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Fire Resistance Requirements for Rubber-Tire Warehouses

D. Yung* and J. R. Mehaffey**

Abstract

The normalized heat load approach is used to analyze the severity of warehouse fires involving a large volume of rubber tires. The results suggest that for a compartment with a fire resistance rating of two hours, the maximum number of tires that can be stored safely per square meter of compartment surface area is 0.8 to 1.2 for normal weight concrete walls, and 0.4 to 0.7 for lightweight concrete walls.

Introduction

Rubber tires are usually stored in warehouses on shelves or racks. The racks are usually arranged in such a way as to provide maximum storage capacity with minimal aisle separations for easy access. The 1985 National Fire Code of Canada¹ does not require that such warehouses be equipped with sprinklers if the volume occupied by the tires is less than 425 m³. A large warehouse, in principle, could be constructed without sprinklers if the warehouse is divided into several smaller fire compartments with each storing no more than 425 m³ of tires. The statement in the Code, however, does not specify what fire resistance rating is required of the fire compartment boundaries. This raises concerns and these concerns led to this study on the fire resistance requirements for the fire compartment boundaries.

In this study, due to the lack of experimental data on the burning characteristics of rubber tires inside a compartment, the rubber tires are modeled as an equivalent cellulosic load with the same heat content as that of the rubber tires. This approach produces a more severe heat assault

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on the boundary walls and hence a conservative estimate of the fire resistance requirements.

Conclusions from this study indicate that rubber-tire fires can be very severe. As a result, the code writing committees have made certain changes to the National Fire Code of Canada.² For example, the volume of tires permitted in an unrated compartment has been reduced from 425 to 375 m³. Also, the fire resistance rating for compartments containing more than 375 m³ of tires has been specified to be not less than 2 h.

Assessing Fire Resistance Requirements

The fire resistance rating of a building element, for example a wall assembly, is usually determined by standard tests conducted in conformance with CAN4-S 101, "Standard Methods of Fire Endurance Tests of Building Construction and Materials."³ (CAN4-S101 is the Canadian counterpart of the American ASTM-E119, "Standard Methods of Fire Tests of Building Construction and Materials.") In the test, the specimen of a building element is exposed on one side to a standard fire exposure in a furnace. The fire follows a prescribed temperature-time curve deemed to be representative of that encountered in actual building fires. The fire resistance rating, τ , is the time in hours or fractions thereof for which the specimen maintains its structural integrity (withstands the passage of the flame) and resists the transmission of heat (temperature on the unexposed surface does not rise more than 139°C). For some products, the fire resistance rating may be determined by either the extension or interpretation of information derived from standard tests or by mathematical modeling.

An actual fire in a compartment within a building seldom resembles the one in the standard fire resistance test. That is, the temperature-time curve encountered in a real fire situation is seldom identical to that of the standard test. To establish fire resistance requirements for compartment boundaries, a mechanism is required to relate the severity of the anticipated fire to that of the test fire. Detailed studies⁴ have shown that the severity of the thermal assault on a boundary, as a result of exposure to a fire, can be quantified by a parameter called the normalized heat load. The normalized heat load, H , is defined as:

$$H = \frac{1}{\sqrt{k\rho c}} \int_0^{\tau^*} q dt, \quad s^{1/2}K \quad (1)$$

where

- q = heat flux penetrating the boundaries, W/m^2
- t = time, s
- τ^* = duration of fire exposure, s

$\sqrt{k\rho c}$	=	thermal inertia of the boundaries, $J \cdot m^{-2} s^{-1/2} K^{-1}$
with k	=	thermal conductivity, $W/(m \cdot K)$
ρ	=	density, kg/m^3
and c	=	specific heat, $J/(kg \cdot K)$

The normalized heat load is the total heat absorbed by unit surface area of the boundaries during the fire divided by the thermal inertia of the boundaries.

