POOL FIRE

Pool Fire

Convective heat flux X Radiative flame heat flux

Convective heat flux: dominates the heat transfer back to the fuel surface for very small pool diameters, on order of **10cm or less**.

Radiative flame heat flux: dominates for **larger** fires

Pool Fire

Modelo via Hc:

$$Q = m'' \Delta H_c x_{chem} \pi \frac{d^2}{4}$$

Q heat release rate (kW) (total, não apenas radiado)

m'' mass burning rate per unit surface area (g / s . m^2)
obtido via: modelo de Babrauska (será apresentado a seguir) ou as tabelas A4 ou B2

ΔHc heat of combustion (kJ / g)
obtido via: tabela B1a, B1b ou B2

Xchem combustion efficiency (tabela B1a ou B1b)

d pool fire diameter (m)

Pool Fire

Modelo via Hc:

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obtido via: modelo de Babrauska (será apresentado a seguir) ou as tabelas A4 ou B2

ΔHc heat of combustion (kJ / g)
obtido via: tabela B1a, B1b ou B2

Xchem combustion efficiency (tabela B1a ou B1b)

Para calcular o calor radiado apenas use esse termo como **fração radiada**.

d pool fire diameter (m)

Pool Fire

Modelo via Hc:

$$Q = m''\Delta H_c x_{chem} \pi \frac{d^2}{4}$$

Equação deduzida anteriormente:

Método via Q teórico (Q) ou Calor de Combustão (Hc)

Qr = Xrad Q = Xrad M Hc

Onde:

Qr: heat release rate (radiation only) (kW)

Xrad: fração radiada (fração emitida como radiação) (tabela A2)

Q: **theoretical** heat release rate (kW) (tabela A3 ou equação Q = M Hc)

M: mass burn rate (g/s) (tabela A4 ou A5)

Hc: theoretical heat of combustion (kJ / g) (tabela A2 ou A4 ou A5)

Pool Fire

Modelo via Hc:

$$Q = m''\Delta H_c x_{chem} \pi \frac{d^2}{4}$$

Método via Q teórico (Q) ou Calor de Combustão (Hc)

$$Qr = Xrad \; Q = Xrad \; M \; Hc$$

Onde:

Qr: heat release rate (radiation only) (kW)

Xrad: fração radiada (fração emitida como radiação) (tabela A2)

Q: **theoretical** heat release rate (kW) (tabela A3 ou equação Q = M Hc)

M: mass burn rate (g/s) (tabela A4 ou A5)

Hc: theoretical heat of combustion (kJ / g) (tabela A2 ou A4 ou A5)

Pool Fire

m'' mass burning rate
per unit surface area (g / s . m²)

Área da piscina circular

$$Q = m''\Delta H_c x_{chem} \pi \frac{d^2}{4}$$

Método via Q teórico (Q) ou Calor de Combustão (Hc)

Qr = Xrad Q = Xrad M Hc

Onde:

Qr: heat release rate (radiation only) (kW)

Xrad: fração radiada (fração emitida como radiação) (tabela A2)

Q: **theoretical** heat release rate (kW) (tabela A3 ou equação Q = M Hc)

M: mass burn rate (g/s) (tabela A4 ou A5)

Hc: theoretical heat of combustion (kJ / g) (tabela A2 ou A4 ou A5)

Pool Fire

Modelo via Hc:

$$Q = m''\Delta H_c x_{chem} \pi \frac{d^2}{4}$$

Método via Q teórico (Q) ou Calor de Combustão (Hc)

Qr = Xrad Q = Xrad M Hc

Onde:

Qr: heat release rate (radiation only) (kW)

Xrad: fração radiada (fração emitida como radiação) (tabela A2)

Q: **theoretical** heat release rate (kW) (tabela A3 ou equação Q = M Hc)

M: mass burn rate (g/s) (tabela A4 ou A5)

Hc: theoretical heat of combustion (kJ / g) (tabela A2 ou A4 ou A5)

Pool Fire

Modelo via Hc:

$$Q = m''\Delta H_c x_{chem}\pi\frac{d^2}{4}$$

Por que calcular Q?

Q

Altura da Chama
(aula passada)

Calor que atinge
o alvo usando
modelo de chama
sólida

Distância
Segura

Pool Fire

Modelo de Babrauskas

Hipótese:
0,2 < D < 5 m

$$m'' = m''_{\infty}\left(1 - e^{-k'D}\right)$$

Onde:

K' effective absorption coefficient (tabela B1a ou B1b) (1 / m)
(é o mesmo parâmetro usado na equação de emissividade do modelo de chama sólida)

m''_{inf} asymptotic burning rate (tabela B1a ou B1b) (g / (m^2 – s))

D pool fire diameter (m)

Conferindo as unidades:

$$\frac{g}{s\ m^2} = \frac{g}{s\ m^2}\left(1 - e^{-\frac{1}{m}\,m}\right)$$

Pool Fire

Modelo de Babrauskas

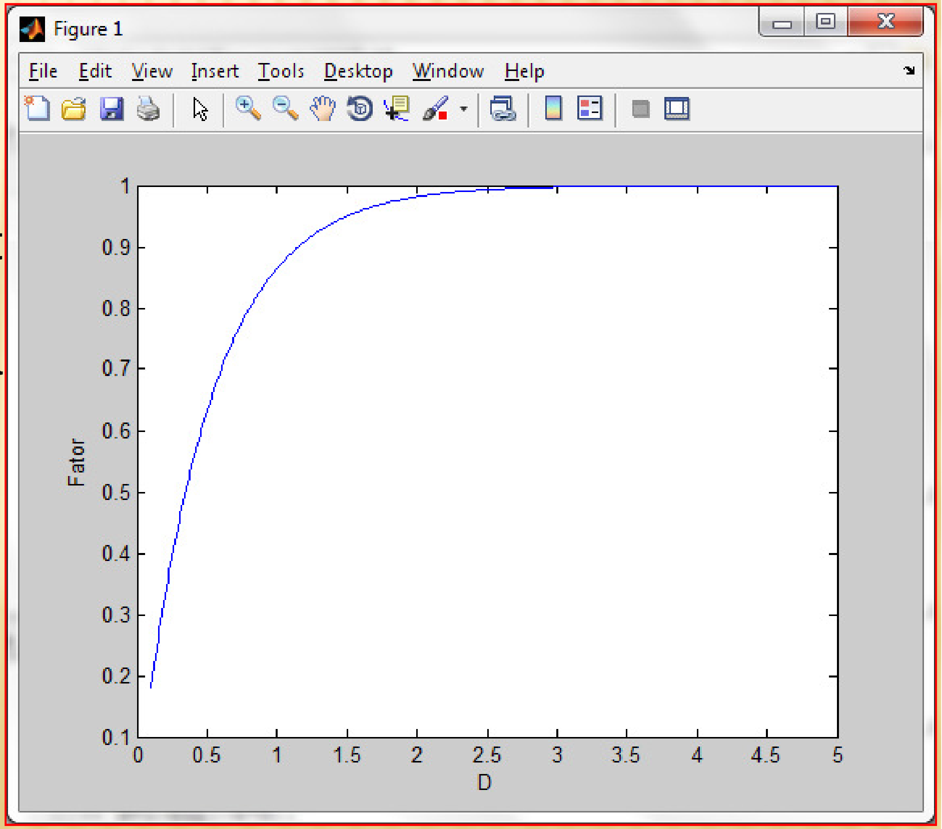
$$m'' = m''_{\infty}\left(1 - e^{-k'D}\right)$$

Onde:

K' effective absorption coefficient

m''_{inf} asymptotic burning rate (ta

D pool fire diameter (m)




```
k=2
D=0.2:0.1:5
X=1-exp(-k*D)
```

$$m'' = m''_{\infty}\left(1 - e^{-k'D}\right)$$

B1a

Table 7.4. Pool fire burning rate data

Liquid	Mass burn rate, m''_{∞} (g/m^2-s)	ΔH_c (kJ/g)	ΔH_v (kJ/kg)	k' (m^{-1})	Density (g/cc)	x_{chem}	x_c	x_r
Acetone	41	25.8	668	1.9	0.79	0.97	0.73	0.24
Benzene	85	40.1	484	2.7	0.87	0.69	0.29	0.40
n-Butane	78	45.7	362	2.7	0.57	0.95	0.68	0.27
Diethyl Ether	85	34.2	382	0.7	0.71	–	–	–
Ethanol	15	26.8	891	∞	0.79	0.97	0.73	0.24
Fuel Oil #6	35	39.7	–	1.7	0.94	–	–	–
Gasoline	55	43.7	330	2.1	0.74	0.92	0.61	0.31
Heptane	101	44.6	448	1.1	0.68	0.92	0.62	0.30
Hexane	74	44.7	433	1.9	0.65	0.92	0.61	0.31
Isopropanol	–	30.2	666	–	0.79	0.97	0.73	0.24
JP-4	51	43.5	–	3.6	0.76	–	–	–
Kerosene	39	43.2	670	0.82	–	–	–	–
Methanol	17	20.0	1195	∞	0.80	0.95	0.81	0.14
M.E. Ketone	–	31.5	444	–	0.81	0.97	0.67	0.30
Styrene	–	40.5	–	–	0.90	0.67	0.27	0.40
Toluene	–	40.5	–	–	0.87	0.67	0.27	0.40
Transformer Oil	39	46.4	–	0.7	0.76	0.84	0.56	0.28
Xylene	90	40.8	543	1.4	0.87	0.67	0.27	0.40

Data Sources

Mass burning rates, densities, heats of combustion, effective absorption coefficients and heats of vaporization are from Babrauskas (1988) for most liquids. Combustion efficiencies and some heats of combustion are from Tewarson (1988).

Hipótese:
0,2 < D < 5 m

Ref: Industrial Fire Protection Engineering – R.G.Zalosh

$$Q = m'' \Delta H_c x_{chem} \pi \frac{d^2}{4}$$

B1a

Table 7.4 Pool fire burning rate data

Liquid	Mass burn rate, m''_∞ (g/m^2-s)	ΔH_c (kJ/g)	ΔH_v (kJ/kg)	k' (m^{-1})	Density (g/cc)	x_{chem}	x_c	x_r
Acetone	41	25.8	668	1.9	0.79	0.97	0.73	0.24
Benzene	85	40.1	484	2.7	0.87	0.69	0.29	0.40
n-Butane	78	45.7	362	2.7	0.57	0.95	0.68	0.27
Diethyl Ether	85	34.2	382	0.7	0.71	–	–	–
Ethanol	15	26.8	891	∞	0.79	0.97	0.73	0.24
Fuel Oil #6	35	39.7	–	1.7	0.94	–	–	–
Gasoline	55	43.7	330	2.1	0.74	0.92	0.61	0.31
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Mass burning rates, densities, heats of combustion, effective absorption coefficients and heats of vaporization are from Babrauskas (1988) for most liquids. Combustion efficiencies and some heats of combustion are from Tewarson (1988).

