ME 382T

Fire Science

Investigation of Safety Egress Time in Residential Fire of Different Construction Material: Wood vs. Brick

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Background

According to study conducted by Center of Fire Statistics, approximately 80% of the fire related fatalities occurred in residential structures worldwide. Different countries in the world have different preferable construction material depends on climate, availability of construction method, material, and economic background. In United States, most of residential structure is build using wood frame and gypsum wall. In other part of the world, such as most part of Asia and South America, the most common residential structure is brick and mortar with concrete frame.

Furthermore, another study conducted by Federal Emergency Management Agency (FEMA) shows that in US there are more residential fire related death per total population compared with less developed part of the world such as Latin America. This is especially surprising due to the fact that 93% of house in US installed with smoke detectors. Meanwhile, for comparison purposes, only 1 out of 1000 of typical residential housing in Latin America installed with smoke detectors [5].

Nonetheless, one can argue that more developed country has more flammable material in average residential compared with less developed country, some of this material not only more flammable but also better toxic smoke generator. Studied shows that almost 60-80% of fire victim died as a result of smoke inhalation [1]. However, it is not the intention of this paper to study the effect of different consumer goods in one residence in fire safety. The main objective of this paper is to analyze fire spread pattern between wood and brick residential structure and to provide recommendation to increase safety egress time.

The fire spread will be modeled with zone modeling software package, CFAST. The Consolidated Model of Fire and Smoke Transport (CFAST) is developed by National Institute of Safety and Technology (NIST) and widely used to simulate the behavior of past or potential fires. Parameter of interest calculated by CFAST will be smoke layer height, temperature profile, and combustion species profile with respect to time.

Fire Scenario

To narrow down the scope of investigation, a fictitious fire accident scenario is presented as follow. It is a typical night in the early fall, Mr. and Mrs. Smith and their 3 year son just about to go to bed. Mr. and Mrs. Smith slept in room 1 and their son in room 2 (Figure 1). Since the weather was comfortable, they had all of the windows in their house open to let the fresh air circulate. They also try to reduce electrical usage by not using central air conditioner to save up some money for their Christmas plan. Both of the room's doors were kept open so the Smith can monitor their baby easier. Because they were busy earlier in the day for their son birthday party, they forgot to blow off scented candle in the living room area. For unknown reason, the couch in the living room caught fire when the family was sleeping. The town that they lived in does not have building code that required smoke detectors nor fire sprinkler to be installed. It is also postulated that in the same parallel universe, there is another fire break out with the same condition with exception of building material. The tasks are to investigate the safety egress time when the fire breaks out in the living room for brick and mortar versus wood and gypsum wall house. Brick and mortar house will be referred as brick house; wood and gypsum house will be referred as wood house from now on.

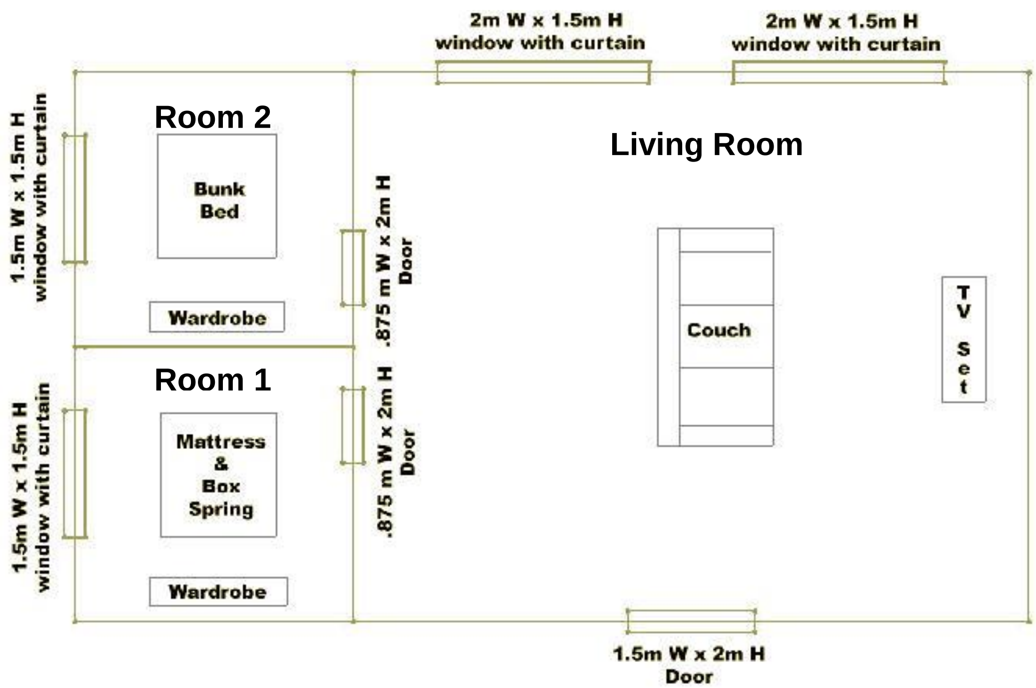


Figure 1. Smith's residence floorplan and dimension. Room A and B have dimension of 3.3 m(W) x 3.25 m(L) x 2.75 m(H). Living room has dimension of 8 m(W) x 6.5 m(L) x 2.75 m(H).

Computer Modeling Set Up

The first task is to set up the simulation environment in CFAST. Since only fire spread comparison between different building materials is of interest, one can argue that the comparison outcome should stay the same as long as the simulation is run on the same environment condition. For argument purposes, ambient temperature of 20^{o}C and interior temperature of 25^{o}C with 40% relative humidity were assumed. Both interior and exterior pressure was set at 1 atm. Exterior wind speed was set at zero.

The house has layout as shown on Figure 1. All of the windows and doors are set to stay open during fire with exception of main entrance is set to be closed at all time. Horizontal natural flow is assumed to occur through the open doors and windows. Meanwhile, it is assumed that none of vertical natural flow such as ceiling or floor holes exists. Furthermore, mechanical flow vents is assumed to be none since the Smith does not operate their air conditioner during the accident.