A compartment fire and a standard test fire have the same equivalent fire severity if they deliver the same normalized heat load to the boundaries. Consequently, fire resistance requirements can be set by requiring building elements to endure, in a standard test fire, a normalized heat load greater than that expected to be imposed on the same element in a real world fire. The relationship between the required fire resistance rating, τ , of a specimen and the maximum normalized heat load, H , it can endure is given as:⁴

$$\tau = 0.11 + 0.16 \times 10^{-4} H + 0.13 \times 10^{-9} H^2 \quad (2)$$

for $H < 9 \times 10^4 s^{1/2} K$. The above equation shows, for example, a required fire resistance rating of two hours for an expected maximum normalized heat load of $7.39 \times 10^4 s^{1/2} K$. That means an element with a two-hour rating can withstand any compartment fire for the whole duration of the fire provided the fire delivers a normalized heat load to the element not greater than $7.39 \times 10^4 s^{1/2} K$.

Modeling Tire Fires

Models for characterizing compartment fires and for predicting the normalized heat load delivered to the compartment boundaries have been developed within the past few years.⁴ These models indicate that the severity of the fire depends on the type of fuel burned, the size of the ventilation opening, and the thermal properties of the compartment boundaries. The models for cellulosic fuels, such as wood, have been developed to a level that they can make quite accurate predictions.⁵ Those for non-cellulosic fuels, such as plastics, have yet to be tested against experiments. Very little is known about the characteristics of warehouse fires involving tires as fuel, except for a limited number of tests conducted to study the effectiveness of using sprinklers to control the fire.⁶

With only limited information on the phenomenology of tire fires, it is difficult to model compartment fires involving tires. However, it has been found, during the course of developing models for compartment fires, that a compartment fire involving a cellulosic fire load is more severe

(i.e., there is more heat assault on the compartment boundaries) than a compartment fire involving a non-cellulosic, but calorifically equivalent, fire load (where generally more heat is lost through the ventilation opening).⁵ For the purpose of this study, the fire load is modeled as an equivalent wood load with equal calorific value. This approach allows a conservative estimate of the severity of the fire, and a safe estimate of the fire resistance requirements of the boundaries.

The typical weight of an average passenger tire is 11 kg, and the heat of combustion is about 34 MJ/kg^7 . The heat of combustion for wood is about 18 MJ/kg^8 . The equivalent wood mass for a tire is therefore about 20.8 kg. The total equivalent fire load is simply:

$$G = 20.8 N \quad (3)$$

where G is the equivalent fire load in kg and N is the total number of tires.

During the fully developed stage of a fire, the rate of burning depends on the amount of fuel in relation to the ventilation of the compartment. When the amount of fuel is relatively small, the burning rate is controlled by the fuel surface area and is considered to be fuel controlled. When the amount of fuel is relatively large, the burning rate is controlled by the rate of entry of fresh air and is considered to be ventilation controlled. In this case, when the fuel load is very large and the door opening is relatively small, the fire can be expected to be ventilation controlled. It should be noted that ventilation controlled fires are more severe than fuel controlled fires.⁵ By modeling the fire as ventilation controlled, a conservative estimate of the severity of the fire is found. Under ventilation control, the burning rate is found to be:⁴

$$R = 0.0236 \Phi \quad (4)$$

where R is the burning rate in kg/s and Φ is the ventilation parameter also in kg/s . The ventilation parameter is defined as:

$$\Phi = \rho_a A_v \sqrt{gh_v} \quad (5)$$

where ρ_a is the density of the atmospheric air (1.2 kg/m^3); A_v is the area of the ventilation opening in m^2 ; g is the gravitational acceleration (9.8 m/s^2); and h_v is the height of the ventilation opening in m .

The maximum normalized heat load absorbed by the boundaries during the fire is given as:⁴

$$H = \frac{1260 G}{A \sqrt{k_{pc}} + 935 \sqrt{\Phi G}} \times 10^4, \text{ s}^{1/2} \text{K} \quad (6)$$

In the above expression, A is the total surface area of the compartment boundaries (walls, ceiling, and floor). For this study, the ceiling and floor are assumed to have the same construction as that of the walls.