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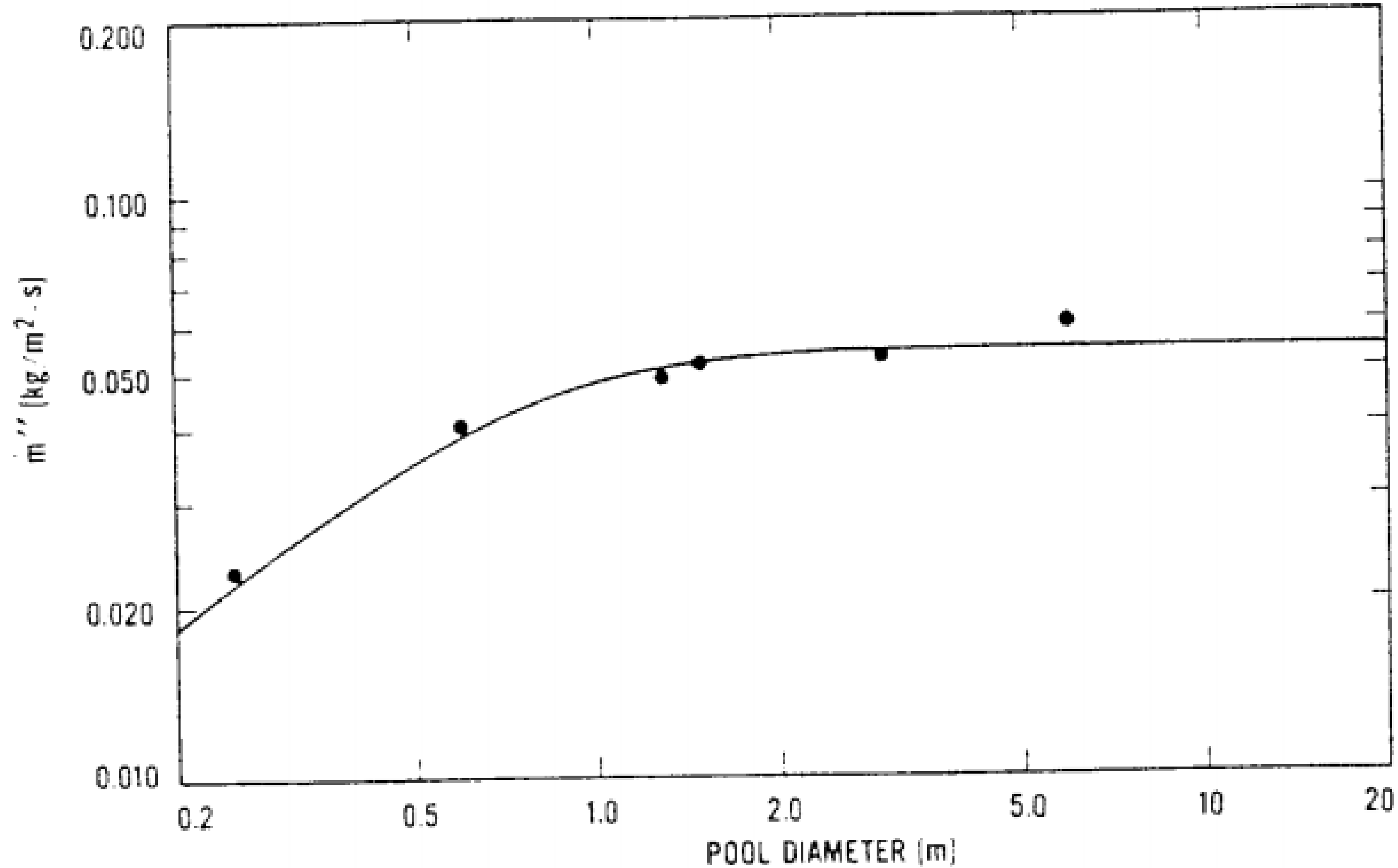

Figure 1. Pool burning rates for gasoline.

O modelo ajusta bem piscinas de líquidos

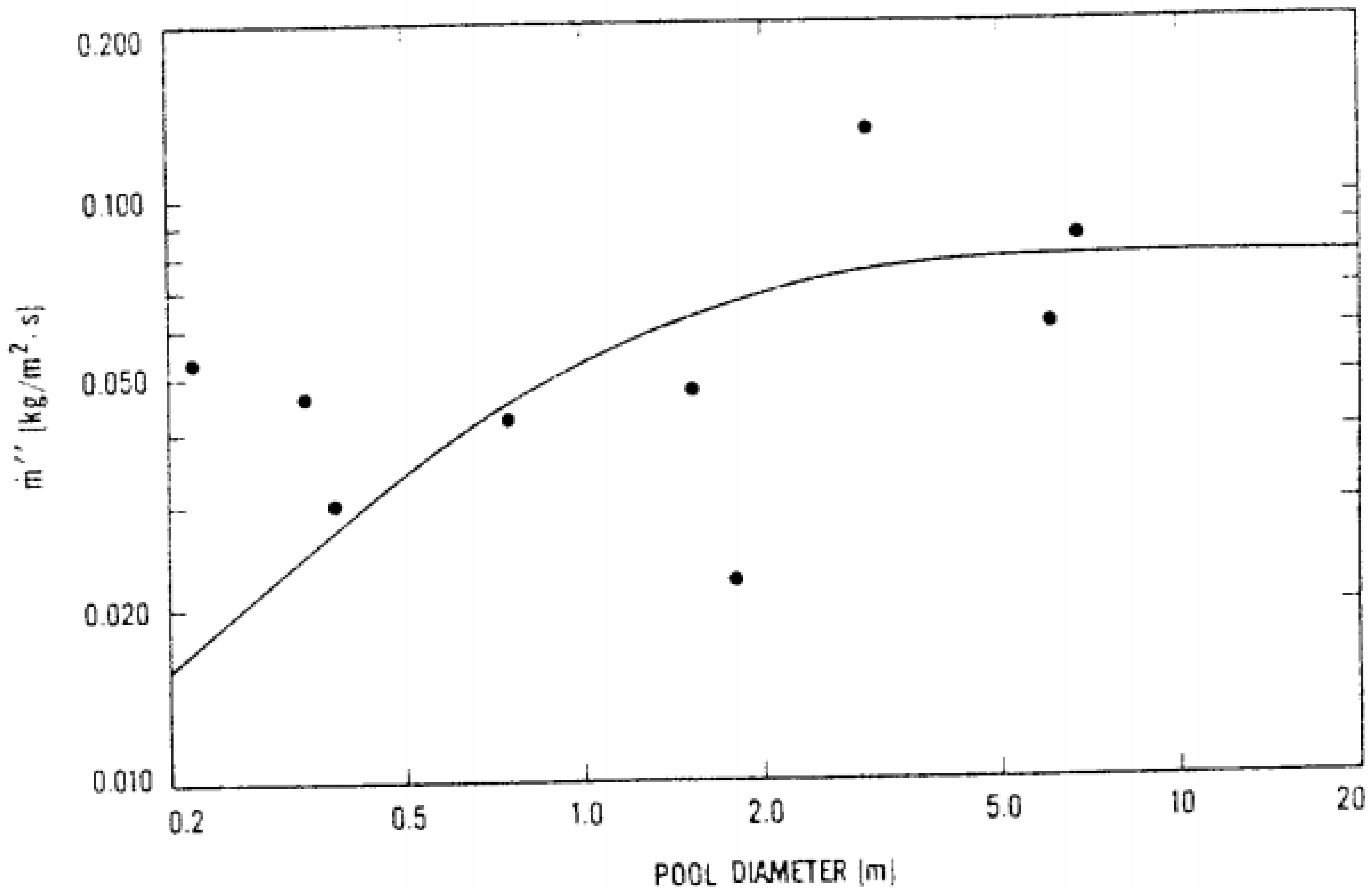

Figure 2. Pool burning rates for LNG, shown as an example of a fuel where experimental data show large variations.

Mas não ajusta bem piscinas de gases liquefeitos

$$\dot{m}'' = \dot{m}''_{\infty} \left(1 - e^{-k\beta D}\right)$$

B1b

Table 1
Data for Large Pool Burning Rate Estimates

Material	Density (kg/m^3)	Δh_g (kJ/kg)	Δh_c (MJ/kg)	$\dot{m}''_{\infty}$ ($kg/m^2 - s$)	$k\beta$ (m^{-1})	k (m^{-1})	T_f (K)
Cryogenics							
Liquid H_2	70	442	120.0	0.017 (±0.001)	6.1 (±0.4)	—	1600
LNG (mostly CH_4)	415	619	50.0	0.078 (±0.018)	1.1 (±0.8)	0.5	1500
LPG (mostly C_3H_8)	585	426	46.0	0.099 (±0.009)	1.4 (±0.5)	0.4	—
Alcohols							
Methanol (CH_3OH)	796	1195	20.0	0.017 (±0.001)	[a]	—	1500
Ethanol (C_2H_5OH)	794	891	26.8	0.015 (±0.001)	[a]	0.4	1490
Simple Organic Fuels							
Butane (C_4H_{10})	573	362	45.7	0.078 (±0.003)	2.7 (±0.3)	—	—
Benzene (C_6H_6)	874	484	40.1	0.085 (±0.002)	2.7 (±0.3)	4.0	1460
Hexane (C_6H_{14})	650	433	44.7	0.074 (±0.005)	1.9 (±0.4)	—	1300
Heptane (C_7H_{16})	675	448	44.6	0.101 (±0.009)	1.1 (±0.3)	—	—
Xylenes (C_8H_{10})	870	543	40.8	0.090 (±0.007)	1.4 (±0.3)	—	—
Acetone (C_3H_6O)	791	668	25.8	0.041 (±0.003)	1.9 (±0.3)	0.8	—
Dioxane ($C_4H_8O_2$)	1035	552	26.2	0.018[b]	5.4[b]	—	—
Diethyl Ether ($C_4H_{10}O$)	714	382	34.2	0.085 (±0.018)	0.7 (±0.3)	—	—
Petroleum Products							
Benzine	740	—	44.7	0.048 (±0.002)	3.6 (±0.4)	—	—
Gasoline	740	330	43.7	0.055 (±0.002)	2.1 (±0.3)	2.0	1450
Kerosene	820	670	43.2	0.039 (±0.003)	3.5 (±0.8)	2.6	1480
JP-4	760	—	43.5	0.051 (±0.002)	3.6 (±0.1)	—	1250
JP-5	810	700	43.0	0.054 (±0.002)	1.6 (±0.3)	0.5	1250
Transformer oil, hydrocarbon	760	—	46.4	0.039[b]	0.7[b]	—	1500
Fuel oil, heavy	940–1000	—	39.7	0.035 (±0.003)	1.7 (±0.6)	—	—
Crude oil	830–880	—	42.5–42.7	0.022–0.045	2.8 (±0.4)	—	—
Solids							
Polymethylmethacrylate ($C_5H_8O_2)_n$	1184	1611	24.9	0.020 (±0.002)	3.3 (±0.8)	1.3	1260
Polyoxymethylene $(CH_2O)_n$	1425	2430	15.7			—	1200
Polypropylene $(C_3H_6)_n$	905	2030	43.2			1.8	1200
Polystyrene $(C_8H_8)_n$	1050	1720	39.7			5.3	1200

(a)—Value independent of diameter in turbulent regime.
(b)—Only two data points available.

Referência:
http://fire.nist.gov/bfrlpubs/fire92/PDF/f92029.pdf

$$Q = m''\Delta H_c x_{chem} \pi \frac{d^2}{4}$$

B1b

Table 1
Data for Large Pool Burning Rate Estimates

Material	Density (kg/m³)	Δh_g (kJ/kg)	Δh_c (MJ/kg)	$\dot{m}''_\infty$ (kg/m² − s)	kβ (m⁻¹)	k (m⁻¹)	T_f (K)
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Liquid H_2	70	442	120.0	0.017 (±0.001)	6.1 (±0.4)	—	1600
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(a)—Value independent of diameter in turbulent regime.
(b)—Only two data points available.

