CERN

Estimating probability of fatalities in long tunnels with FDS and 1D human behavior

FCC Study Case

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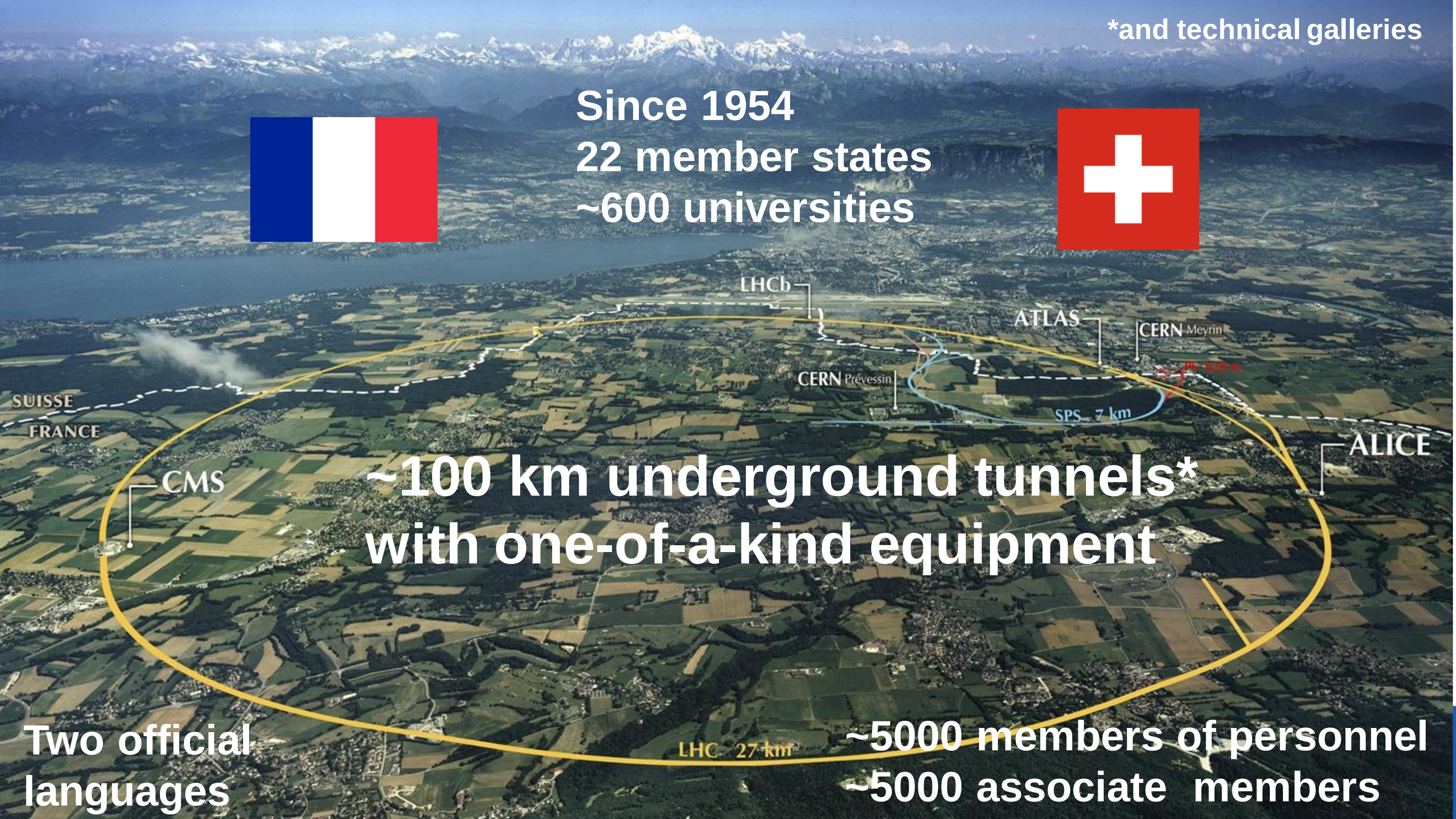
HSE-OHS-XP

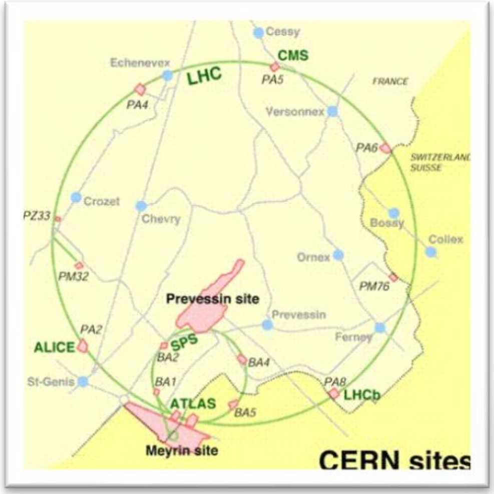
02-October - 2018

HSE

Fire Safety Engineering Team

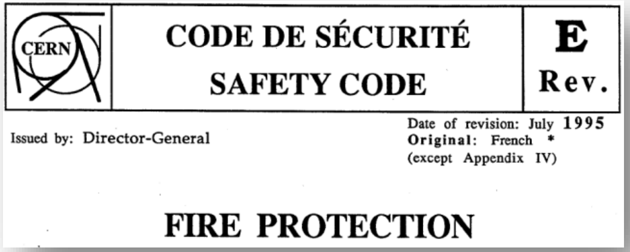

*and technical galleries
Since 1954
22 member states
~600 universities
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
~100 km underground tunnels*
with one-of-a-kind equipment
LHC 27 km
Two official
languages
~5000 members of personnel
~5000 associate members

Underground tunnels at CERN



5 km

27km length



CERN

CODE DE SÉCURITÉ

SAFETY CODE

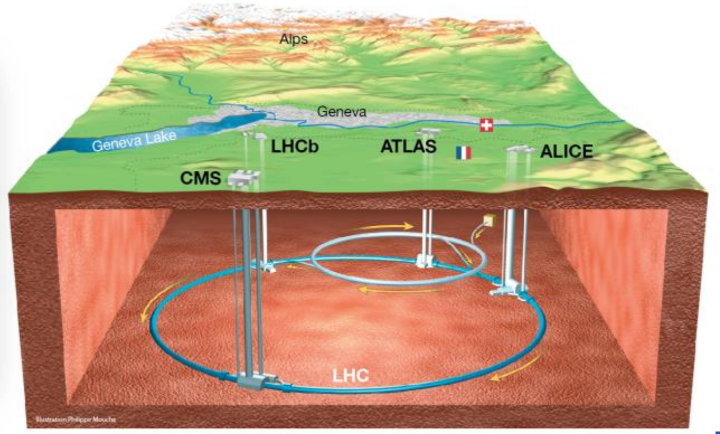
E

Rev.

Issued by: Director-General

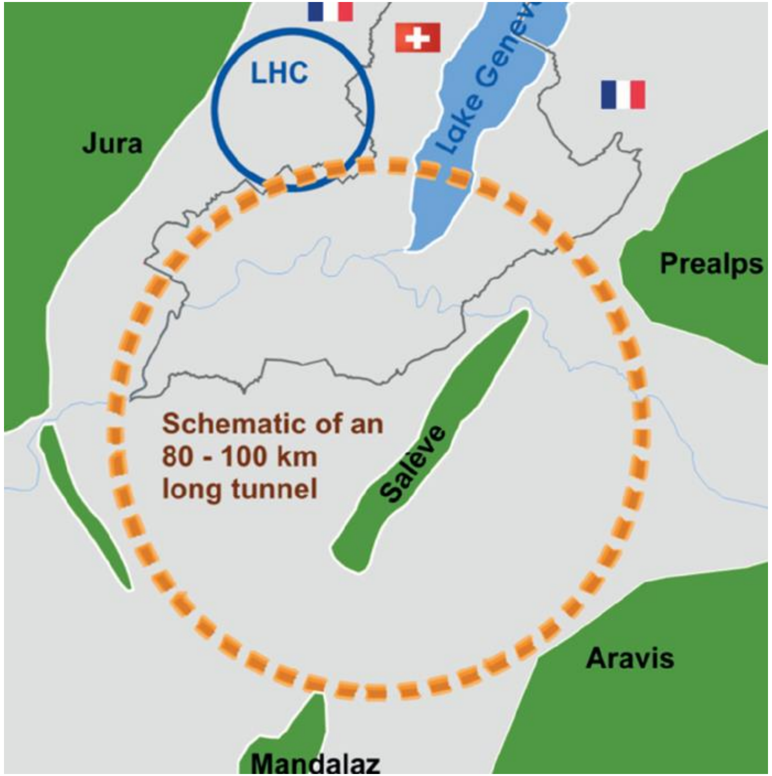
Date of revision: July 1995
Original: French *
(except Appendix IV)

FIRE PROTECTION

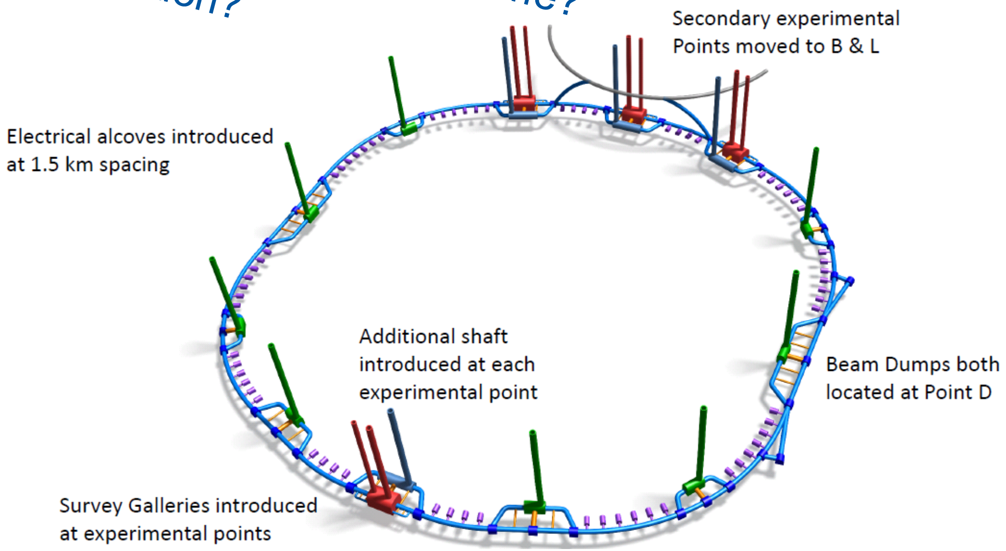


Future Circular Collider. FCC project

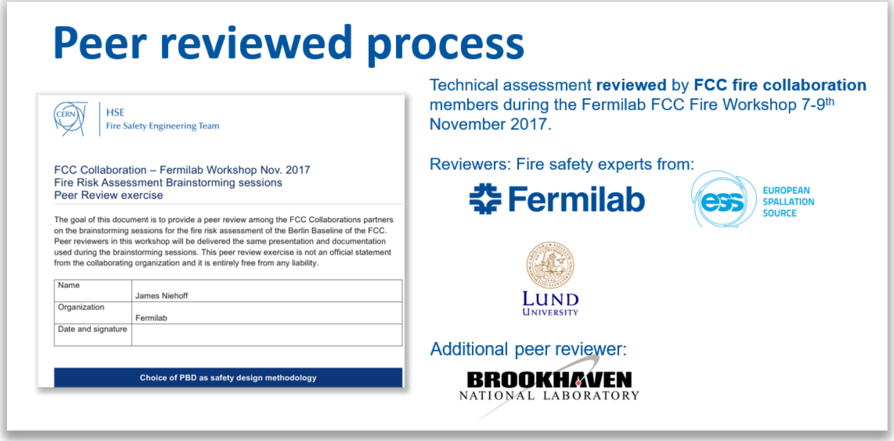
In numbers
~ 98km
~ 300-500 m underground
~ 6-10km between shafts

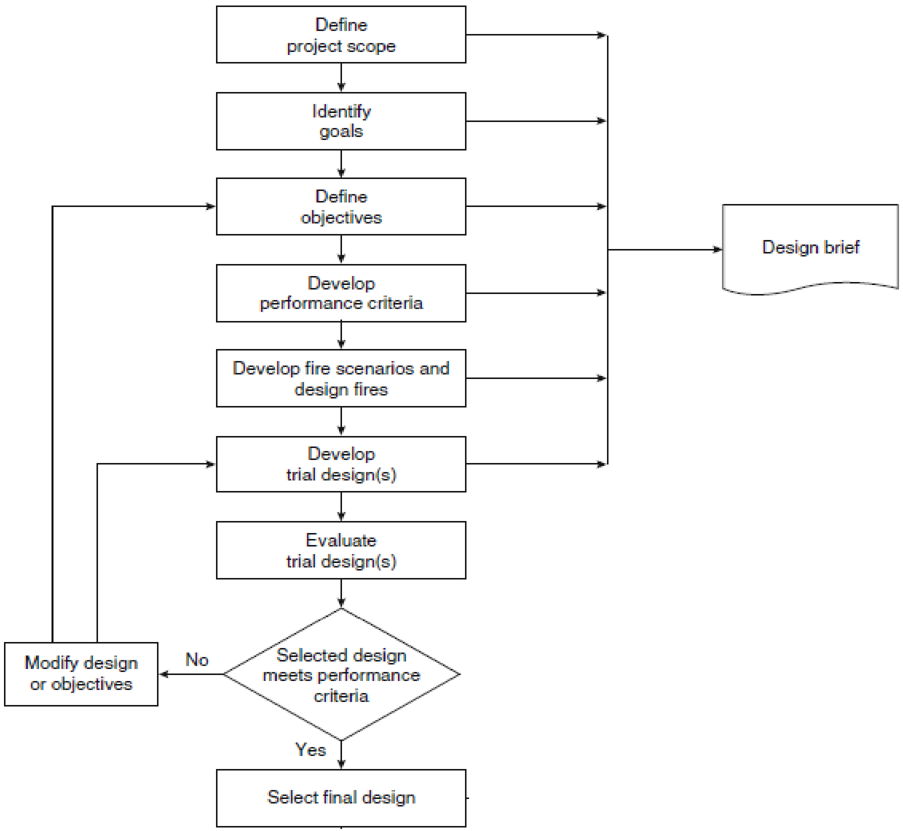


Evacuation time?
Intervention?
Response time?