In applying the above model to warehouse fires involving tires, the following assumptions are implied:

- The ceiling-roof assembly stays in place during the fire.
- There are no sprinklers or any other fire-fighting efforts within the compartment.
- The release of heat due to combustion takes place completely within the compartment.
- Fresh air enters and fire gases exit the compartment through one opening only.
- The fire within the compartment reaches flashover.
- Uniform conditions prevail within the compartment.

If any of these conditions are violated, except the last one, the fire conditions within the compartment would be less severe than the model predicts. The last assumption is made to render simplification in the present modeling.

Model Predictions: Compartment with 425 m³ of Tires

For a compartment containing 425 m³ of tires, the compartment size, after allowing for racks and aisles providing access to the tires, is assumed to be as shown in Figure 1 (drawn to scale): 22.5 m long, 13.5 m wide, and 7 m high with a typical door of 3.6 m high by 2.4 m wide. The largest number of tires that can be put into 425 m³ — hence the most severe fire load — is by piling all the tires into a single pile. This is shown in Figure 1 with a probable pile size of 9.22 m by 9.22 m by 5 m high. A typical passenger tire is 0.750 m in diameter and 0.175 m in width. The arrangement of the tires is therefore probably 12 across by 12 deep by 25 high, a total of 3600 tires.

With 3600 tires, the equivalent wood fire load G is 74,900 kg (Equation 3). Based on the dimensions of the ventilation door, the ventilation factor, Φ , is 61.6 kg/s (Equation 5). Assuming the walls, ceiling, and floor are made of normal weight concrete, the thermal inertia $\sqrt{k\rho c}$ is $2192 J \cdot m^{-2} s^{-1/2} K^{-1}$.⁴ The total surface area of the boundaries is 1100 m². Substituting these parameters into Equation 6, the normalized heat load H is $21.4 \times 10^4 s^{1/2} K$. This is a very high normalized heat load, out of the applicable range of Equation 2 for estimating the required fire resistance rating. This means the required fire resistance rating is extremely high. If lightweight concrete is used, similar calculations would show the normalized heat load to be even higher because of its

Figure 1: Assumed warehouse dimensions for storing 425 m³ of tires.

lower thermal inertia ($\sqrt{k\rho c} = 931 \text{ J} \cdot \text{m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$).

The fact that the fire is so severe is not unexpected because of the large fire load inside the compartment. If Equation 4 is used, the burning rate is found to be 1.45 kg/s. With an equivalent heat of combustion of 18 MJ/kg and assuming a combustion efficiency of 80%, the heat generation rate is very high, 20.9 MW. Because of the large fire load, 74,900 kg, the duration of the fire is also very long, 14.3 hours. A strong fire burning for a long time imposes a very severe thermal assault on the boundaries.

Since the fire is of long duration, a steady state heat transfer calculation was performed to shed some light on how thick the walls have to be in order to resist the fire. In the steady state heat transfer calculation, the heat generated from combustion is dissipated via conduction through the boundaries and subsequently free convection on the outside of the boundaries, and via convection and radiation through the ventilation

door. The formulation and calculation methods are shown in the Appendix on p. 110.

The results of the calculation are shown in Figure 2 where the outside surface temperature rise of the boundaries is plotted as a function of the boundary thickness for both normal weight concrete and lightweight concrete. As mentioned previously, the criteria for satisfactory performance are structural integrity and an outside surface temperature rise not greater than 139°C . Assuming the concrete boundaries can maintain the structural integrity, Figure 2 shows that the required thickness to meet the temperature criterion is enormous: about 3 m for normal weight concrete and close to 1 m for lightweight concrete. This confirms the results of the normalized heat load approach that the fire severity is indeed very high.