Referência:
http://fire.nist.gov/bfrlpubs/fire92/PDF/f92029.pdf

$$\dot{m}'' = \dot{m}_\infty'' \left(1 - e^{-k\beta D}\right)$$

Apenas uma questão de nomenclatura

$$m'' = m''_\infty \left(1 - e^{-k' D}\right)$$

Table 7.4. Pool fire burning rate data

Liquid	Mass burn rate, m''_∞ (g/m^2-s)	ΔH_c (kJ/g)	ΔH_v (kJ/kg)	k' (m^{-1})	Density (g/cc)	x_{chem}	x_c	x_r
Acetone	41	25.8	668	1.9	0.79	0.97	0.73	0.24
Benzene	85	40.1	484	2.7	0.87	0.69	0.29	0.40
n-Butane	78	45.7	362	2.7	0.57	0.95	0.68	0.27
Diethyl Ether	85	34.2	382	0.7	0.71	–	–	–
Ethanol	15	26.8	891	∞	0.79	0.97	0.73	0.24
Fuel Oil #6	35	39.7	–	1.7	0.94	–	–	–
Gasoline	55	43.7	330	2.1	0.74	0.92	0.61	0.31
Heptane	101	44.6	448	1.1	0.68	0.92	0.62	0.30
Hexane	74	44.7	433	1.9	0.65	0.92	0.61	0.31
Isopropanol	–	30.2	666	–	0.79	0.97	0.73	0.24
							–	–
							–	–
							0.81	0.14
							0.67	0.30
							0.27	0.40
							0.27	0.40
							0.56	0.28
							0.27	0.40

from Babrauskas

Table 1
Data for Large Pool Burning Rate Estimates

Material	Density (kg/m³)	Δh_g (kJ/kg)	Δh_c (MJ/kg)	$\dot{m}''_\infty$ (kg/m² – s)	$k\beta$ (m^{-1})	k (m^{-1})	T_f (K)
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Alcohols							
Methanol (CH_3OH)	796	1195	20.0	0.017 (±0.001)	*	—	1500
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Simple Organic Fuels							
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Xylenes (C_8H_{10})	870	543	40.8	0.090 (±0.007)	1.4 (±0.3)	—	—
Acetone (C_3H_6O)	791	668	25.8	0.041 (±0.003)	1.9 (±0.3)	0.8	—

Pool Fire

Para tanques muito grandes **(D > 5 m)**, mistura ineficiente de vapores do combustível com o ar na superfície. Logo a queima fica limitada pelo oxigênio.

Melhor usar:

Tabela B1a ou B1b

$$m''_{inf} = 0.80\ m''_{inf}$$

Hipótese:
D > 5m

Pool Fire

Para cenários "lip height" a realidade aproxima-se mais do valor:

$$m'' = 0.80\, m''$$

<u>Não</u>, não esqueci o inf aqui!

Tabela de m” mass burning rate per unit surface area (g / s . m^2)

$$Q = \dot{m}'' \Delta H_c \chi_{chem} \pi \frac{d^2}{4}$$

B2

Essa tabela é uma opção para não usar Babrauska.

TABLE 3.2
Burning Rate per Unit Area and Complete Heat of Combustion for Various Materials

Material (values in brackets indicate pool diameters tested)	$\dot{m}''$ (kg/m²s)	ΔH_c (MJ/kg)
Aliphatic Carbon–Hydrogen Atoms		
Polyethylene	0.026	43.6
Polypropylene	0.024	43.4
Heavy fuel oil (2.6–23 m)	0.036	—
Kerosene (30–80 m)	0.065	44.1
Crude oil (6.5–31 m)	0.056	—
n-Dodecane (0.94 m)	0.036	44.2
Gasoline (1.5–223 m)	0.062	—
JP-4 (1–5.3 m)	0.067	—
JP-5 (0.6–1.7 m)	0.055	—
n-Heptane (1.2–10 m)	0.075	44.6
n-Hexane (0.75–10 m)	0.077	44.8
Transformer fluids (2.37 m)	0.025–0.030	—
Aromatic Carbon–Hydrogen Atoms		
Polystyrene (0.93 m)	0.034	39.2
Xylene (1.22 m)	0.067	39.4
Benzene (0.75–6.0 m)	0.081	40.1

ftp://ftp.stru.polimi.it/corsi/Felicetti%20-%20Fire%20resistance%20of%20materials%20and%20structures/Books/Enclosure%20fire%20dynamics/1300_PDF_C03.pdf

Tabela de m'' mass burning rate per unit surface area (g / s . m^2)

Aliphatic Carbon–Hydrogen–Oxygen Atoms		
Polyoxymethylene	0.016	15.4
Polymethylmethacrylate, PMMA (2.37 m)	0.030	25.2
Methanol (1.2–2.4 m)	0.025	20
Acetone (1.52 m)	0.038	29.7
Aliphatic Carbon-Hydrogen–Oxygen–Nitrogen Atoms		
Flexible polyurethane foams	0.021–0.027	23.2–27.2
Rigid polyurethane foams	0.022–0.025	25.0–28.0
Aliphatic Carbon–Hydrogen–Halogen Atoms		
Polyvinylchloride	0.016	16.4
Tefzel™ (ETFE)	0.014	12.6
Teflon™ (FEP)	0.007	4.8

Source: Tewarson, A., in *SFPE Handbook of Fire Protection Engineering*, 2nd ed., National Fire Protection Association, Quincy, MA, 1995. With permission.

B2

Essa tabela é uma opção para não usar Babrauska.

ftp://ftp.stru.polimi.it/corsi/Felicetti%20-%20Fire%20resistance%20of%20materials%20and%20structures/Books/Enclosure%20fire%20dynamics/1300_PDF_C03.pdf

Pool Fire

Para cenários de D pequeno, ou elevado vento, usar a correção de Mudan e Croce:

$$Dw / D = \{ 1,25 [uw^2] / [(g D) ^{0,069}] \} (\rho v / \rho a)^{0,48}$$

Onde:

Dw diâmetro efetivo na presença de vento (m)
D diâmetro real (m)
uw vento (m/s)
g aceleração da gravidade (m/s2)
ρv densidade do vapor
ρa densidade do ar

Pool Fire

Velocidade de descida do nível de líquido (m/s):

Velocidade de descida do nível = m'' / ρ

$$\frac{g / (m2 . s)}{g / m3} = m / s$$

Onde:

m'' mass burning rate per unit surface area ($g / s . m^2$)

ρ densidade do líquido (g/m^3) (Tabela B1)

Pool Fire

Exemplo:

Assumindo taxa de queima de 0.039 kg/m2s e sabendo que a densidade do querosene é de 820 kg/m3,

Velocidade de descida do nível = m'' / ρ

Velocidade de descida do nível = 0.039 / 820 = 4.75 10^-5 m/s

ou 0.0475 mm/s

Se, por exemplo, o nível de líquido inicialmente era de 2.44m, o material levará **14 horas** para queimar.

Relembrando...

Por que calcular Q?

Q

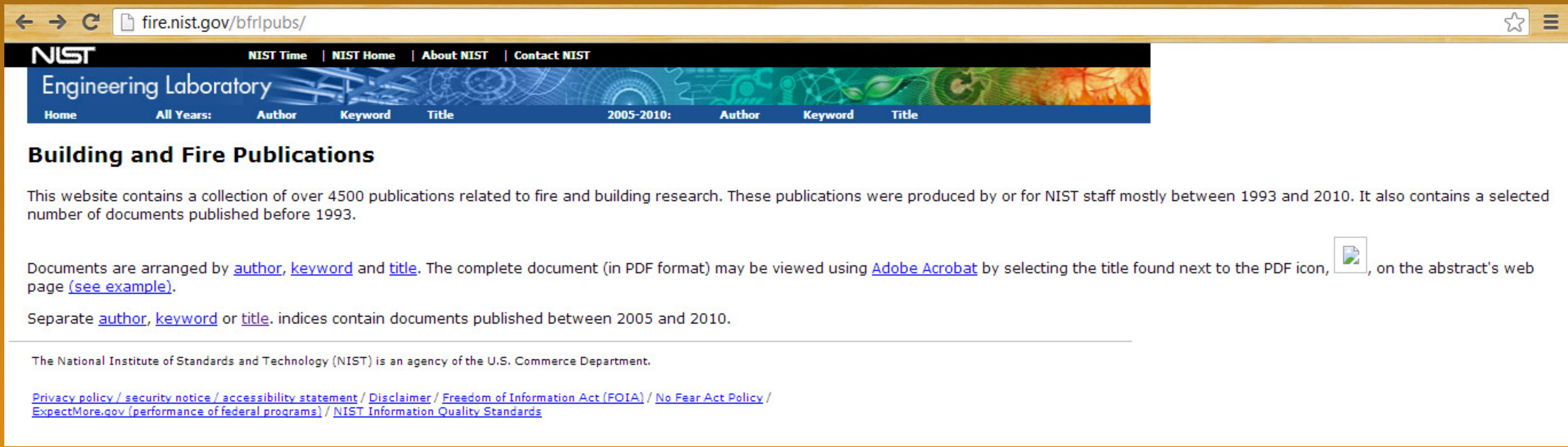
Altura da Chama
(aula passada)

Calor que atinge
o alvo usando
modelo de chama
sólida

Distância
Segura

Pool Fire

Biblioteca de referências técnicas da NIST:



http://fire.nist.gov/bfrlpubs/

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NIST Time | NIST Home | About NIST | Contact NIST

Engineering Laboratory

Home All Years: Author Keyword Title 2005-2010: Author Keyword Title

Titles All Entries

All A B C D E F G H I K L M N O P Q R S T U V W X

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  NISTIR 7425; 13 p. April 2007.
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Outras referências...

- http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf
- http://fire.nist.gov/bfrlpubs/fire92/PDF/f92029.pdf
- http://www.haifire.com/Resources/presentations/Spill%20Fire%20Dynamics%20-%20NFPA%202000-.pdf

Pool Fire

Modelos complementares (apostila NIST)

NISTIR 6546

Thermal Radiation from Large Pool Fires

Kevin B. McGrattan
Howard R. Baum
Anthony Hamins

NIST National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce

http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

Pool Fire

"A review by the Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) of the 1975 HUD guidelines for thermal radiation flux has revealed that for certain fire scenarios the methodology can **produce estimates of radiation flux that are up to an order of magnitude larger than those actually measured in field experiments**."

"The principal reason for this discrepancy is the assumption **that large fires are unobscured by smoke**, that is, a person watching the fire from a distance sees the entire extent of the combustion region. In reality, large fires of most combustible liquids and gases generate an **appreciable amount of smoke that shields much of the thermal radiation** from striking nearby structures or people."

http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

Em piscinas grandes, ocorre muita queima parcial. Logo ocorre muita formação fumaça escura. Isso bloqueia a radiação.

