

A COMPARISON OF THE NIST WORKSTATIONS EXPERIMENT WITH THE B-RISK DESIGN FIRE GENERATOR

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Abstract. *A B-RISK produces modelling outputs in a format that fire engineers will be able to compare against probabilistic statements of building performance. The Design Fire Generator is one of the modules within the overall B-RISK model, which creates a unique probabilistic design fire. The design fires generated for an open plan single workstation and for multiple workstations in compartment are compared with NIST experimental results. The design fire inputs are created in the form of heat release rate (HRR) time histories that are generated by the DFG. This paper compares the HRR of commercial scale occupancies; item-to-item fire spread sequences and its time line of DFG output of B-RISK modelling with experimental results.*

1 INTRODUCTION

The New Zealand Building Code has two types of compliance, one is prescriptive through “Acceptable solution” and the other is performance based. The regulatory group, Ministry of Business, Innovation and Employment (MBIE), introduced new performance based fire safety designs to follow a fire engineering process and methods under the compliance document. A new performance based verification method C/VM2 [1] directs a technical determination of fire safety analysis in buildings that depends heavily on engineering methods such as fire modelling.

A joint BRANZ and University of Canterbury research project is underway to improve the quality and methodology to support performance based fire safety designs in New Zealand. The research is currently developing a quantitative risk assessment (QRA) tool named B-RISK [2] that produces modelling outputs in a format that fire safety engineering practitioners will be able to compare against probabilistic statements of building performance. The approach that has been taken in the current research project is to develop a so-called design fire generator (DFG) as one module within the overall B-RISK [2] model. Essentially the DFG creates a unique probabilistic design fire for each of a large number of deterministic calculation runs that are repeated in an iterative manner.

This project uses the DFG for commercial-scale office occupancy by using the model B-RISK. The design fire inputs are created in the form of heat release rate (HRR) time histories that are generated by the DFG. The DFG populates the compartment of fire origin for the particular occupancy under consideration, by sampling items from a customised item database where the model user may select appropriate fuel items from a general item database. Otherwise, the user may create the item database for particular items to populate the compartments. The sampling process to populate the compartment is random as well as manual, depending upon model user and a number of “rules” which are in-built into the model. The random population is the standard DFG functionality and the manual placement is a special option. In this project, all the items are manually populated to imitate the experimental single workstation and multiple workstations.

To determine the accuracy of the DFG predictions for commercial office-scale occupancy, a single workstation and multiple workstations are modelled in B-RISK, replicating experiments done in the

National Institute of Standards and Technology (NIST) fire laboratory by Madrzykowski and Walton [3]. The design fires for open plan single workstation and multiple (a cluster of four) workstations are generated to compare with the experimental results [3], as a part of the main objective of this project. A second objective is to compare the parametric design fire curve proposed in the new C/VM2 [1].

2 SINGLE WORKSTATION

2.1 Layout and description of furnishings

A full-scale experiment of a single workstation was conducted under an exhaust hood by NIST. The burning condition was typically fuel limited and there were minimal compartment effects and ventilation limits. To replicate the same effect, a single workstation is set up in a 20 m x 20 m x 2.7 m room size with three sides open, in B-RISK. The workstation fuel package included desktops, a computer with monitor and keyboard, an office chair, a sled base chair and side panels. In addition were papers, notebooks, a telephone and a telephone book placed on the desk. In this project, instead of individual items of papers and books, a total of 15 kg paper with cardboard fuel load is given in the input data of B-RISK. A final list of items with size, material and mass used in DFG simulation are given in a tabular form in Table 1.

