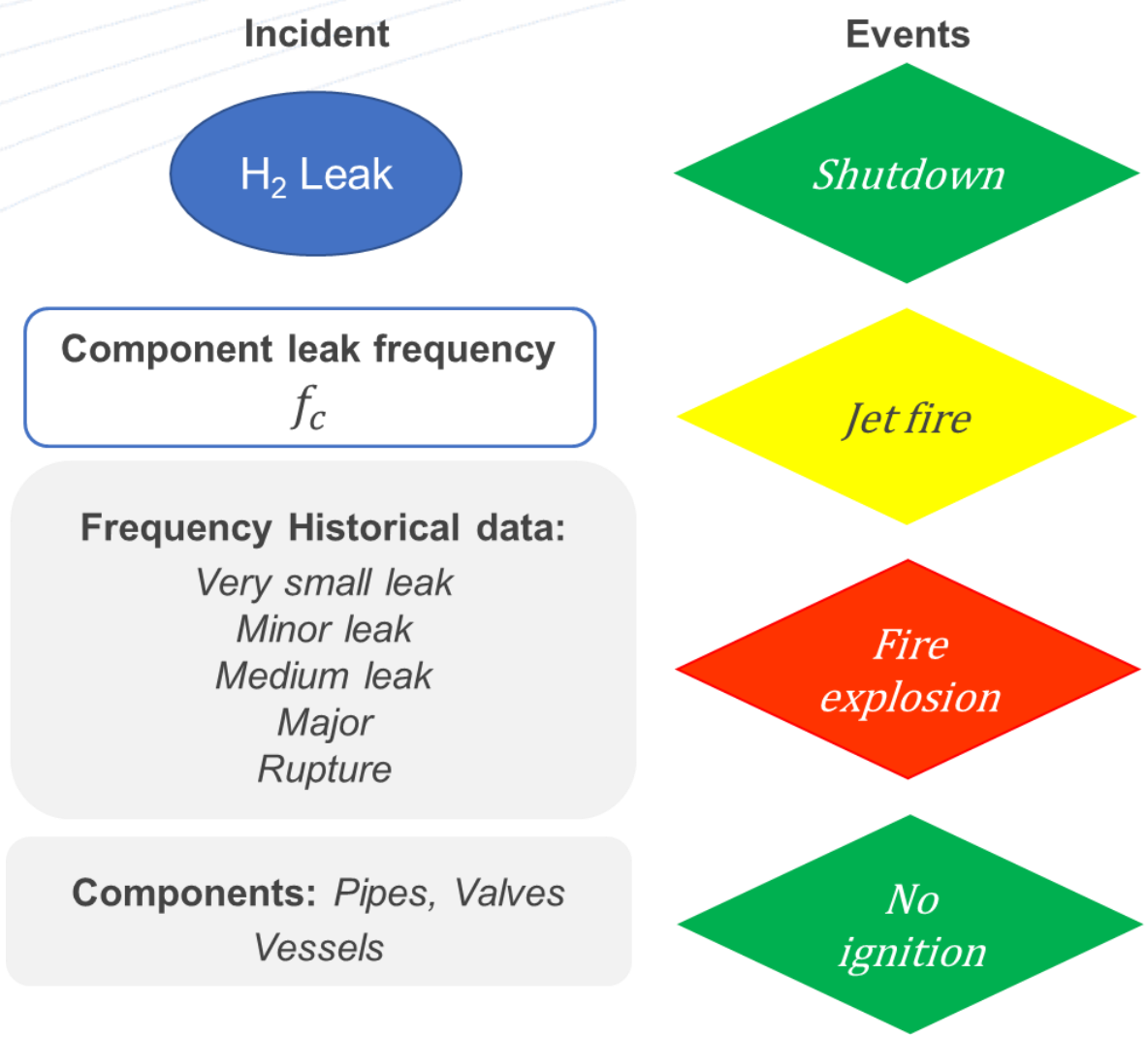
$\boldsymbol{P_{Shutdown}}$
$P_{detection}$

$\boldsymbol{P_{Jet\ fire}}$
$(1 - P_{detection}) \cdot P_{immediate}$

$\boldsymbol{P_{Explosion}}$
$(1 - P_{detection}) \cdot (1 - P_{immediate}) \cdot P_{delayed}$

$\boldsymbol{P_{No\ ignition}}$
$1 - P_{shutdown} - P_{Jet\ fire} - P_{Explosion}$

Quantitative Risk Assessment: Likelihood



Event Frequency = f_c × probability (P)

Hydrogen leak rate (kg s^{-1})	Ignition probability	
	$P_{Immediate}$	$P_{Delayed}$
< 0.125	0.008	0.004
0.125–6.25	0.053	0.027
> 6.25	0.230	0.120

Tchouvelev et al., Canadian Hydrogen Safety Program

Quantitative Risk Assessment: Risk Evaluation

Risk Evaluation

→ **Risk Metric** → **Average Individual Risk (AIR)**

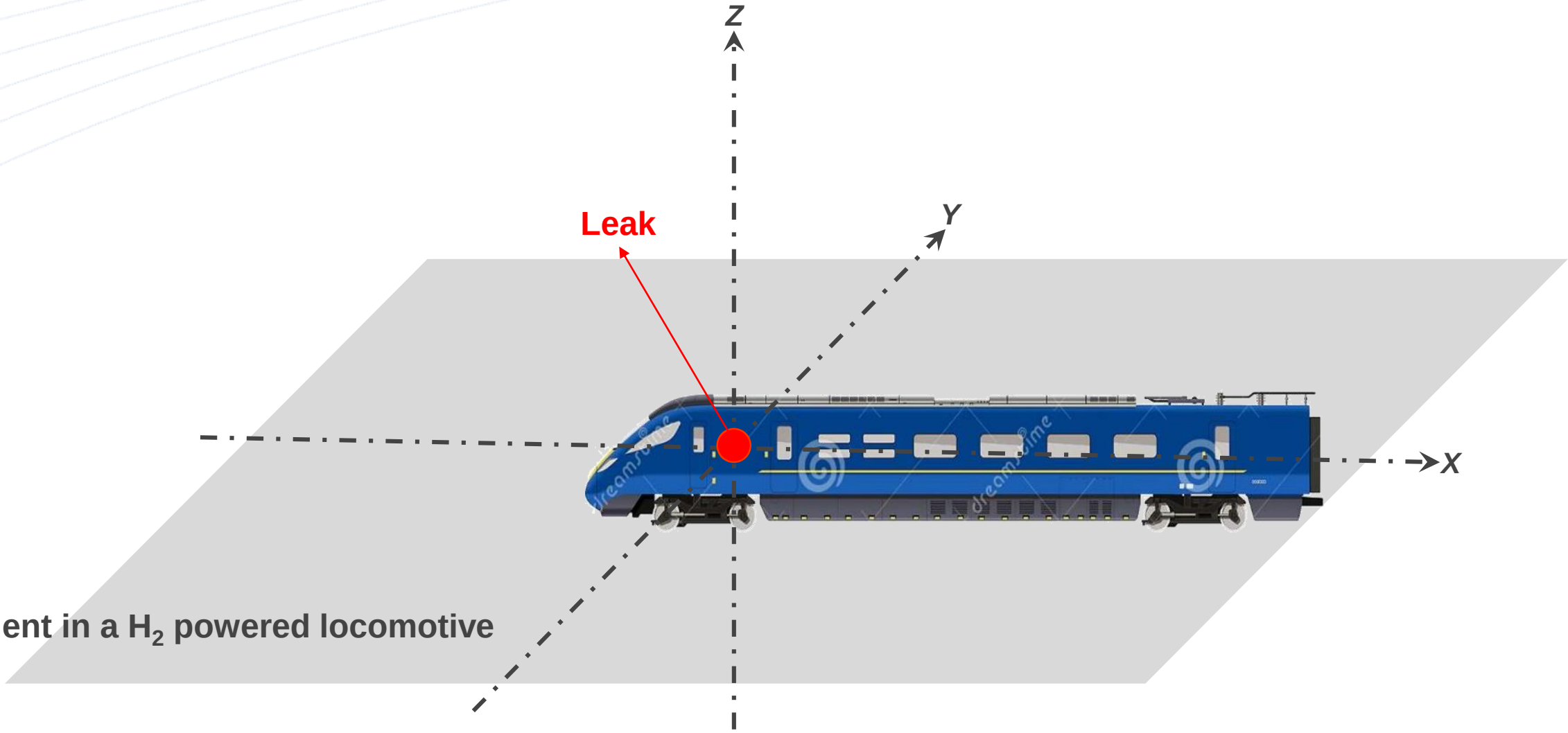
Total fatality per individual per system per year