The dimensions of the compartments are shown on Figure 1. For brick house, the ceiling, wall and floor materials are assumed to be 6” light concrete, 3” common brick, and 6” light concrete respectively. Meanwhile, for wood house, the ceiling, wall and floor materials are assumed to be 5/8” gypsum board, 3/4” common brick, and 6” light concrete respectively.

The fire source is couch at living room. The rest of the combustible material as shown on Figure 1 are set to be ignited when the room reaches certain temperature. Table 1 shows the ignition temperature used for different fire objects. For the unavailable ignition temperature of fire object, it is assumed to be ignition temperature of the main material contained in the object. For example, wardrobe is assumed to be primarily wood. Thus, wood ignition temperature will be used. The lower oxygen limit for all fire objects are set at 10%.

Table 1. Ignition temperature of fire object.

Fire Object	Assumed Material	Ignition Temperature (^oC)
TV SET	Polyethylene	349
Bed	95 % Foam	390
Curtains	100% Polyester	490
Wardrobe	Wood	390
Sofa	PMMA	278

Hand Calculation

In order to get a better understanding of the basic theory in compartment fire and to validate CFAST’s result, upper layer temperature is calculated using correlation developed by others. There are many way to predict the behavior of compartment fire depend on the level of detail desired. But for comparison with method employed by CFAST, mathematical model used will be based on two zone compartment fire model on developing fire phase (pre-flashover phase).

Figure 2 depicts basic principle of two zone model. A fire starts somewhere below the ceiling and releases heat. Due to the buoyancy, hot air will start to rise and create hot upper layer and cool air will be drawn from outside to create cooler lower layer. On two zone model, it is assumed that there is a distinguishable separation between upper and lower layer. The air in lower and upper part is assumed to have interaction only through the plume. At some point in time, the hot upper layer will reach the opening of the compartment and flow out of the compartment.

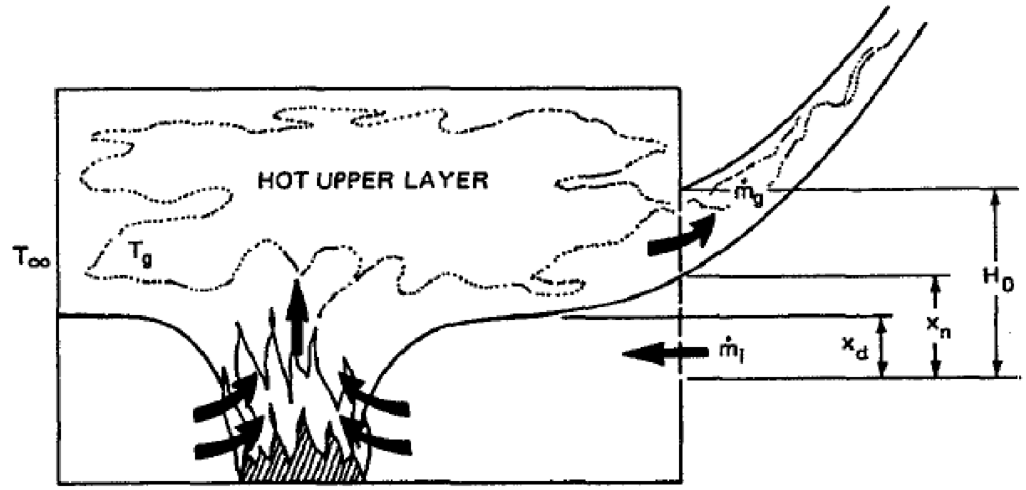


Figure 2. Two-layer (two zone) model schematic [2].

To calculate temperature for the above model, conservation of energy equation is used by assuming that the energy generated by the fire and added to the hot layer must be equal the energy lost from the hot layer through radiation and convection plus the energy convected out the compartment openings [2]. This can be expressed using the following equation:

$$\dot{Q} = \dot{m}_f c_p \left(T - T_\infty\right) + q_{loss} \tag{1}$$

$\dot{Q}$ = energy (heat) release rate of the fire (kW)

$\dot{m}_f$ = gas flow rate out the opening (kg/s)

c_p = specific heat of gas (kJ/kg. K)

T = temperature of the upper gas layer (K)

T_∞ = *ambient* temperature (K)

q_{loss} = *net* radiative and convective heat transfer from the upper gas layer (kW)

The heat loss term can be approximated by assuming conduction through the wall is the primary heat loss:

$$q_{loss} = h_k A_T \left(T - T_\infty\right) \tag{2}$$

h_k = effective heat transfer coefficient (kW/m. K)

A_T = total area of the compartment enclosing surfaces (m^2)

For developing fire phase, McCaffrey, Quintiere and Harkleroad have developed correlation for this region known as MQH correlation [3]. MQH correlation only applicable for developing fire phase on compartment 0.3m – 3m high, fuels centered at the compartment and overventilated case. The fire scenario described previously satisfies all of the aforementioned criteria.

$$\Delta T = 480 \cdot \left(\frac{\dot{Q}}{\sqrt{g} \cdot c_p \cdot \rho_\infty \cdot A_0 \cdot T_\infty \cdot \sqrt{H_0}} \right)^{2/3} \cdot \left(\frac{h_k \cdot A_T}{\sqrt{g} \cdot c_p \cdot \rho_\infty \cdot A_0 \cdot \sqrt{H_0}} \right)^{-1/3} \qquad (3)$$

H_0 = opening height (m)
ρ_∞ = ambient air density (kg/m^2)
g = acceleration due to gravity, 9.8 (m/s^2)
h_k = effective heat transfer coefficient (kW/m. K)
A_T = total area of the compartment enclosing surfaces (m^2)

By using the same heat release rate (HRR) and material properties for fuel defined by CFAST, the equations above can be used to calculate upper layer temperature of a compartment. For validation purposes, upper layer temperatures at 50 s increments up to 400 s are calculated (Figure 3) for living room. A detail sample calculation is included in Appendix A.