Table 1: Workstation item data list

Item	Material	Size	Mass
Workstation panels	5 mm thick hardboard, 25 mm thick bat of fibreglass covered with 100% polyester at both side	3.4 m long, 1.04 m high, 0.054 m thick	84 kg
Work surface table	Particleboard with a face laminate on the top, total thickness 32 mm	0.61 m x 1.07 m and 0.76 m x 1.52 m	50 kg
Computer monitor and accessories	Fire retarded ABS	0.41 m x 0.57 m x 0.41 m high	27 kg
Office chair	0.08 m thick polyurethane foam with 100% polyester fabric	0.51 m x 0.56 m x 1.04 m high	20.45 kg
Sled base chair	0.08 m thick polyurethane foam with 100% polyester fabric	0.58 m x 0.61 m x 0.91 m high	11.82 kg
Papers with cardboard	2 mm thick cardboard over 216 mm by 279 mm of 500 sheets ream of papers	0.5 m x 0.5 m x 0.1 m high	15 kg

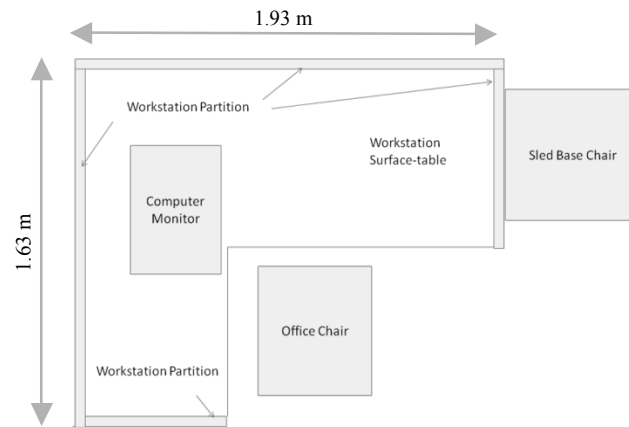


Figure 1 Single Workstation Schematic Layout

As shown in Figure 1, the workstation covered a floor area of approximately 1.93 m by 1.63 m. The side panels were 54 mm thick and 1.04 m high, which formed two complete sides of the workstation and two partial sides.

2.2 First item ignited rules and item to item fire spread

In this project, all the items are manually fixed to imitate the experimental single workstation. Each item in the database from the DFG has a number of “properties” and ignition properties are calculated based on NIST cone calorimeter tests of each item sample under two heat fluxes, 35 kW/m² and 70 kW/m². The geometry of the item such as length, width and height are calculated to replicate the NIST workstation set up. An elevation of the item identifies the height where the item is located with reference to floor level. Each item in the database has its own HRR (free-burning); taken from SFPE handbook [4] except office and sled base chair, which are taken from NIST report [3]. Refer to Figure 2 for HRR curves of each individual item.

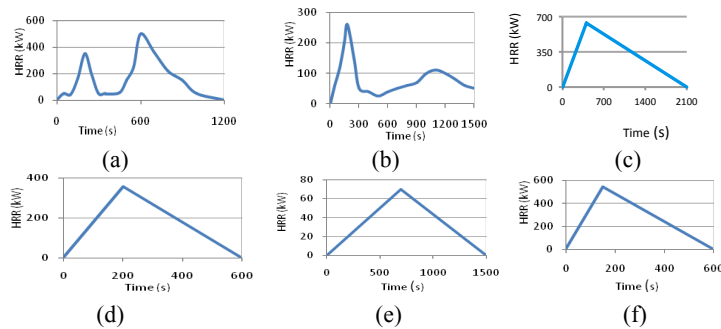


Figure 2 Individual item HRR of single workstation (a) Sled base chair (b) Office chair (c) Work surface table (d) Partition (e) Computer monitor (f) Paper with cardboard

The combustion chemistry of an item such as the heat of combustion, soot yield and CO₂ yield, are based on the cone calorimeter test results done by NIST [3]. The heat of gasification is often considered as a fundamental property of solids and is used to estimate burning rates at specific heat fluxes in the calculation. A radiant loss fraction χ_R has been decided by calculating the ratio between ΔH_{rad} to ΔH_T , from the SFPE handbook [4], Table 3-4.16, ΔH_{rad} = radiative heat of combustion (kJ/g) and ΔH_T = Net heat of complete combustion per unit mass of fuel consumed (kJ/g). In a single workstation, multiple items exist and igniting the first item can be selected using the 'FIRST IGNITE' button in DFG model. Two scenarios have been modelled to check effect of ignition sources on DFG predictions. An office chair is the first item ignited in Scenario 1. In Scenario 2, a gas burner of 50 kW has been imported to match up with the experiment. Once the item ignites, the secondary item is ignited either by radiation directly from the initial burning object or by radiation from the upper layer and as soon as other items in the compartment ignite, the total HRR for the compartment is the sum of the HRR of the individual items.

