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# Probabilistic fire simulation assessment using simplified model and zone modelling of a fire scenario

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# RESEARCH BACKGROUND

- Performance-based design applies engineering calculations to establish architectural designs that comply to fire safety and building regulations.
- The approach allows flexibility for engineers to use any suitable method to achieve life safety goals.
- One of the method include fire modelling that able to predict the behavior of fire development usually in terms of heat release rate.
- Several models that allow the prediction for specific compartment geometry include:

  (i) Simplified model

| FUNCTION | MECHANISM | BENEFIT | LIMITATION |
|---|---|---|---|
| Governed by mathematical or empirical equation | Combine several individual properties over several time steps | Determine immediate results for simple fire dynamics | Posteriori – customed for a particular single feature of a fire event |

# RESEARCH BACKGROUND

(ii) Zone model

| FUNCTION | MECHANISM | LIMITATION | EXAMPLE |
| --- | --- | --- | --- |
| Governed by several algebraic equations that represent two uniform zones which formed during fire; hot and cool layer | More sophisticated – predict transfer of mass, energy, momentum and species between zones | No specific representation of object geometry; objects are illustrated in simple box | B-RISK, CFAST, FASTlite, FIERAsystem, OZONE, ASET-B |

- Fire modelling can be characterized to deterministic and probabilistic;
  ~ Deterministic – Use specific input to generate fully determined model
  ~ Probabilistic – Use random input to generate a statistical estimation of the true model

- Since fire has complicated behavior, probabilistic assessment gains interest when it capable to represent possible fire scenarios for:
  ~ Risk estimation
  ~ Optimization of fire protection measure in a cost and time effective manner

# RESEARCH BACKGROUND

- In fire application, model is valid when the percentage of intersection of the experimental curve within the probabilistic region achieves >20%.
- Probabilistic method is reviewed to contribute to the prediction of:

(i) Accumulated heat release rate for multiple vehicle fires in car parking building

~ Comparison with seven experimental vehicle fires show that **simplified model** gives reasonable predictions (Tohir & Spearpoint, 2014)

(ii) Ignition time for multiple furniture fires in room compartment

~ Comparison with sets of experiments show that **B-RISK** model gives low robustness for armchair, and high robustness for television and cabinet only with consideration of radial distance (Sazegara et. al, 2016)

# PROBLEM STATEMENT

- Probabilistic simulation currently important in performance-based design since deterministic approach has limited data to justify the difficulty in predicting and prescribing well the wide scatter of simulated **fire development** within compartment in the case of realistic scenarios.
- However, lack of probabilistic assessment using simplified and zone models was evaluated recently to provide information in selecting reliable model to represent a specific fire event.
- A simple algebraic modelling is subject to debate when radiation is not considered, nor extinction or flash over can be modeled, and no significant vents can be represented. While a more sophisticated zone model has no significant horizontal layer's growth and limited to properly model fire in small enclosure with elementary radiation.
- This project was carried out to determine when fire engineers can be confident in using simplified and zone models to simulate development of fire and prevent unnecessary simulations due to the model limitations.

# OBJECTIVE

The main aim of this work is to compare whether probabilistic simulation of fire spread using zone models can produce better representation of the fire phenomena as compared to using simplified model.

A full-scale kitchen fire experiment conducted by National Institute of Standards and Technology (NIST), United States of America is selected due to completeness of information (interaction of fire growth in compartment).

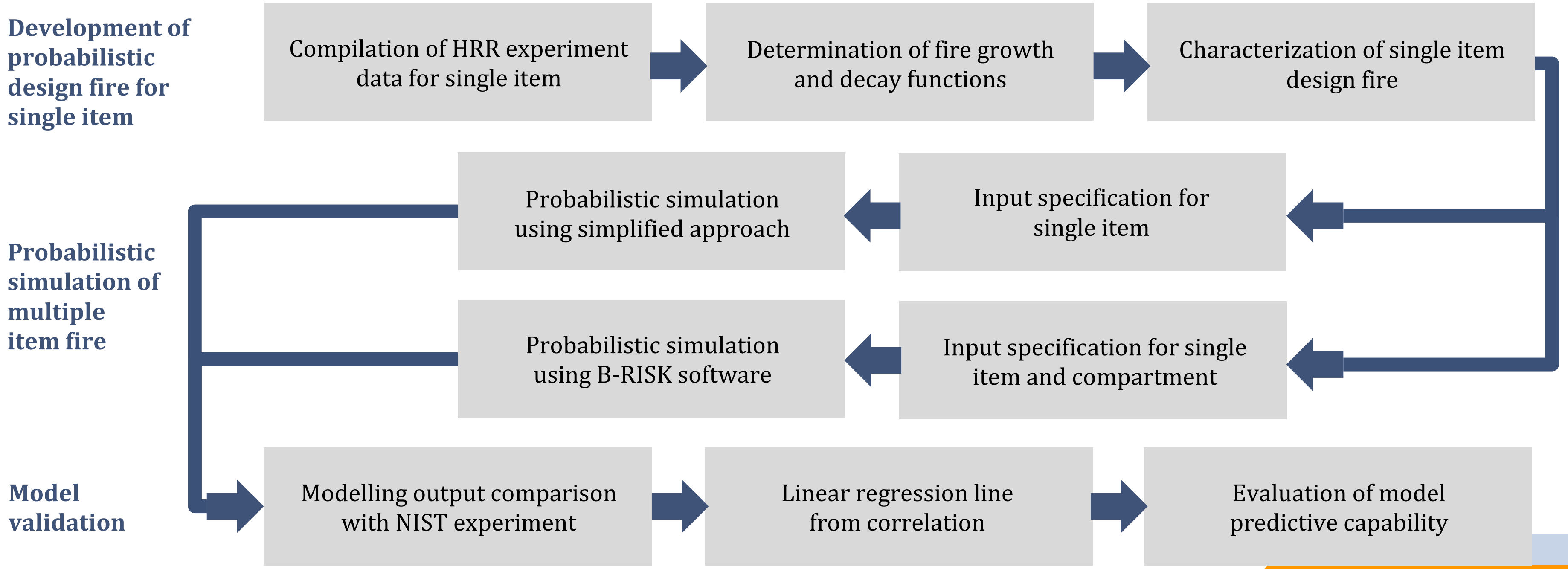
The objectives of the project are:

- To conduct probabilistic simulation of multiple item fire spread in a compartment using simplified model and B-RISK zone model
- To assess predictive capability for multiple item fire through comparison of the results obtained from using simplified approach and B-RISK with NIST kitchen fire experiment