Parte visual da chama

"Depending on the fuel and the size of the fire, up to 20 % of the fuel mass is converted to smoke particulate in the combustion process. This **smoke shields much of the luminous flame region** from the viewer, and it is this luminous flame region that is the source of most of the thermal radiation. This shielding effect is most pronounced for fires that are **tens or hundreds of meters in diameter** because of the decreased efficiency of combustion at these scales."

http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

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http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

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http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

Pool Fire

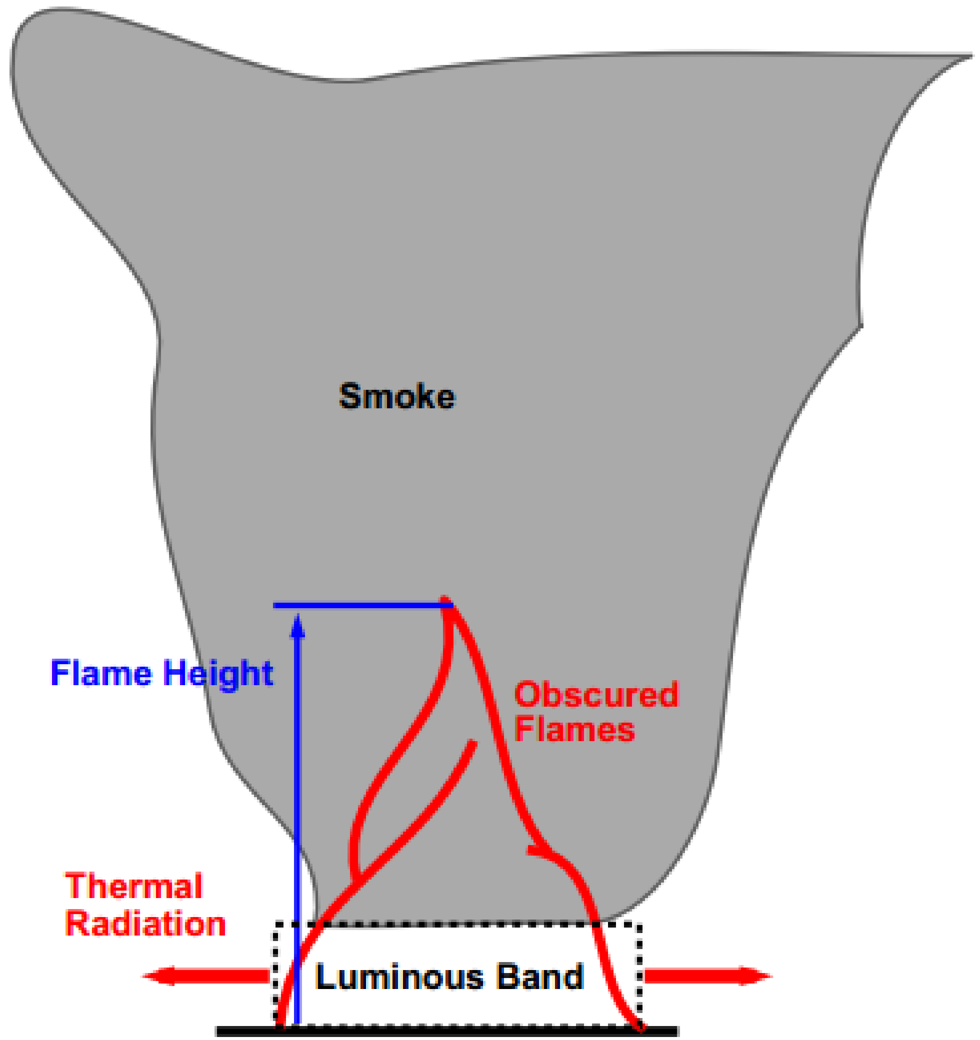


Figure 1: Schematic diagram of a large liquid fuel fire.

http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

Pool F

Em poças pequenas esse efeito da fumaça bloqueando a radiação fica menos importante.

Pool Fire

Distância de Separação Aceitável (ASD)

Lembrando o critério de segurança para radiação térmica:

"The Department of Housing and Urban Development (HUD) has established thermal radiation flux levels of **31.5 kW/m2 (10,000 Btu/h/ft2) for buildings** and **1.4 kW/m2 (450 Btu/h/ft2) for people** as guides in determining an "**Acceptable Separation Distance" (ASD) between a fire consuming combustible liquids or gases and nearby structures and people** (24 CFR Part 51, Subpart C (paragraph 51.203))."

http://www.wbdg.org/pdfs/24cfr51.pdf

Pool Fire

Tipos de modelos disponíveis:

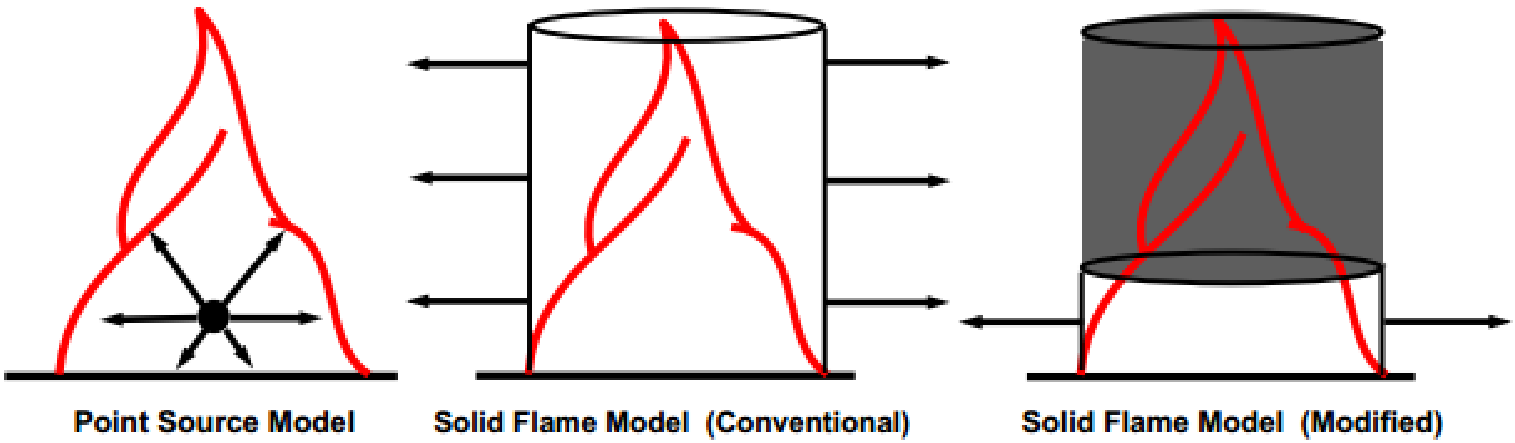


Figure 2: Schematic diagram of thermal radiation models.

Pool Fire

Tipos de modelos disponíveis:

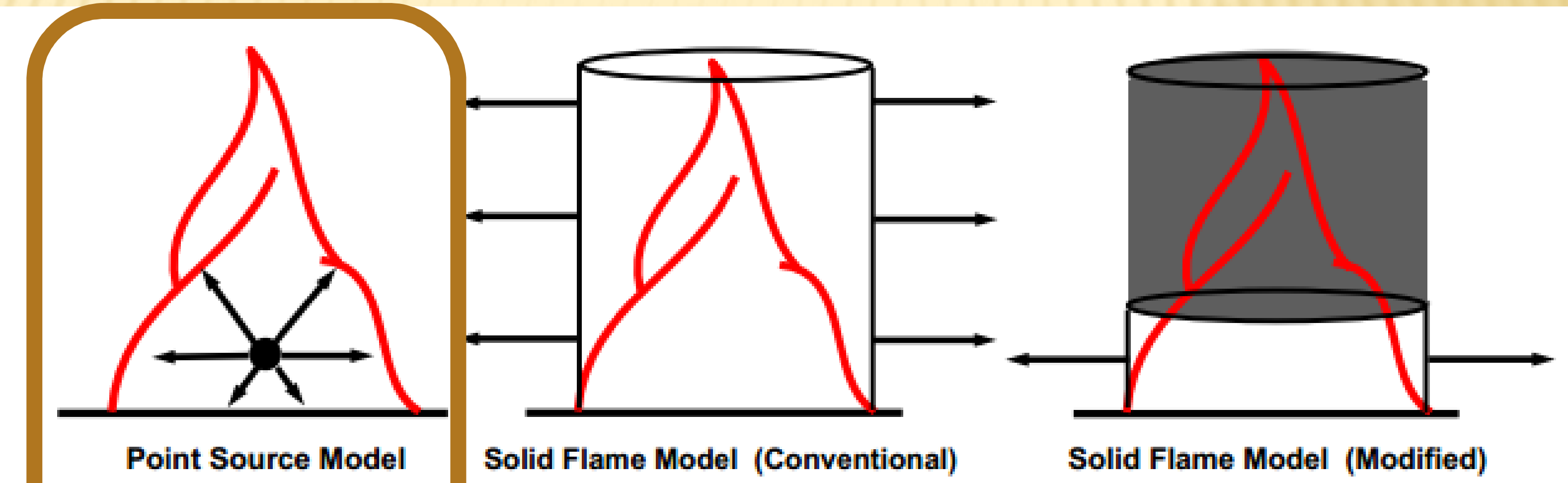


Figure 2: Schematic diagram of thermal radiation models.

Fácil de usar, mas tende a ser exagerado para alvos próximos. Pois todo o calor emana de um único ponto. Não considera que a emissão se faz de forma distribuída ao longo de toda a superfície da chama. É a solução quando temos poucos dados reais disponíveis, como no caso de gases liquefeitos.

Pool Fire

Tipos de modelos disponíveis:

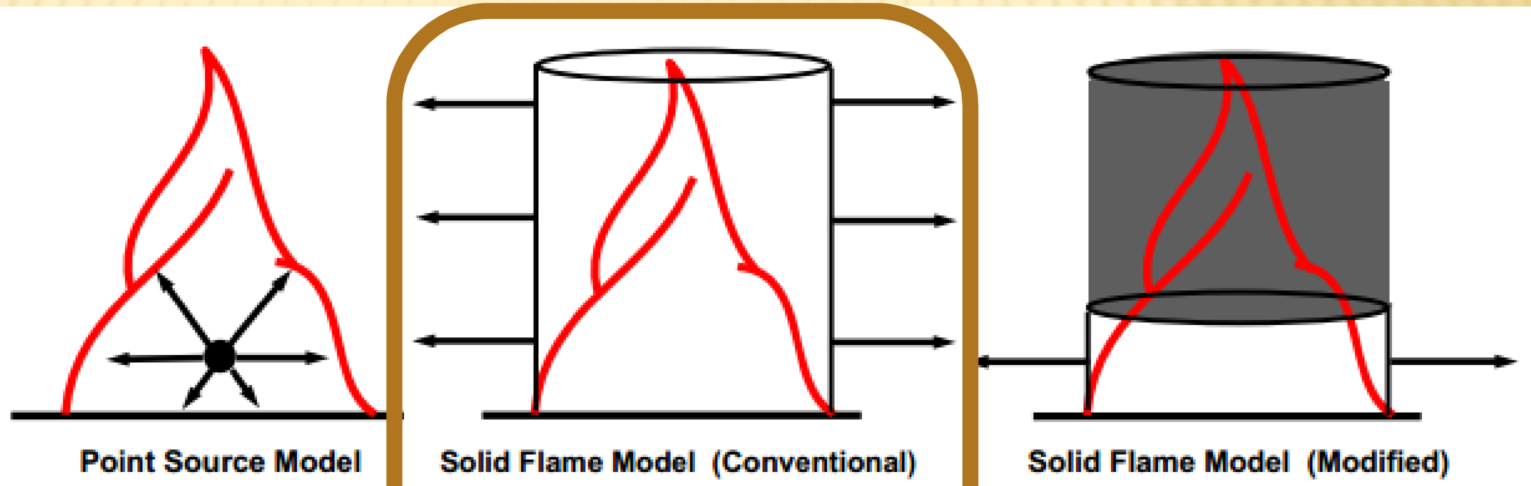


Figure 2: Schematic diagram of thermal radiation models.