PBD process:


Peer reviewed process
HSE
Fire Safety Engineering Team
FCC Collaboration – Fermilab Workshop Nov. 2017
Fire Risk Assessment Brainstorming sessions
Peer Review exercise
The goal of this document is to provide a peer review among the FCC Collaborations partners on the brainstorming sessions for the fire risk assessment of the Berlin Baseline of the FCC. Peer reviewers in this workshop will be delivered the same presentation and documentation used during the brainstorming sessions. This peer review exercise is not an official statement from the collaborating organization and it is entirely free from any liability.
Name James Niehoff
Organization Fermilab
Date and signature
Choice of PBD as safety design methodology
Technical assessment reviewed by FCC fire collaboration members during the Fermilab FCC Fire Workshop 7-9th November 2017.
Reviewers: Fire safety experts from:
Fermilab
ess EUROPEAN SPALLATION SOURCE
LUND UNIVERSITY
Additional peer reviewer:
BROOKHAVEN NATIONAL LABORATORY


Define project scope
Identify goals
Define objectives
Develop performance criteria
Develop fire scenarios and design fires
Develop trial design(s)
Evaluate trial design(s)
Selected design meets performance criteria
No
Modify design or objectives
Yes
Select final design
Design brief

Safety Objectives

Fire induced radiological hazard (to environment, to evacuees or interveners) is not in this study scope. Research in progress: FIRIA project.

	Life	Environment	Property	Continuity of operation
	A	B	C	D
1	Occupants shall be able to evacuate through protected areas, free from smoke/gas and other hazards at any time	Limit the release of polluting (incl. activated) agents to the environment in case of incident	The continuity of essential services and structural stability is assured in case of fire or gas release and other incidents	Limiting the downtime in case of incident
2	Victims and other occupants, not able to self-evacuate, shall reach protected areas, and wait there to be rescued by the intervention teams	Limit the volume of polluted (incl. activated) water released to the environment in case of incidents	An incident shall not cause other potentially dangerous accidental events	-
3	Rescue teams shall be able to intervene safely and according to current CERN SOPs	-	Limiting the property loss in case of incident	-

Acceptance Criteria (for Life Safety Objectives)

- **Occupants**

  Occupants shall be able to evacuate through protected areas, free from smoke/gas and other hazards at any time

- **Victims**

  Victims and other occupants, not able to self-evacuate, shall reach protected areas, and wait there to be rescued by the intervention teams

01 Any able occupant has a ***reasonable opportunity*** of **evacuating** the facility without reaching any of the following criteria:

- Visibility < 10m at 1.8m high
- Fractional Effective Dose (FED) > 0.1
- T > 60°C
- Heat flux > 2.5KW/m^2

In a later stage, the **probabilistic concept** could be introduced. (needs a call for a background study in the **acceptable individual risk** by the organization)
i.e.
reasonable opportunity = frequency greater than 10^{-3}/year

ces:
13571:2012. Life-threatening components of fire - Guidelines for the estimation of to compromised tenability in fires.
o Nazionale dei Vigili del Fuoco (2015). Codice di prevenzione incendi DM 3-8-2015

Acceptance Criteria (for Life Safety Objectives)

- **Occupants**

  Occupants shall be able to evacuate through protected areas, free from smoke/gas and other hazards at any time

- **Victims**

  Victims and other occupants, not able to self-evacuate, shall reach protected areas, and wait there to be rescued by the intervention teams

- **Firefighters**

  Rescue teams shall be able to intervene safely and according to current CERN SOPs

04 Firefighter safety requires that closest **safe area** for firefighting (no imminent risk and no breathing apparatus needed) is **less than 450m away** from the door of the fire compartment.

05 In order to ensure firefighter safety and protection: during offensive operations, **extinguishing media available** for attack and search & rescue teams **matches fire development**, allowing firefighter protection and fire control under 3 minutes:

- 3 extinguishers of 9kg CO_2 if fuel mass is below 25kg;
- 100L portable CAFS on trailer up to 5MW;
- or 500LPM water hose line up to a maximum HRR of 20MW.

06 Firefighter safety is only guaranteed if engaged teams remain in **communication** at all times with surface incident command post

07 Structural stability of the premises during operations

Acceptance Criteria (for Life Safety Objectives)

- ## Occupants

  Occupants shall be able to evacuate through protected areas, free from smoke/gas and other hazards at any time

- ## Victims

  Victims and other occupants, not able to self-evacuate, shall reach protected areas, and wait there to be rescued by the intervention teams

- ## Firefighters

  Rescue teams shall be able to intervene safely and according to current CERN SOPs

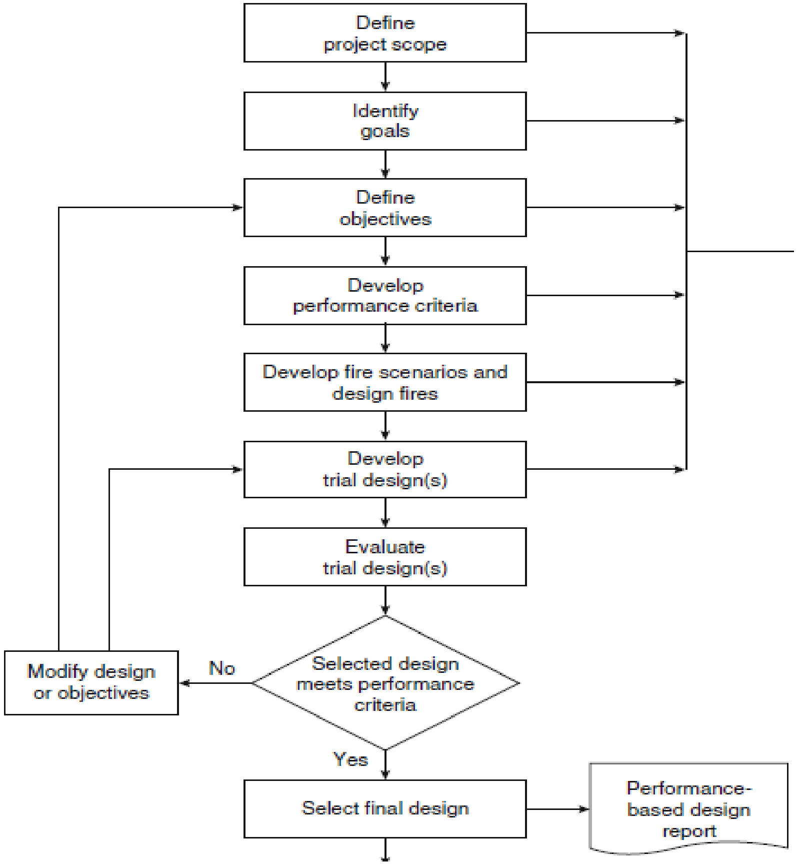
02 Any victim **outside the fire compartment** of the seat of the fire has *reasonable opportunity* of **not reaching a FED>0.1** before being rescued by intervention teams

03 Within the fire compartment of the seat of the fire, any of the two following criteria is met:

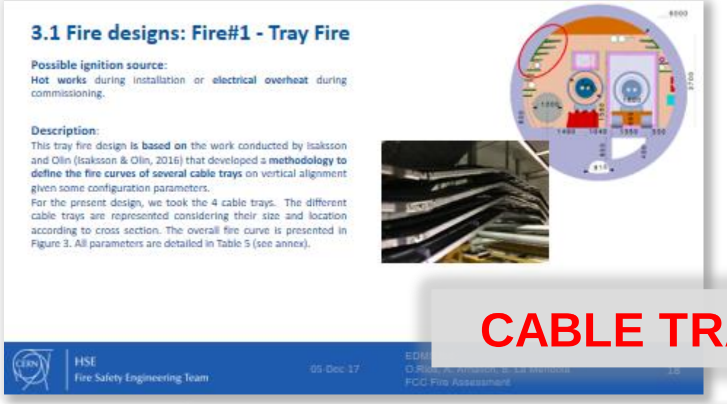
03a Fire compartment size and layout is such that there is a *reasonable opportunity* of **not having a victim in the interior**

03b Any victim has a *reasonable opportunity* of **not reaching a FED>0.3** before being rescued by intervention teams

PBD process:

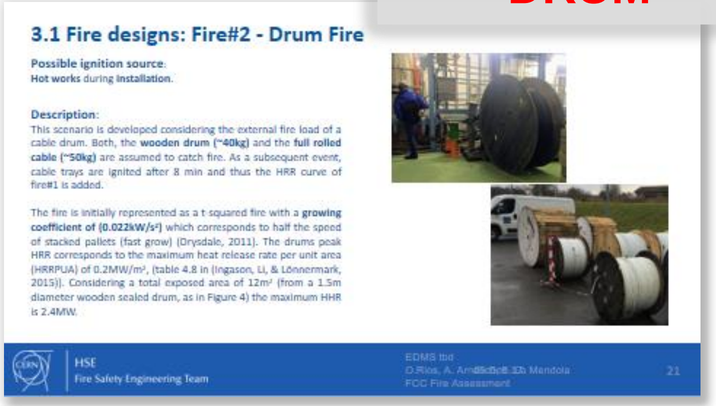

Define
project scope
Identify
goals
Define
objectives
Develop
performance criteria
Develop fire scenarios and
design fires
Develop
trial design(s)
Evaluate
trial design(s)
Selected design
meets performance
criteria
No
Modify design
or objectives
Yes
Select final design
Performance-
based design
report

Scenarios and Fire Designs



CABLE TRAY

DRUM

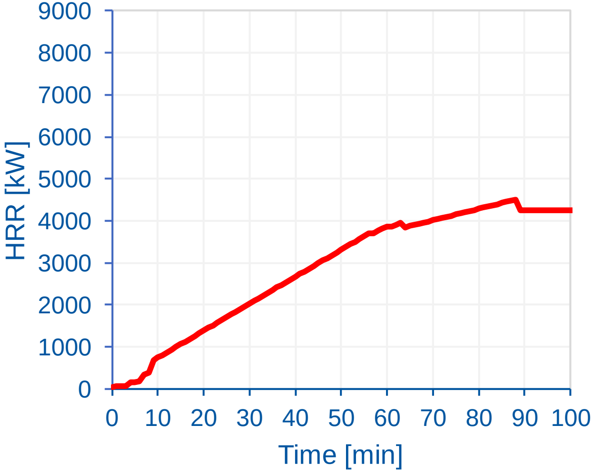


KUKA

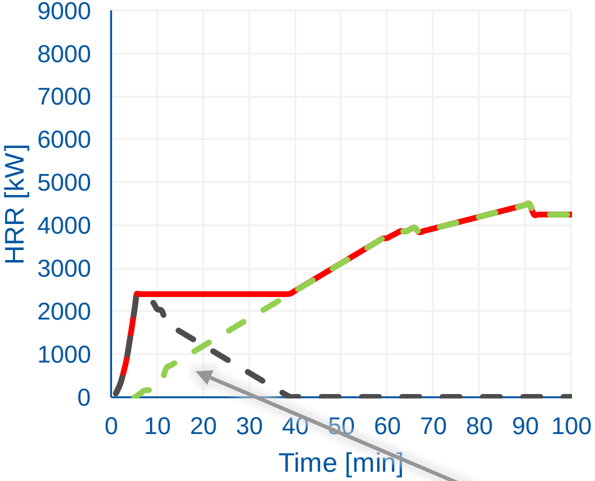
- Those 3 scenarios are considered to be more representatives ones
- Only fire scenarios are considered.
- Fire Scenarios resulting from explosions are not accounted for.