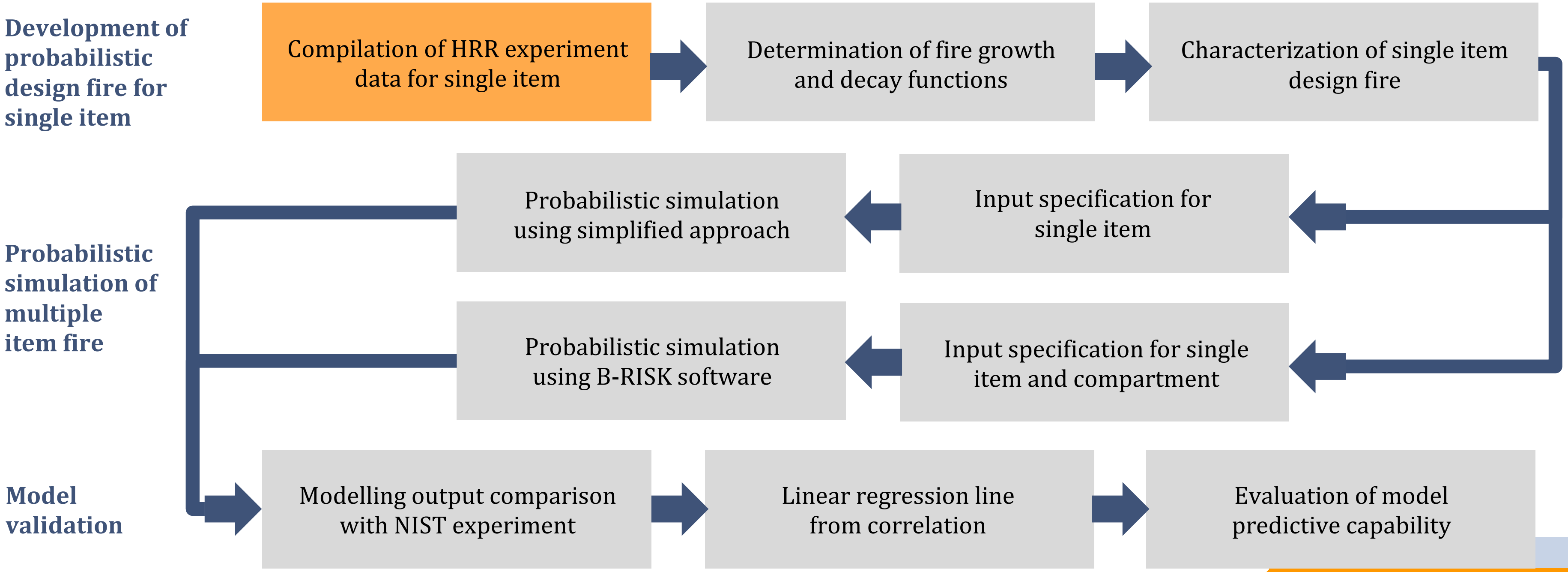
# SCOPE AND LIMITATION

- Fire simulation uses B-RISK software that involved random ignition, and simplified model that employed item ignition time from experiment.
- Modelling utilizes probabilistic design fire of single item that was characterized statistically using peak growth and exponential decay functions at lower and upper boundary limit of $5^{th}/95^{th}$ percentile, $25^{th}/75^{th}$ percentile and $33^{rd}/66^{th}$ percentile.
- Modelling represents multiple kitchen item fire within single compartment involving corn oil, chair, table, countertop, sink and wall cabinet that were made of white wood material.
- Modelling input (room design, ventilation and fuel properties) were collected from NIST journal, fire database and available literature. Geometry of enclosure and fuel were modelled in simple box; no architectural features were considered.
- Modelling output of accumulated heat release rate (HRR) is mainly considered, and the robustness was evaluated through fit quantification method using an experimental set of NIST kitchen fire.

# METHODOLOGY



# METHODOLOGY



# METHODOLOGY

## Experimental HRR for single item

| Single item | Item material | Item dimension | Number of test |
|---|---|---|---|
| Cooking oil | Corn oil | Diameter: 4 – 12 (inch) | 5 |
| Sink and wall cabinet | Plywood | Length: 0.94 – 1.22 (meter)<br>Width: 0.30 – 0.62 (meter)<br>Height: 0.79 – 1.82 (meter) | 6 |
| Chair | *Frame:* Pine wood<br>*Foam:* Urethane, California, FR cotton stuffing<br>*Fabric:* Polyolefin, Haitian cotton, cotton, polyester batting | Length: 0.44 (meter)<br>Width: 0.56 (meter)<br>Height: 0.81 (meter) | 10 |
| Table and countertop | Oak wood | Length: 1.20 (meter)<br>Width: 0.60 (meter)<br>Height: 0.80 (meter) | 1 |