Depende da altura e diâmetro de chama. Usado para piscinas de combustíveis líquidos, onde existem mais dados experimentais disponíveis. Por levar em conta o formato da chama e a emissão de calor ao longo de toda a superfície, é mais realista para alvos próximos. Quanto mais afastado o alvo estiver, mais a fonte se aproxima de pontual.

Pool Fire

Tipos de modelos disponíveis:

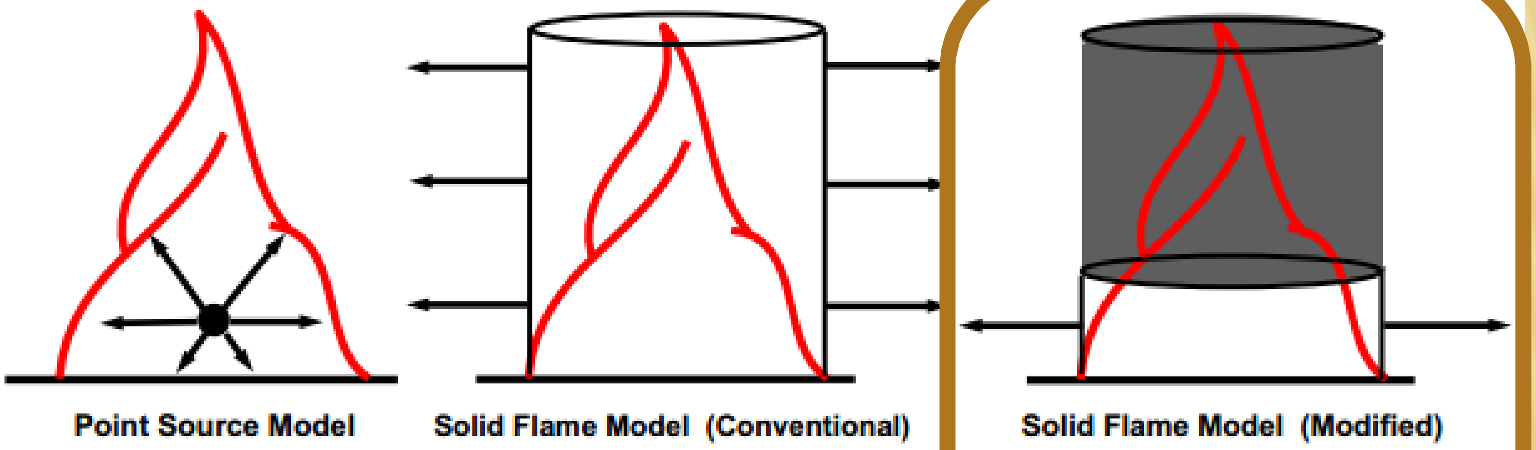


Figure 2: Schematic diagram of thermal radiation models.

Correção do modelo Solid Flame para cenários com muita fumaça. Ideal para piscinas com diâmetros significativos (dezenas de metros). Modelo NIST.

Pool Fire

Tipos de modelos disponíveis:

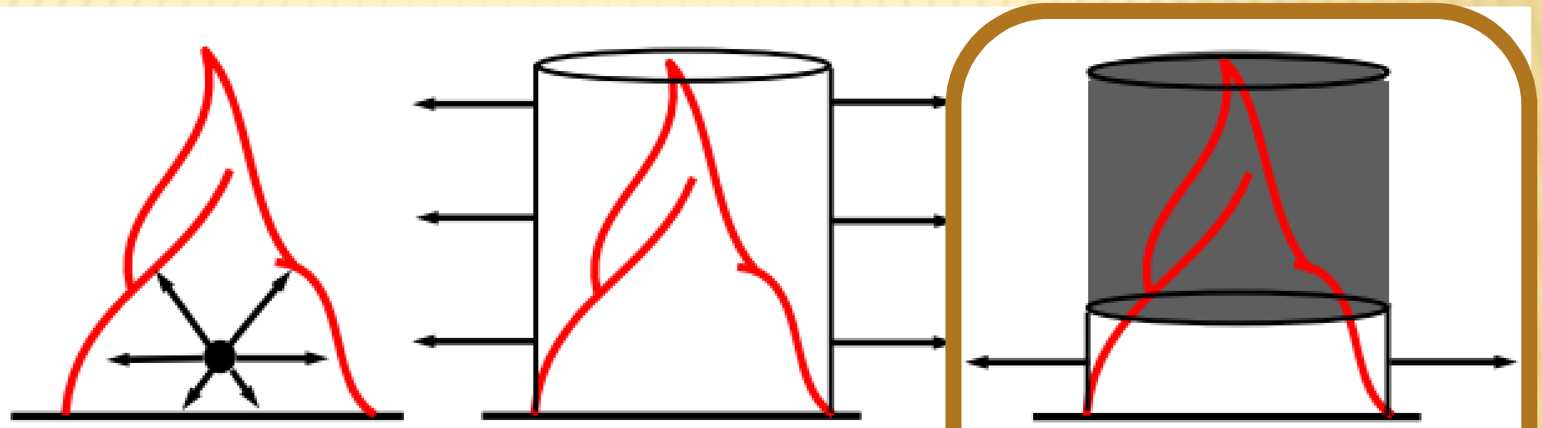


Figure 2: Schematic diagram of thermal radiation models.

"Modelo NIST"

Dedução da Altura da Chama

Heat Release Rate (HRR):

$$\chi_r \, \dot{Q} = P \, H \, E_f$$

Eq. 1

Fração radiada (ver correção da NIST - prox. slide)

HRR Total (kW)

Perímetro da chama (m)

Altura da Chama (m)

Emissive Power (kW/m2)

Poder Emissivo da Superfície da Chama

Área lateral da chama

HRR radiado

Dedução da Altura da Chama

Heat Release Rate (HRR):

Ambas as equações são equivalentes

$$E = Qr / Af$$

(apresentada anteriormente)

$$\chi_r \, \dot{Q} = P \, H \, E_f$$

Área Superficial da chama

Dedução da Altura da Chama

Fração Radiada Para Piscinas (NIST):

Eq. 2

$$\chi_r = \chi_{r_{\max}} \, e^{-kD}$$

Equação e parâmetros que melhor ajustam os dados experimentais.

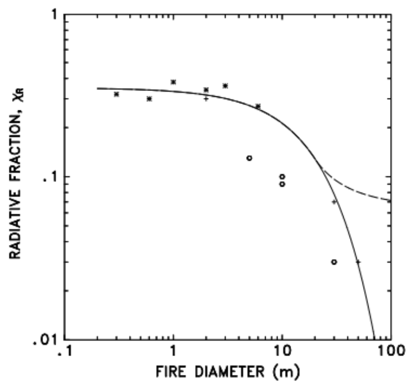


Figure 3: Radiative fraction, χ_r, as a function of fire diameter D for heptane (*), crude oil (○), and kerosene (+). The solid line is a curve fit $\chi_r = 0.35\exp(-kD)$ where $k = 0.05$ (see Eq. 3).

where $\chi_{r_{\max}} = 0.35$ and $k = 0.05\ \mathrm{m}^{-1}$.

Parâmetros ajustados aos dados experimentais.

Ref. Complementar:
"Combustion efficiency and its radiative component"
Archibald Tewarson

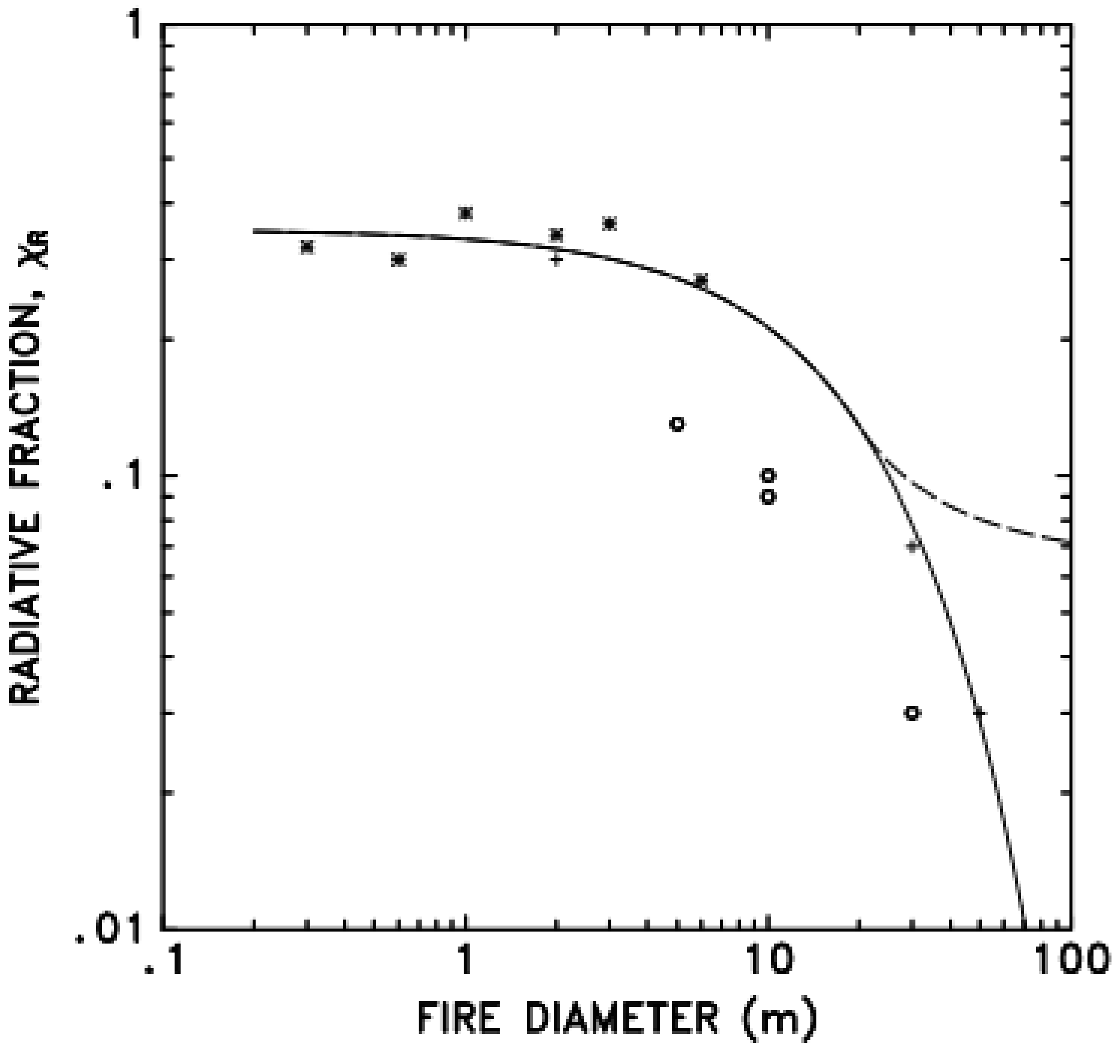


Figure 3: Radiative fraction, χ_r, as a function of fire diameter D for heptane (*), crude oil (○), and kerosene (+). The solid line is a curve fit $\chi_r = 0.35\exp(-kD)$ where $k = 0.05$ (see Eq. 3).