Since the construction of concrete walls of these thicknesses is not practical, other calculations were performed, shown in the next section, to determine whether fire resistance requirements can be reduced if the compartment is limited to a smaller size with a correspondingly smaller fire load.

Figure 2: Compartment outside surface-temperature rise as a function of wall thickness for two different types of concrete: normal weight and lightweight.

Model Predictions: Compartments with Two-hour Fire Resistance Requirements

In this section, calculations are performed using the normalized heat load approach to determine which arrangements of compartment sizes and tire loads would not result in a fire resistance requirement of more than two hours. For the walls to perform satisfactorily throughout the fire, the normalized heat load absorbed by the walls must be less than $7.39 \times 10^4 \text{ s}^{1/2} \text{ K}$, as was discussed earlier in this paper. The normalized heat load, H , as shown by Equation 6, depends on the compartment surface area, A , the boundary thermal inertia, $\sqrt{k\rho c}$, the fuel load, G , and the ventilation factor, Φ . In what follows, the fuel load, G , is determined (indirectly the number of tires, N , through Equation 1) for six different reasonable combinations of A and Φ , and for both normal weight concrete and lightweight concrete.

Three compartments are considered (affecting the compartment surface area A): large, $22.5 \text{ m} \times 13.5 \text{ m} \times 7 \text{ m}$ high; medium, $10 \text{ m} \times 10 \text{ m} \times 7 \text{ m}$ high; small, $10 \text{ m} \times 10 \text{ m} \times 4 \text{ m}$ high. The door is considered to be $2.4 \text{ m} \times 3.6 \text{ m}$ high. Two door openings are considered (affecting the ventilation parameter Φ): full, in which the door is fully open; and half, in which the door is half open (i.e., $2.4 \text{ m} \times 1.8 \text{ m}$ high, in the event something is blocking the doorway). The case when the door is fully closed is not considered here because the fire would not be a severe one as it could not develop into a severe one without the supply of fresh air. As discussed earlier, thermal inertia is $2192 \text{ J} \cdot \text{m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ for normal weight concrete and $931 \text{ J} \cdot \text{m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ for lightweight concrete. To achieve a two-hour fire resistance rating, the wall thickness must be 113 mm (masonry) to 130 mm (monolithic) for normal weight concrete, and 95 mm (masonry) to 103 mm (monolithic) for lightweight concrete.⁹

Table 1: Maximum number of tires permitted (N) for normal weight concrete compartments with a two-hour fire resistance rating

Compartment	Opening	N	Fire Duration (hrs)	Fire Load (MJ/m^2)	$N/\text{Floor Area}$ (m^{-2})	$N/\text{Surface Area}$ (m^{-2})
Large	Full	975	3.9	1200	3.2	0.9
Large	Half	845	9.5	1040	2.8	0.8
Medium	Full	505	2.0	1880	5.1	1.1
Medium	Half	405	4.5	1510	4.1	0.9
Small	Full	410	1.6	1530	4.1	1.2
Small	Half	315	3.6	1190	3.2	0.9

Results are shown in Table 1 for normal weight concrete and in Table 2 for lightweight concrete. In both tables, the number of tires permitted, N , the fire duration, and the fire load per floor area are shown. Also shown in the two tables is the number of tires permitted per floor area and per compartment surface area. It is interesting to note that the number permitted per compartment surface area is in a narrow range of 0.8 to 1.2 for normal weight concrete walls and 0.4 to 0.7 for lightweight concrete walls. It is suggested that these numbers be used as guidelines for the maximum number of tires permitted to be stored in a single two-hour rated fire compartment.

Tables 1 and 2 show that the maximum number of tires permitted in compartments with lightweight concrete boundaries is roughly half of what is permitted in compartments with normal weight concrete boundaries, even though both have the same two-hour fire resistance rating. This is because lightweight concrete has higher thermal resistance than normal weight concrete. In a standard fire test, the fire follows a prescribed temperature curve. In a real fire situation, however, the temperature inside a compartment is affected by the thermal resistance of its boundaries. If the same amount of fire load is present, the temperature inside a lightweight concrete compartment is much hotter than that inside a normal weight concrete compartment, causing a higher thermal assault on the lightweight concrete boundaries. This is why results show that the maximum number of tires permitted in lightweight concrete compartments is lower than permitted in normal weight concrete compartments.