**TOTAL EXPERIMENT:**
22 sets

**CLASSIFIED BASED ON:**
- Material
- Dimension

**INTEREST DATA:**
Heat release rate tested under open calorimeter

# METHODOLOGY

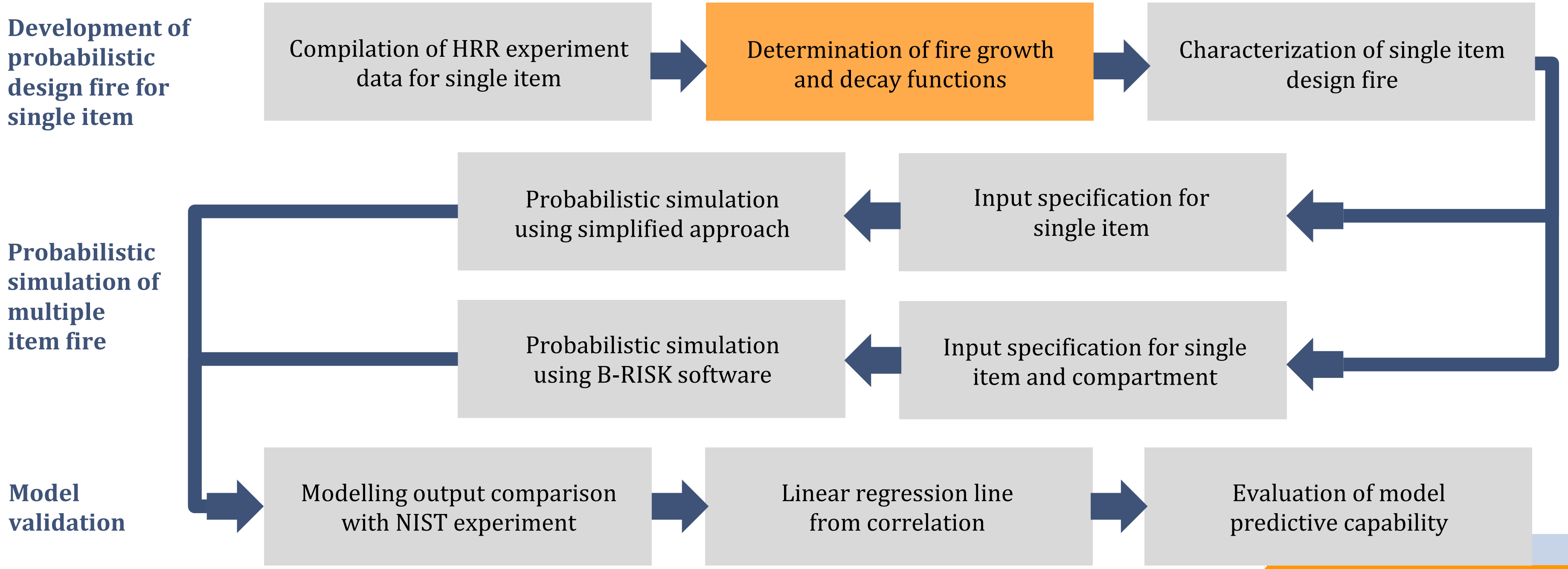
## Statistical analysis of fire severity characteristic for single item

| Single item | Peak heat release rate (kW) | | | | Time to peak heat release rate (min) | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Standard deviation | Max. value | Min. value | Mean | Standard deviation | Max. value | Min. value |
| Pan with cooking oil | 148.2 | 143.0 | 400.0 | 50.0 | 1.9 | 1.1 | 3.7 | 0.1 |
| Dining chair | 643.7 | 501.5 | 1960.0 | 11.0 | 3.9 | 2.8 | 0.8 | 10.8 |
| Table and countertops | 640.0 | N/A | N/A | N/A | 6.0 | N/A | N/A | N/A |
| Sink and wall cabinet | 4248.1 | 1620.4 | 6400.0 | 2938.8 | 1.6 | 0.4 | 1.0 | 2.1 |

**INTEREST DATA:**
- Peak HRR
- Time to peak HRR

**DATA ANALYSIS:**
- Mean
- Standard deviation
- Minimum value
- Maximum value

# METHODOLOGY



# METHODOLOGY

## Peak fire growth function

| Single item | $\alpha_{peak}$ (kW/min²) 5th percentile of lower BL | 95th percentile of upper BL | 25th percentile of lower BL | 75th percentile of upper BL | 33rd percentile of lower BL | 66th percentile of upper BL |
|---|---|---|---|---|---|---|
| Pan with cooking oil | 79.46 | 11.30 | 34.07 | 14.69 | 25.90 | 17.23 |
| Dining chair | 115.81 | 25.85 | 63.13 | 32.22 | 50.99 | 36.74 |
| Table and countertops | N/A | N/A | N/A | N/A | N/A | N/A |
| Sink and wall cabinet | 1724.44 | 1473.18 | 1684.27 | 1547.00 | 1653.80 | 1583.87 |

**FIRE GROWTH COEFFICIENT:**

- $\dot{Q}(t) = \alpha_{peak}\, t^2$

  $(t \leq t_{max})$

# METHODOLOGY

## Exponential fire decay function

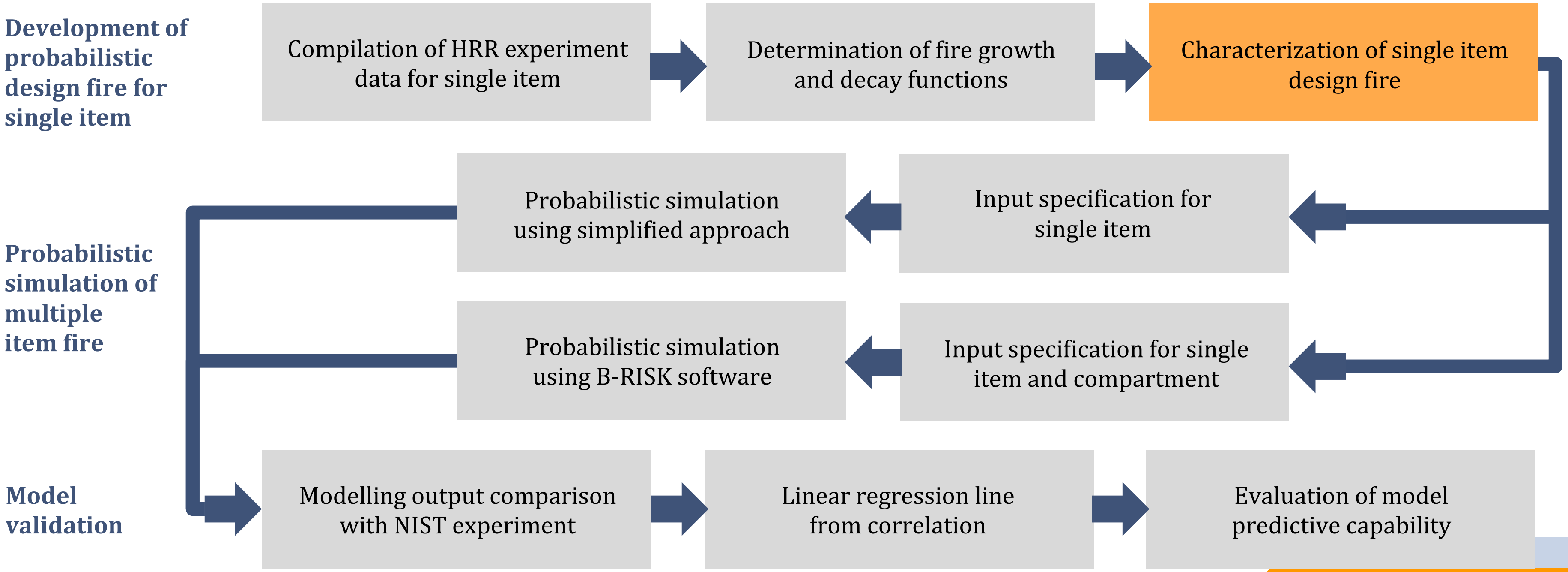
| Single item | $\beta_{exp}$ (kW/min$^2$) 5th percentile of lower BL | 95th percentile of upper BL | 25th percentile of lower BL | 75th percentile of upper BL | 33rd percentile of lower BL | 66th percentile of upper BL |
|---|---|---|---|---|---|---|
| Pan with cooking oil | 2.99 | 1.14 | 2.10 | 1.34 | 1.84 | 1.47 |
| Dining chair | 1.57 | 0.87 | 1.33 | 0.98 | 1.22 | 1.05 |
| Table and countertops | N/A | N/A | N/A | N/A | N/A | N/A |
| Sink and wall cabinet | 1.55 | 0.56 | 1.06 | 0.66 | 0.92 | 0.73 |