IEA: employees AIR ≤ 1×10^{-4}, public AIR ≤ 1×10^{-5}

Risk Acceptance Criteria

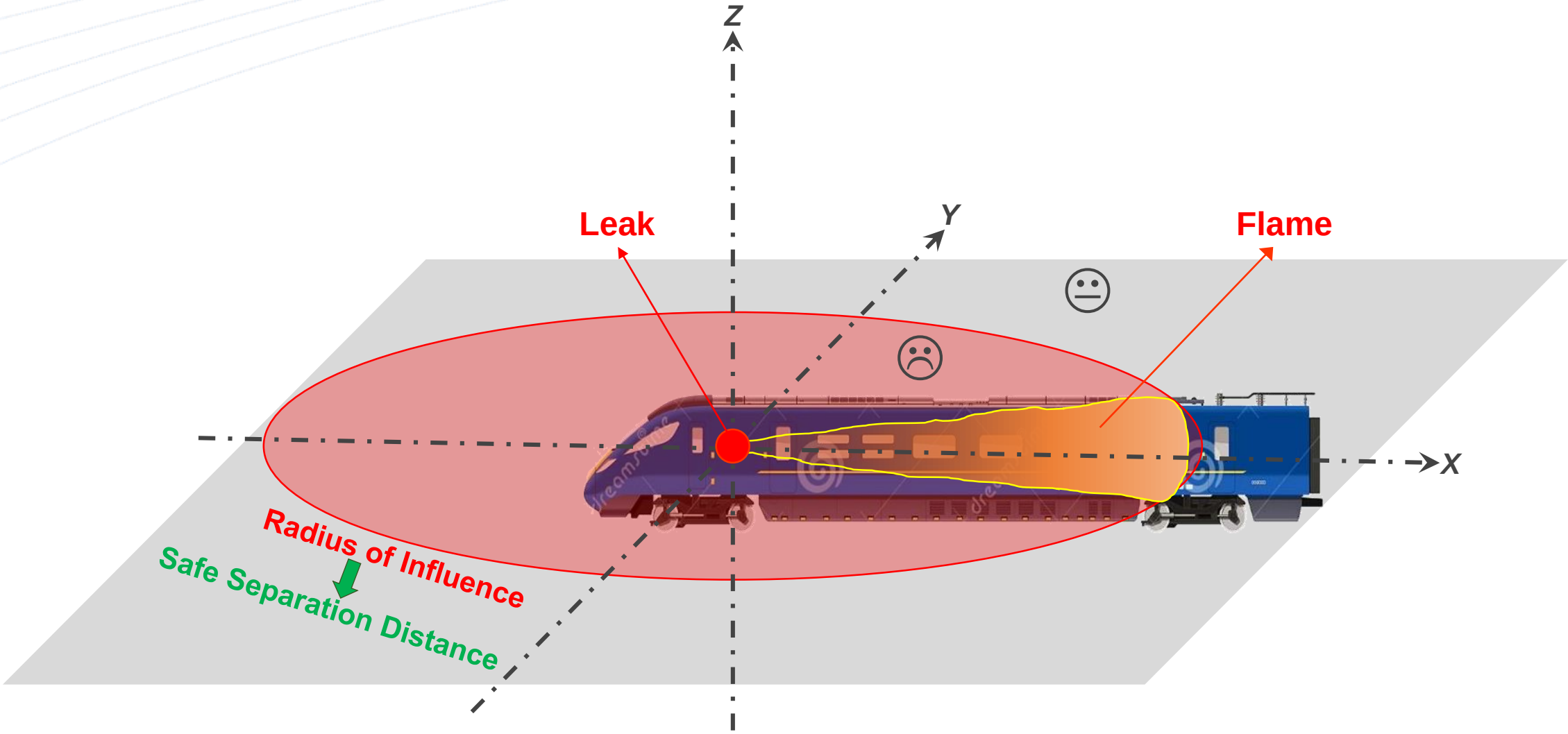
Ehrhart et al., HyRAM V 5.0 Technical Reference Manual

Case Study: Hydrogen Freight Locomotive



Incident in a H_2 powered locomotive

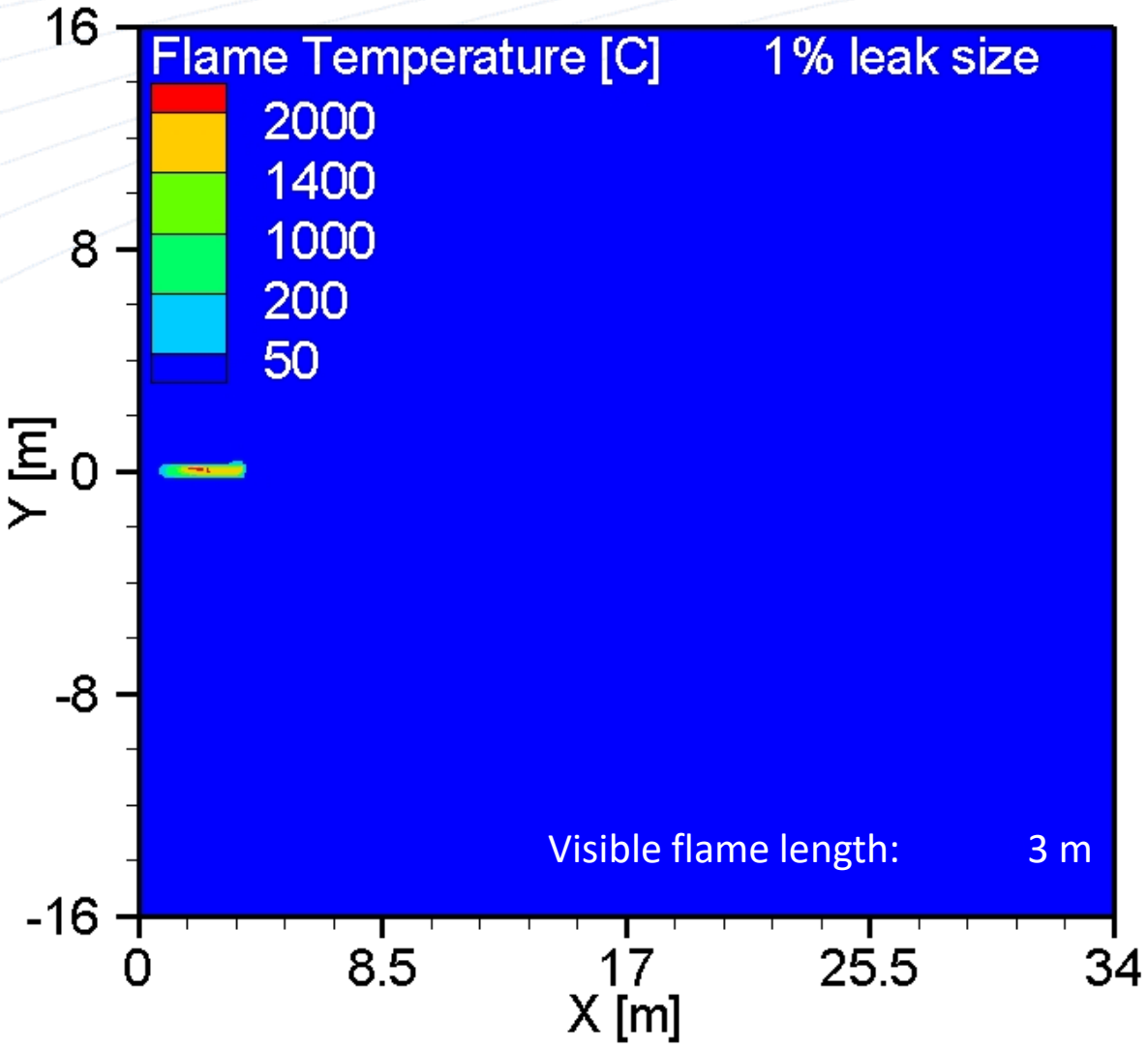
Case Study: Hydrogen Freight Locomotive



Case Study: Key Parameters

Parameter [unit]	Value
Pipe size [inch]	¾ OD
Gas pressure [bar]	350
Gas Temperature [°C]	15
Components	Cylinders, pipes, instruments, flanges, filters
Leak sizes [% of flow area]	Very small, Minor, Medium, Major, Rupture 0.01, 0.1, 1, 10, and 100
Locomotive dimensions [m]	6.3 × 1.6
Refueling frequency (per day)	1
No. of occupants	1–4
Probability for sensor to detect and isolate a leak	**90%**