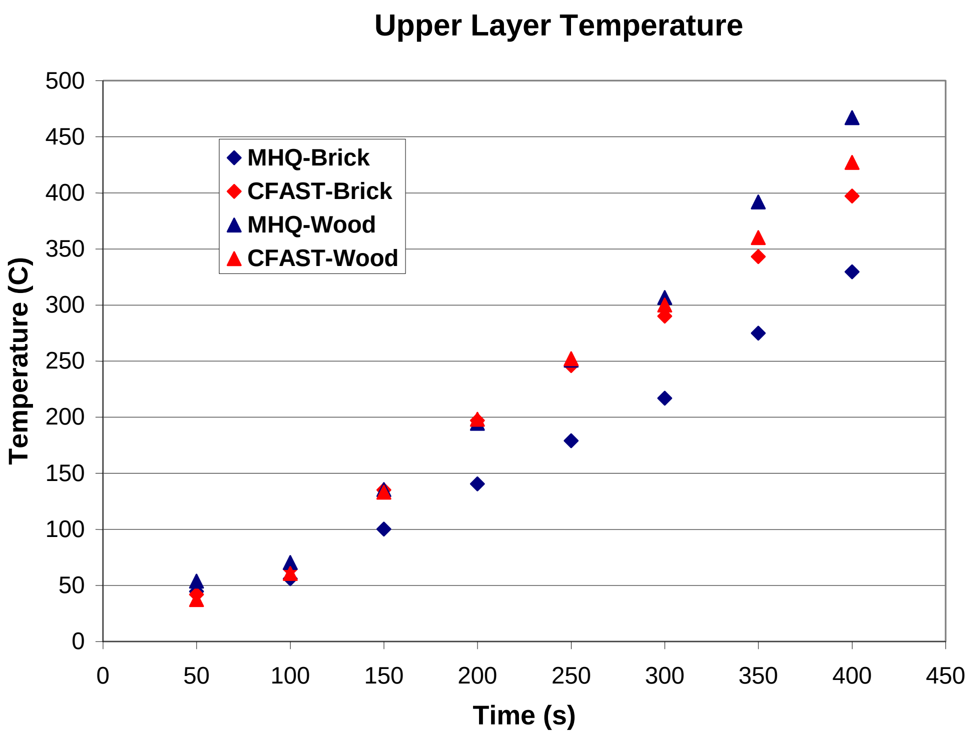


Figure 3. Upper layer temperature for CFAST versus MHQ correlation.

As shown on the above figure, the trends for both MHQ and CFAST show a relatively good agreement especially during initial 100 s after the fire started. However, for extended period of time, the different between MHQ calculation and CFAST can be as high as 50% for the brick case and 15% for the wood case. This discrepancy can be attributed to incomplete data, slightly different method and assumptions that were used during the development of computer program or the correlation. Nevertheless, both MHQ correlation and CFAST showed results within the same order of magnitude which means that assumptions made on the fire scenario are relatively accurate. Both correlation and computer modeling only as good as the person that used them. Good understanding on the physics and processes of fire phenomena are needed in order to accurately applying method and assumption to solve fire problem whether using basic formula or state of the art computer modeling software.

Results and Discussion

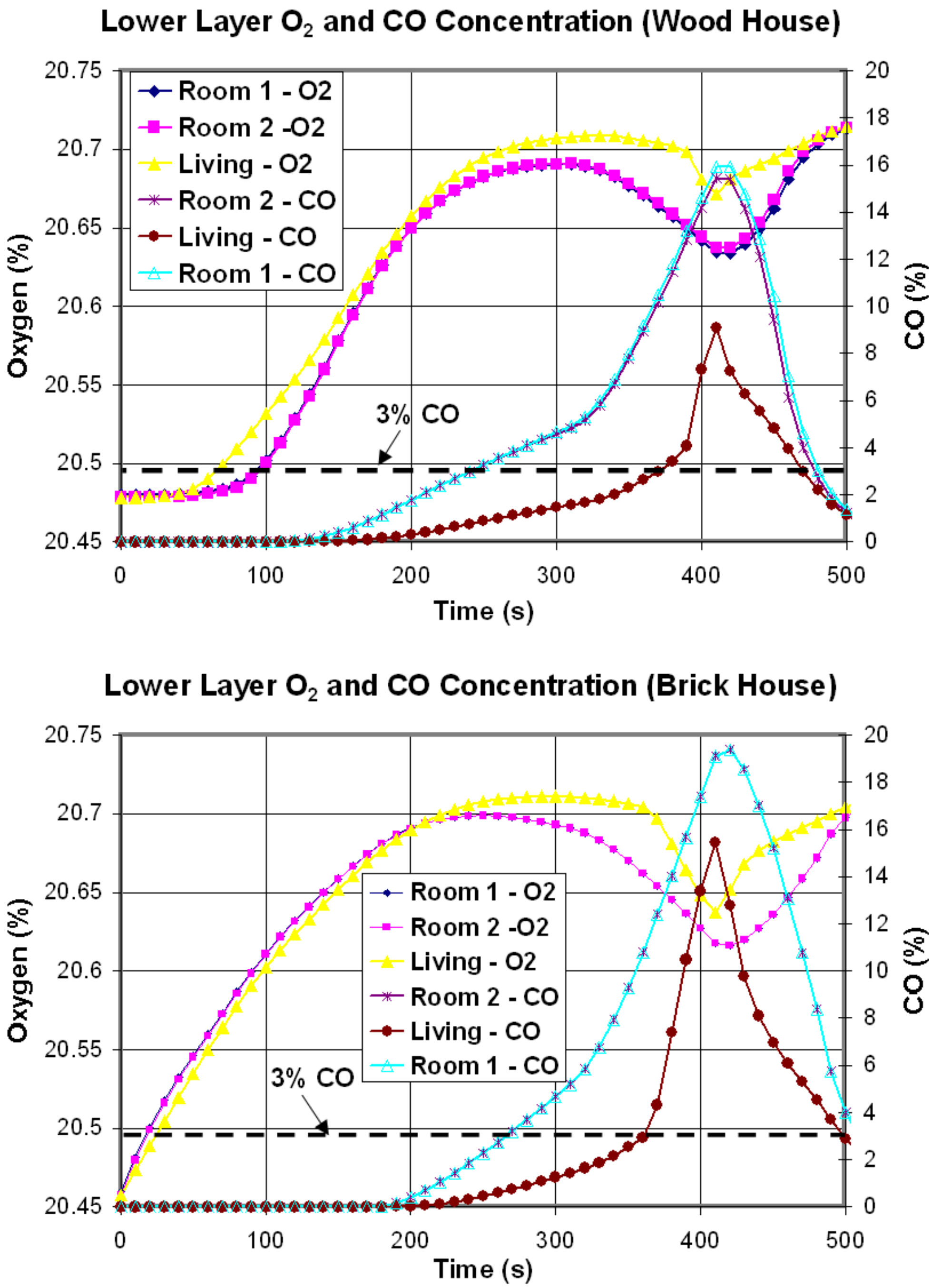


Figure 4. Lower layer O_2 and CO concentration with respect to time at each compartment for wood (top) and brick (bottom) house.