**FIRE DECAY COEFFICIENT:**

- $\dot{Q}(t) = \dot{Q}_{max} \exp(\beta_{exp} t)$

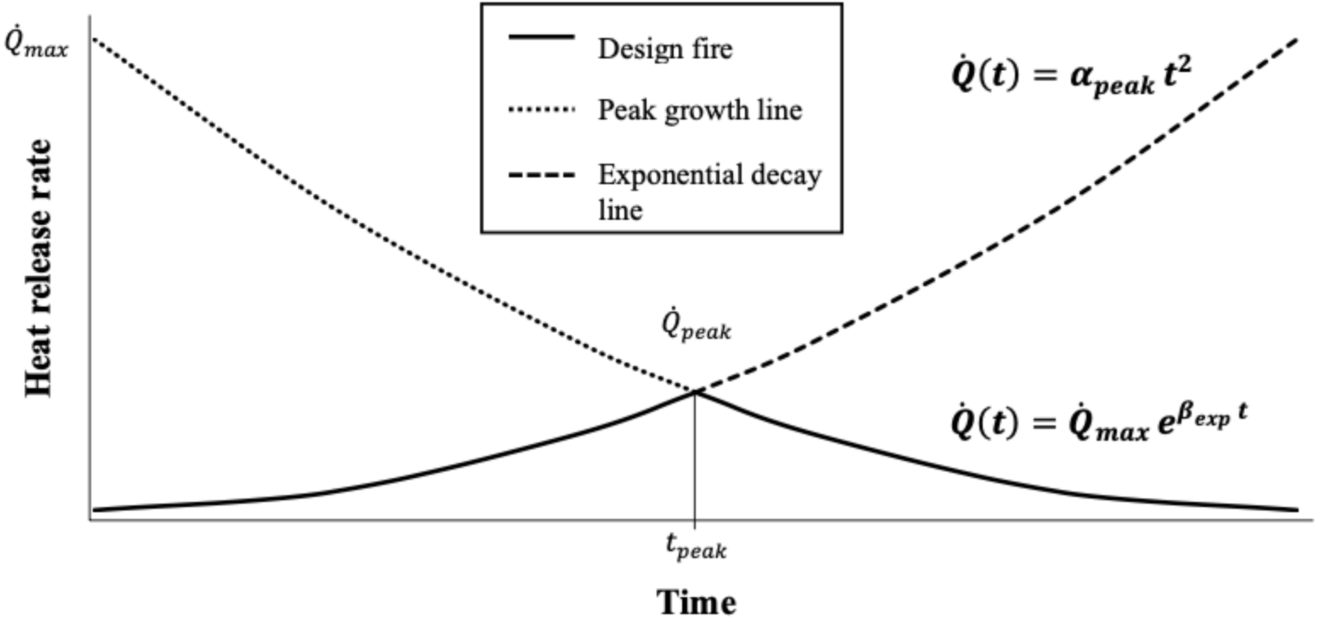
  $(t \geq t_{max})$

# METHODOLOGY



# METHODOLOGY

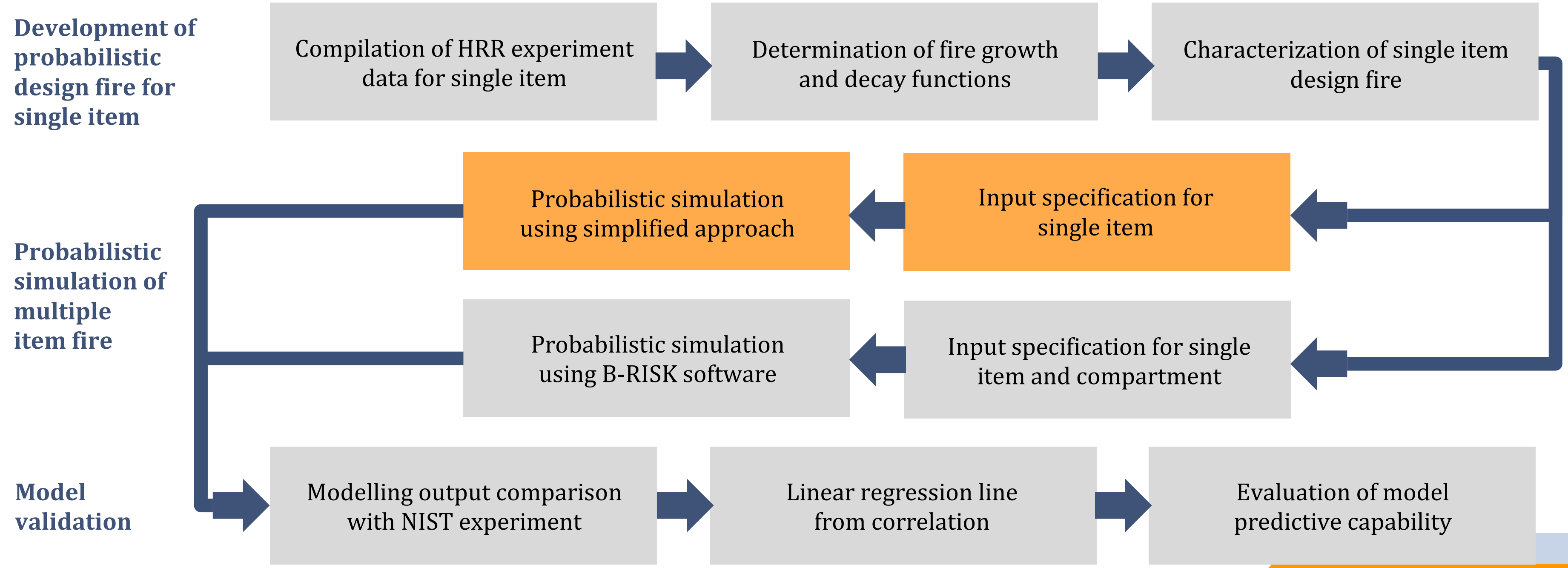
## Probabilistic design fire for single item