Dedução da Altura da Chama

Relacionando HRR Total(Q), HRR por unidade de área (qf) e área da base (A):

$$\dot{Q} = \dot{q}_f'' A$$

Eq. 3

HRR Total
(Taxa)
(kW)

HRR por unidade
de área da base
(kW/m2)
Ver Tabela próximo slide

Área da base
(m2)

Equação apresentada anteriormente.

Método via HHR por unidade de área da base

Q = qf'' A

$\dot{q}''_f$

HRR
por unidade de área

Liquid	Mass Burning Rate, $\dot{m}''$ kg/m^2/s	Heat of Combustion kJ/kg	HRR Per Unit Area, $\dot{q}''_f$ kW/m^2	Screen ASD Struct. m	Screen ASD People m	Reference
Acetic Acid	0.033	13,100	400	10	90	Ref. [10]
Acetone	0.041	25,800	1,100	10	250	Ref. [9]
Acrylonitrile	0.052	31,900	1,700	15	390	Ref. [10]
Amyl Acetate	0.102	32,400	3,300	30	750	Ref. [10]
Amyl Alcohol	0.069	34,500	2,400	20	550	Ref. [10]
Benzene	0.048	44,700	2,100	20	480	Ref. [9]
Butyl Acetate	0.100	37,700	3,800	35	860	Ref. [10]
Butyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
m-Cresol	0.082	32,600	2,700	25	620	Ref. [10]
Crude Oil	0.045	42,600	1,900	15	430	Ref. [9]
Cumene	0.132	41,200	5,400	50	1220	Ref. [10]
Cyclohexane	0.122	43,500	5,300	45	1200	Ref. [10]
No. 2 Diesel Fuel	0.035	39,700	1,400	12	320	Ref. [9]
Ethyl Acetate	0.064	23,400	1,500	15	340	Ref. [10]
Ethyl Acrylate	0.089	25,700	2,300	20	530	Ref. [10]
Ethyl Alcohol	0.015	26,800	400	10	90	Ref. [9]
Ethyl Benzene	0.121	40,900	4,900	40	1100	Ref. [10]
Ethyl Ether	0.094	33,800	3,200	30	730	Ref. [10]
Gasoline	0.055	43,700	2,400	20	550	Ref. [9]
Hexane	0.074	44,700	3,300	30	750	Ref. [9]
Heptane	0.101	44,600	4,500	40	1000	Ref. [9]
Isobutyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
Isopropyl Acetate	0.073	27,200	2,000	20	460	Ref. [10]
Isopropyl Alcohol	0.046	30,500	1,400	15	320	Ref. [10]
JP-4	0.051	43,500	2,200	20	500	Ref. [9]
JP-5	0.054	43,000	2,300	20	530	Ref. [9]
Kerosene	0.039	43,200	1,700	15	400	Ref. [9]
Methyl Alcohol	0.017	20,000	340	10	80	Ref. [9]
Methyl Ethyl Ketone	0.072	31,500	2,300	20	530	Ref. [10]
Pentane	0.126	45,000	5,700	50	1300	Ref. [10]
Toluene	0.112	40,500	4,500	40	1000	Ref. [10]
Vinyl Acetate	0.136	22,700	3,100	25	700	Ref. [10]
Xylene	0.090	40,800	3,700	30	850	Ref. [9]

Dedução da Altura da Chama

Assumindo poça circular:

Área do círculo

Eq. 3

$$\dot{Q} = \dot{q}_f'' A$$

Eq. 4

$$\dot{Q} = \pi \left(D/2\right)^2 \dot{q}_f''$$

Dedução da Altura da Chama

Eq. 1

$$\chi_r \, \dot{Q} = P \, H \, E_f$$

Perímetro do círculo

$$P = \pi \, D$$

Eq. 4

$$\dot{Q} = \pi \, (D/2)^2 \, \dot{q}''_f$$

Eq. 2

$$\chi_r = \chi_{r_{\max}} \, e^{-kD}$$

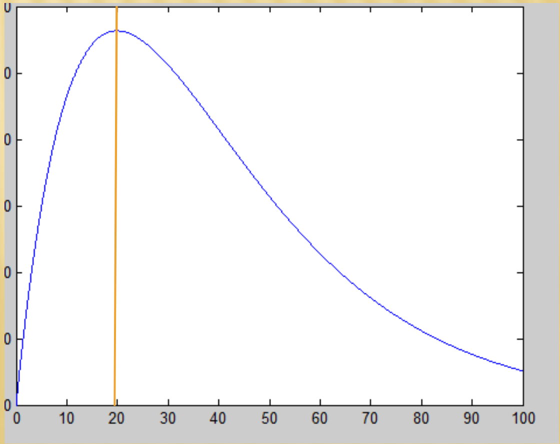
Dedução da Altura da Chama

A partir das equações anteriores é possível determinar a altura H para piscinas circulares:

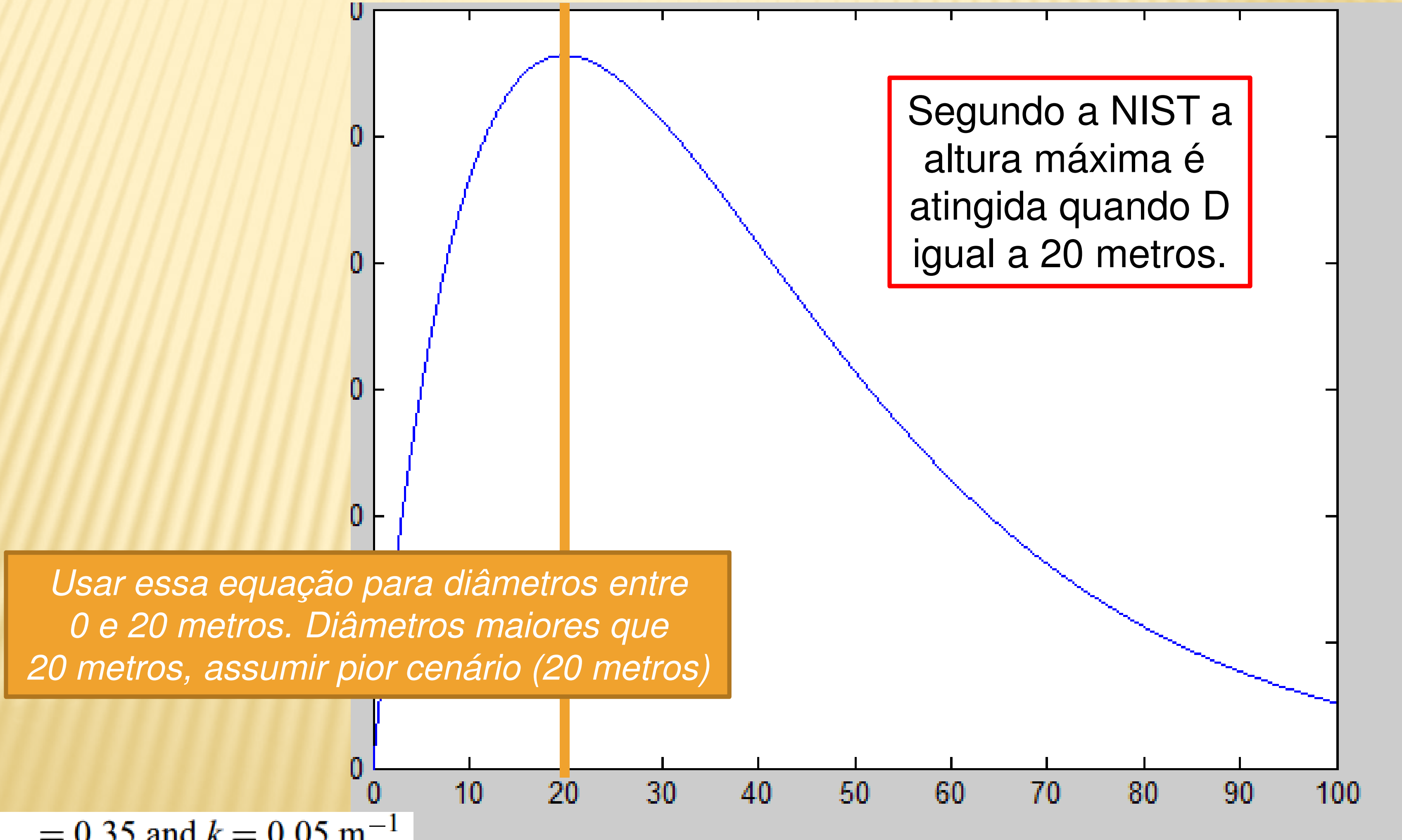
$$H = \frac{\chi_{r_{max}} \, e^{-kD} \, D \, \dot{q}''_f}{4 \, E_f}$$

Eq. 5

Usar essa equação para diâmetros entre 0 e 20 metros. Diâmetros maiores que 20 metros, assumir pior cenário (20 metros)



Dedução da Altura da Chama



where $\chi_{r_{\max}} = 0.35$ and $k = 0.05\ \mathrm{m}^{-1}$.

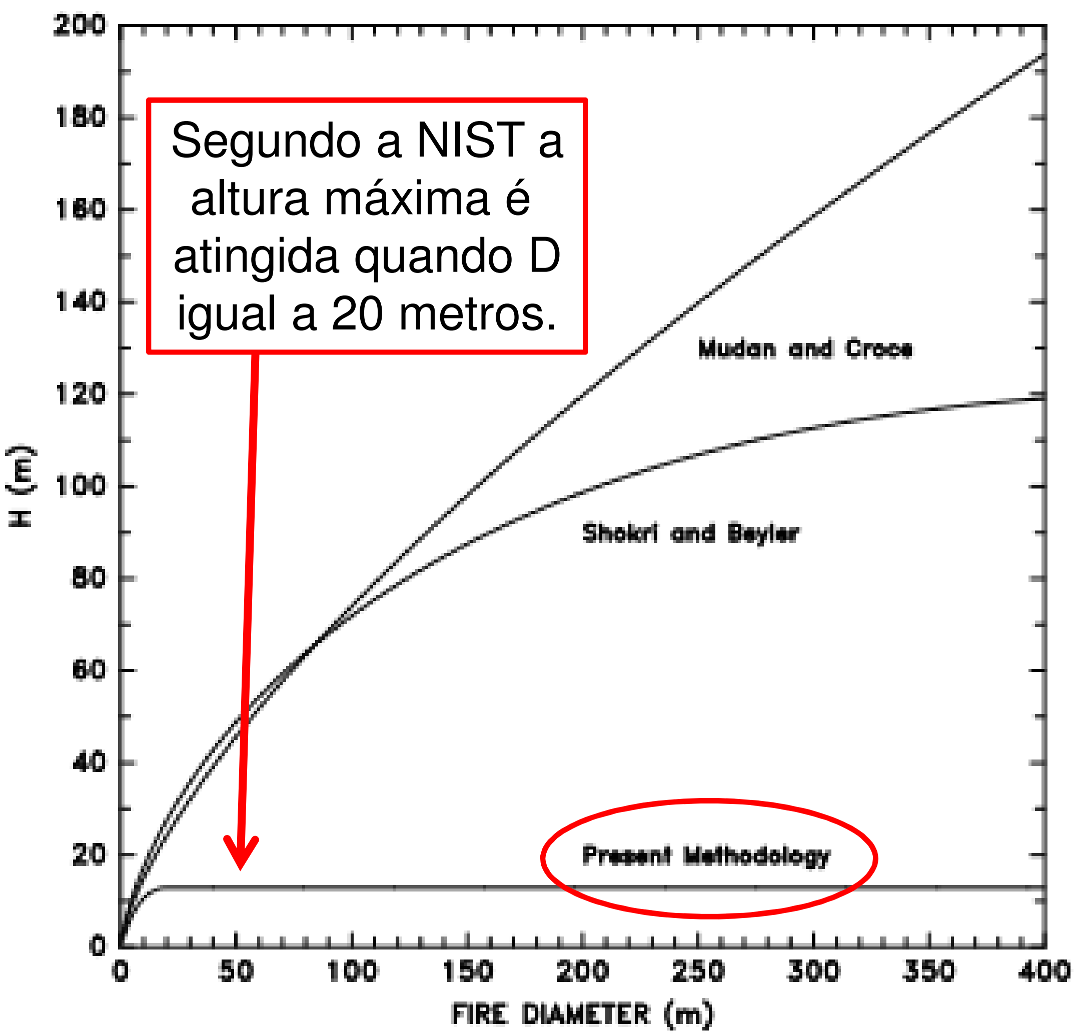


Figure 6: Flame height as a function of fire diameter for a gasoline pool fire.