CFAST simulation is used to determine the amount of O_2, CO, ambient heat flux, layers interface height and temperature for 500 s after the fire started. Limiting criteria will be discussed initially before a conclusion is drawn. From the simulation, since both brick and wood cases assuming well ventilated room, the O_2 concentration hardly reaches below 18 % volume for all compartments as shown on Figure 4. Therefore, incapacitation due to asphyxiation is unlikely to happen in our case.

However, it is totally different case for CO concentration. Figure 5 shows the amount of time to incapacitate human during different activities excerpt from SFPE Handbook for Fire Protection Engineering [2]. The graph shows that it only takes one minute to incapacitate human being after inhalation of air with 3% CO concentration. From Figure 4, it clearly shows that the CO level on all of the compartments exceed 3% after ~250 s. Therefore, carbon monoxide level will be one of the limiting criteria for safety comparison between the two cases.

On the side note, CO level peaks at 20% and 16% for brick house and wood house respectively. This maybe due to different conductivity of material, brick has higher conductivity that it losses more heat to the environment. Lower burning temperature might causes incomplete combustion that drives the CO level up.

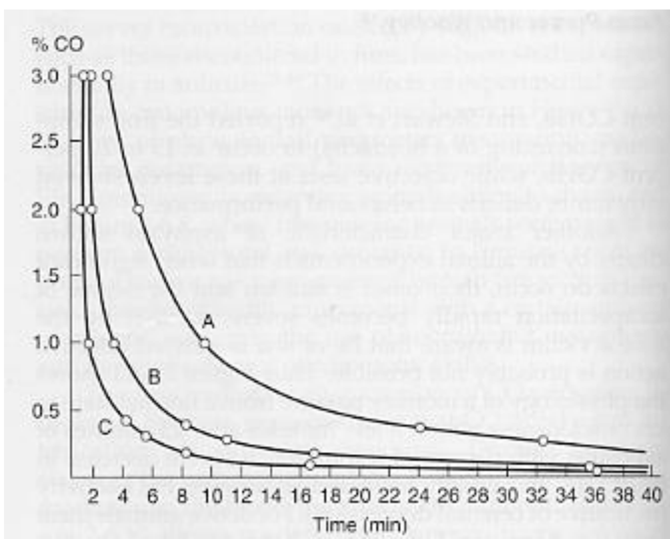
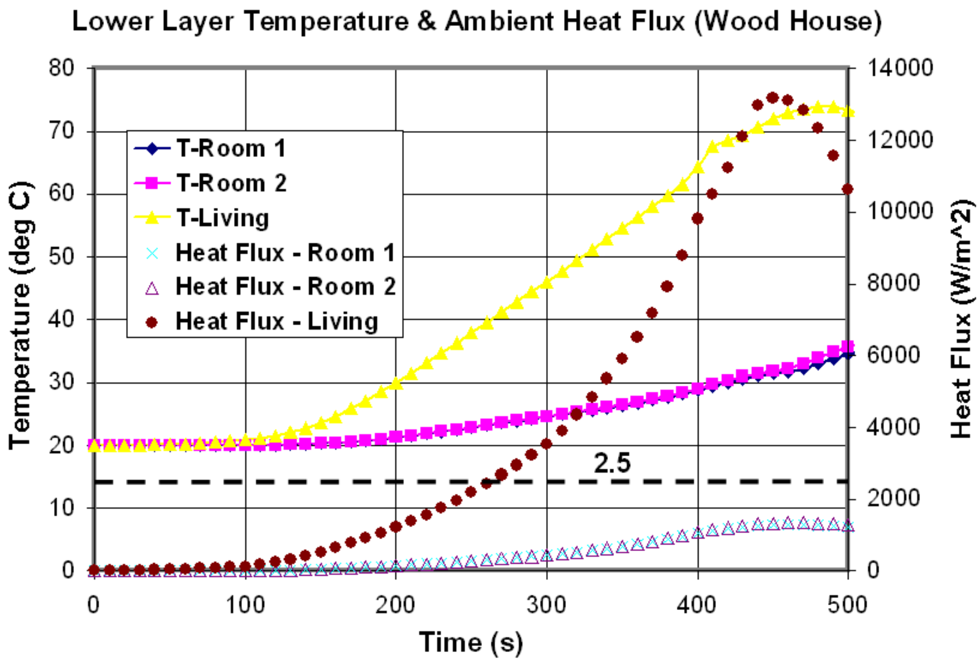


Figure 5. Time to incapacitation by CO for a 70 kg human at different levels of activity. Curve A – 40% carboxyhemoglobin RMV 8.5 L/min at rest sitting; Curve B – 30% carboxyhemoglobin RMV 25 L/min, light work (e.g., walking 6.4 km/h); Curve C – 20% carboxyhemoglobin RMV 50 L/min, heavy work (e.g., slow running 8.5 km/h) (or for walking 5.6 km/h up a 17% gradient) [2].