Case Study: Physics Model Results – Flame and Heat Flux



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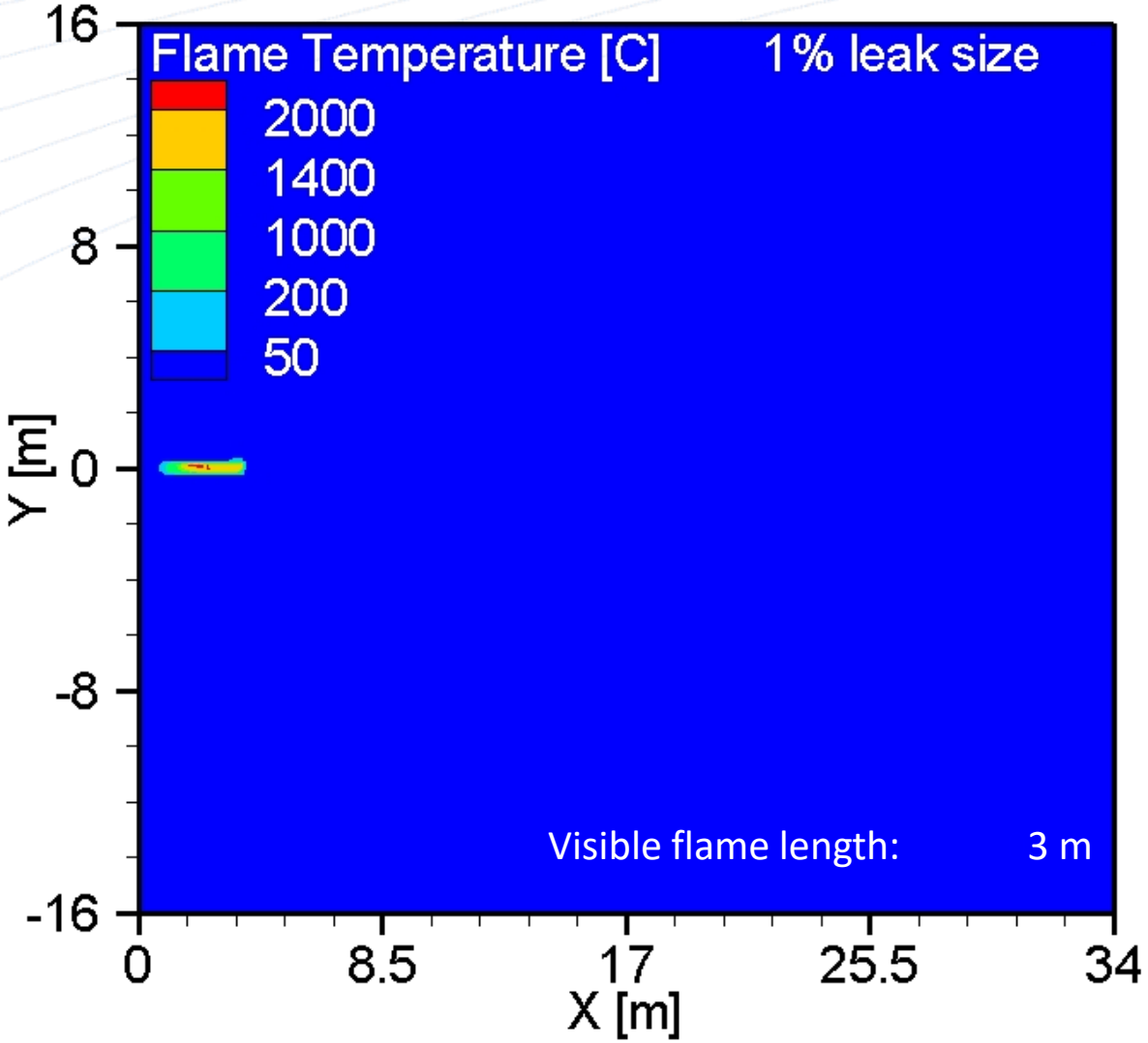

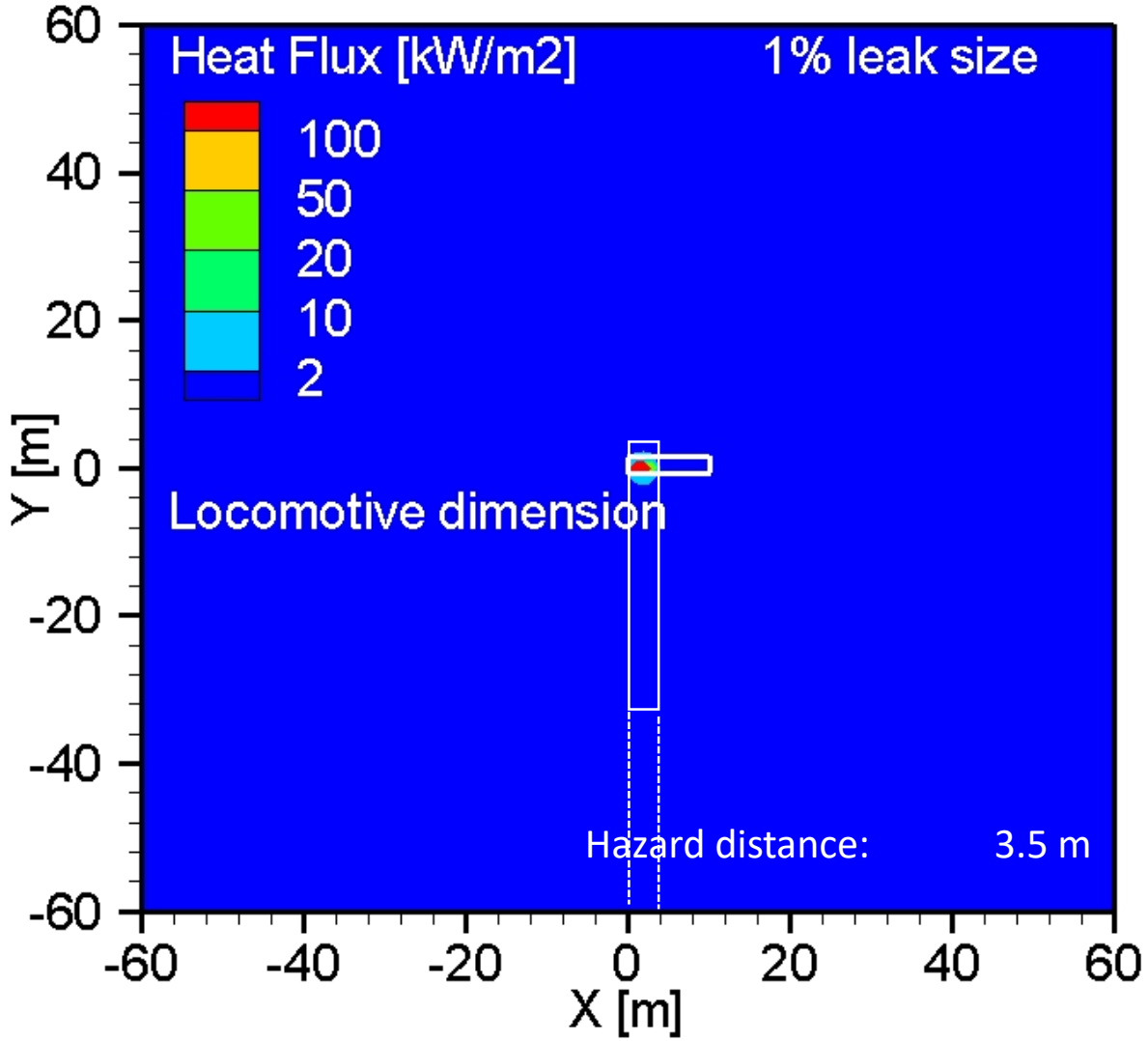

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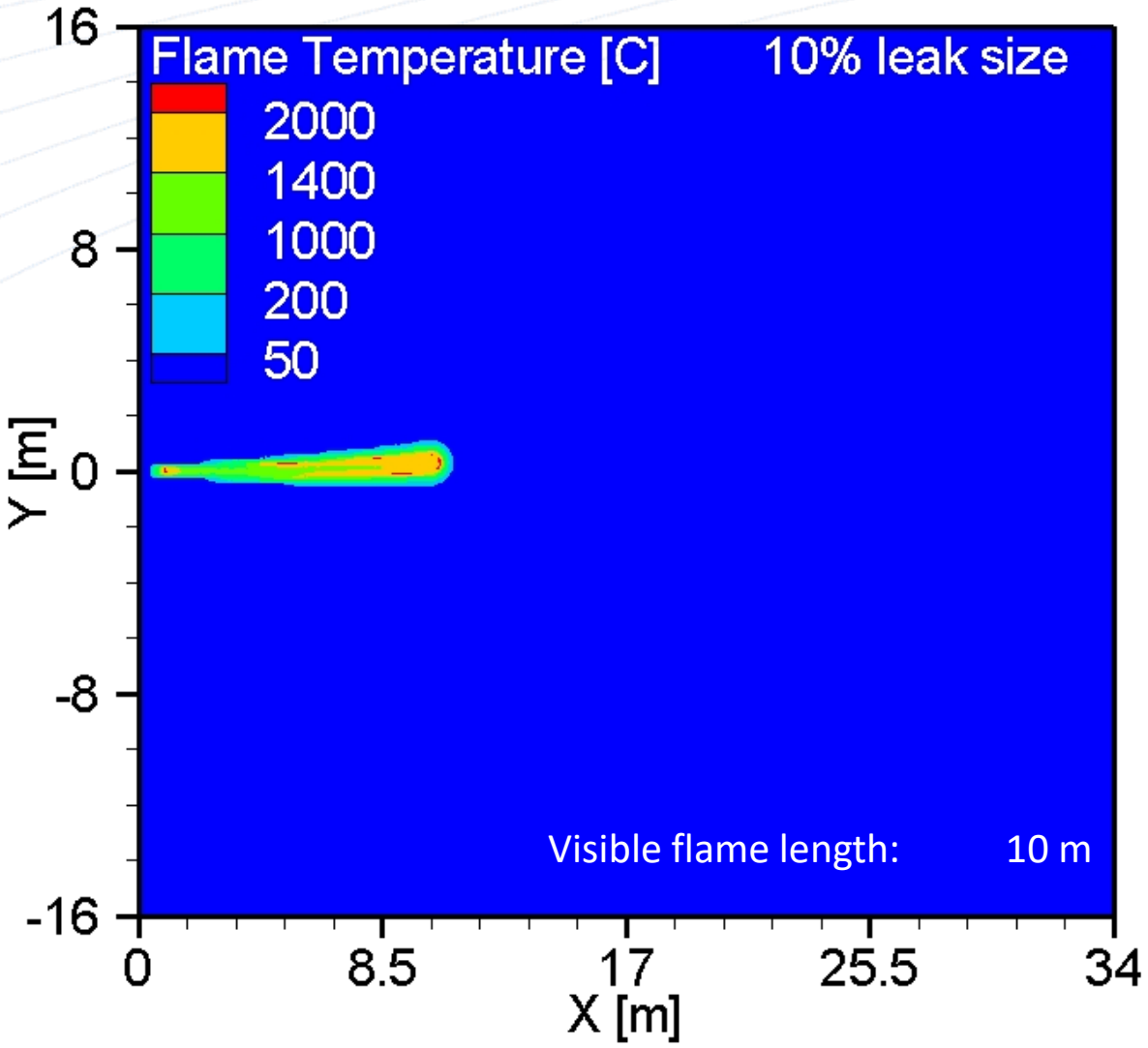