The calculation of target ignition of each item is important to ignite secondary items in the fire spread algorithm which is the part of the DFG submodel of B-RISK. The flux time product (FTP) concept is a simple way to predict the piloted ignition of a combustible material when subjected to a time-varying incident radiation (flux). The FTP technique is included in the submodel for the piloted ignition mode. The ignition criterion associated with the FTP method is based on accumulated incident flux and Baker *et al* [5] provide details of that ignition criterion procedure and its implementation into the submodel. The relationship of a time-to-ignition, t_{ig} for a sample under the impact of an effective flux ($\dot{q}'' - \dot{q}_{cr}''$) is expressed by [6]

$$FTP = t_{ig} (\dot{q}'' - \dot{q}_{cr}'')^N \quad (1)$$

Where, N is the FTP index which represents thermal thickness, \dot{q}'' is the external heat flux and \dot{q}_{cr}'' is the critical heat flux (kW/m²). The FTP index N depends upon the thermal thickness and if N=2 the material is regarded as thermally thick. For intermediate thickness N=1.5 and for thermally thin material index N=1.0. Shields *et al* [6] rearranged the above equation to give a linear relationship between the external heat flux \dot{q}'' , and the reciprocal of the time-to-ignition, t_{ig} , to the power of 1/N:

$$\dot{q}'' = (FTP)^{1/N} / t_{ig}^{1/N} + \dot{q}_{cr}'' \quad (2)$$

By using the above equation to plot $1/t_{ig}^{1/N}$ on the x-axis versus \dot{q}'' on the y-axis and determining $FTP^{1/N}$ and \dot{q}_{cr}'' . Since the FTP method only applies to the piloted ignition mode, Baker *et al* developed an approximation for the auto ignition mode, which is used here for the auto ignition dataset in the DFG modelling

2.3 Radiation

The radiation is either directly from the flames of burning items or from the underside of the hot upper layer that forms in a pre-flashover fire. The Point Source Model (PSM) was used as the flame radiation submodel within the DFG, represented mathematically as:

$$\dot{q}_{fl}'' = \dot{Q} \chi_r / 4 \pi R^2 \quad (3)$$

In equation (3), \dot{q}_{fl}'' (kW/m²) is the heat flux received by the target, \dot{Q} (kW) is the heat output from the burning item, χ_r is the radiative fraction and R (m) is the radial distance from the point source to the target. In the DFG, the point source is located at the centre in plan. The radial distance R is the distance from the centre of the burning item to the point of secondary object in the horizontal plane.

The DFG checks two radiation/ignition mechanisms concurrently. The first case is where secondary items are relatively close to burning items, and PSM radiation is assumed to be received by the closest vertical surface of a secondary item and the DFG uses the piloted ignition mode. The second case may be more important for more remote items where radiation from the underside of the hot upper layer is received by the top surface of the secondary object.

2.4 Single workstation simulation

In the Scenario 1 set up, the office chair is ignited first as an alternative ignition source to investigate the impact on the DFG predictions and in Scenario 2, a 50 kW gas burner is used as the ignition source, but as part of the project, as well as DFG modelling of the actual experiments.

2.4.1 Scenario 1: Office Chair first ignited

The sequence of fire spread to other items after the office chair ignited at 0 s, are as below. At 200 s after the office chair ignited, the work surface table is ignited. Between 200 s to 250 s, the sled base chair, computer monitor and one of the side partitions are ignited in the DFG simulation. After 360 s, almost all the items of workstation are ignited and heat release rate at that time is 2.2 MW. The peak heat release rate of 3.3 MW is reached at 600 s in the DFG simulation. A comparison of the HRR curve for Scenario 1 of the DFG by using B-RISK simulation and NIST experiment are showing in Figure 3(a).