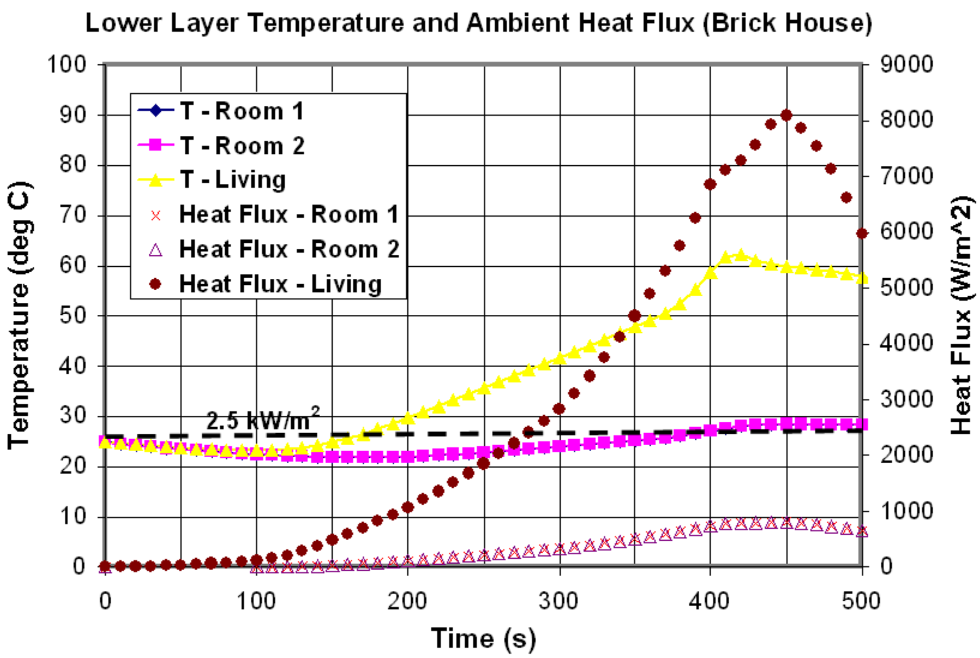


Figure 6. Lower layer temperature and ambient heat flux with respect to time at each compartment for wood (top) and brick (bottom) house.

According to reference [2], exposure to heat radiation greater than 2.5 kW/m^2 for longer than 30 s can incapacitate healthy human. Both wood and brick house, the heat flux will exceed 2.5 kW/m^2 as shown on Figure 6. Brick house shows lower maximum heat flux compared with wood house since it has higher conductivity. Heat losses due to convection and radiation on a fully developed fire usually can be neglected as stated previously. Thus, assuming that conduction through the wall is the primary heat transfer method, brick wall will have lower heat flux. Meanwhile, lower layer temperature will not be our controlling criteria since it lingers around 30°C at the time where heat flux and CO concentration level are lethal. This temperature is obviously within human tolerance.

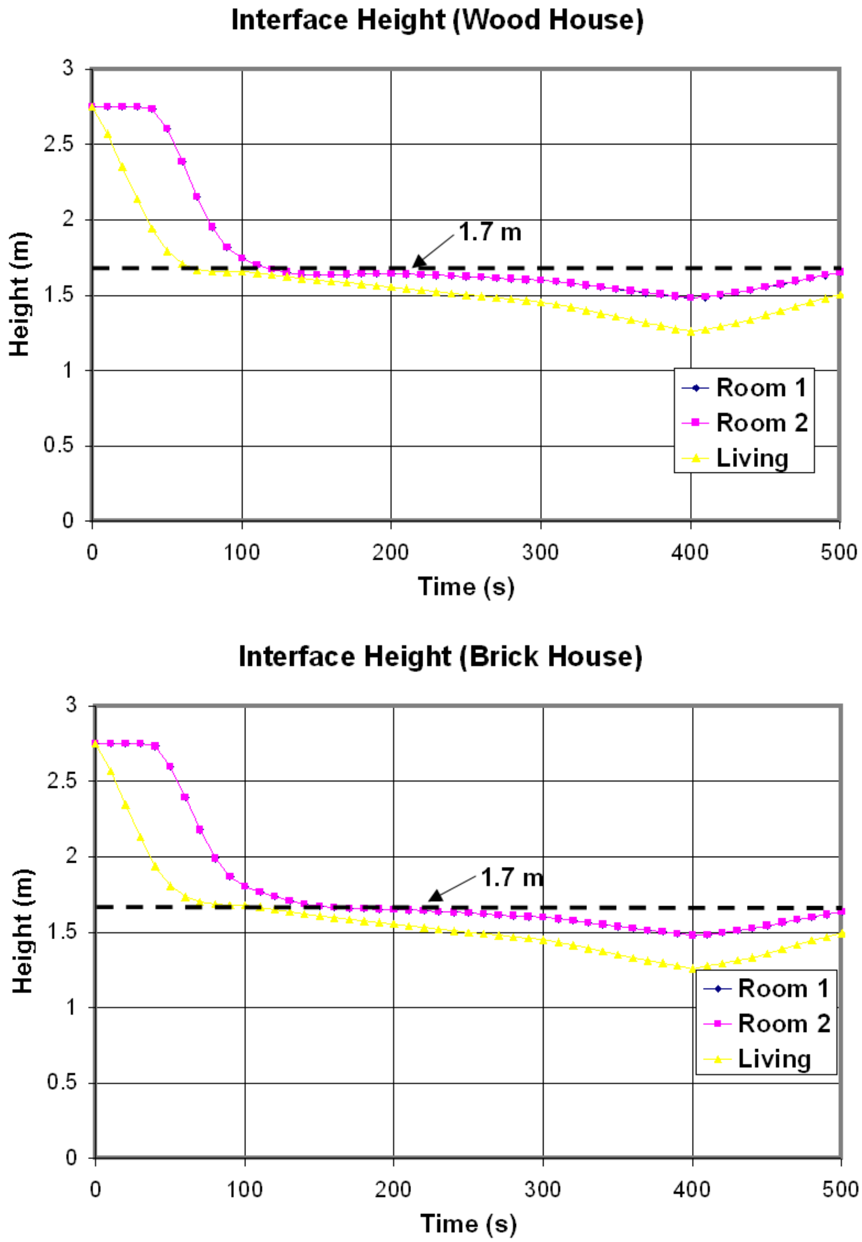


Figure 7. Upper and lower layers interface height with respect to time at each compartment for wood (top) and brick (bottom) house.

For upper and lower layers interface height, assuming that average human height is 1.7 m, there is only less than 70 s available before it reaches critical height for both cases. However, both wood and brick house interface height never lower than one meter. Assuming that all of the occupants are able to crawl out the burning compartment, layers interface height is not very critical on our investigation compared with other criteria.