3.1 Fire designs: Enveloping cases

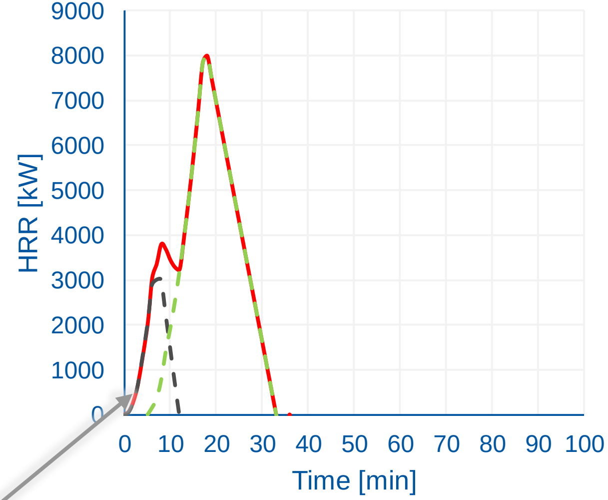
Fire#1 - Tray Fire



Fire#2 – Drum Fire



Fire#3 - Kuka Fire

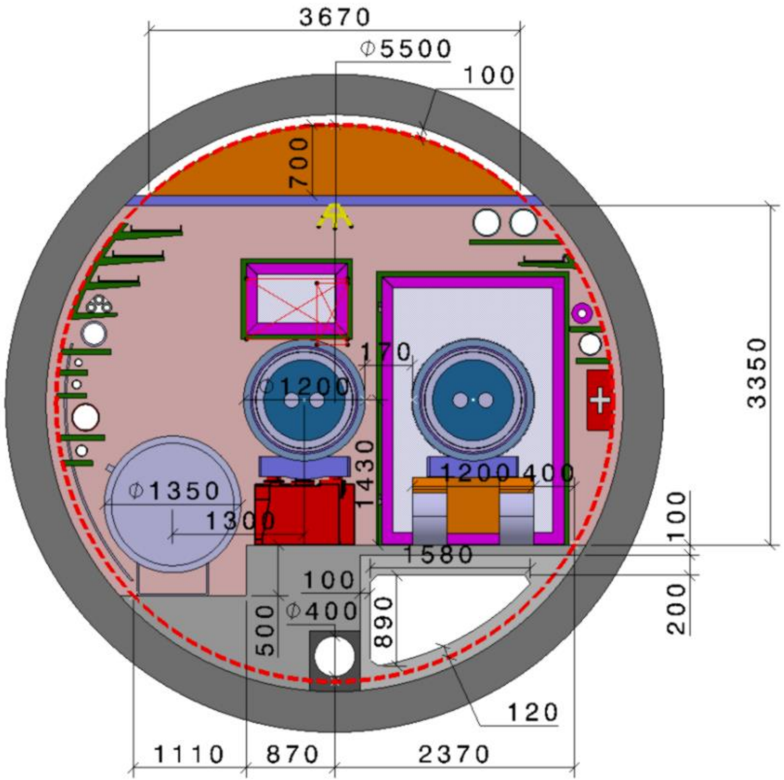


If compartmentation works, with current ventilation system HRR_{max} < 5MW (ventilation limited)

Fire#2 and Fire#3 have same growth up to 8min!

In all cases, the fire is assumed to be located at 1/3 of the length of the compartment

Geometry and safety measures

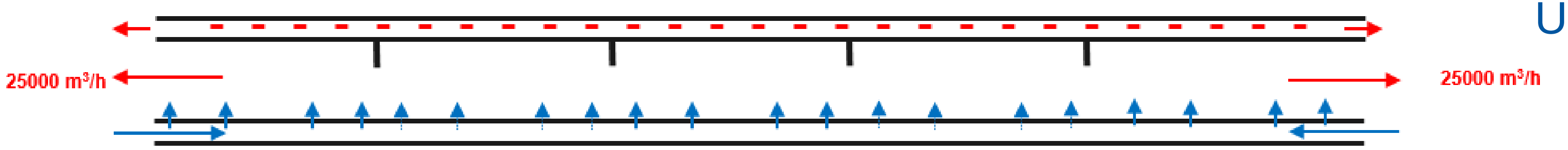


Baseline Safety Features

- Fire compartment = 440m
- Smoke extraction
- Air supply

Ventilation: Proposed Strategy

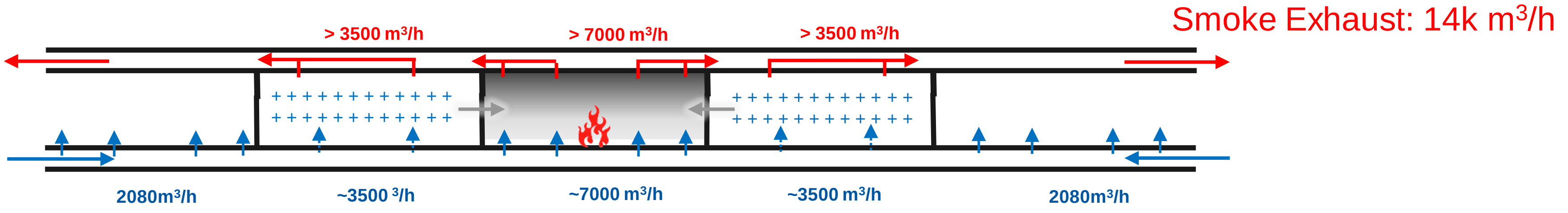
Normal Ventilation Condition



Uo=~ 0.5

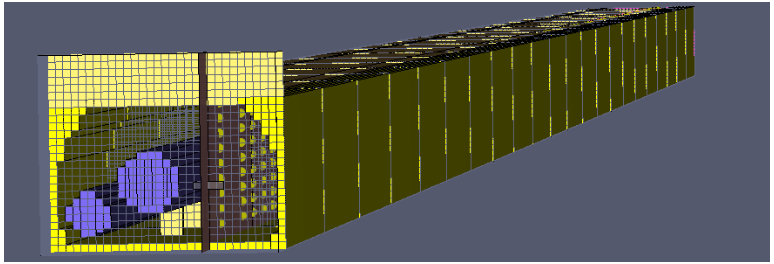
Ventilation: Proposed Strategy

When Fire is detected in a compartment



- 3 compartment doors closes (fire compartment and neighbours)
- Air inlets remain as normal condition.
- All arc outlets close, except for:
  - 4 in the fire compartment
  - 2 in adjacent compartments
- Exhaust duct extracts total flow of **14000m^3/h (~1/3 of nominal fans power)**
- **Overpressure** created in neighbouring compartments
- Normal longitudinal ventilation in all other compartments (or not, not influence)
- Fast reaction. Only action dampers in the fire compartment. Duct under pressured.

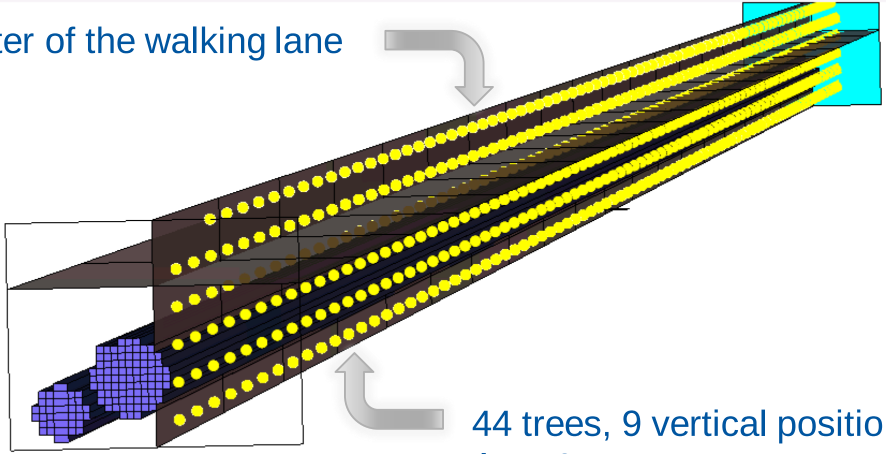
FDS set up
1 Compartment (440m) modelled



$\sim 2 - 16 \cdot 10^6$ cells

HPC to get reasonable computational times

Center of the walking lane



2m from floor

44 trees, 9 vertical positions
$\Delta z = 0.4m$
$\Delta x = 10m$

OUTPUTS

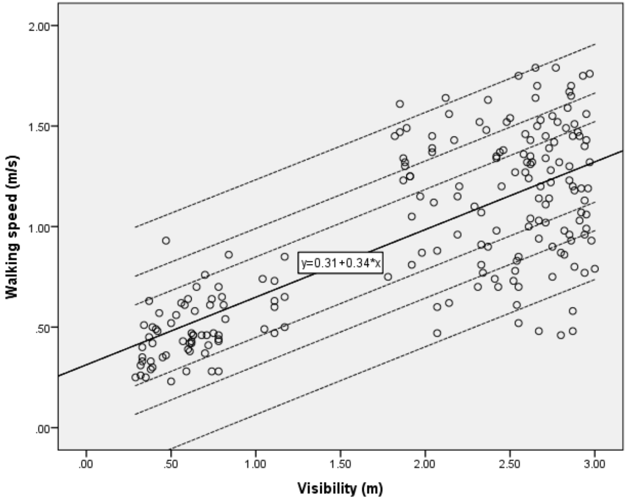
Slide Files
- Temperature
- Velocity

Vertical Trees
- Temperature
- O_2
- CO
- Visibility
- FED

Visibility Model & Human Behavior

Human Speed

Reduced velocity due to visibility



Walking speed as a function of visibility by Fridolf et al (2016).

$$v' = 0.34V + 0.31 \qquad V_{cor} = \min(v', v_o)$$

S. Arias, E, Ronchi, Lund University

Yields of toxic and asphyxiants

Polyurethane data from Beard et al. (2005)