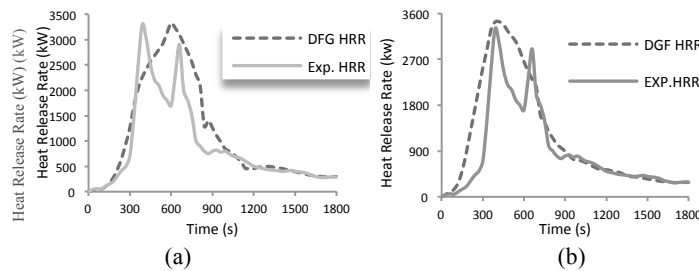


Figure 3 (a) HRR curve of DFG scenario 1 and experiment (b) HRR curve of DFG scenario 2 and experiment

2.4.2 Scenario 2: 50 kW gas burner ignited first

In the DFG simulation, the 50 kW gas burner is ignited and burned for 200 s before the gas supply is shut off. The 50 kW gas burner is positioned under the edge of the workstation table and near the office chair. After ignition of the burner, in the first 30 s, the office chair and work surface table are ignited. At 60 s the computer monitor is ignited, and by nearly 170 s one of the side partitions and sled base chair are ignited which follow quite a similar sequence of item to item fire spread to the experiment. A comparison of the heat release rate curve of DFG Scenario 2 and the experiment are shown in Figure 3(b).

2.5 Results and discussion

The comparison between the heat release rate obtained from the DFG simulation and experiment can be observed from Figure 4(a) for different scenarios and with medium and fast t^2 fires. The fire growth is "medium", if the office chair is to be ignited first. The Scenario 2 fire growth is "fast" compared to "medium" growth of the experiment but after the peak HRR, the curve closely matches with the experimental results. In Scenario 2, the DFG over-predicts the ignition times in initial curve.

The item-to-item distance, time HRR history and radiation fraction are governing factors in the DFG simulation. In the single workstation simulation, the upper layer radiation is not the governing case due to the free burning effect; therefore, PSM is the prevailing case. Item-to-item distance, calculation of R and radiative fraction χ_r might be different for item-to-item fire spread from the experimental fire spread. The DFG results show that all the items are ignited by piloted ignition mode.

The total heat release rates of simulation influenced by the material properties and distance between items and particularly in material properties, another possible reason is the parameter of radiative fraction.

VM2 is a verification method for the specific design of buildings to demonstrate compliance with the New Zealand Building Code clauses relating to Protection from Fire. For commercial-scale office

occupancy, design fire parameters and modelling instructions are as below: The fire growth rate $0.0469t^2$, radiative fraction 0.35 and peak HRR 20 MW. These parameters are already in-built in to the DFG, which gives a time to HRR curve as shown in Figure 4(b). The VM2 HRR curve grows as a “fast” t^2 curve and reaches up to 9.5 MW for office occupancy due to ventilation effect which is quite a conservative in comparison to the DFG HRR of 3.3 MW. The peak HRR of VM2 is almost triple than the DFG HRR.

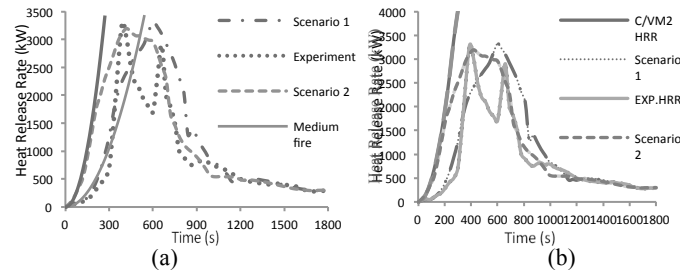


Figure 4 (a) Comparison of DFG, experiment HRR with medium and fast t^2 fire (b) Comparison of VM2 with DFG HRR curve