### CHARACTERIZATION METHOD:

- Combine the fire growth and decay function for respective limit

# METHODOLOGY



# METHODOLOGY

## Input for simplified model

### (I) IGNITION TIME FROM NIST EXPERIMENT

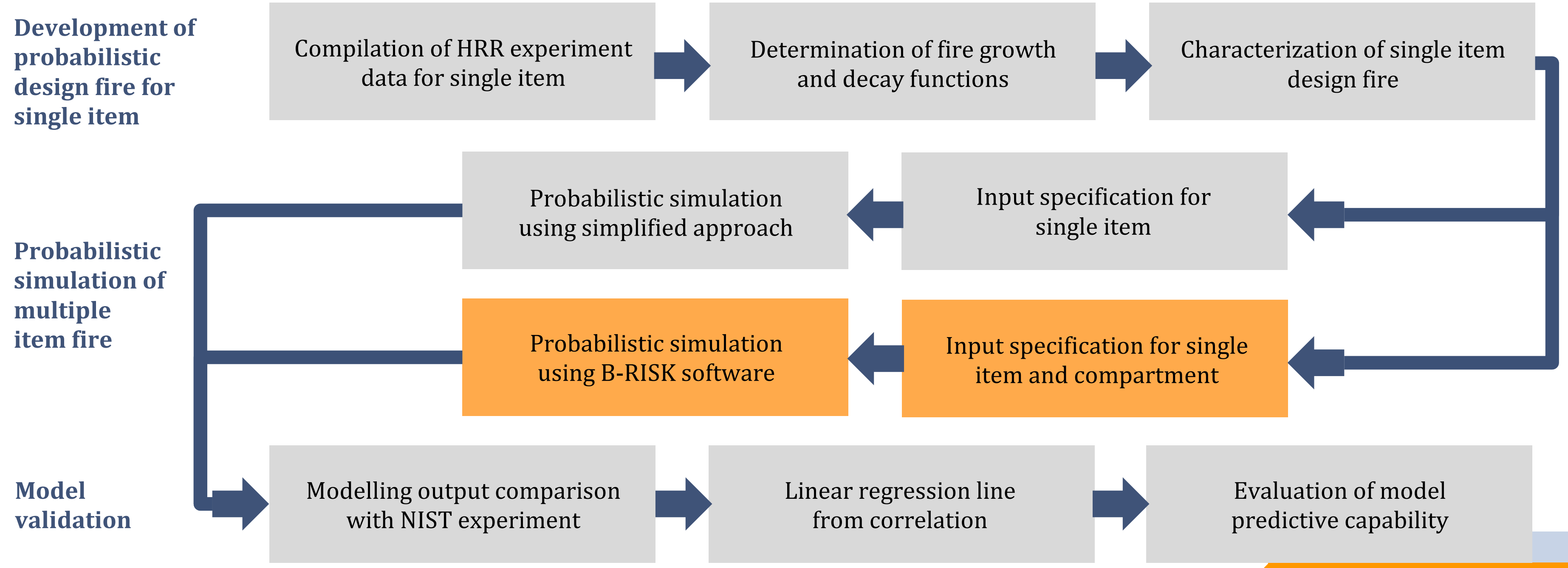
| Single item | Ignition time (min) |
|---|---|
| Pan with cooking oil | 16.0 |
| Wall cabinet | 19.5 |
| Countertop | 22.6 |
| Sink cabinet | 23.8 |
| Chair | 24.9 |
| Table | 27.5 |
| Chair | 32.0 |
| Sink cabinet | 35.0 |
| Countertop | 36.2 |
| Wall cabinet | 37.5 |

### (II) SIMULATION

- Design fire superposition at respective ignition time.
- Total HRR:

$$\dot{Q}(t)_{tot} = \sum \dot{Q}\ t_i$$

# METHODOLOGY



# METHODOLOGY

## Input for B-RISK model

### (I) CHEMISTRY DATA

| Parameter | Unit | Cooking Oil | Sink and wall cabinet | Chair | Table and countertop |
|---|---|---|---|---|---|
| Heat of combustion | kJ/g | 37.81 | 16.90 | 20.84 | 18.87 |
| Soot yield | g/g | 0.070 | 0.700 | 0.017 | 0.359 |
| $CO_2$ yield | g/g | 0.096 | 3.100 | 2.825 | 2.963 |
| Latent heat of gasification | kJ/g | 0.611 | 0.421 | 0.244 | 0.333 |
| Radiant loss fraction | - | 0.637 | 0.599 | 0.466 | 0.586 |
| HRRPUA | kW/m2 | 145 | 252 | 252 | 252 |

### (II) IGNITION DATA

| FTP dataset | Unit | Cooking oil | MDF cube |
|---|---|---|---|
| FTP Limit | $kWs^n/m^2$ | 100.82 | 237.08 |
| FTP Index | - | 1.00 | 1.75 |
| Critical Flux | $kW/m^2$ | 19.877 | 6.916 |

# METHODOLOGY

## Input for B-RISK model

### (III) SIMULATION

Random multiple item fire within compartment

- Radiation received by second item:

$$\dot{q}_{fl} = \frac{\dot{Q}\lambda_r}{4\pi r^2}$$

- Radiation from hot upper layer:

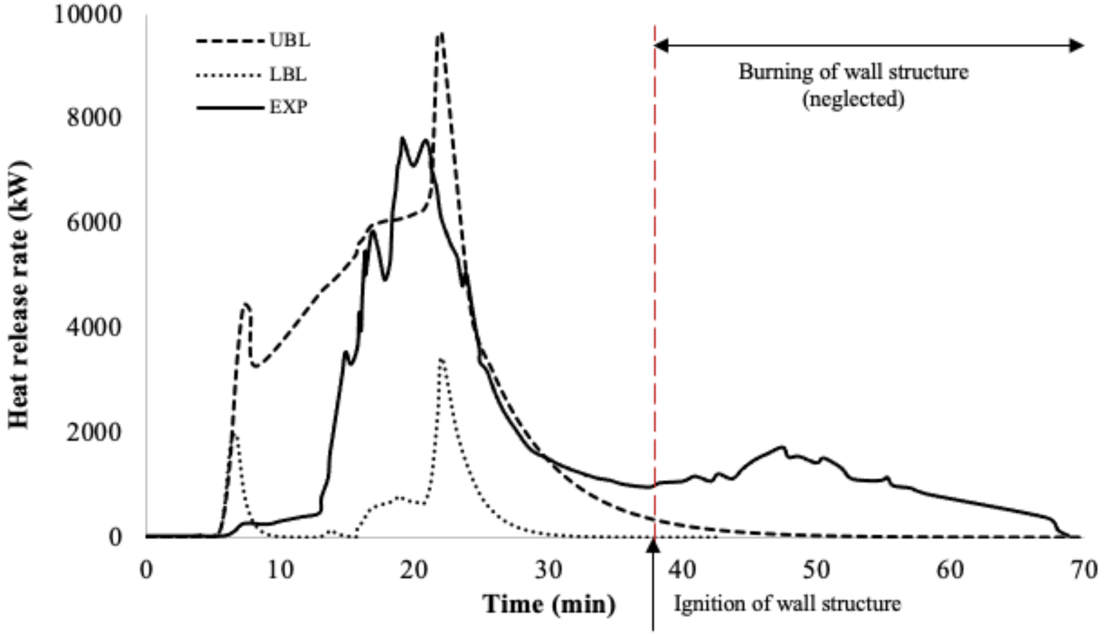
$$\dot{q}_v = \varepsilon_V \sigma T_V^4 F$$

- Ignition time of secondary item:

$$FTP = \sum_{i=1}^{m} (\dot{q}_i - \dot{q}_{cr})^n \Delta t_i$$

# RESULTS AND DISCUSSION

## Simplified model: 5th/95th percentile (Figure 1)




### POINT INTERSECTION

- 71.0 %

### FIRE GROWTH STAGE

- No intersection at the beginning – lower and upper limits have high HRR
- Most intersect at the middle to the end – upper limit has high HRR

### PEAK HRR STAGE

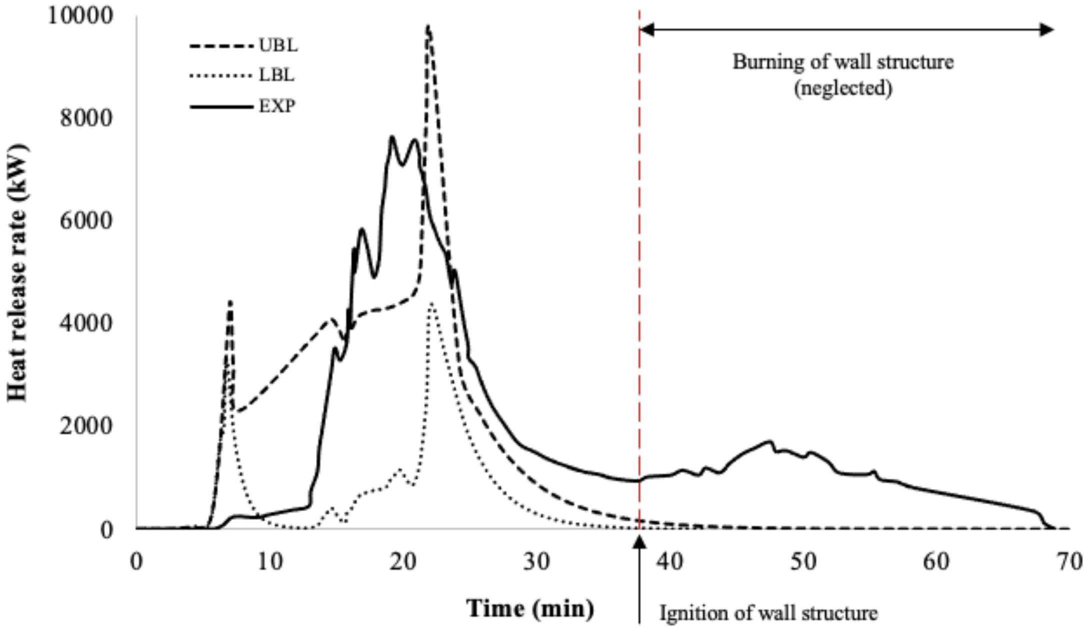
- No intersection for both peaks – lower and upper limits have slow rate to reach peak HRR

### FIRE DECAY STAGE

- Most intersect at the beginning and middle – upper limit has high HRR
- No intersection at the end – upper limit has low HRR

# RESULTS AND DISCUSSION

## Simplified model: $25^{th}/75^{th}$ percentile (Figure 2)




### POINT INTERSECTION

- 40.3 %

### FIRE GROWTH STAGE

- No intersection at the beginning – lower and upper limits have high HRR
- Most intersect at the middle – upper limit has high HRR
- No intersection at the end – upper limit has low HRR

### PEAK HRR STAGE

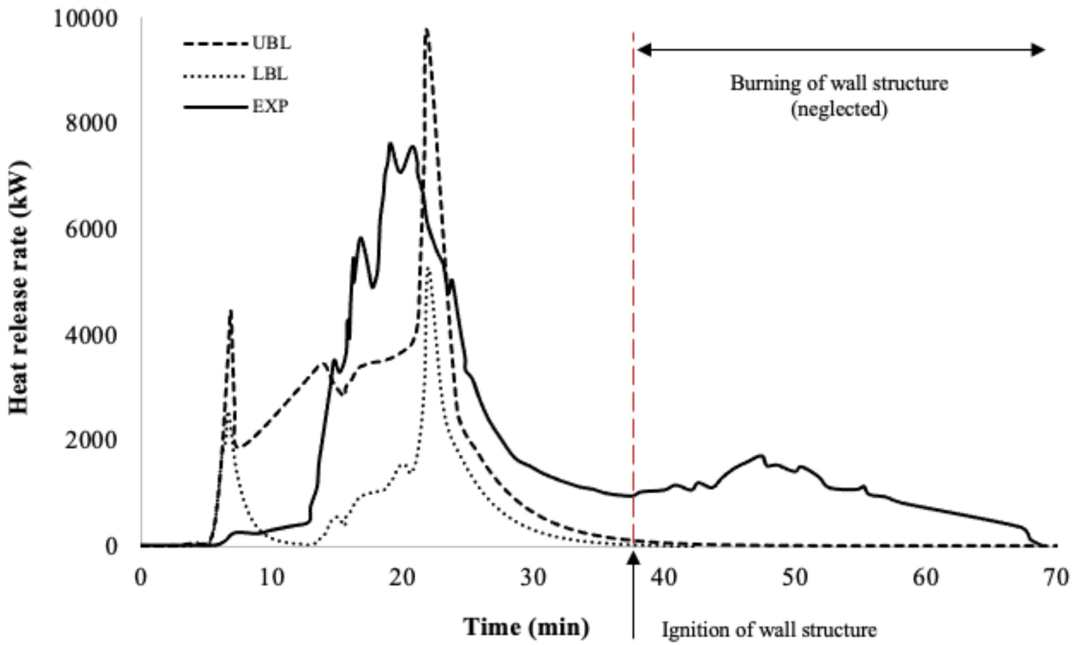
- No intersection for both peaks – lower and upper limits have slow rate to reach peak HRR