Species	Yield [-]	Molar Mass [g]
CO_2	1.5	44
CO	0.027	28

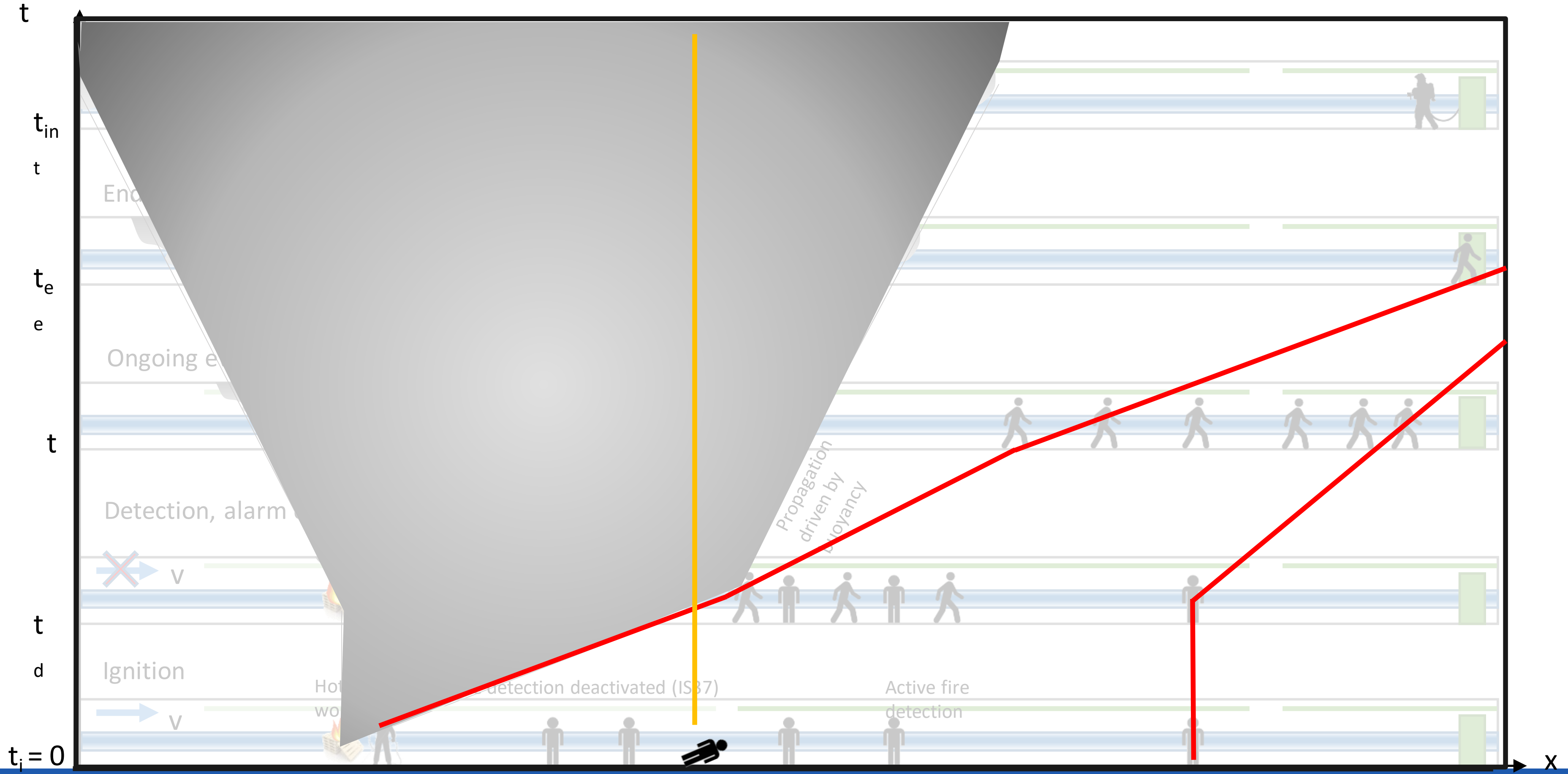
Soot Yield = 0.1

Hyperventilation

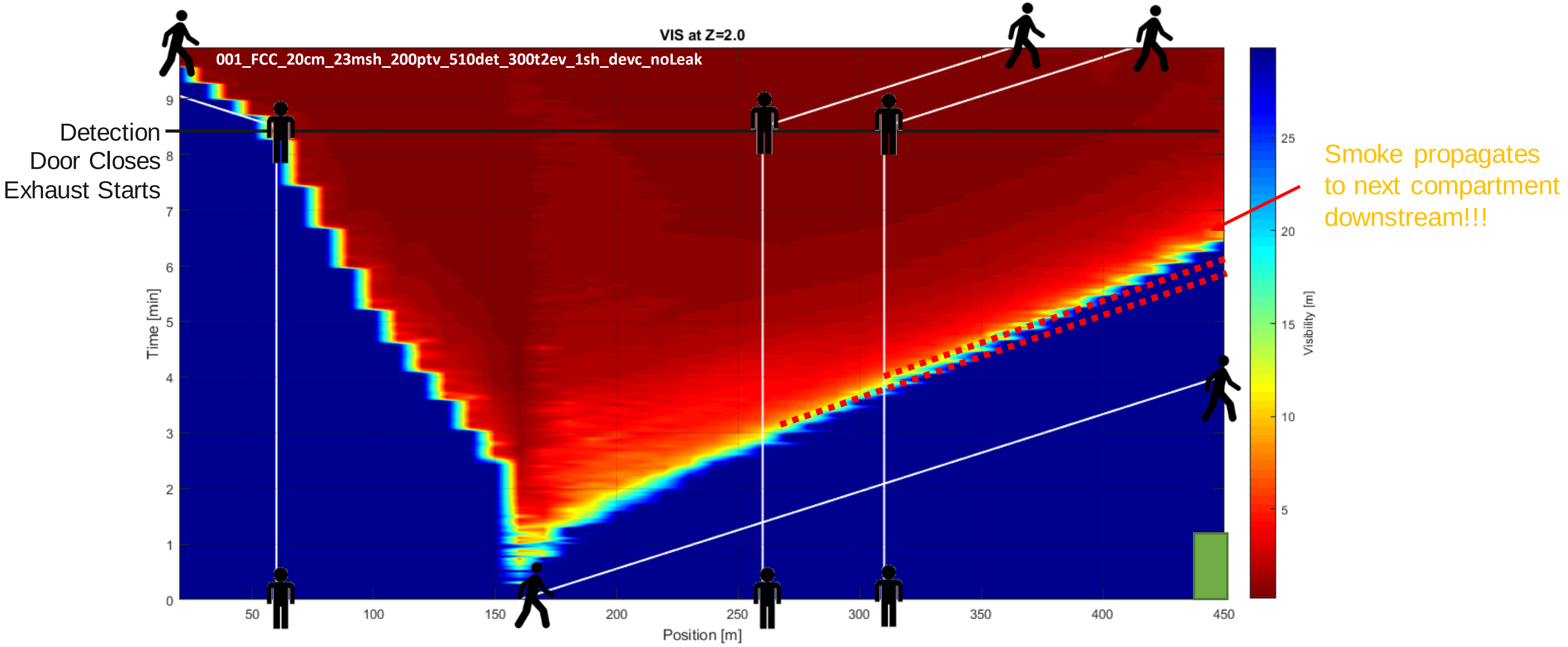
$$v_{co2} = \begin{cases} 1, & X_{co2} < 2\% \\ e^{co2/5}, & X_{co2} < 2\% \end{cases}$$

Unimpeded Human speed, $v_o = 1$ m/s

As: ISO/TS 13571(International Standards, 2012, Purser, 2008)

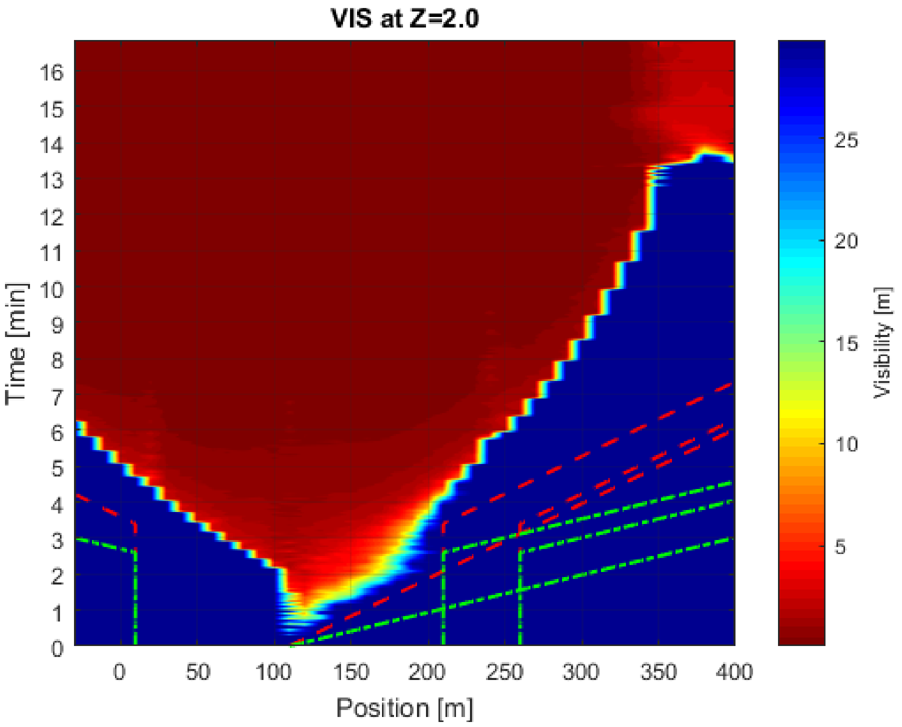

t
t_{in}
t
End
t_e
e
Ongoing e
t
Propagation driven by buoyancy
Detection, alarm
v
t
d
Ignition
Hot wo
detection deactivated (IS37)
Active fire detection
v
$t_i = 0$
x

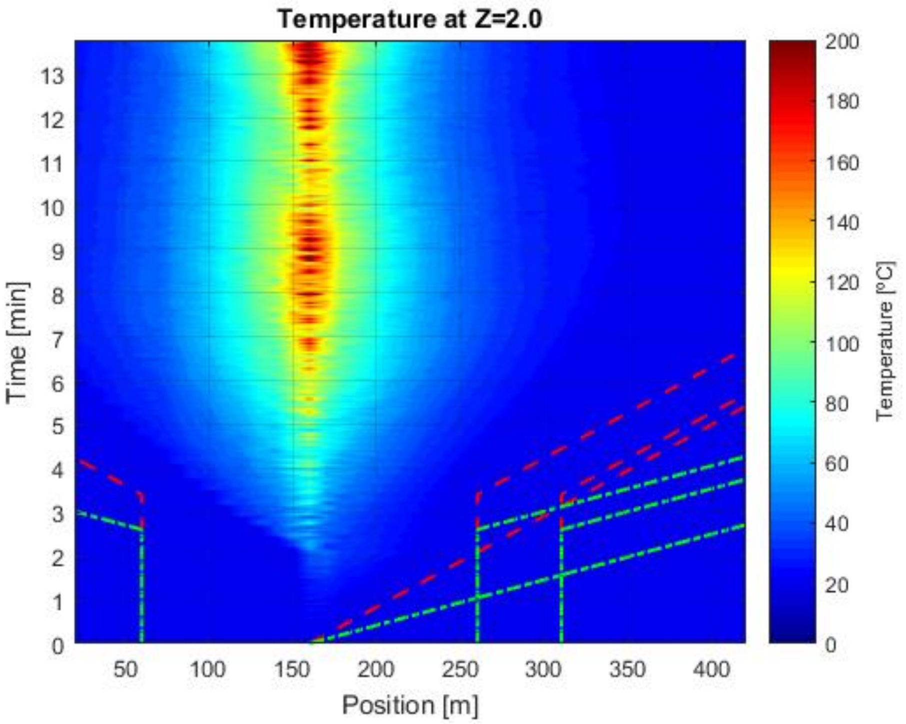
Berlin Baseline. Det. 510s. No supply. Emergency extraction 300s to ramp up. FIRE#2 and FIRE#3



Visibility and Temperature: Fire#3

Life Safety objective met !





Victims: FED calculations

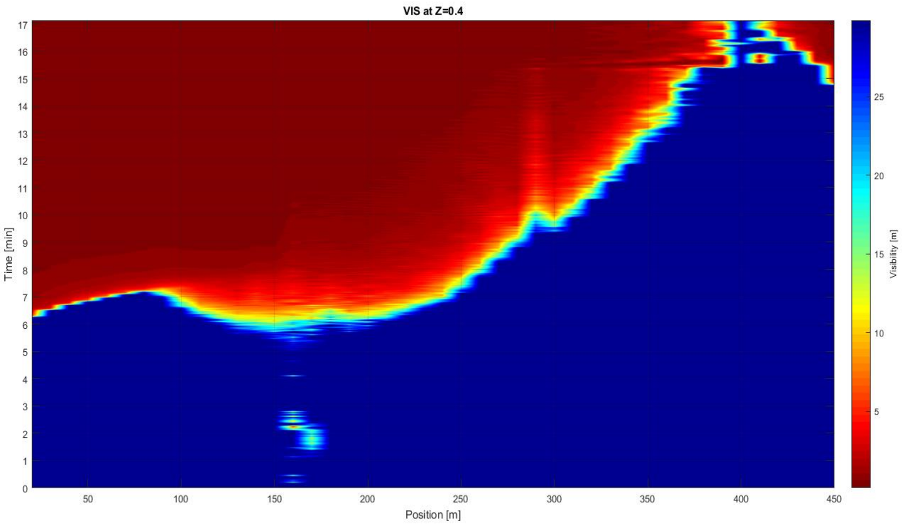
03 Within the fire compartment of the seat of the fire, any of the two following criteria is met:

03a Fire compartment size and layout is such that there is a *reasonable opportunity* of not having a victim in the interior

03b Any victim has a *reasonable opportunity* of not reaching a FED>0.3 before being rescued by intervention teams

1

Visibility at Z=0.4m



2

FED calculations

$$FED_{total} = (FED_{co} + FED_{CN} + FED_{NO_x}) \times HV_{CO_2} + FED_{O_2}$$

$$\mathrm{FED}_{O_2} = \int_0^t \frac{dt}{\exp[8.13 - 0.54(20.9 - C_{O_2}(t))]}$$

$$\mathrm{HV}_{CO_2} = \frac{\exp(0.1903\, C_{CO_2}(t) + 2.0004)}{7.1}$$

- CO intoxication
- O_2 ODH
- CO_2 hyperventilation

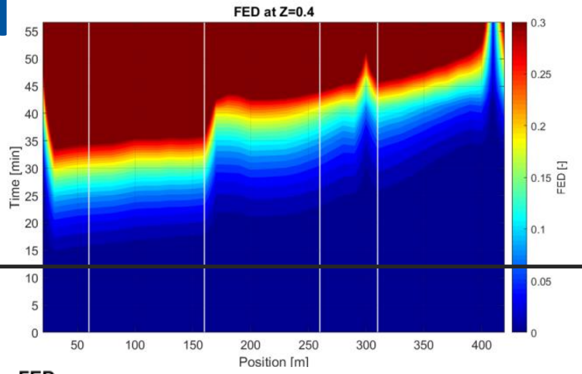
Further knowledge of combustion material not available