3 MULTIPLE WORKSTATIONS

3.1 Layout and fuel load

A full-scale experiment of a four workstations that were loaded in a similar manner to the single workstation by NIST, but instead of free burning under an exhaust hood they were assembled in a 7.0 m wide by 7.3 m deep enclosure. The ceiling height of the enclosure was 3.4 m with suspended ceiling at height of 2.7 m above the floor. The compartment was enclosed on all sides top and bottom with only the front side open for observation of the experiment. The four workstations assembled together covered an area 3.83 m long and 3.12 m wide. Schematics of the workstation enclosure from NIST experiment are shown in Figure 5(a).

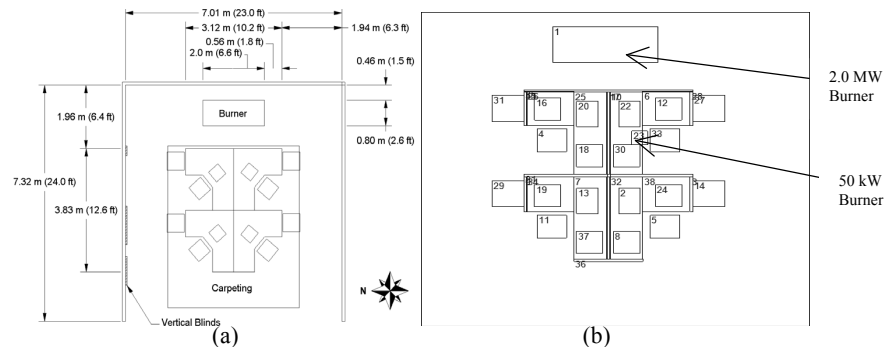


Figure 5 (a) Multiple workstation experimental arrangement taken from NIST (b) B-RISK multiple workstations layout

The description of the furnishings and number of items for each of the four workstations are the same as explained in Section 2.1 and Table 1 of the single workstation. The ceiling, floor and three walls of the enclosure were covered with 25 mm of calcium silicate fire resistant board. Over the calcium silicate board, the interior surface of the enclosure was covered with 12 mm thick gypsum board. Four ceiling

vents were installed in the suspended ceiling, two vents on the north side and two vents on the south side just above the centre of each workstation.

In B-RISK, the similar arrangements of four workstations are created, which is shown in Figure 5(b). The geometry of the room and vents locations are replicated in B-RISK except for the suspended ceiling in the enclosure. Due to specific vent location and not having a facility to input exact grid vents in ceiling, three DFG simulations were done with a ceiling of 2.7 m (plus ceiling vent 1.48 m²), 3.4 m (no vent) and 3.4 m (vent). The DFG simulation operated for different stud height, with and without vents to check the effect on HRR and upper layer temperature, to adjust the effect of the experimental room geometry. The input data of all furnishing items are entered for FTP index N = 1.

In experiment, the workstation in the southeast corner of the grouping had a 50 kW natural gas burner positioned under the work surface, similar to the single workstation arrangement. The heptane burner heat release rate of 2.0 MW was used to create large flames. This was representative of the fire from other burning objects in the area to create radiation effects for the workstation.

In B-RISK, the layer height and upper layer temperature as a function of time are given by the DFG simulation outputs, which represent a mean condition of the compartment. In this project, interface height and upper layer temperature calculated by Integral ratio method or density integral method, the original concept developed by Quintiere *et al.* [7] as given in equations. (4) and (5).

$$\int_0^H T(z) dz = (H - z_i) T_U + z_i T_L \quad (4)$$

$$\int_0^H \frac{dz}{T(z)} = (H - z_i) \frac{1}{T_U} + z_i \frac{1}{T_L} \quad (5)$$

where H is the ceiling height in m, z is height in elevation in m, z_i is the interface height in m, T(z) is temperature at elevation z in °C, T_U is upper layer temperature in °C and T_L is lower layer temperature in °C. To calculate interface height z_i and upper layer temperature T_U , the NIST experimental thermocouple graphs are used. Although somewhat arbitrary, the density integration method followed the approach by Keski-Rehkonen *et al* [8]:

1. The lower layer temperature T_L is taken to be an arithmetic average of the thermocouple readings of the lowest measurement points for each timeline.
2. The interface height and upper layer temperature are to be calculated from the integral equations (4) and (5).