### FIRE DECAY STAGE

- Some intersect at the beginning – upper limit has high HRR
- No intersection at the middle to the end – upper limit has low HRR

# RESULTS AND DISCUSSION

## Simplified model: 33rd/66th percentile (Figure 3)




### POINT INTERSECTION

- 32.3 %

### FIRE GROWTH STAGE

- No intersection at the beginning – lower and upper limits have high HRR
- Some intersect at the middle – upper limit has high HRR
- No intersection at the end – upper limit has low HRR

### PEAK HRR STAGE

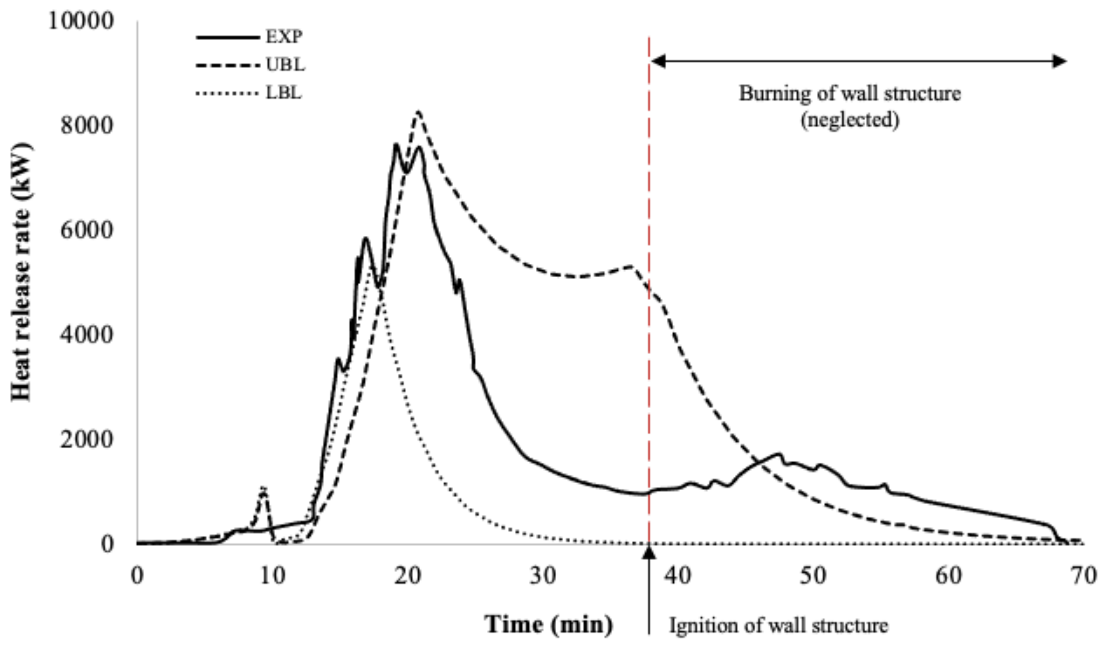
- No intersection for both peaks – lower and upper limits have slow rate to reach peak HRR

### FIRE DECAY STAGE

- Least intersection at the beginning – upper limit has high HRR
- No intersection at the middle to the end – upper limit has low HRR

# RESULTS AND DISCUSSION

## B-RISK model: 5th/95th percentile (Figure 4)




### POINT INTERSECTION

- 68.3 %

### FIRE GROWTH STAGE

- No intersection at the beginning – lower and upper limits have high HRR
- Some intersect at the middle to the end – upper limit has low HRR

### PEAK HRR STAGE

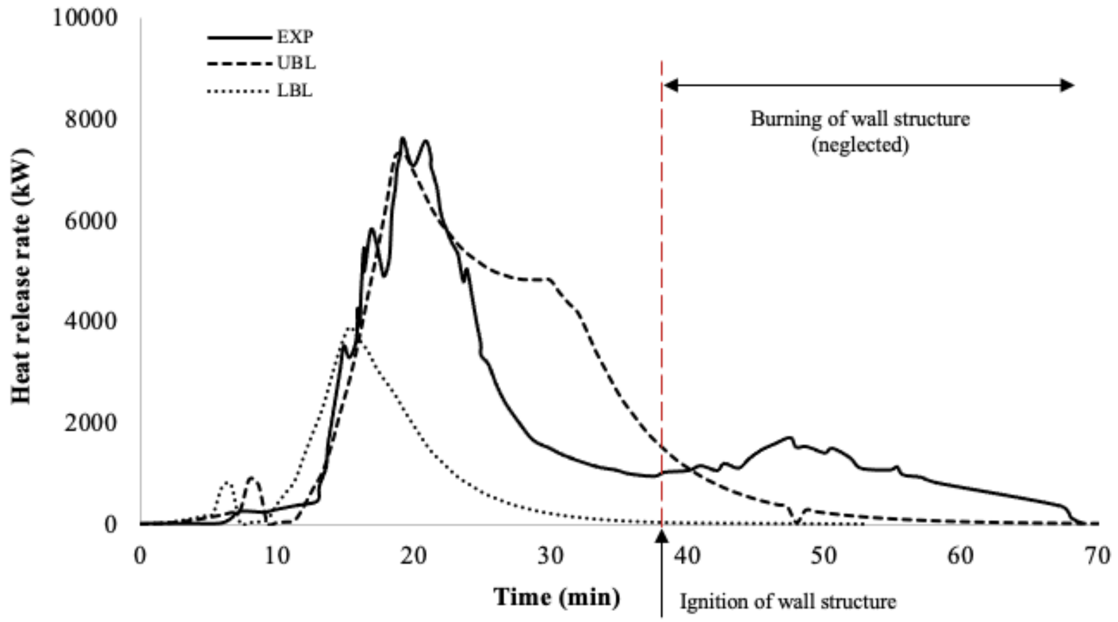
- Intersect at the second peak – upper limit has slow rate to reach peak HRR