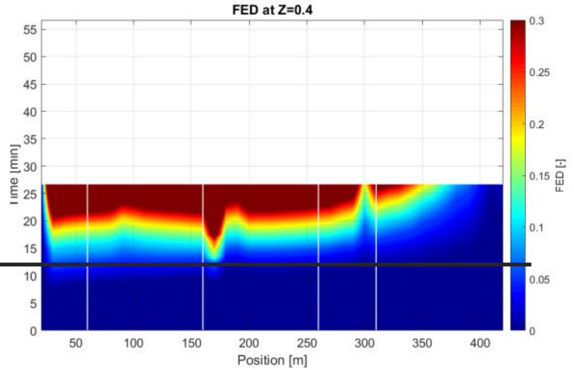
Extrapolation required

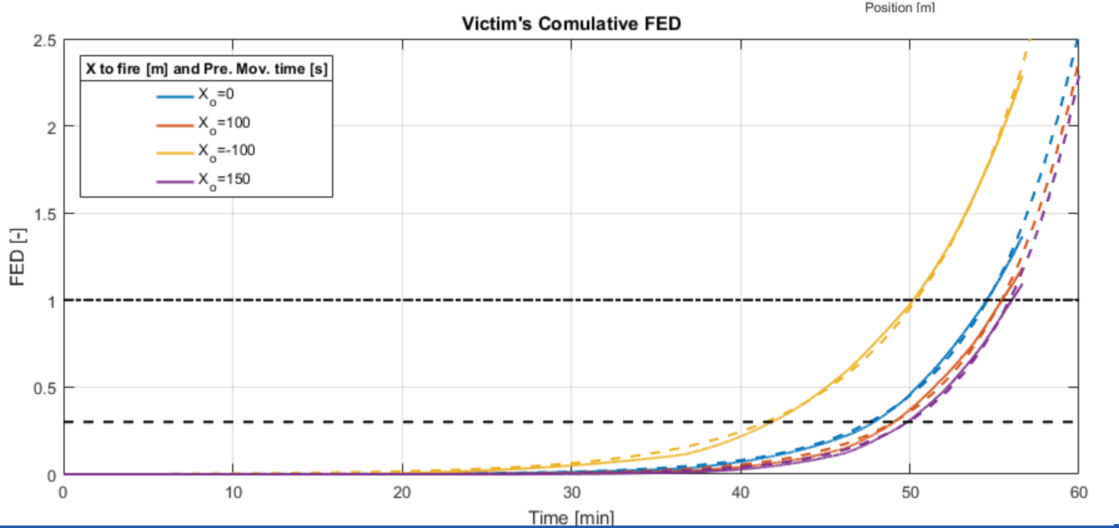
$$FED(t) = ae^{b(t-t_o)}$$

$t_o \rightarrow FED(t_0) > 1e-16$

Different t_o

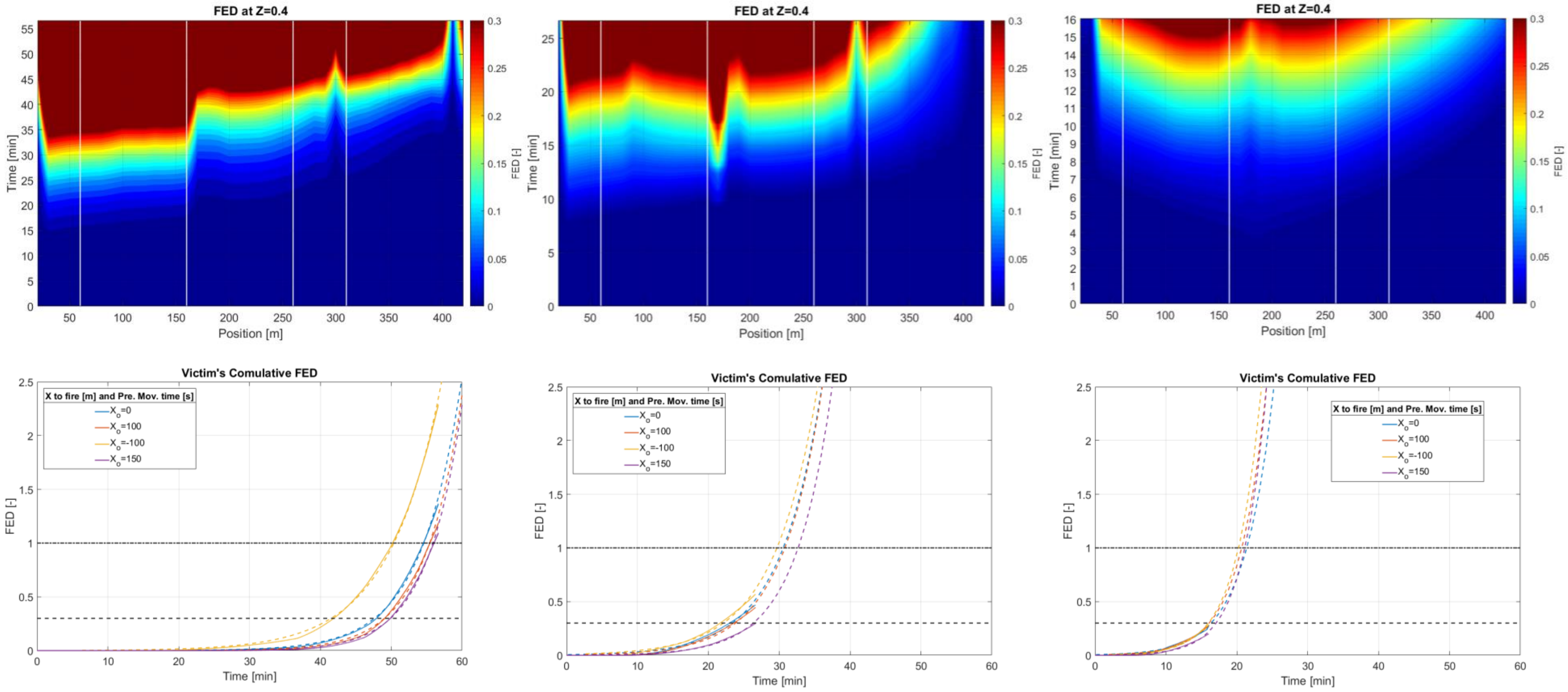




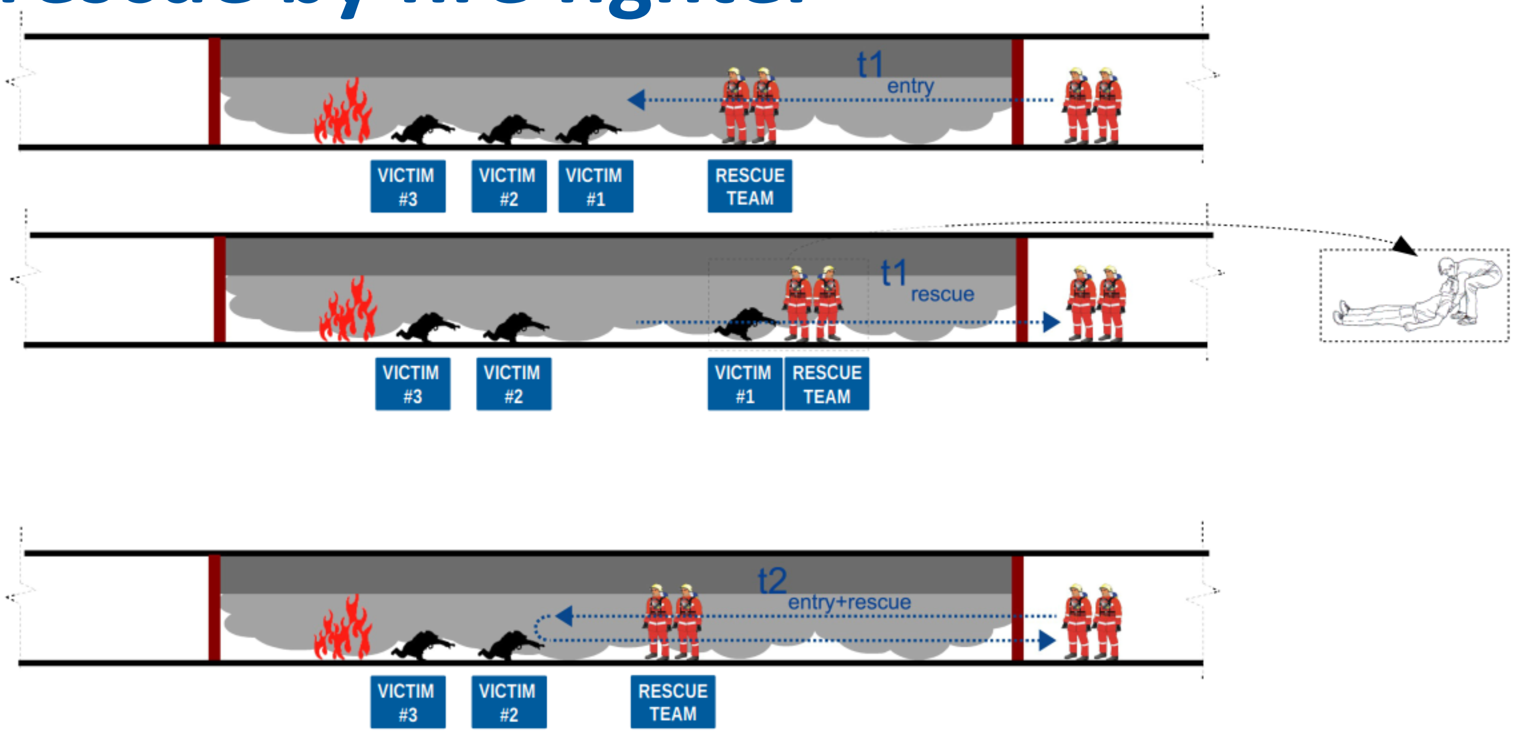


Extremely good fitting!
(data coming from CFD model...)

Fire#1 Fire#2 Fire#3



Victims rescue by fire fighter



⋮ ***n*** **victims...**

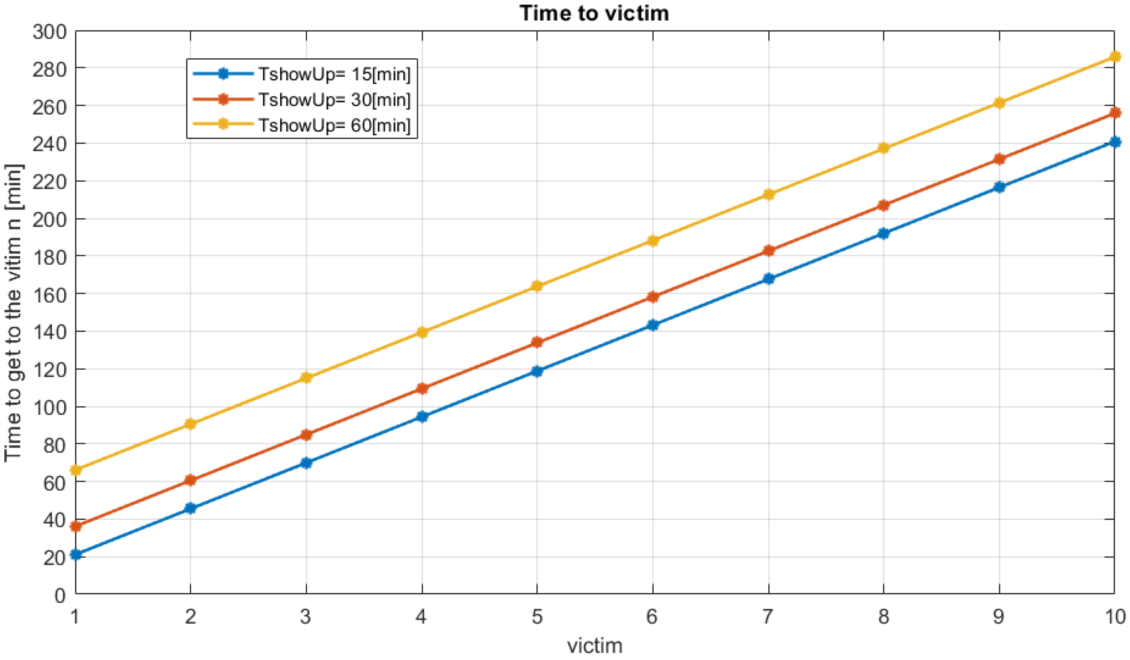
Fire Fighting Victims rescue

SPS Fire Safety Study Group / Firefighting Tactical Approach , July 2015

Operation	Speed
Blind progression	0.8m/s
Carrying victim	0.26m/s

Rescue mask considered!

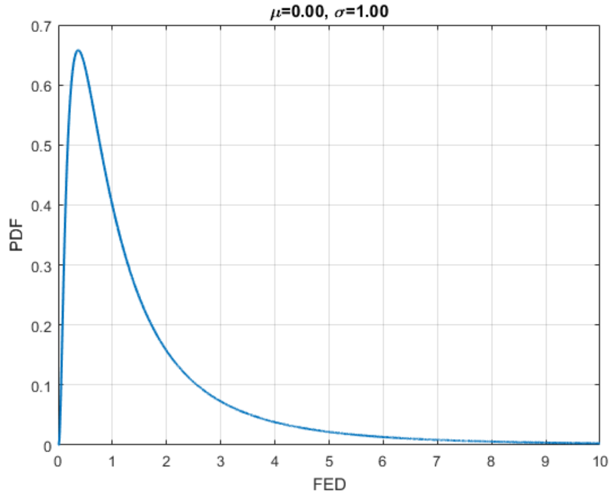
Fire Fighting Victims rescue

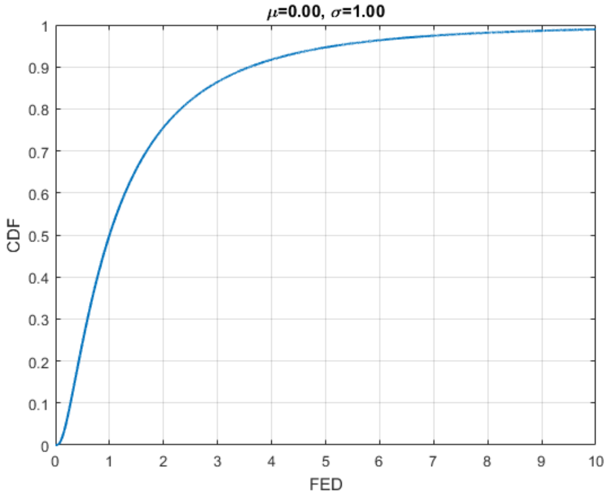


T Show Up [min]	Case
15	FF ready at the bottom of each shaft (LTS, ST)
30	FF on each shaft (surface)
60	FF every two shaft (surface)

On FED distribution

$$\mathbf{LogNormal}(\mu = 0, \sigma = 1)$$





Meaning

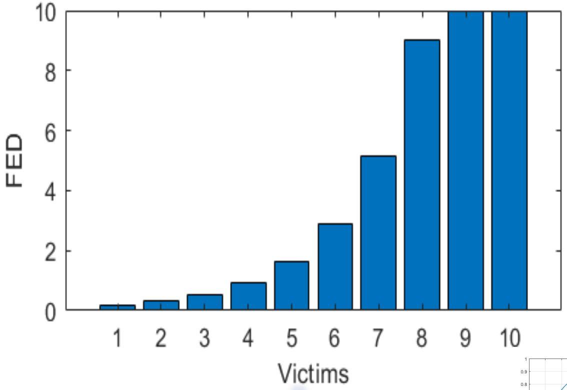
FED	P dying*
0.1	1%
0.3	11%
1	50%
2	76%
3	86%
4	92%

*or being incapacitated

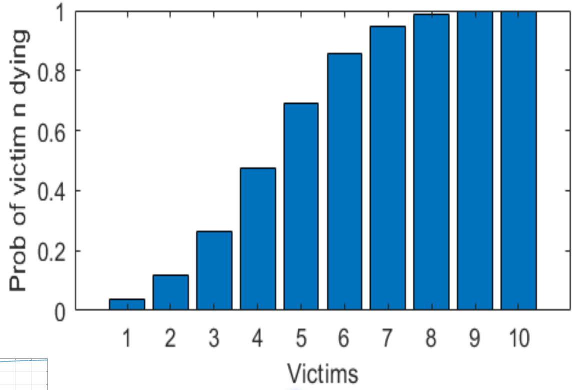
FED to every victim and dying probability

TshowUp = 30min
Victims Location = 50m from door

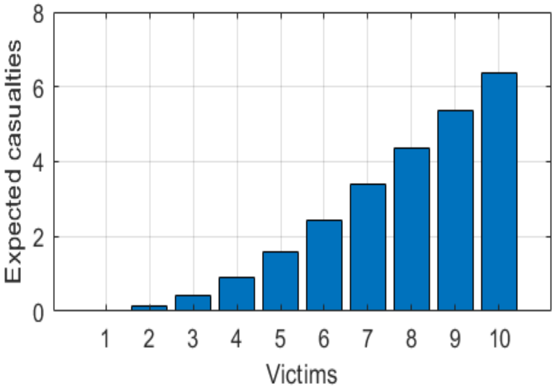
FED

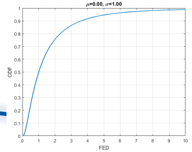


FED → Dying prob.