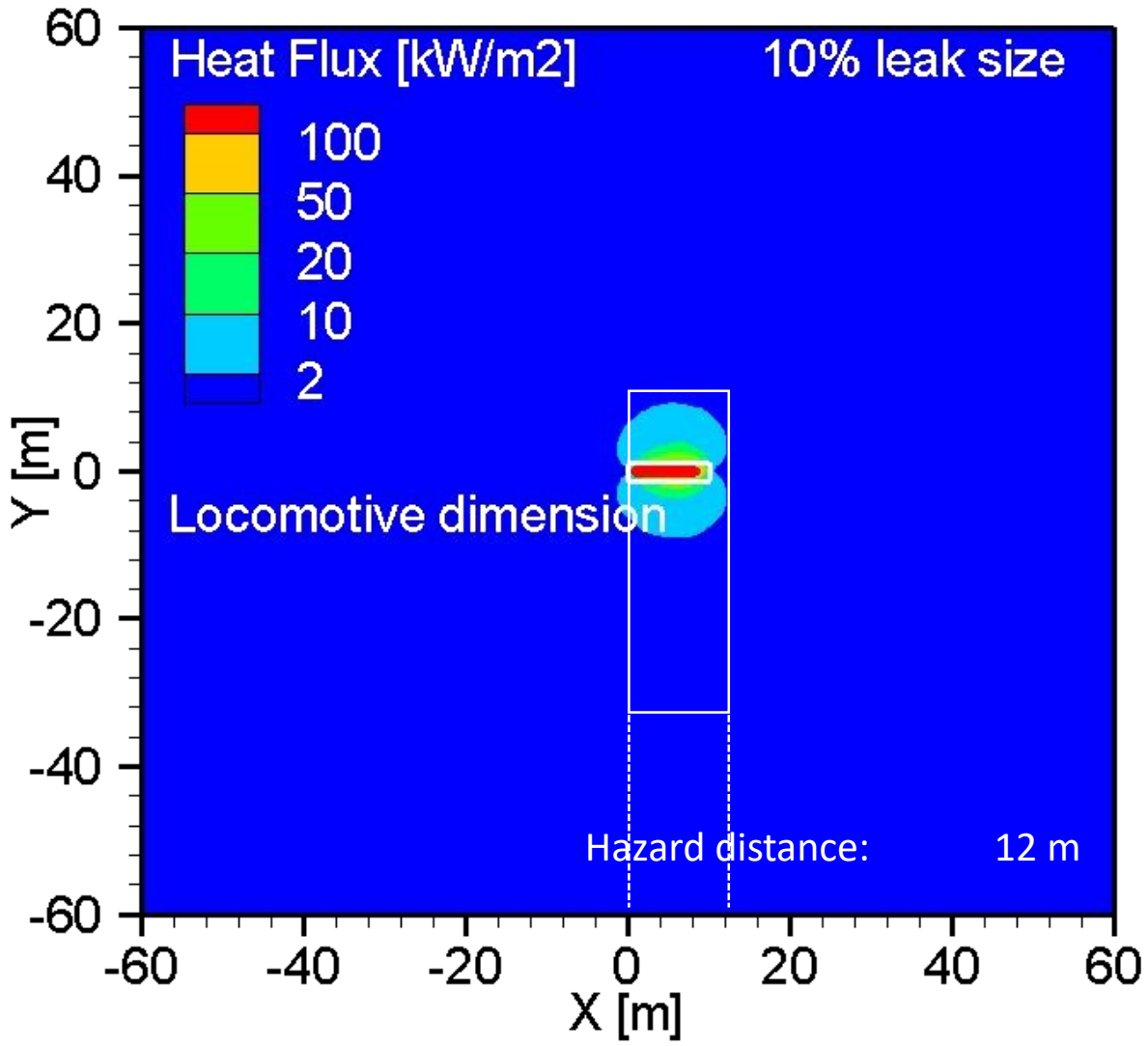

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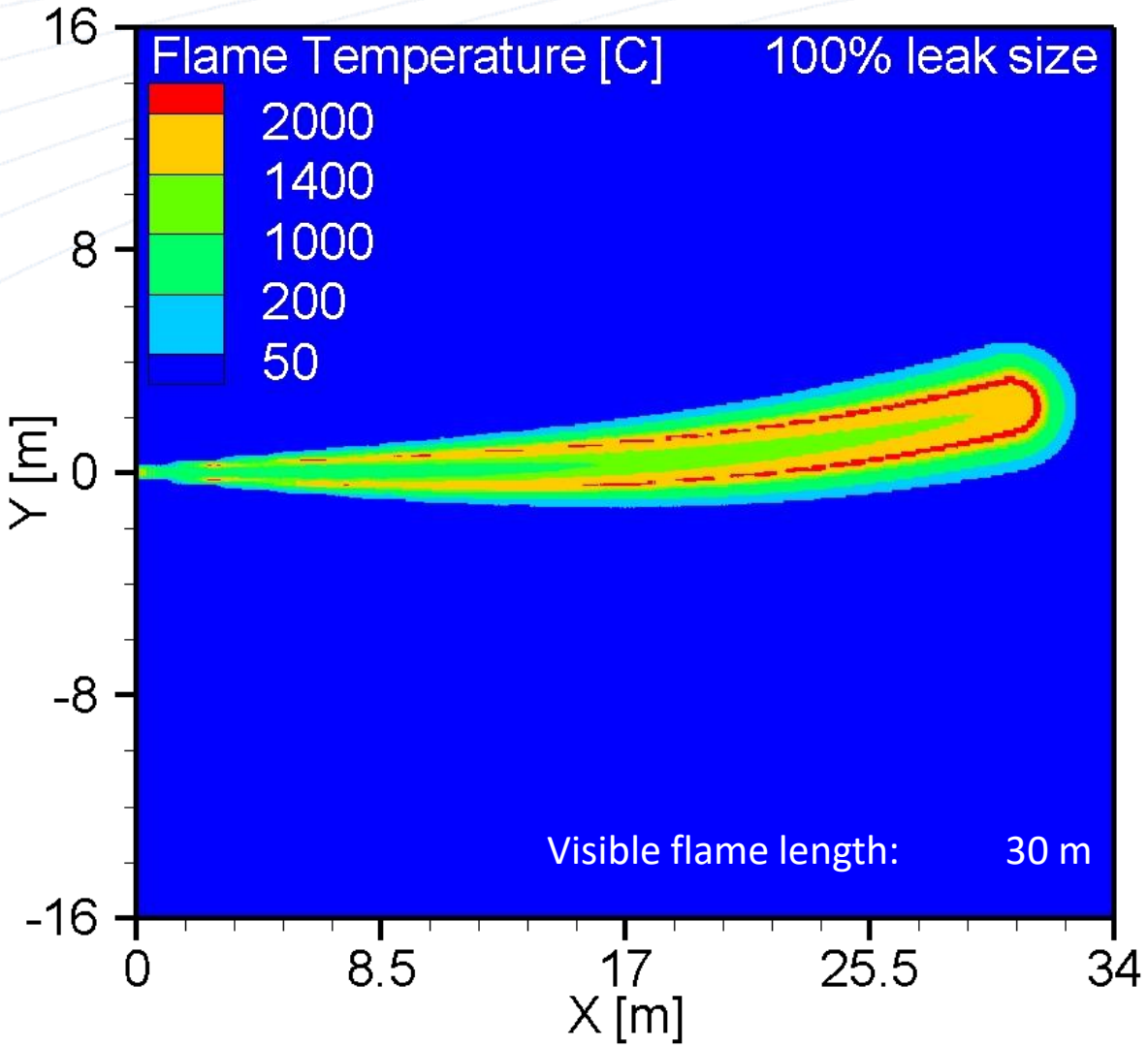
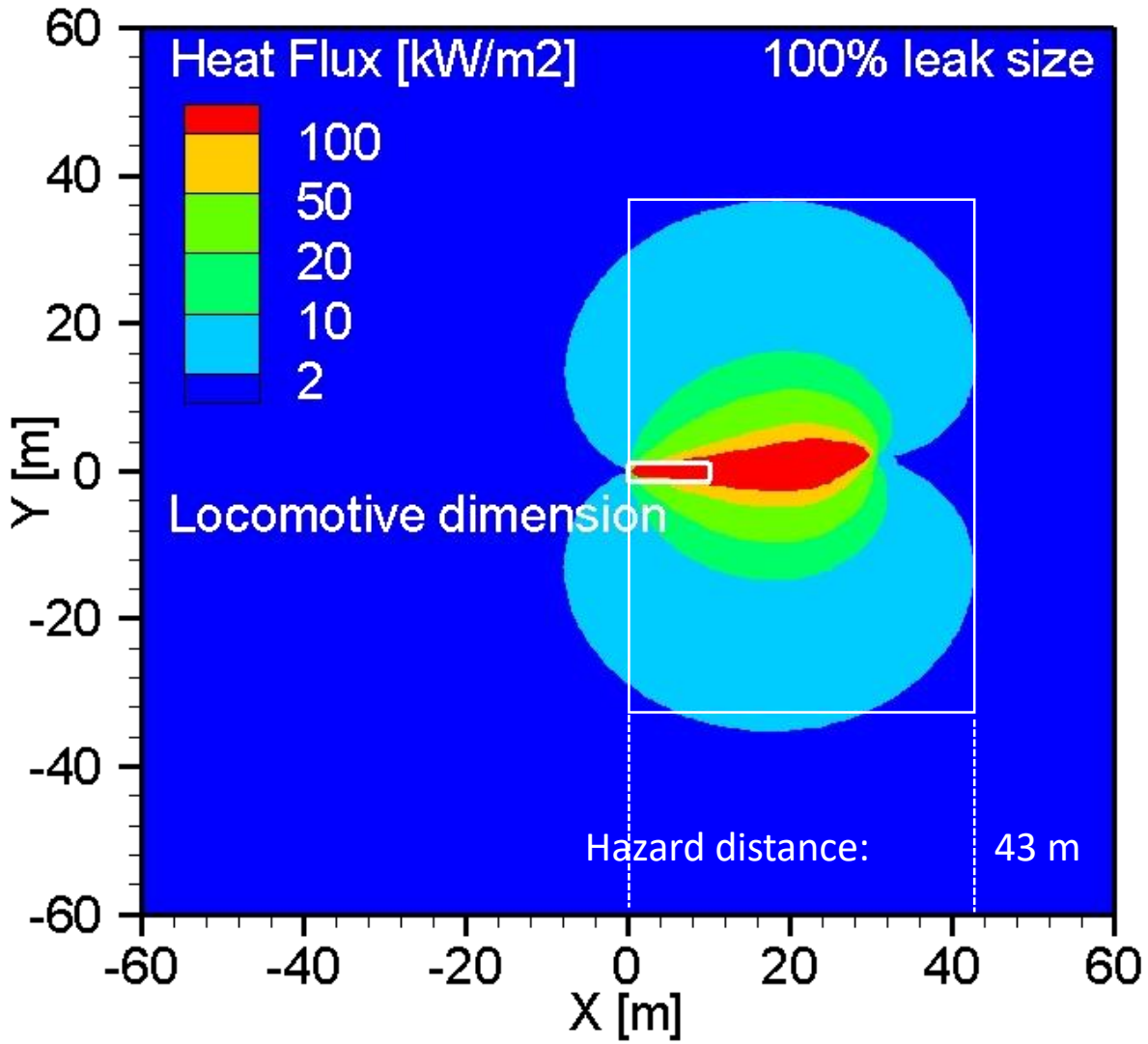