Conclusions

The normalized heat load approach was used to analyze the severity of warehouse fires involving 425 m³ of rubber tires. The fire safety re-

Table 2: Maximum number of tires permitted (N) for lightweight concrete compartments with a two-hour fire resistance rating

Compartment	Opening	N	Fire Duration	Fire Load	$N/\text{Floor Area}$	$N/\text{Surface Area}$
			(hrs)	(MJ/m ²)	(m ⁻²)	(m ⁻²)
Large	Full	500	2.0	620	1.6	0.5
Large	Half	400	4.5	500	1.3	0.4
Medium	Full	280	1.1	1060	2.8	0.6
Medium	Half	205	2.3	760	2.1	0.4
Small	Full	240	0.9	890	2.4	0.7
Small	Half	165	1.8	610	1.7	0.5

quirements of the 1985 National Fire Code do not apply if the volume of tires stored in a compartment is less than 425 m^3 . With limited information on compartment fires involving tires, the tire load was modeled as a calorifically equivalent wood load. Results show the severity of such a fire to be extremely high, requiring the walls to have a fire resistance rating of much larger than two hours. The fire was shown to have a heat generation rate of 20.9 MW and a duration of 14.3 hours. Separate calculations based on steady-state heat transfer analysis also confirmed the extreme severity of such a fire, requiring the walls to have a thickness of about 3 m for normal weight concrete and close to 1 m for lightweight concrete in order to be able to prevent the spread of fire.

Because of the extreme severity of compartment fires involving a large volume of tires, other arrangements of smaller compartment sizes and reduced tire loads were studied to determine what the allowable tire loads would be if the fire resistance rating of the compartment boundaries is limited to two hours. Twelve different cases were studied, involving three different compartment sizes, two different ventilation openings, and two different wall constructions. Results show that the permissible number of tires per square meter of compartment surface area is in the narrow range of 0.8 to 1.2 for normal weight concrete and 0.4 to 0.7 for lightweight concrete. It is suggested that these numbers be used as a guide for determining the maximum number of tires permitted to be stored in a single two-hour rated fire compartment.

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Appendix: Steady State Heat Transfer Calculation

Under steady state conditions, the heat generated by the fire within the compartment, Q_c , is dissipated partly through the boundary wall, Q_w , and partly through the door via both convection, Q_v , and radiation, Q_r . This heat balance can be written as:

$$Q_c = Q_w + Q_v + Q_r \quad (A1)$$

The heat loss through the boundary wall, Q_w in W , can be written as:

$$Q_w = \frac{(T_g - T_a)A}{(\delta/k) + (1/h)} \quad (A2)$$

where T_g is the fire gas temperature in K ; T_a is the outside ambient temperature in K ; A is the total surface area of the compartment boundaries in m^2 ; δ is the wall thickness in m ; k is the wall thermal conductivity in $W/(m \cdot K)$; and h is the outside free convection heat transfer coefficient in $W/(m^2 \cdot K)$. Equation A2 assumes that the heat transfer between the fire gases and the outside air is carried out via heat conduction through the wall and free convection on the outside surface. This implies that the thermal resistance between the fire gases and the inside surface of the compartment wall is negligible compared with that of the wall and that of the outside surface. This assumption, however, is a reasonable one and it helps to eliminate the necessity to evaluate the heat transfer coefficient on the inside surface, which is usually quite difficult to do. In the present fire resistance study, the consequence of this assumption is that a slightly higher than actual amount of heat is allowed to pass through the wall, and hence a more conservative estimate of the temperature rise on the outside surface.