Expected #fatalities| #vict.





$\mathbf{LogNormal}(\mu = 0, \sigma = 1)$

FED

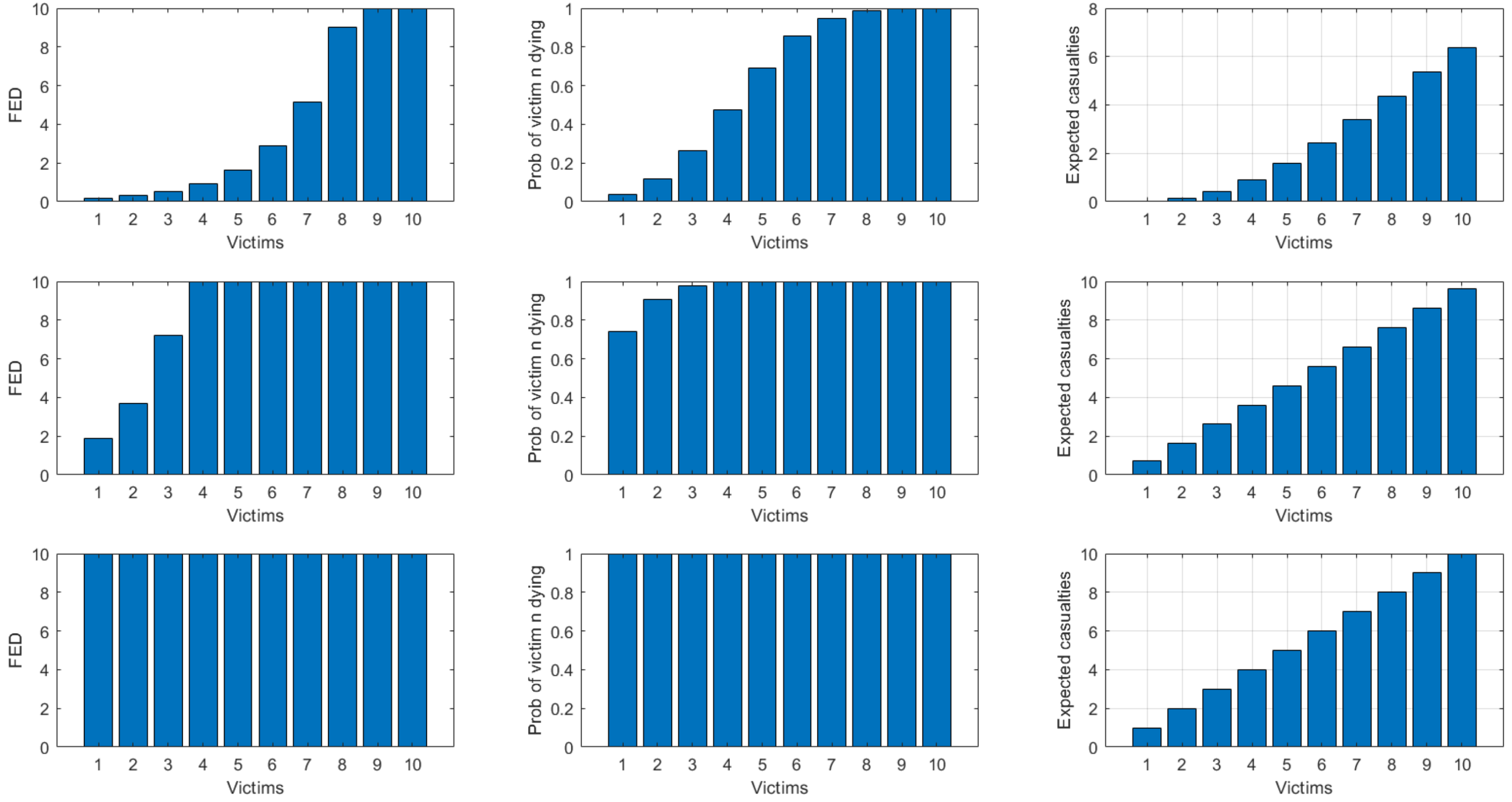
TShowUp=30min, 50m from door

FED | **FED → Dying prob.** | **Expected #fatalities| #vict.**

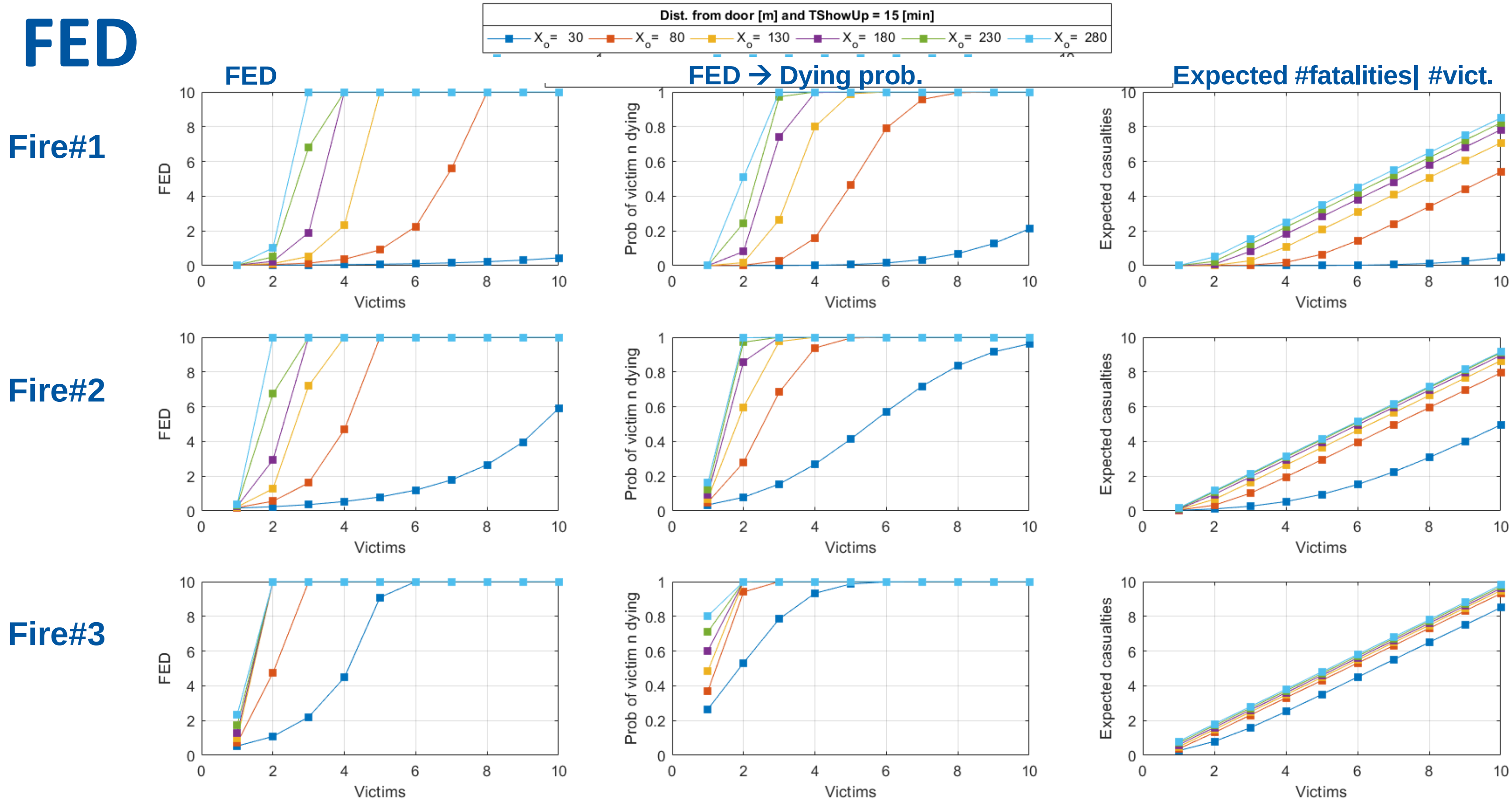
Fire#1

Fire#2

Fire#3



FED


Dist. from door [m] and TShowUp = 15 [min]
X_o = 30
X_o = 80
X_o = 130
X_o = 180
X_o = 230
X_o = 280
FED
FED → Dying prob.
Expected #fatalities| #vict.
Fire#1
Fire#2
Fire#3
FED
Prob of victim n dying
Expected casualties
Victims

Conclusions on Victims assessment

Victims (impeded occupants) that can be potentially saved*.

10 victims (impeded occupants) considered

Vict. Loc.	FIRE #1		FIRE #2		FIRE #3	
Show Up t	30m	280m	30m	280m	30m	280m
15 min	ALL	2	1	0	0	0
30 min	6	1	0	0	0	0
60 min	0	0	0	0	0	0

*A victim with a dying probability > 0.8 → fatality

Conclusions

- PBD approach was a sound approach to help designing a safe infrastructure and proof the safety systems performance
- FDS was necessary to solve the ventilation scenarios and corresponding flows
- Some uncertainties and discrepancies behind FED calculations. If used consistently, it could be an indicator for probabilistic quantification of consequences
- Quantitative risk analysis might be necessary to stablish the cost-benefit solutions and check the results against acceptable risk profile limits

Further work

- Use FED as a robust indicator for Quantitative Risk assessments.
- Exploration of FED addition throughout victims and probabilistic meaningful
- Better characterization of yields of our combustibles