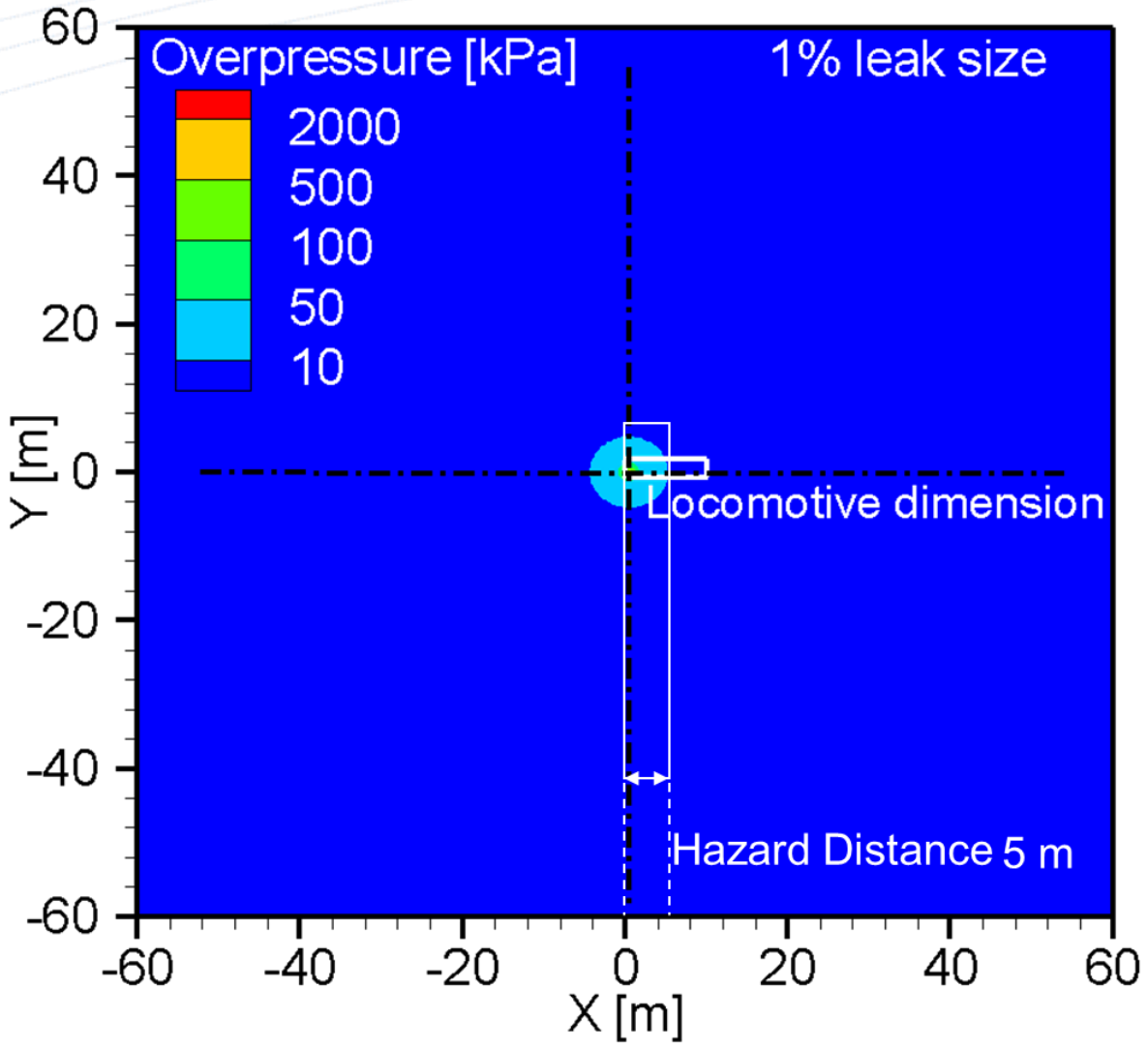




Case Study: Physics Model Results - Overpressure



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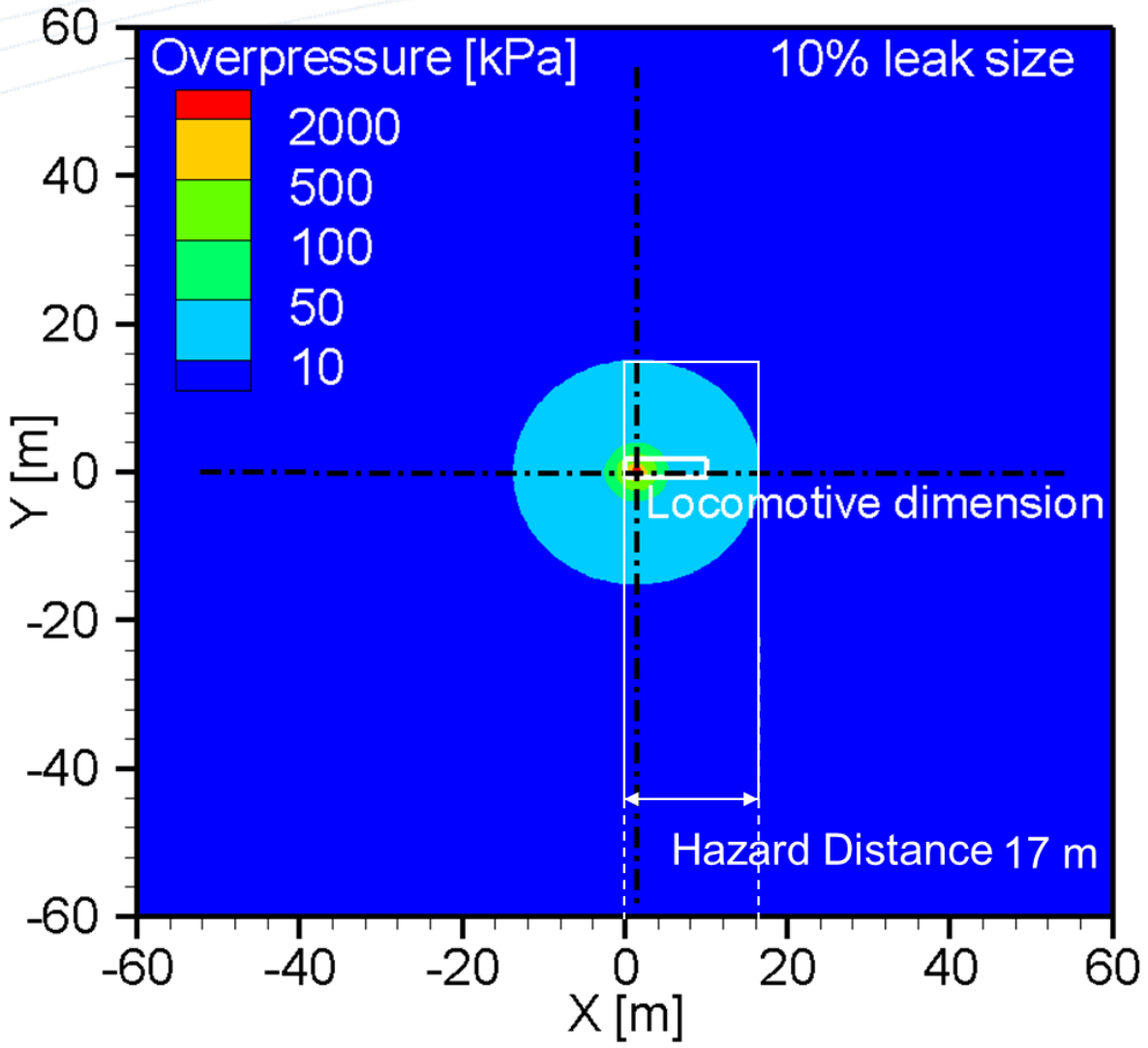