3.2 Multiple workstation simulation

Figure 5(b) shows the four workstations arrangement replicated in B-RISK with burner locations of 2.0 MW and 50 kW. In this simulation, the ceiling vents are provided from 2.7 m stud height of the fire room to outside. The other two simulations are attempted in B-RISK, one with a 3.4 m height stud with similar vents and the other without ceiling vents, to check the effects on HRR, layer height and upper layer temperature as a sensitivity analysis.

In the NIST experiment, the burners were ignited simultaneously at both locations; the large burner located at the east end of the enclosure and the small natural gas burner located under the southeast workstation.

In B-RISK, the large burner of 2.0 MW is ignited and burned for 500 s before the gas supply was shut off, while the 50 kW burners is burned for 200 s before the gas supply shut off, same as NIST experiment.

The item-to-item fire spread information was not available in detail unlike that of the single workstation from the NIST report [3] however the sequence of fire spread to other items after igniting burners in experiment are as stated below.

Between 30 s to 60 s after ignition, some of the paper material on the SE workstation work surface had begun to burn, an office chair and other items were pyrolyzing due to the radiation from the heptane burner. Between 60 s to 120 s, the office chair of the SE workstation started burning and fire had spread to a number of items including computer monitor and top of the work surface table in SE workstation, at

this stage HRR was 3.0 MW. At 240 s after ignition, the SE workstation was totally engulfed in fire and within another 15 s, the NE workstation was heavily involved in fire and during this time HRR increased rapidly from 5.0 MW to 10.0 MW. By 300 s after ignition, most of the combustible materials in the SE and NE portion of the enclosure had ignited and many of the ceiling tiles had dropped. The HRR was reached at first peak of approximately 16 MW. At approximately 305 s after ignition, the southwest portion of the ceiling grid had collapsed and appeared to have reduced the amount of visible fire in the enclosure and the HRR was dropped up to 10 MW.

All the chairs of the enclosure were fully engulfed in the fire after ignition of 360 s and HRR appeared to be increasing in graph. At 400 s after ignition, the fire growing with flames extending along the north wall and most of the fuel was burning within the enclosure. Manual suppression of the fire was began at 455 s after ignition in NIST experiment and suppressed within 30 s, therefore in B-RISK, the simulation also runs up to 455 s to match with the experiment.

The HRR curve generated by DFG simulation for 2.7 m height, 3.4 m height with vents and without vents to compare with experiment is shown in Figure 6.

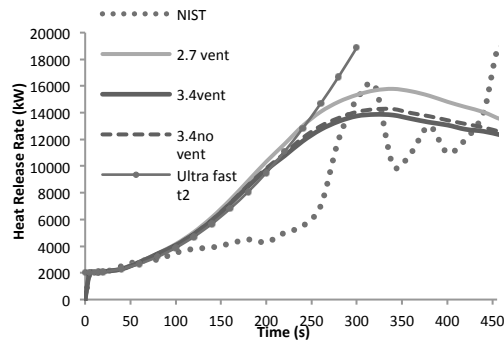


Figure 6 HRR curve comparison of DFG, experiment and with ultra fast t^2 fire

All HRR curves start with 2.0 MW fire growths due to effect of burner and then started to follow an ultra-fast t^2 fire. The DFG simulation and experimental curve closely followed up to 100 s, and after that, the DFG curve continued to follow an ultra fast t^2 growth but experimental HRR curve slowed down due to gradual fire spread from item-to-item. Three different simulations run in the DFG as explained before, and the simulation of 2.7 m stud height with vent HRR curve, is reasonably close to that followed in the experimental one. The peak HRR of DFG simulation for 2.7 m height with vents reached 15.8 MW at 320 s, compared to experiment first peak HRR of 16 MW after 280 s. The other two simulations of 3.4 m height with and without vent are reached up to 14 MW peak, having 2.0 MW HRR difference compared with the experimental one.