Based on the above discussion, CO level concentration and ambient heat flux will be limiting criteria for safety comparison between the two cases. Figure 8 and 9 shows the detail snapshot of the two controlling criteria. Figure 8 shows that brick house reaches its 3% CO level at 270 s compared with wood house at 240 s. In other words, people lives in brick house have extra 30 s to escape before the CO level becomes hazardous. Moreover, brick house always shows lower level of CO at the same period of time compared with wood house. This is very important since breathing minute amount of CO in prolong period can result in dizziness, visual impairment and decrease brain function.

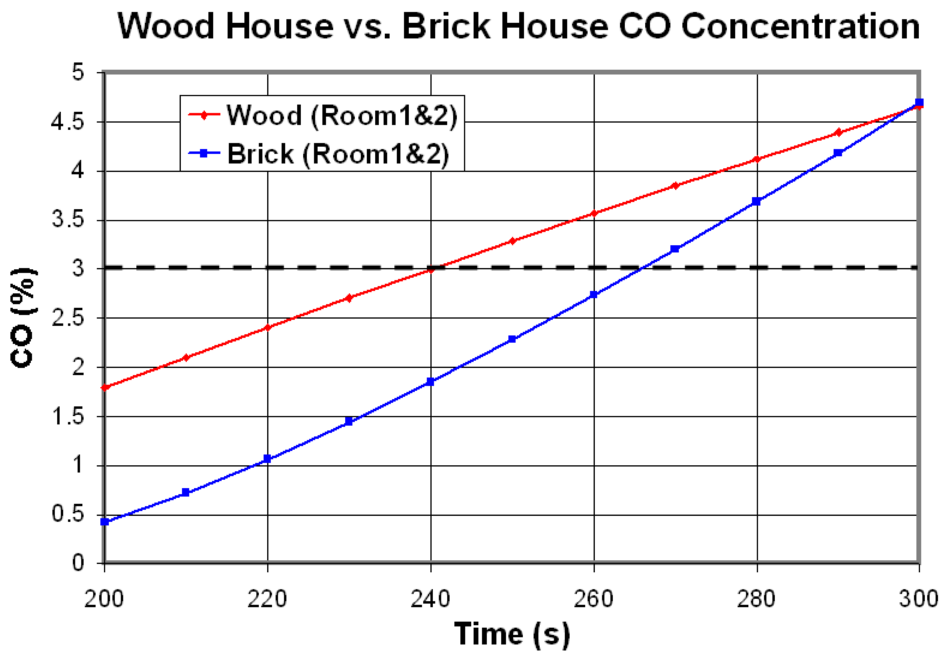


Figure 8. Carbon monoxide concentration from 200 – 300 seconds after fire started.

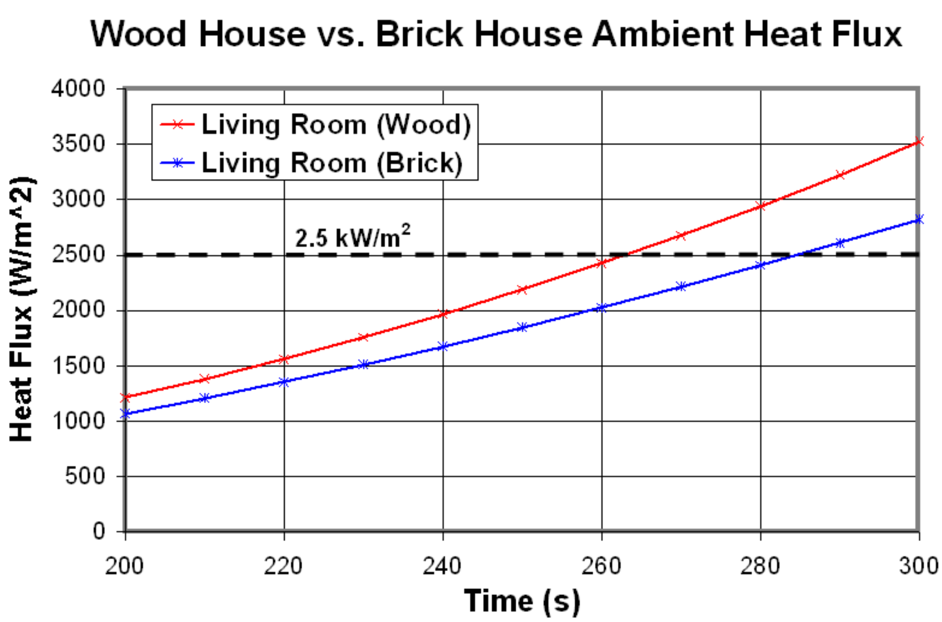


Figure 9. Ambient heat flux from 200 – 300 seconds after fire started.

Figure 9 shows that wood house reaches its 2.5 kW/m^2 level almost 20 s earlier compared with brick house as expected. Based on both CO concentration and heat flux criteria, one can conclude that brick house is safer than wood house if house material is the only contributing factor. Wood house occupants have less than 4 minutes to escape while brick house occupants have less than 5 minutes. However, one cannot draw conclusion that US has more residential death per population due to its construction material. There are many other contributing factors that have not been addressed such as different fire scenario, environment condition, and house layout.

Smoke Detector and Fire Sprinkler Installation

From previous discussion, it is concluded that wood house's occupants will have less time to escape in the case of fire break out. In this section, the effect of smoke detector and fire sprinkler installation will be investigated using CFAST.

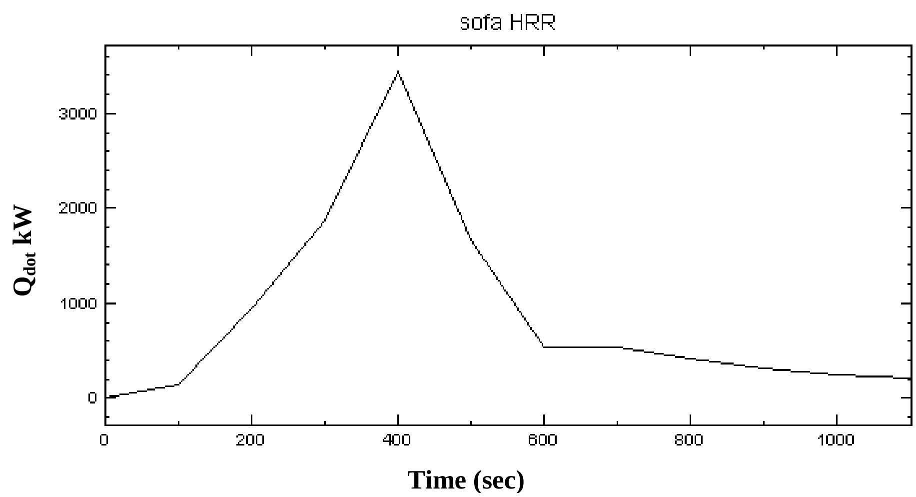


Figure 10. Sofa Heat Release Rate curve from CFAST.