FIRIA
PROJECT

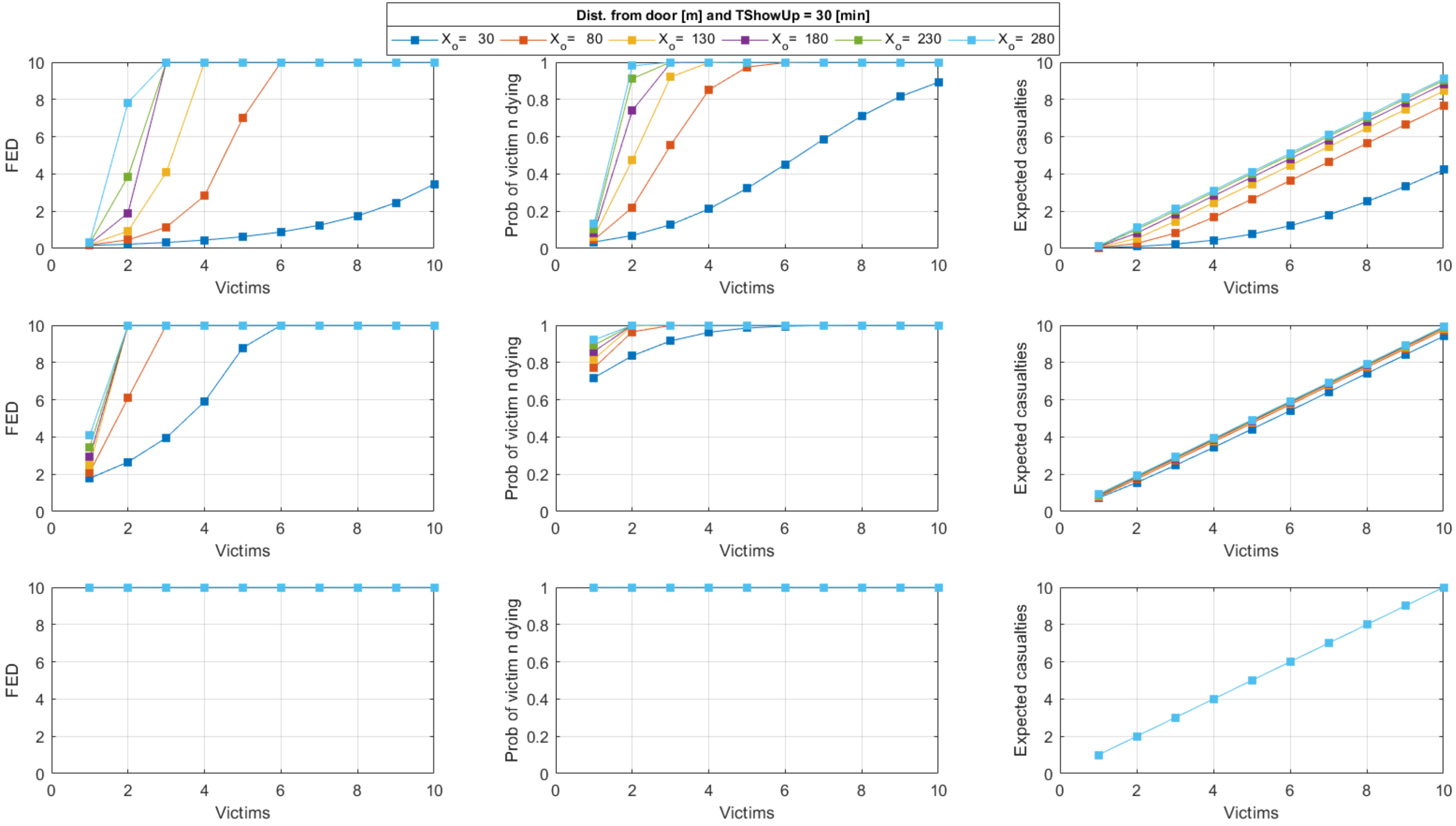
CERN

FED

Fire#1

Fire#2

Fire#3

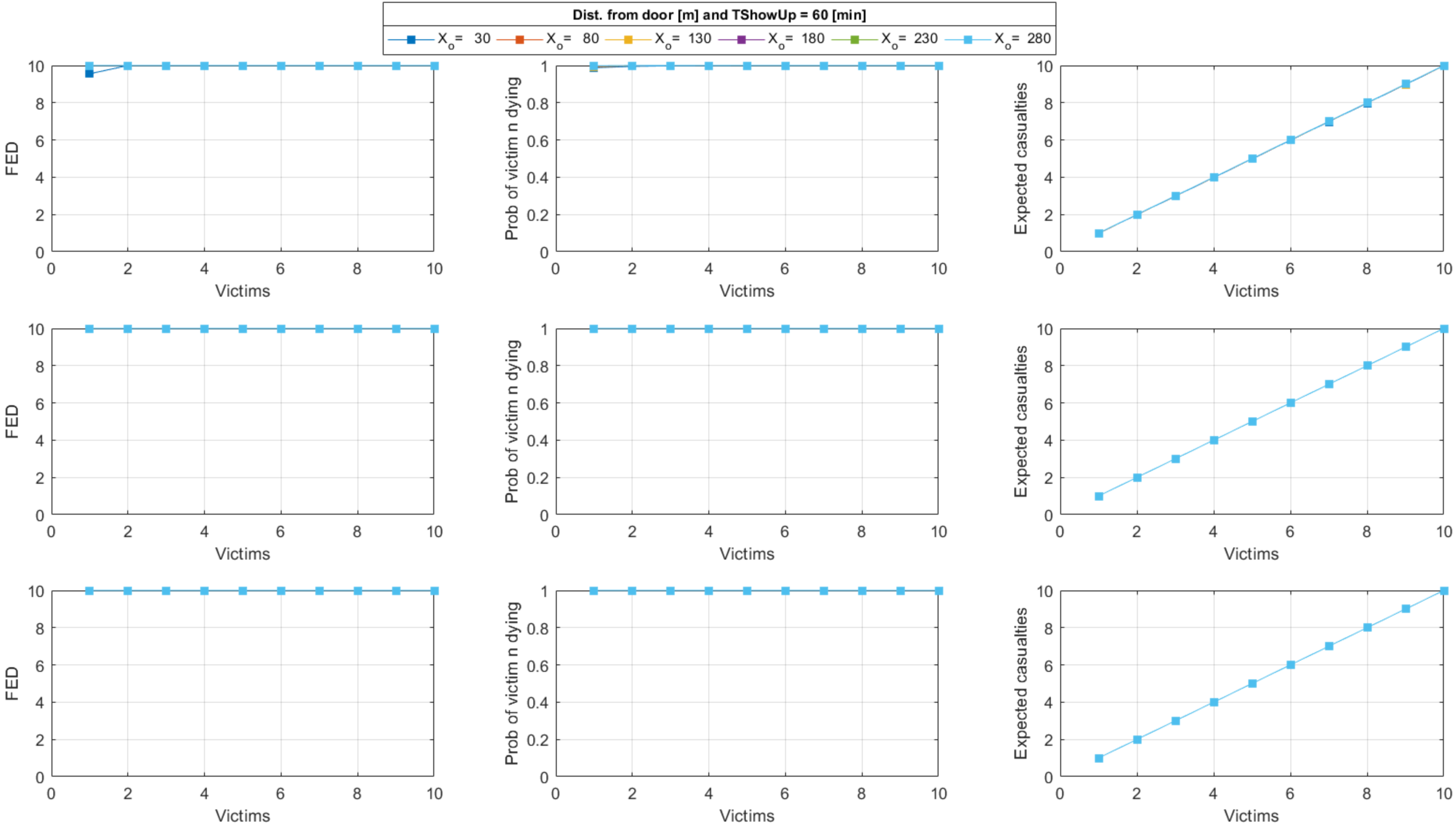


FED

Fire#1

Fire#2

Fire#3

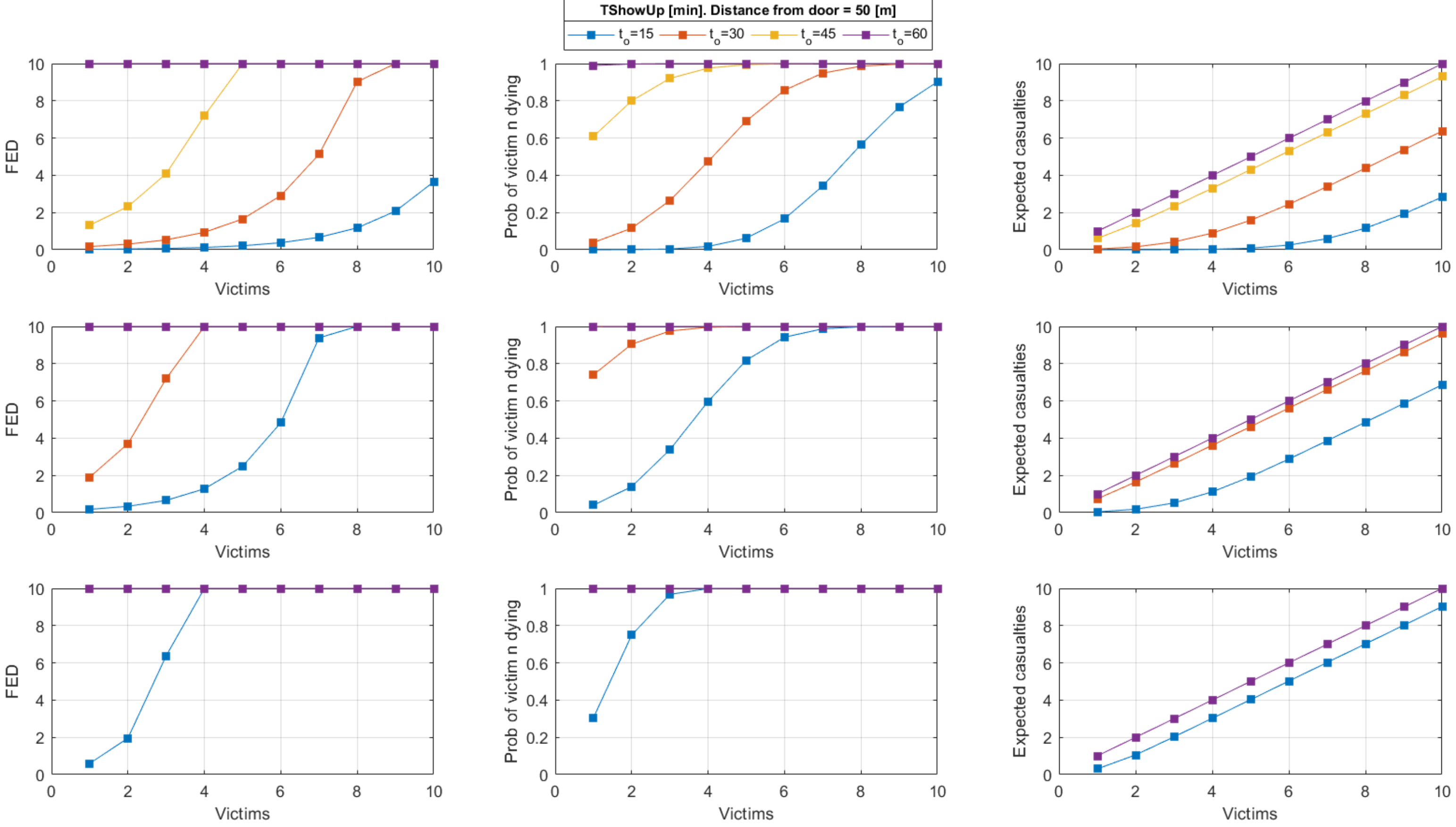


FED

Fire#1

Fire#2

Fire#3

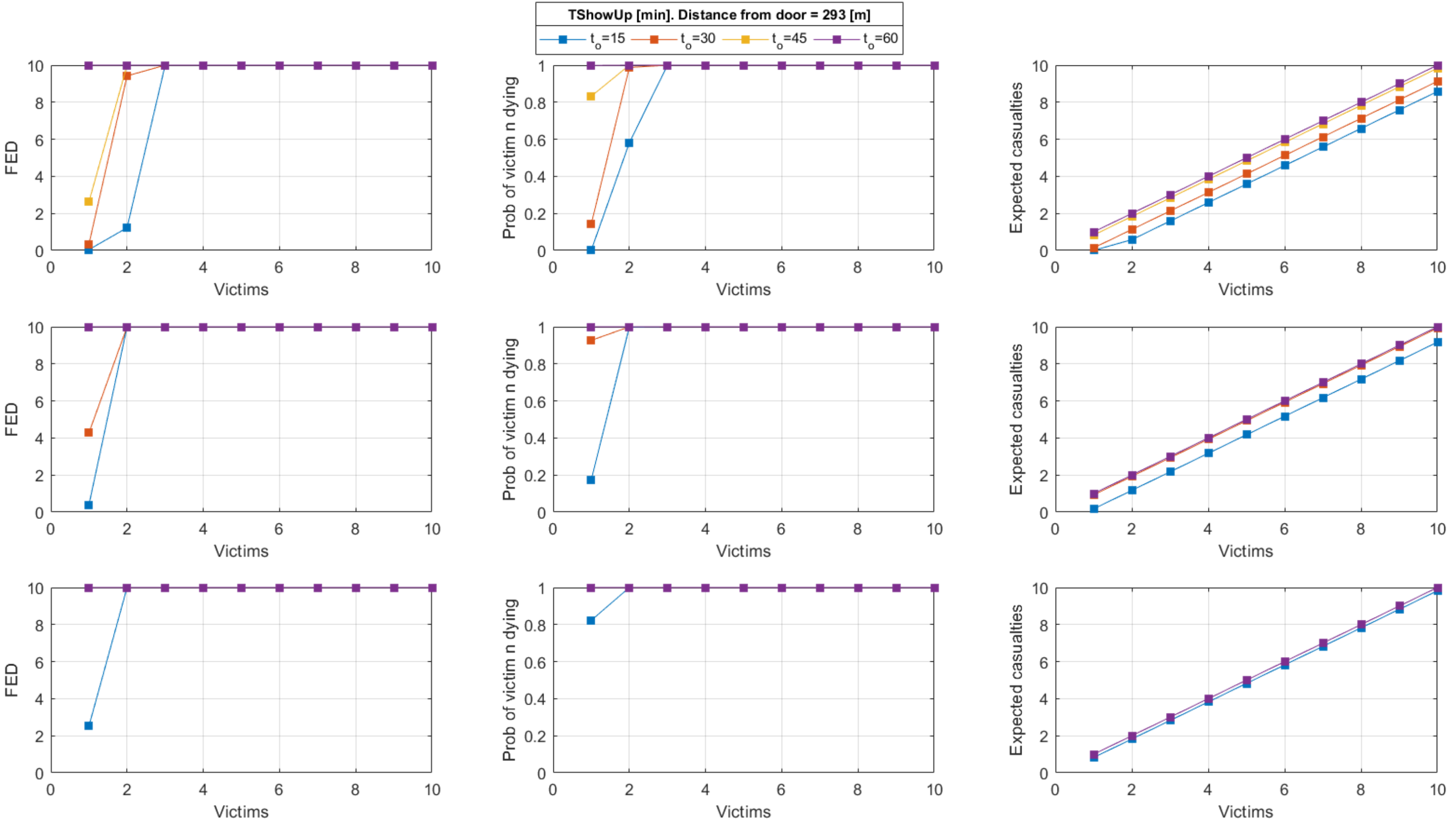


FED

Fire#1

Fire#2

Fire#3

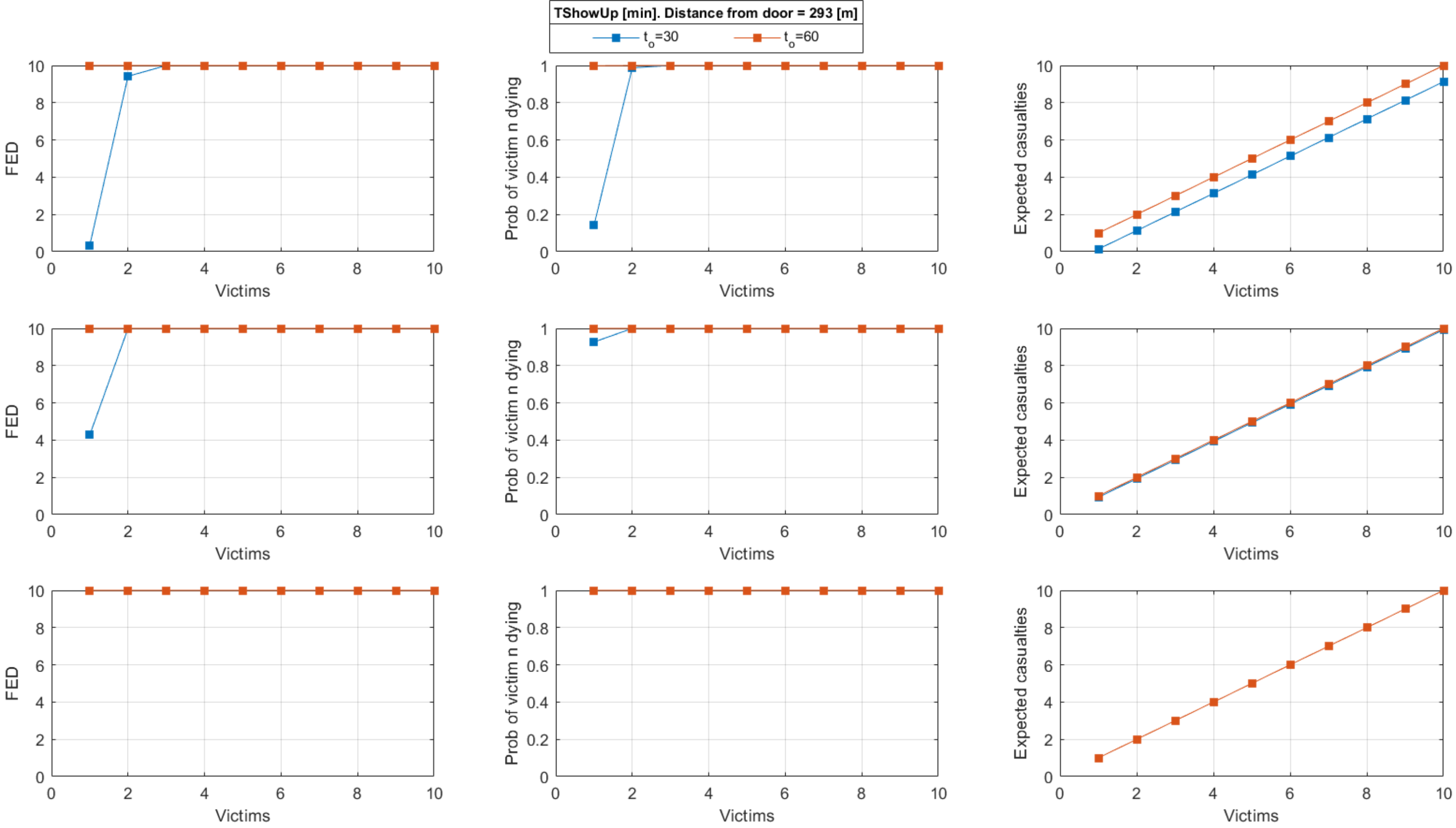


FED

Fire#1

Fire#2

Fire#3



Scenarios

3.1 Fire Scenarios: Scenario A: RUN

Description:

- During Run
- No occupants in the tunnel
- Electrical cable fire (**FIRE#1**)
- Automatic detection triggered
- Fire doors close and emergency ventilation starts

Life Safety for FF
Criteria: 04-07

04 Firefighter safety requires that closest safe area for firefighting (no imminent risk and no breathing apparatus needed) is less than 450m away from the door of the fire compartment.

05 In order to ensure firefighter safety and protection: during offensive operations, extinguishing media available for attack and search & rescue teams matches fire development, allowing firefighter protection and fire control under 3 minutes:

- 3 extinguishers of 9kg CO_2 if fuel mass is below 25kg;
- 100L portable CAFS on trailer up to 5MW;
- or 500LPM water hose line up to a maximum HRR of 20MW.

06 Firefighter safety is only guaranteed if engaged teams remain in communication at all times with surface incident command post.

07 Structural stability of the premises during operations.

3.1 Fire Scenarios: Scenario B: LSD Drum

Description:

- During Long Shut Down
- **20 people*** in the compartment
- Welding works, cable drum catches fire and spreads to some cable trays (**FIRE#2**)
- Detector does not trigger (disconnected according to IS37 procedure)
- Manual Alarm triggered
- Workers not able to put out the fire
- Fire doors closed and emergency ventilation starts

*probabilistic approach to be done in CDR?

3.1 Fire Scenarios: Scenario C: SSD Transport

Description:

- During Short Shut Down
- 10 people in the compartment