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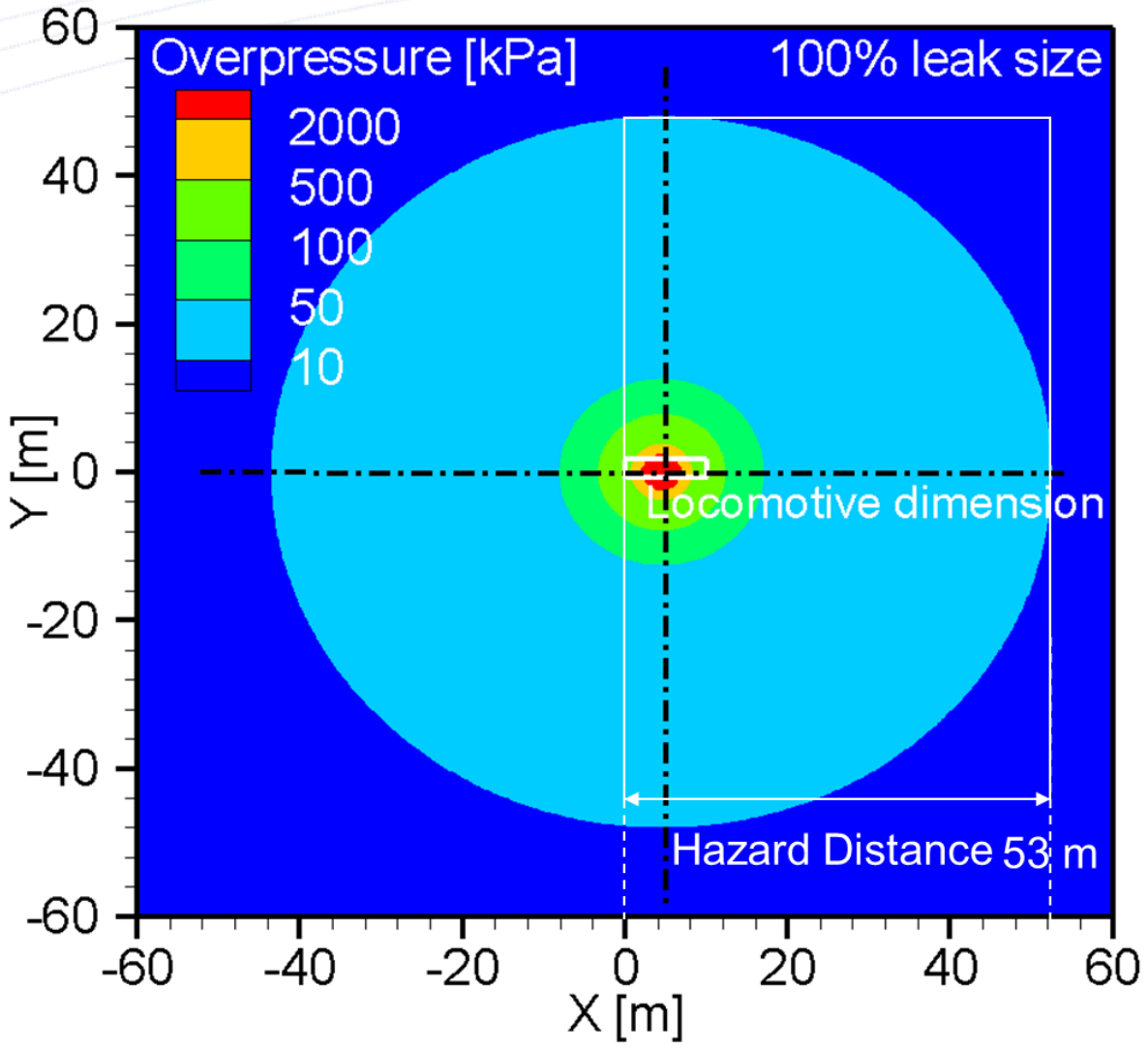
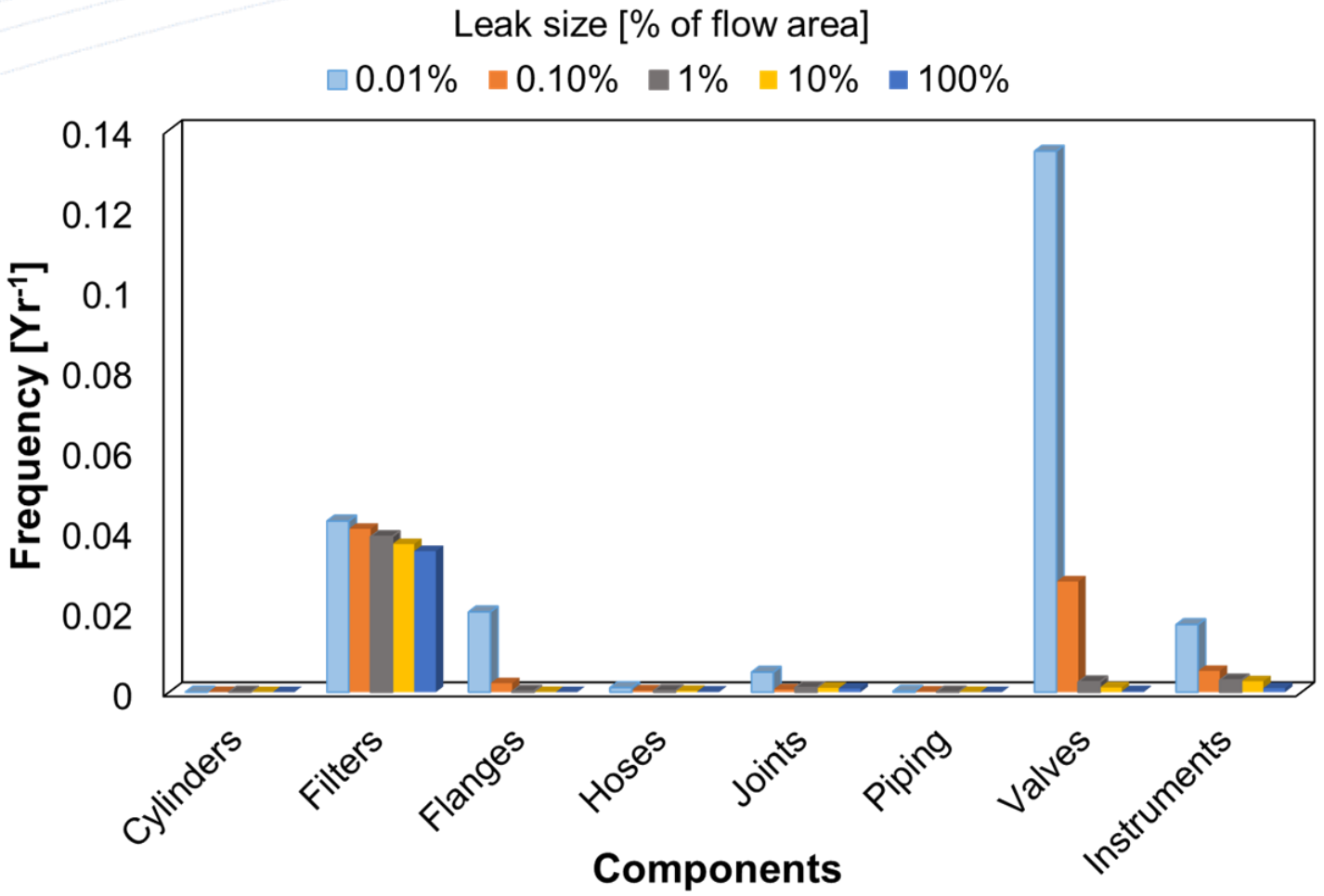
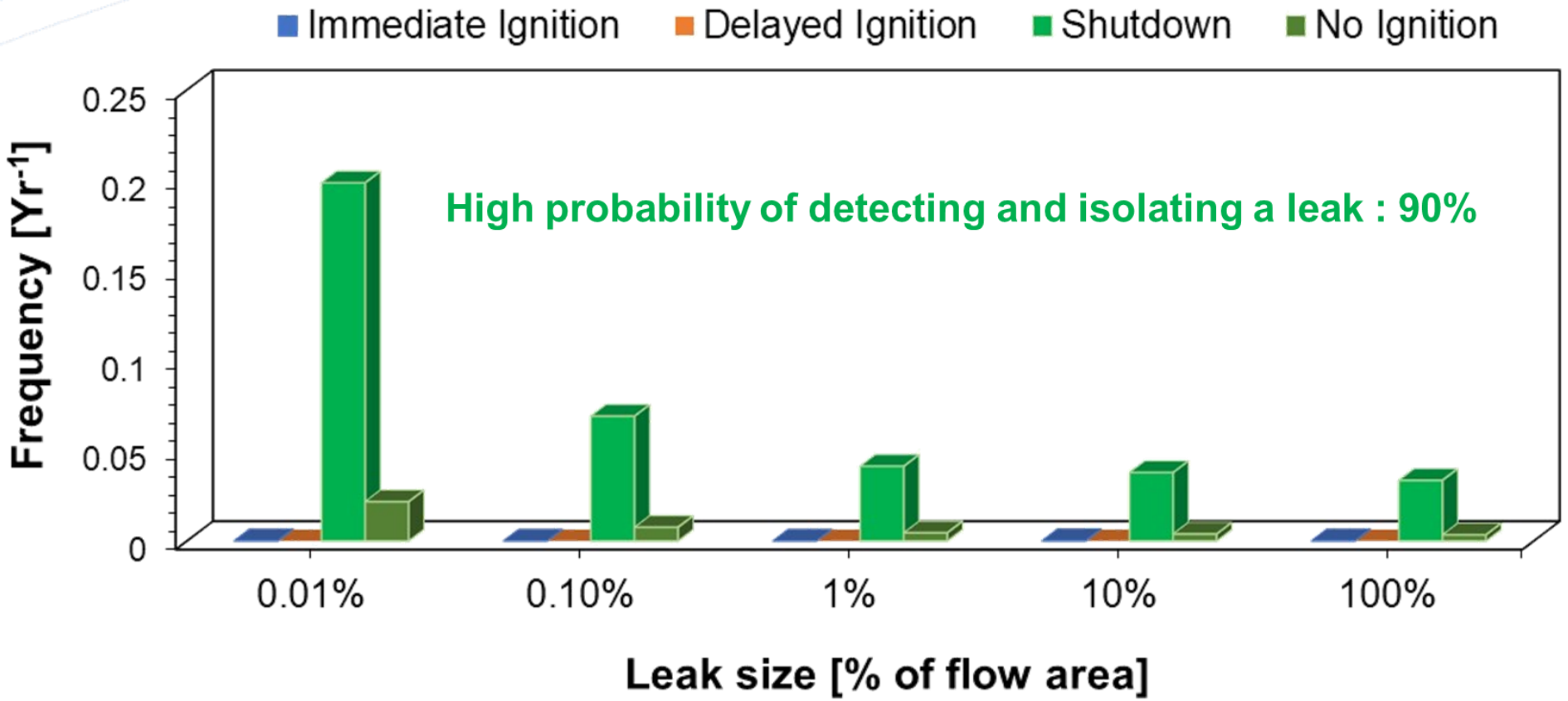