From earlier CFAST simulation, it was shown that heat flux at living room will reach dangerous threshold of 2.5 kW/m^2 at approximately 260 sec (Figure 9). By using sofa HRR curve supplied by CFAST's property database, one can estimate heat release to be ~1390 kW assuming steady burning after 250 sec (Figure 10). The amount of water that needede to suppress that amount of heat can be estimated using the following formula proposed by Quintiere:

$$\dot{m}_F'' \cdot L = \frac{h_c}{c_p}\left(\frac{\dot{m}_F'' \cdot c_p / h_c}{e^{\dot{m}_F'' \cdot c_p / h_c} - 1}\right) \cdot \left[\frac{Y_{O_2,\infty} \cdot \Delta h_c}{r - c_p\left(T_v - T_\infty\right)}\right] + \dot{q}_{f,r}'' + \dot{q}_e'' - \sigma\left(T_v^4 - T_\infty^4\right) - \dot{m}_W'' L_W \qquad (4)$$

With known values as follow:

$\dot{Q}$ = 1390 KW (maximum heat release design point)

Δh_c = 18.9 KJ/g (sofa heat of combustion)
$\dot{m}_F''$ = 36.77 g/m^{2}s
h_c = 8 x 10^{-3} KW/m^{2}K (assumed typical value from Quintiere)
r = 1.45 $\left(\frac{\Delta h_c}{\Delta h_{oxy}} = \frac{18.9}{13} = 1.45 \right)$
$Y_{O_2,\infty}$ = 0.233
c_p = 1 KJ/Kg
$\dot{q}_{f,r}''$ = 229.35 KW/m^2 ($\dot{Q}$ x X_r = 1390 KW with X_r = 0.33)
$\dot{q}_e''$ = 0 (assumed zero external heat)
L_W = 2.6 KJ/g (typical value for water)
L = 1.23 KJ/g (heat of gasification from CFAST)
T_v = 523 K (room temperature at t = 260 s)
T_∞ = 298 K
σ = 5.67x10^{-11} KW/m^2 K^4

By inserting the known value, the water application rate is determined to be:

$\dot{m}_W'' = 70.75 \frac{g}{m^2 s} = 0.1034 \frac{gpm}{ft^2}$ or $\dot{m}_W'' = 7x10^{-5} \frac{m}{s}$ assuming ρ_{water} = 1000 kg/m^3

The calculated water application rate is under typically prescribed sprinkler densities range from 0.05 gpm/ft^2 (light application) to 0.5 gpm/ft^2 (extremely hazardous) [3].

By using the above water application rate result, detection and suppression system are defined in the CFAST for wood house at all compartments. Both of them are positioned in the center of each compartment. The sprinkler and smoke detector are defined to have activation temperature of 60^{o}C and 71^{o}C respectively.

Table 2. Activation time after fire started at each compartment.

	Smoke Detector Activation Time	**Fire Sprinkler Activation Time**
Room 1	160 s	380 s
Room 2	160 s	380 s
Living Room	100 s	240 s

As shown on Table 2, for the same fire accident scenario defined earlier, the smoke detectors are activated well before the time needed for CO to reach lethal 3% concentration (Figure 8). The smoke detector in the living room is the first one to be activated, almost 100 seconds before CO concentration rise significantly. These additional seconds should provide sufficient time for the occupants to escape in case of fire break outs.

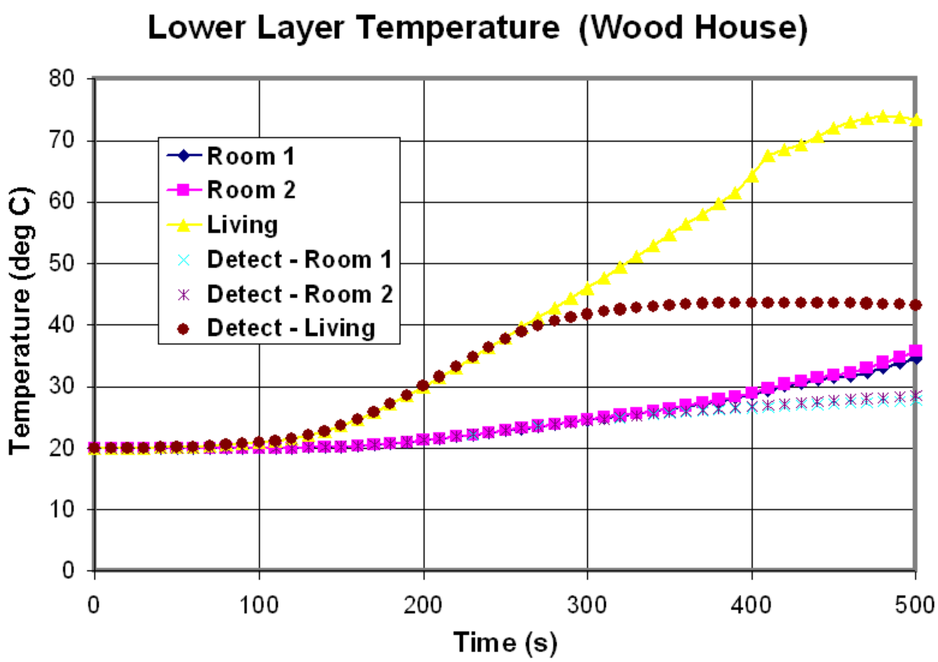


Figure 11. Lower layer temperature with and without detection/suppression system.