In applying Equation A2 to this study, the ambient temperature, T_a , is assumed to be 298 K. The heat transfer coefficient on the outside surface, h , can be evaluated following standard free convection analysis.^{A1} In this study, the temperature rise on the outside surface is in the range of 200 K to 1000 K. Within this temperature range, the value found for h is quite constant, $5.95 W/(m^2 \cdot K)$, and this constant value is assumed in the present calculation.

The next term is the heat convection term through the door, Q_v in W. This term can be expressed as:

$$Q_v = \dot{m}_g c_g (T_g - T_a) \quad (\text{A3})$$

where $\dot{m}_g$ is the mass flow rate of the fire gases out of the door in kg/s, and c_g is the constant pressure specific heat of the fire gases in J/(kg · K). The mass flow rate, $\dot{m}_g$, can be expressed as:⁴

$$\dot{m}_g = 0.138 \Phi + 0.47 R \quad (\text{A4})$$

where Φ and R are the ventilation parameter and burning rate defined by Equations 5 and 4, respectively, in the text. The specific heat, c_g , in Equation A3 for fire gases is difficult to assess because of the unknowns in the fire gases. In the absence of that information, its value can be taken to be that of the air at that temperature. The temperature expected for the fire gases is in the range of 1400 K to 1700 K, and the specific heat of air in this temperature range is relatively constant, at 1.24×10^3 J/(kg · K). This value is assumed for c_g in this study.

The last term in Equation A1 is the radiative heat loss through the door, Q_r in W. This term can be expressed as:^{A2}

$$Q_r = \frac{1}{3} A_v \sigma (T_g^4 - T_a^4) \quad (\text{A5})$$

where A_v is the door opening in m², σ is the Stefan-Boltzmann constant, 5.67×10^{-8} W/(m² K⁴). The factor 1/3 takes care of the fact that the gas emissivity is not 1 and that the gas temperature is not uniform over the whole door. In addition, radiant heat is lost through the door primarily through the bottom 1/3 of the door.

If the heat generated by the fire, Q_c , is known, Equations A1 to A5 can be used to iterate for the fire gas temperature, T_g . Once the fire gas temperature is determined, the heat loss through the wall, Q_w , can be determined (Equation A2) and subsequently the temperature rise on the outside surface, $(T_o - T_a)$, can be determined via the following heat transfer relationship:

$$(T_o - T_a) = \frac{Q_w}{h} \quad (\text{A6})$$

where T_o is the outside surface temperature in K.

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Nomenclature

A	total surface area of compartment boundaries, m^2
c	constant pressure specific heat of boundary walls, $J/(kg \cdot K)$
c_g	constant pressure specific heat of fire gases, $J/(kg \cdot K)$
g	gravitational acceleration, 9.8 m/s^2
G	total wood equivalent fire load, kg
h	outside free convection heat transfer coefficient, $W/(m^2 \cdot K)$
h_v	height of ventilation opening, m
H	normalized heat load, $s^{1/2} K$
k	thermal conductivity of boundary walls, $W/(m \cdot K)$
$\sqrt{k\rho c}$	thermal inertia of boundary walls, $J \cdot m^{-2} s^{-1/2} K^{-1}$
$\dot{m}_g$	mass flow rate of fire gases, kg/s
N	total number of tires
q	thermal assault on the boundaries, W/m^2
Q	heat rate, W
R	wood equivalent burning rate, kg/s
t	time, s
T	temperature, K

Greek Letters

δ	boundary wall thickness, m
ρ	density of boundary walls, kg/m^3
ρ_a	density of outside air, kg/m^3
σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8} \text{ W/(m}^2\text{K}^4)$
τ	fire resistance rating, hrs
τ^*	fire duration, s
Φ	ventilation parameter, kg/s

Subscripts

a	outside air
c	combustion
g	fire gases
o	outside surface of boundary walls
r	radiation
v	ventilation opening, or convection
w	boundary walls