Case Study: Component Leak Frequency



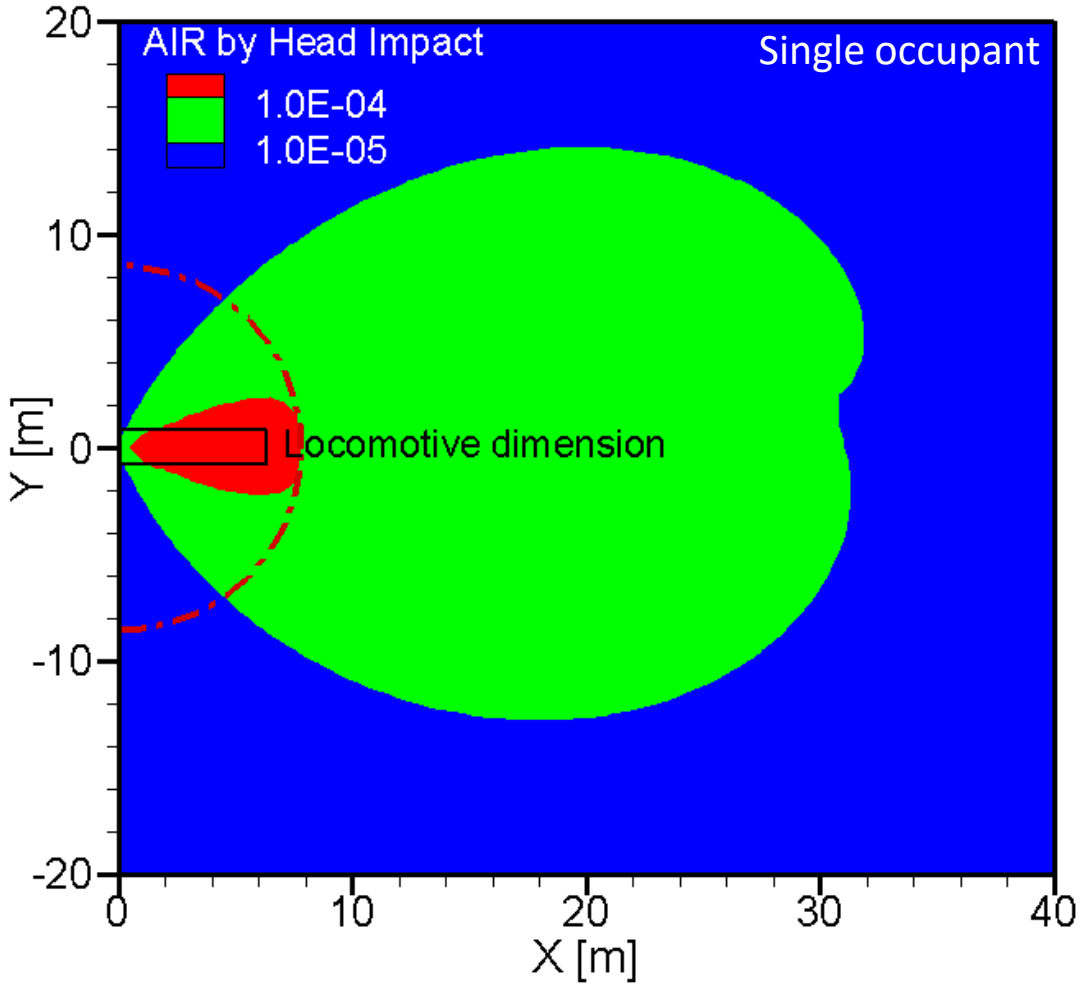
Ehrhart et al., HyRAM V 5.0 Technical Reference Manual

Case Study: All Event Frequencies



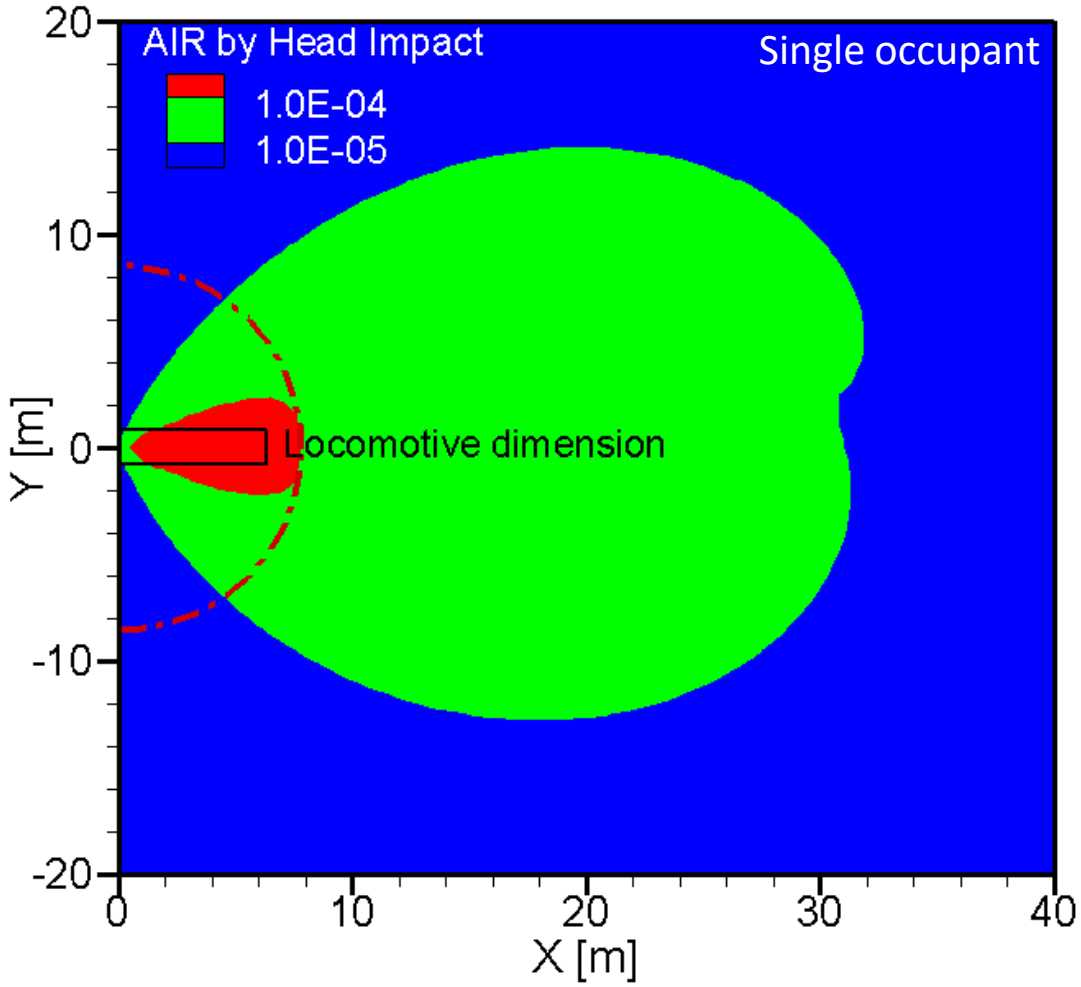
Case Study: Risk Metrics: Safe Separation Distance