With installation of fire sprinkler system, the lower layer temperature of each compartment is lowered significantly as shown on Figure 11. On the onset of first smoke detector activation, the lower layer temperature is approximately the same as ambient temperature, which should not posed problem for occupants to escape. The same case applied for the ambient heat flux and carbon monoxide level, all of the compartments show less than 2.5 kW/m^2 of heat flux and less than 3% of CO concentration at all time (Figure 12 and 13).

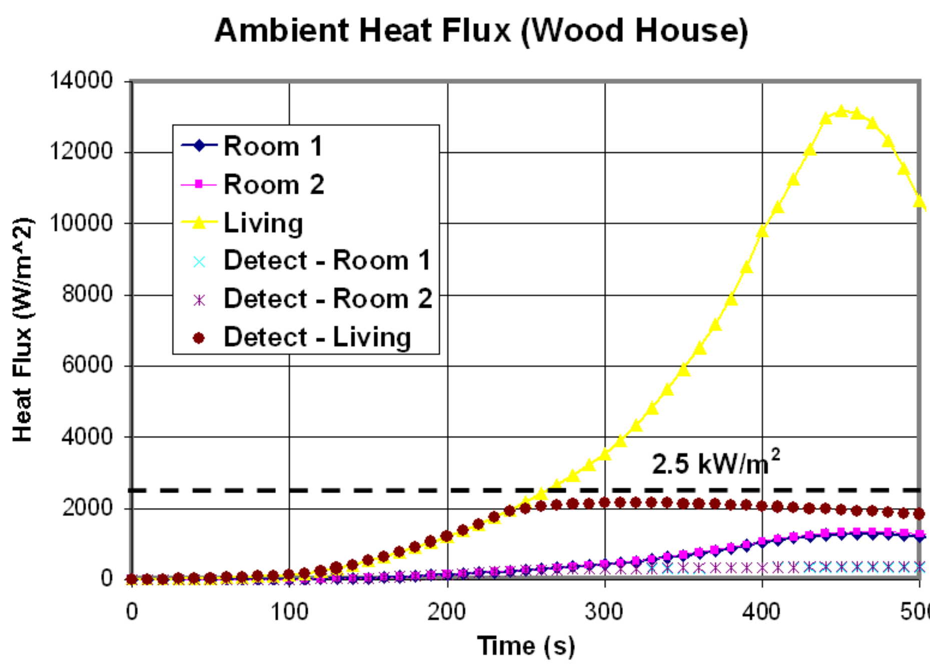


Figure 12. Ambient heat flux with and without detection/suppression system.

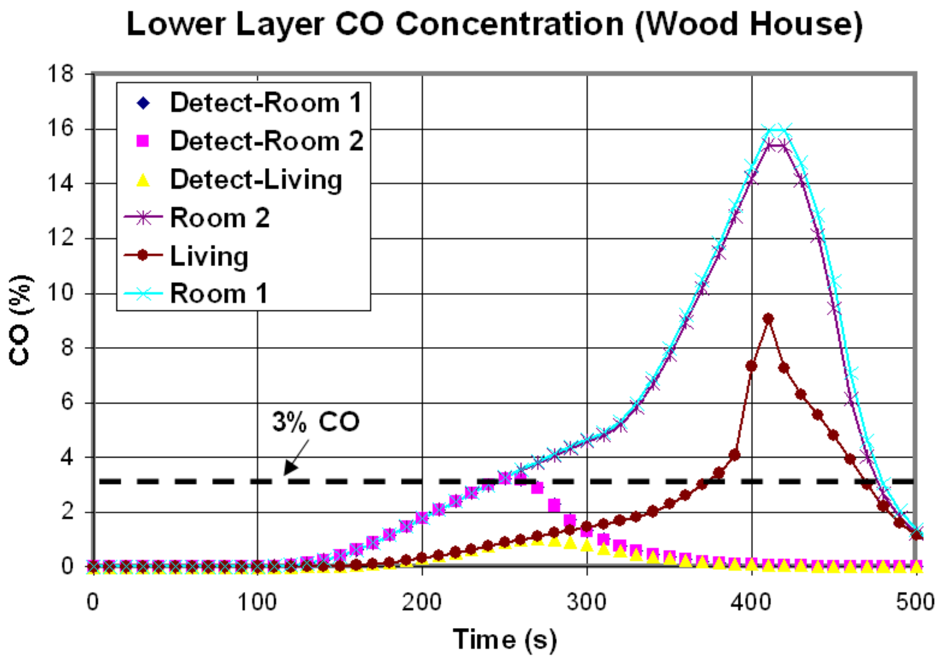


Figure 13. Lower layer CO concentration with and without detection/suppression system.

Installation of smoke detectors in three compartments house will typically cost less than \$100 assuming each smoke detector cost around \$20. Meanwhile, fire sprinkler system will cost around \$10/m^2 which translates to \$750 in our case study. By only installing smoke detector, one already increases his chance to escape from raging fire. Considering the relatively cheap price, smoke detector shall be incorporated in every residential house whenever possible. Meanwhile, every homeowner should consider installation of fire sprinkler as an investment. Fire sprinkler system in residential house typically will cost one percent of the total home cost.

Conclusion

"Over the envelope" calculation of upper layer temperature using McCaffrey, Quintiere and Harkleroad MHQ correlation is on the same order of magnitude compared with CFAST simulation. Both of the results show similar trends with little deviation. The deviation can be attributed to incomplete data, slightly different method and assumptions that were used during the development of computer program or the correlation.

For the fire scenario defined previously, it is concluded that brick house is safer than wood house if house material is the only contributing factor. CFAST simulation and calculation show that water application rate of $7x10^{-5}$ m/s maintains CO and heat flux below dangerous level for the wood house. Smoke detector provides warning as early as 100 s before CO and heat flux reach lethal level if sprinkler system was not installed. This result is not surprising partly due to other research [3] that showed fire deaths in US dropped from 8000 annual deaths in 1971 to 4000 annual deaths in 1998 due to installation of nearly none smoke detector to over 66% after 1981. Smoke detector is proven to be a relatively cheap investment considering the positive impact it brings.

In addition to physical understanding and processes of fire phenomena, tabulated heat release rate and properties of different material are proven to be a very valuable tool in designing fire suppression system. It is not surprising that a lot of effort has been put into gathering this information in order to design a better performing fire suppression system.

References:

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