### FIRE DECAY STAGE

- Most intersect at the decay stage – upper limit has high HRR

# RESULTS AND DISCUSSION

## B-RISK model: 25th/75th percentile (Figure 5)




### POINT INTERSECTION

- 63.5 %

### FIRE GROWTH STAGE

- No intersection at the beginning – lower and upper limits have high HRR
- Some intersect at the middle to the end – lower limit has high HRR while upper limit has low HRR

### PEAK HRR STAGE

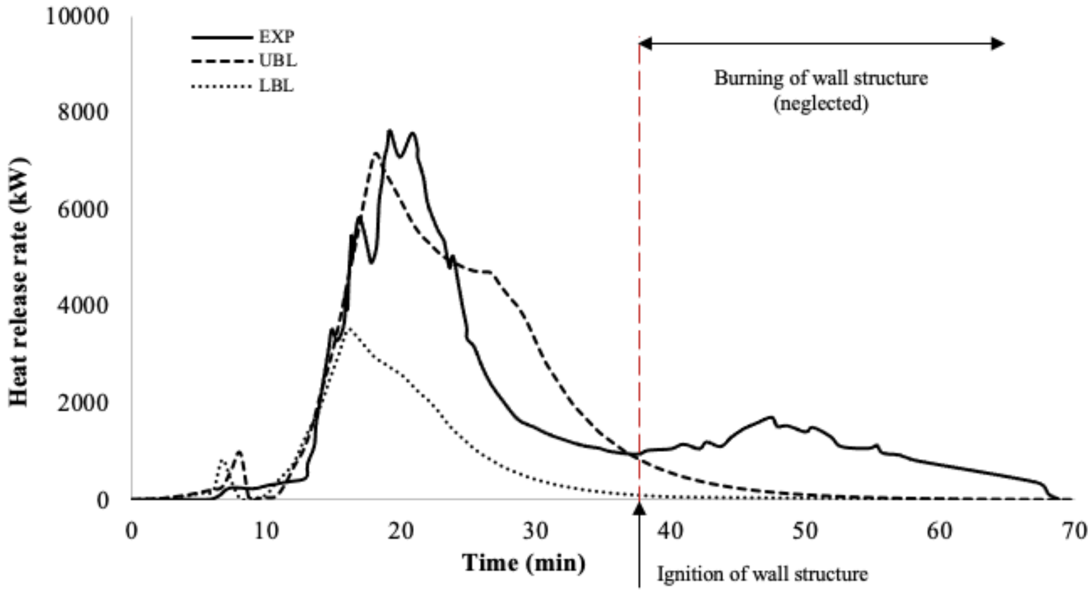
- Intersect at the first peak – upper limit has low peak HRR

### FIRE DECAY STAGE

- No intersection at the beginning – upper limit has low HRR
- Most intersect at the middle to the end – upper limit has high HRR

# RESULTS AND DISCUSSION

## B-RISK model: 33rd/66th percentile (Figure 6)




### POINT INTERSECTION

- 58.7 %

### FIRE GROWTH STAGE

- No intersection at the beginning – lower and upper limits have high HRR
- Least intersection at the middle to the end – lower limit has high HRR while upper limit has low HRR

### PEAK HRR STAGE

- No intersection at both peaks – upper limit has low peak HRR

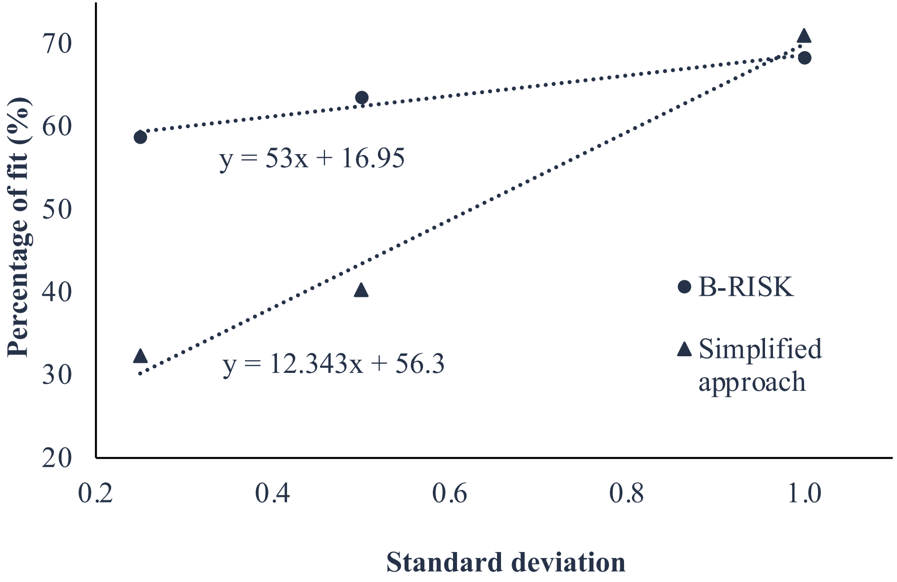
### FIRE DECAY STAGE

- No intersection at the beginning – upper limit has low HRR
- Most intersect at the middle to the end – upper limit has high HRR

# RESULTS AND DISCUSSION

## Summary

| Boundary limit of standard deviation | Percentage of experimental data within probabilistic design fire region | |
|---|---|---|
| | Simplified approach | B-RISK |
| $5^{th}$ / $95^{th}$ | 71.0 | 68.3 |
| $25^{th}$ / $75^{th}$ | 40.3 | 63.5 |
| $33^{rd}$ / $66^{th}$ | 32.3 | 58.7 |




- B-RISK able to represent the multiple item fire at higher robustness than simplified model at a narrower region.
- Linear regression lines allow extrapolation to describe how the robustness of modelling would deviate over different boundary of standard deviation.

# CONCLUSION

- Simplified model and B-RISK are both capable to generate probabilistic accumulated HRR within an acceptable range of fire application under different lower and upper boundary limit; $5^{th}$ / $95^{th}$ percentile, $25^{th}$ / $75^{th}$ percentile and $33^{rd}$ / $66^{th}$ percentile.
- The probabilistic relationship has proposed that B-RISK has high fit percentage as the limit increased, which is reasonable to suggest that zone model of B-RISK is more accurate than simplified model to produce a better representation of multiple item heat release rate within a compartment.

# THANK YOU