3.3 Layer height and upper layer temperature

As shown in Figure 7 (a) the smoke layer height of DFG suddenly dropped down at 100 s due to quick item-to-item fire spread and ultra fast t^2 fire growth. After 100 s of ignition, the smoke layer declined gradually at 280 s when HRR reached at its peak. The experimental layer height calculation by density integral method gives quite reasonable results of each workstation except for the SW workstation. The ceiling grid collapsed at 300 s so the SW workstation layer height and upper layer temperature results are available up to 300 s, refer Figure 7.

The NE and SE thermocouple array was located closer to the heptane burner so the calculations of upper layer temperature curves are higher compared to the NW and SW curves. The upper layer temperature curve from the SE thermocouple array increases sooner than its NE counterpart due to

additional heat and smoke generated by the ignition of the SE workstation from the 50 kW burner. An average temperature curve of four workstations has been shown in Figure 7(b).

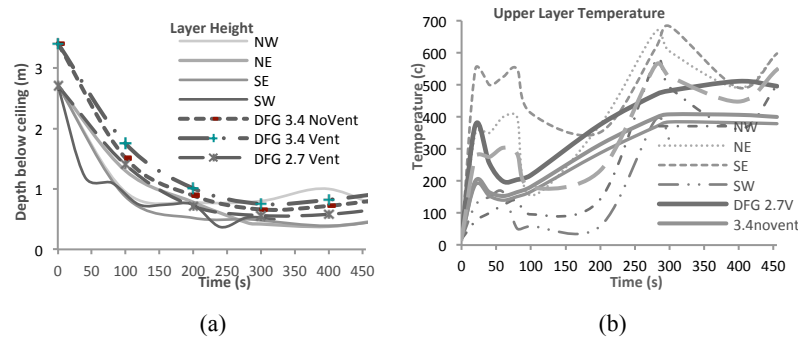


Figure 7 (a) Layer height (b) Upper layer temperature: comparisons of DFG and experiment workstations

4 CONCLUSION

The simulation of a single workstation in the DFG in B-RISK has given reasonable results as compared with experiment [3]. The DFG calculated a 3.2 MW peak HRR for Scenario 2 compared to 3.3 MW from the experimental result. The time line comparison and item to item fire spread of the DFG were compared moderately well to the sequence in the experiment. The only difference found between DFG and experiment was initial fire growth, being "fast" t^2 in DFG and "medium" t^2 in the experiment.

The DFG simulation of multiple (four) workstations in B-RISK results are moderately matched up with the experiment. The item-to-item fire spread sequence of experiment are similar with the DFG simulation, however the time line comparison do not match due to slow fire spread. The HRR curve of experiment and DFG simulations of 2.7 m stud height are closely followed to 100 s and after that, experimental HRR slowed down from ultra fast to fast fire growth. The DFG HRR curve gradually followed ultra fast t^2 curve and at 340 s reached to a peak HRR of 15.8 MW compared to 16 MW of experimental HRR at 300 s. The experimental HRR curve had a second peak at 450 s due to additional fuel load of the collapsed ceiling.

The average layer height of compartment of DFG simulation for 2.7 m stud height fits closely with the calculated layer height from thermocouple array reading of NE and SE workstations. Similarly, calculated upper layer temperature curves of NE and SE workstations by integral methods are relatively higher than the DFG simulation temperature curves. The workstations NW and SW temperature curves are lower than the DFG simulation temperature curve up to 250 s and then follow the simulation curve. But the DFG simulation temperature curve is quite an average upper layer temperature curve of the compartment so by referring to Figure 16, it can be concluded that DFG upper layer temperature curve for 2.7 m stud height is reasonably fit between the four different workstation upper temperature curves.

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