AIR accounts for all leak sizes and events



Safe Separation Distance: 7.8 m

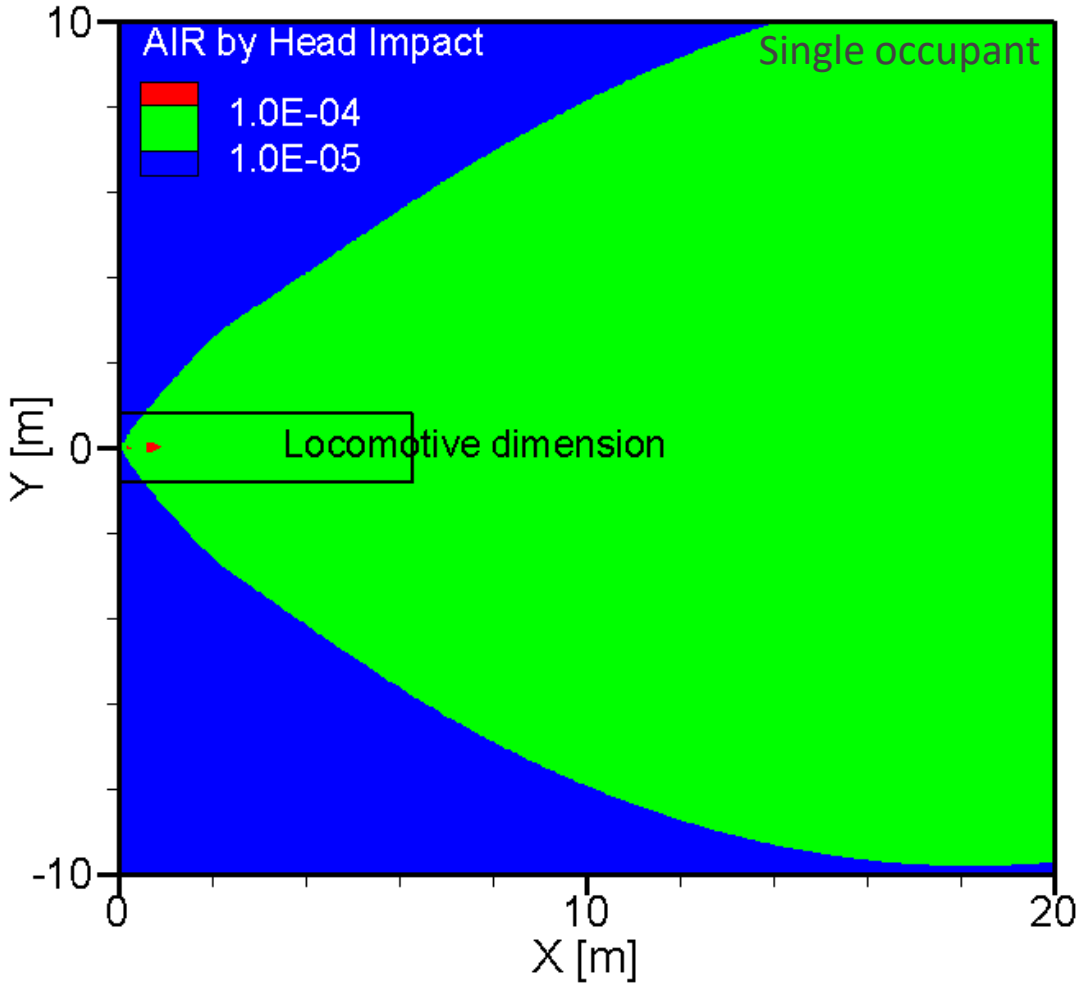
Case Study: Risk Metrics: Random Leak Frequency



100% leak size random frequency: 0.037 Yr^{-1}

Safe Separation Distance: 7.8 m

Case Study: Risk Metrics: Random Leak Frequency



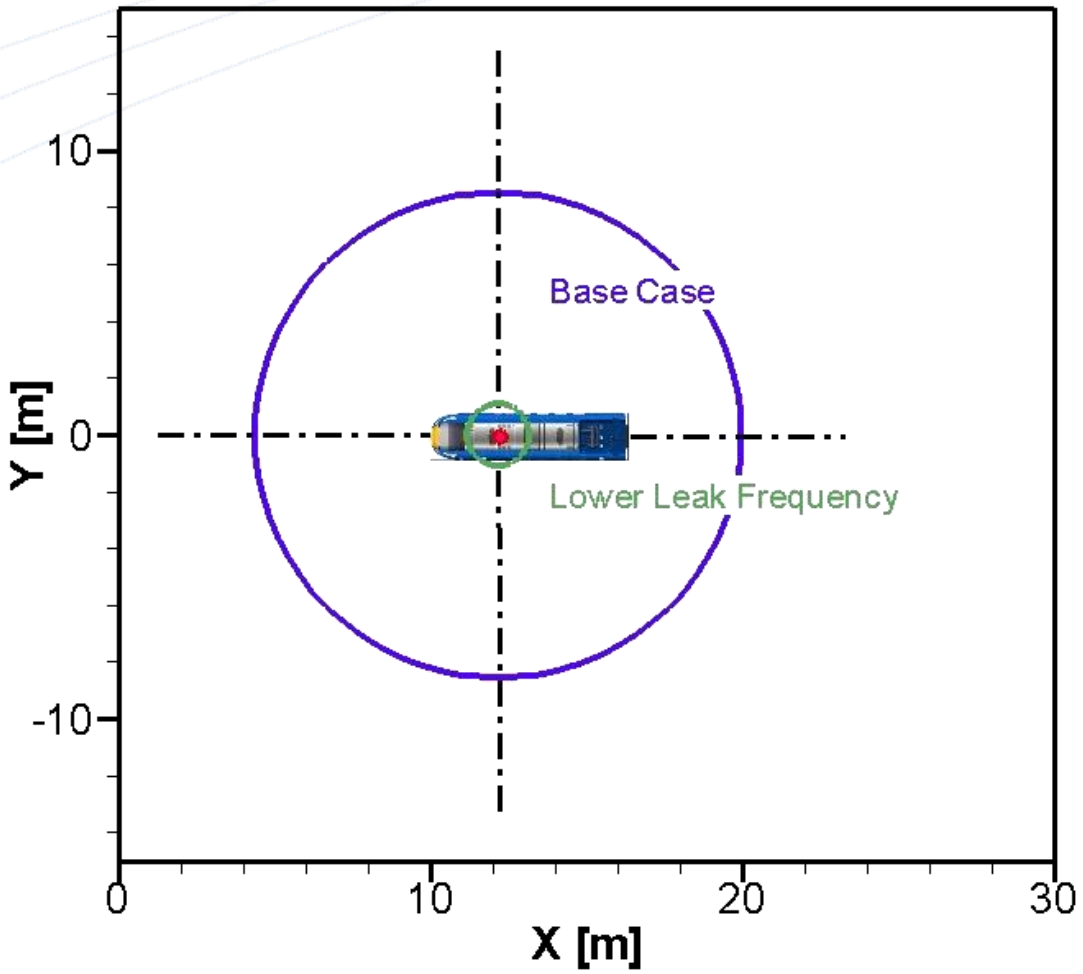
100% leak size random frequency: 0.037 Yr^{-1}

100% leak size random frequency: 0.012 Yr^{-1} ($^1/_2$ order low)

Safe Separation Distance: 7.8 m

Safe Separation Distance: ~ 1 m

Conclusions



- Scheduled Routine Maintenance
- Corrective and Preventive Action (CAPA) Plan
- Validated standard operating procedures
- Operating equipment within
  - Its recommended service life and
  - Manufacturer's allowable limits

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QUESTIONS