- Kuka catches in the middle of one compartment (**FIRE#3**)
- Automatic detection triggers normally
- Manual Alarm triggered
- Workers not able to put out the fire
- Fire doors closed and emergency ventilation started

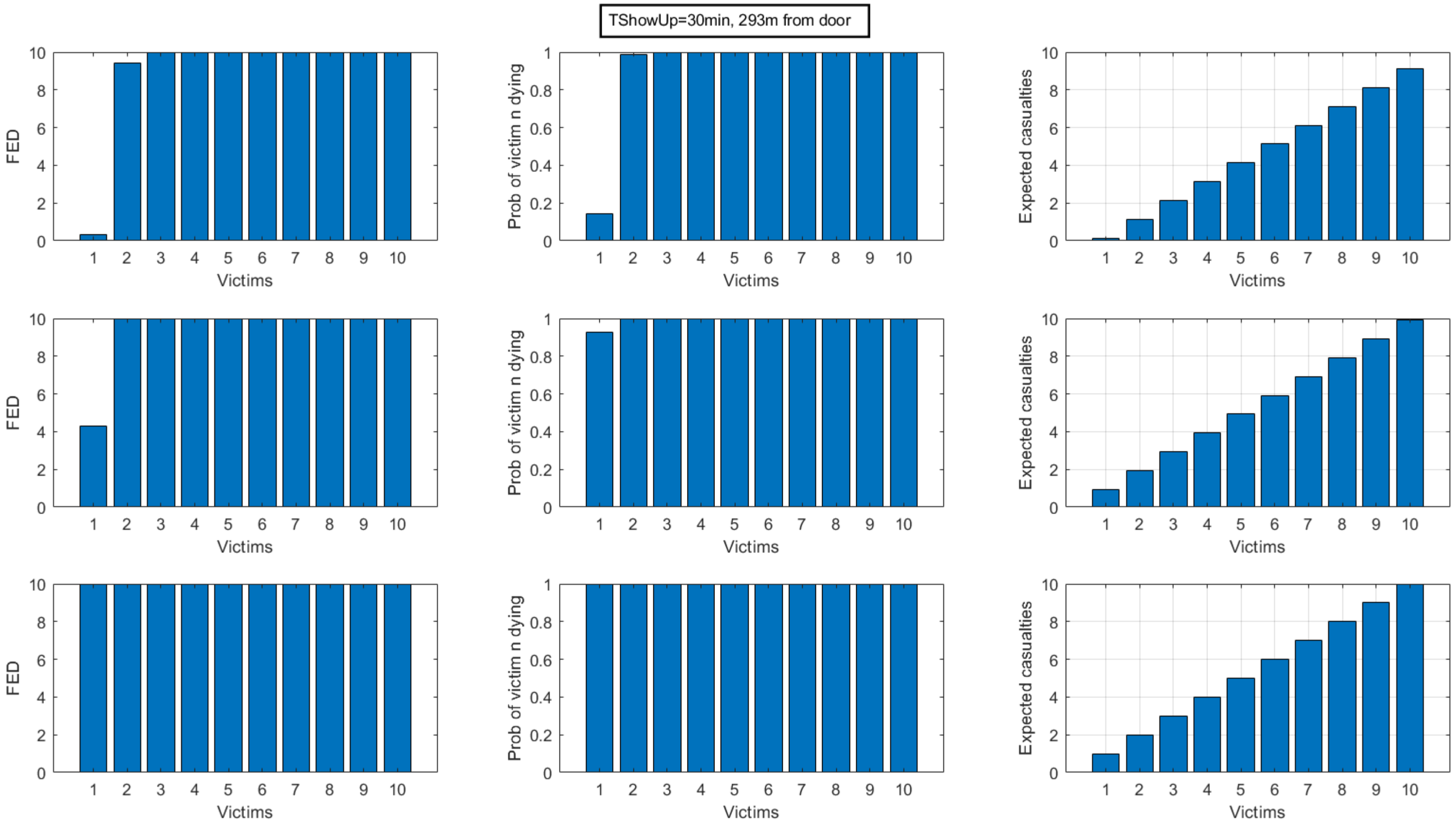
A probabilistic approach might be considered for the TDR

FED

Fire#1

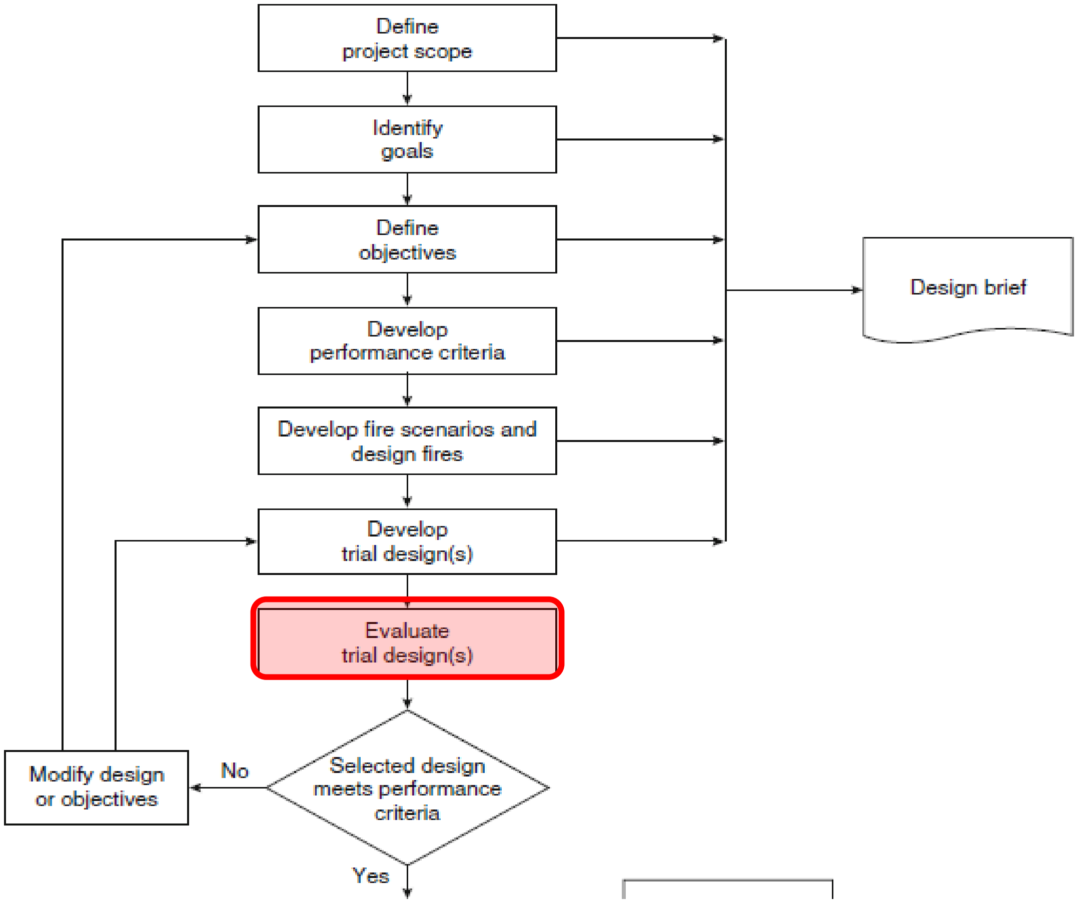
Fire#2

Fire#3



PBD process: EVALUATE TRIAL DESIGN

Victim's FED assessment

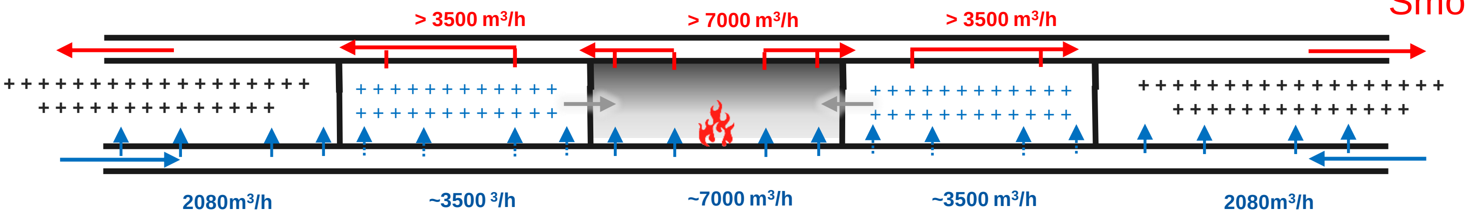


Abstract:
Life Safety is frequently the primary goal in a Performance Based Design (PBD) process. Tenability limits based on visibility, temperature and heat flux thresholds are often used to establish the performance criteria. However, exposure to these limits does not imply fatalities but rather impeded evacuees requiring Fire Service intervention in order to be rescued.
In the scope of a preliminary design of a large new particle accelerator, featuring a 98 km tunnel ring laying 400 m underground, CERN FSE team conducted a full PBD, where the impact of the fire brigade intervention on the survivability of potential victims was studied in depth. Given a simple layout scenario from an evacuation standpoint, 1D egress models were coupled with FDS simulations to quantify the Fractional Effective Dose (FED) received by both evacuating occupants and victims unable to self-evacuate. The Fire Service search&rescue operation was also simulated by using experimental data on zero-visibility intervention access speeds. Multiple tentative configurations of the in-house fire brigade (in terms of locations and staffing) were tested to evaluate the potential benefit of each one. The results show the advantage and capability of the PBD approach to deal with non-standard complex infrastructures out of the scope of the regulatory framework.

If fire spreads: Replicate logics

When Fire is detected in a compartment

Smoke Exhaust: 14k m^3/h



If Fire is detected in a adjacent compartment too

Smoke Exhaust: 21k m^3/h