Ref Complementar: http://ir.canterbury.ac.nz/bitstream/10092/4959/1/thesis_fulltext.pdf

Dedução da Altura da Chama

Segundo a NIST, Ef vale 100 kW/m2, sendo constante para gasolina e querosene:

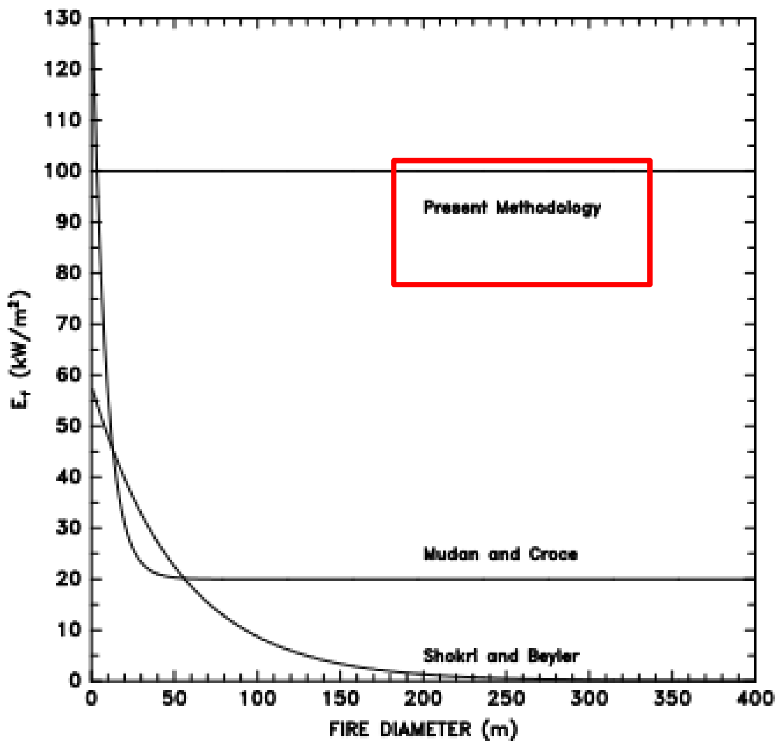


Figure 5: Emissive power as a function of fire diameter for a gasoline pool fire.

Ref Complementar: http://ir.canterbury.ac.nz/bitstream/10092/4959/1/thesis_fulltext.pdf

Dedução da Altura da Chama

$$E = Qr / Af$$

A equação de E é Qr sobre Af. Como nos outros modelos a altura da chama cresce muito, Af também aumenta. Porém, como o calor radiado na prática não aumenta na mesma proporção, o E acaba caindo.

No caso da NIST, como a altura fica sempre muito pequena, Af é pequena, logo, para uma mesma quantidade de calor (Qr), o valor de E é maior.

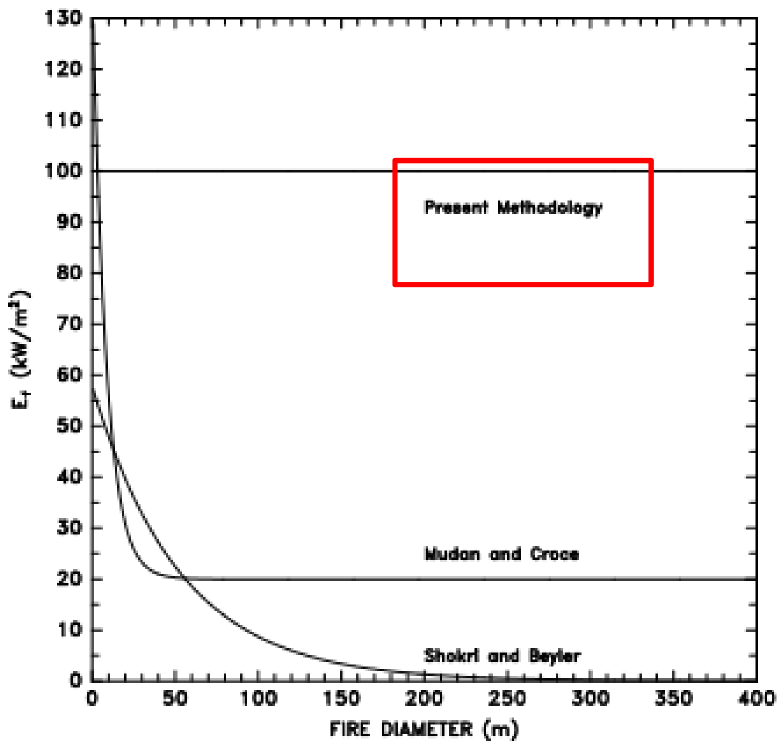


Figure 5: Emissive power as a function of fire diameter for a gasoline pool fire.

Ref Complementar: http://ir.canterbury.ac.nz/bitstream/10092/4959/1/thesis_fulltext.pdf

Dedução da Altura da Chama

Então temos uma altura máxima de chama (Hmax):

$$H = \frac{\chi_{r_{\max}}\, e^{-kD}\, D\, \dot{q}''_f}{4\, E_f}$$

Eq. 5

Use H = Hmax para poças com mais de 20 metros de diâmetro.

Assumindo Ef = 100

$$H_{\max} = \frac{0.35\, e^{-1}\, 20 \dot{q}''_f}{4 \cdot 100} = 6.4 \times 10^{-3}\, \dot{q}''_f$$

Eq. 6

metros

where $\chi_{r_{\max}} = 0.35$ and $k = 0.05\ \mathrm{m}^{-1}$.

D=20 m

kW/m2

HRR
por unidade de área
(tabelado por combustível)

Dedução da Altura da Chama

Note:

Ef = 100 kW/m2 para avaliação em campo aberto.

Ef = 50 kW/m2 para situações com barreiras.
Gera um H (ou Hmax) maior, pois Ef está no denominador.

Distância Aceitável – Cálculo Completo

Cálculo da Distância Aceitável

Altura da Chama

Calor que atinge o alvo usando modelo de chama sólida

Distância Segura

Distância Aceitável – Cálculo Completo

Altura da Chama:

(0,05)

(0,35)

Diâmetro de poça (no máx. 20m)

$$H = \frac{\chi_{r_{\max}} \, e^{-kD} \, D \, \dot{q}''_f}{4 \, E_f}$$

Tabelado

Eq 5

Obtenho!

Assumo igual a 100 (campo livre)
ou 50 (com barreiras)

Distância Aceitável – Cálculo Completo

Achando a radiação que atinge o alvo:

Thermal Radiation Flux
(fluxo de radiação térmica que atinge um determinado alvo)

kW/m2

$$\dot{q}'' = F\,\tau\,\varepsilon_f\,E_f$$

Eq 7

View factor (função do tamanho da chama e distância ao alvo)

Atm. Transmissivity
(=1 pior caso)

Effective Emissivity

ε_f $1 - e^{-\kappa D}$

(=1 pior caso)

Emissive Power

Distância Aceitável – Cálculo Completo

Achando a distância até o alvo:

Thermal Radiation Flux
(fluxo de radiação térmica que atinge um determinado alvo)

$$\dot{q}'' = F\,\tau\,\varepsilon_f\,E_f$$

Eq 7

View factor
(função do tamanho da chama e da **distância ao alvo**)

Atm. Transmissivity
(=1 pior caso)

Effective Emissivity

ε_f $1 - e^{-\kappa D}$

(=1 pior caso)

Emissive Power

Distância Segura – Método Gráfico

Cálculo simplificado para distância segura (NIST):

If the fuel is liquid at atmospheric temperature and pressure, if the fire is roughly circular around its base, and if there are **no obstructions** to be considered, use:

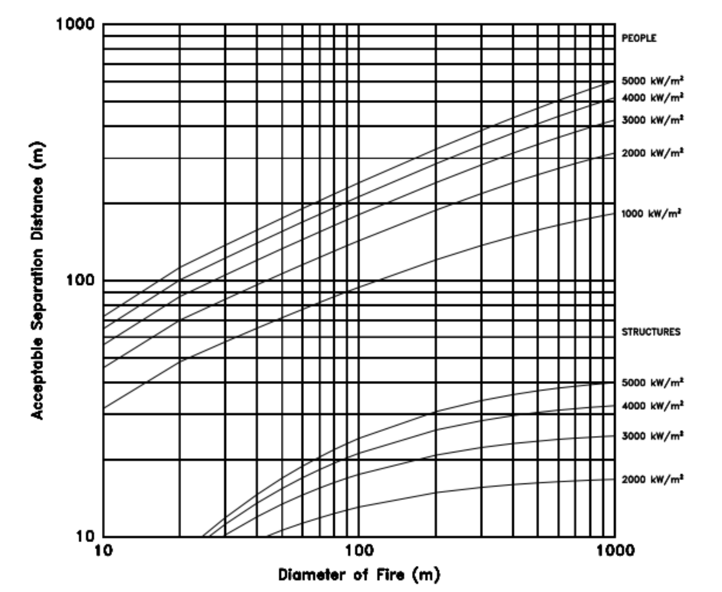
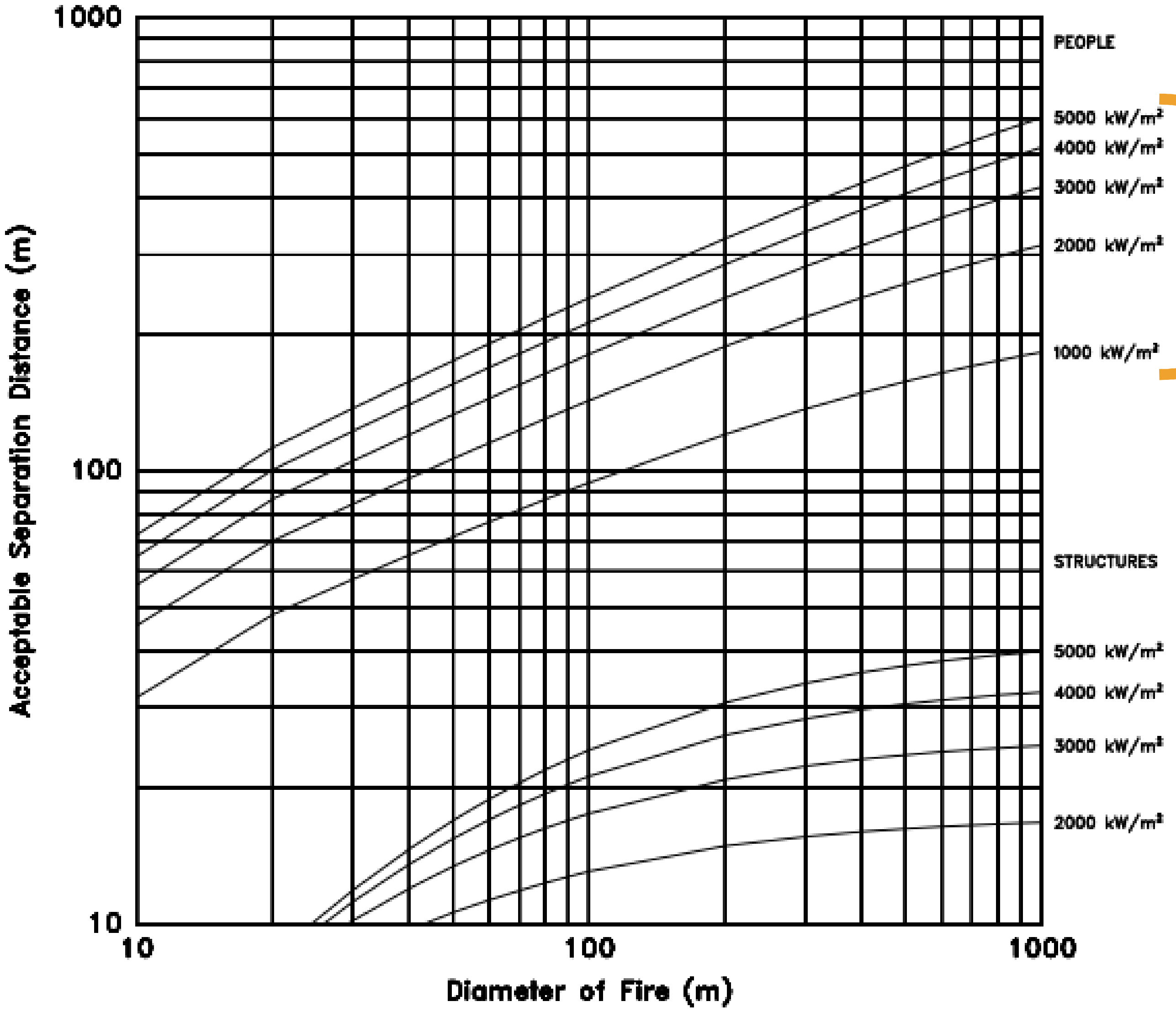


Figure 10: Acceptable Separation Distance (ASD) from nearly cylindrical fires resulting from spills of hazardous liquids, metric units. The upper curves are ASDs for people, the lower curves for combustible structures. The numbers associated with each curve are heat release rates per unit area of burning surface, $\dot{q}''_f$, in units of kW/m^2. These values for various fuels are obtained from Table 1.



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$\dot{q}''_f$

Valores tabelados para cada combustível

$\dot{q}''_f$

Valores tabelados para cada combustível

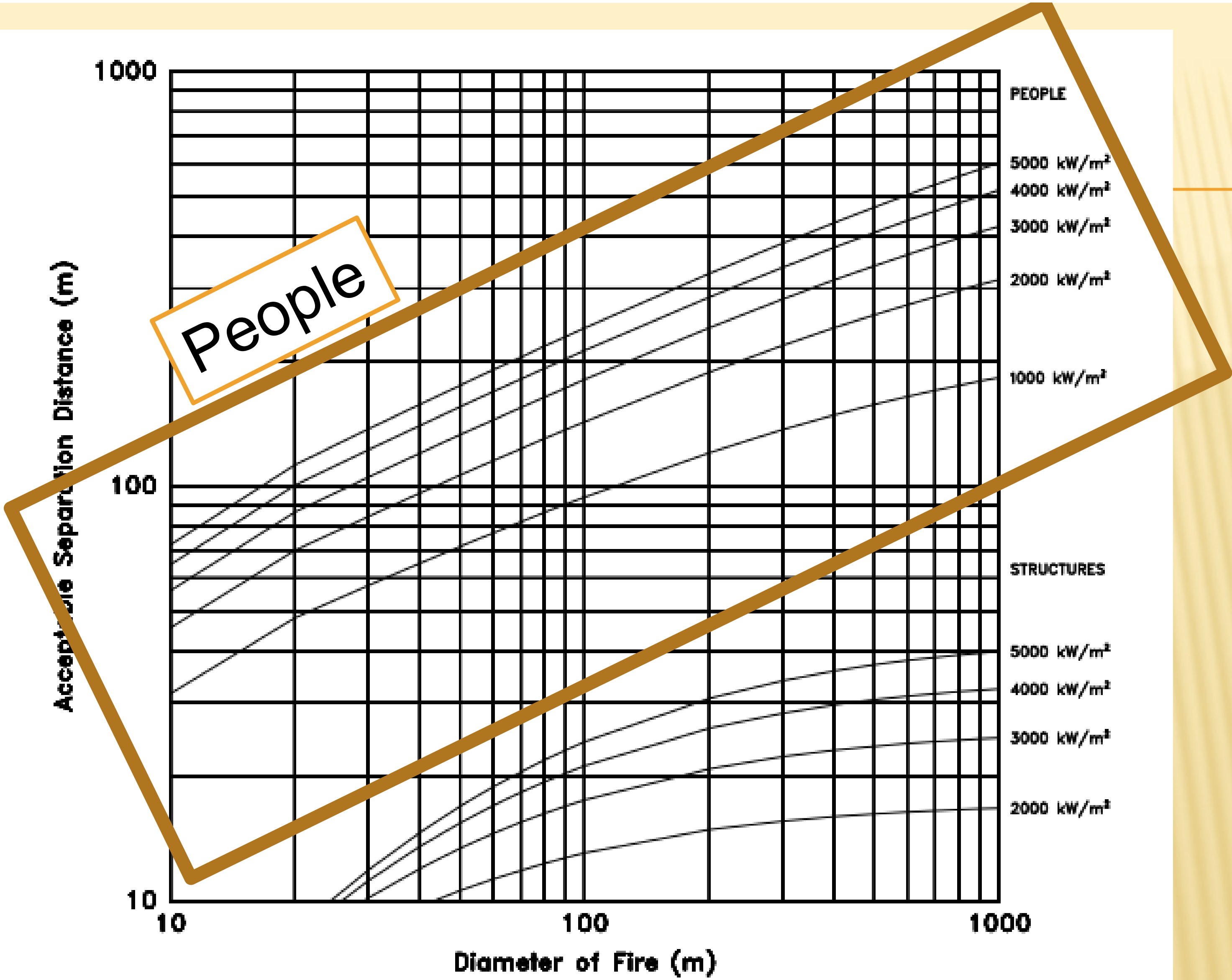
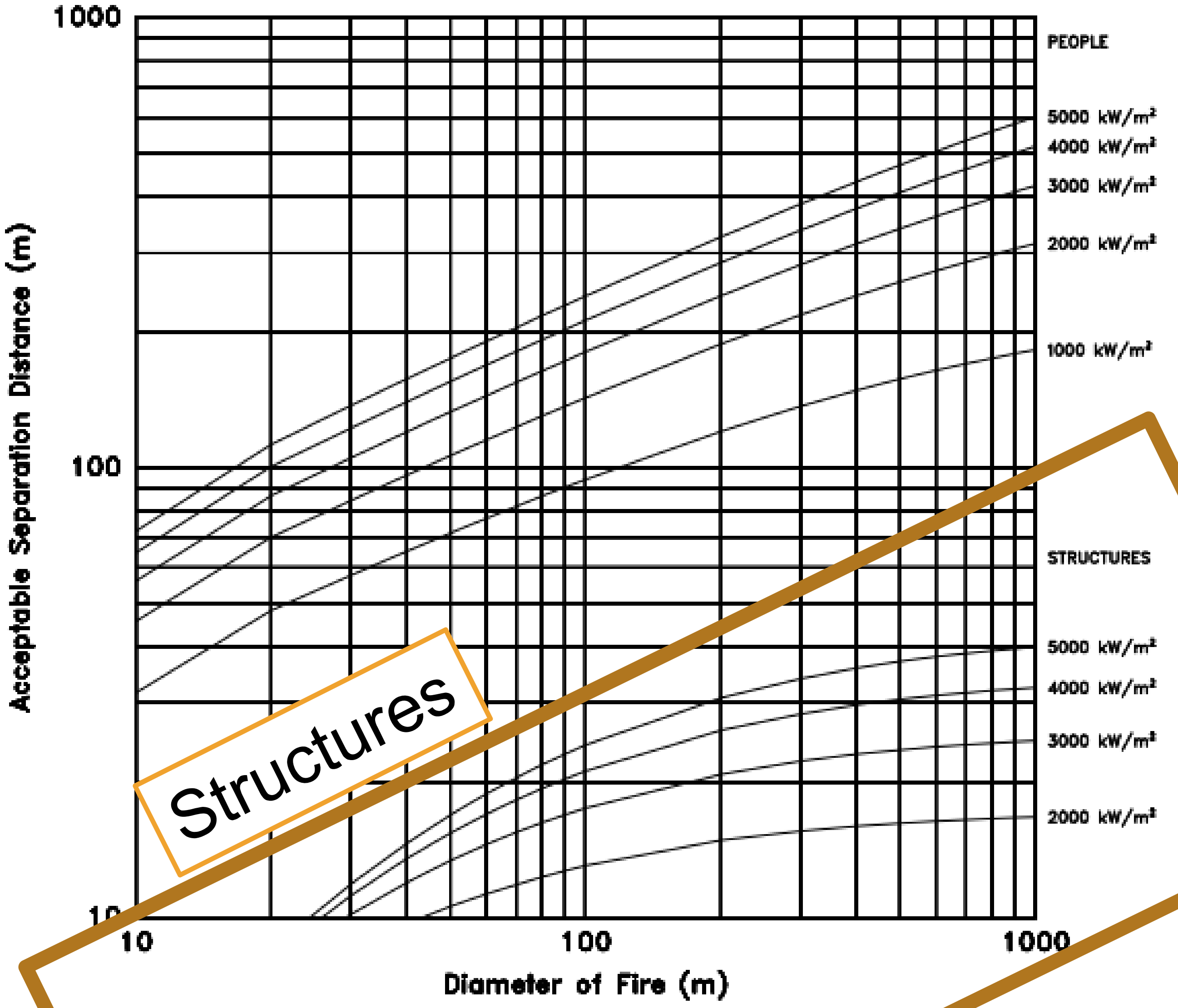


Figure 10: Acceptable Separation Distance (ASD) from nearly cylindrical fires resulting from spills of hazardous liquids, metric units. The upper curves are ASDs for people, the lower curves for combustible structures. The numbers associated with each curve are heat release rates per unit area of burning surface, $\dot{q}''_f$, in units of kW/m^2. These values for various fuels are obtained from Table 1.



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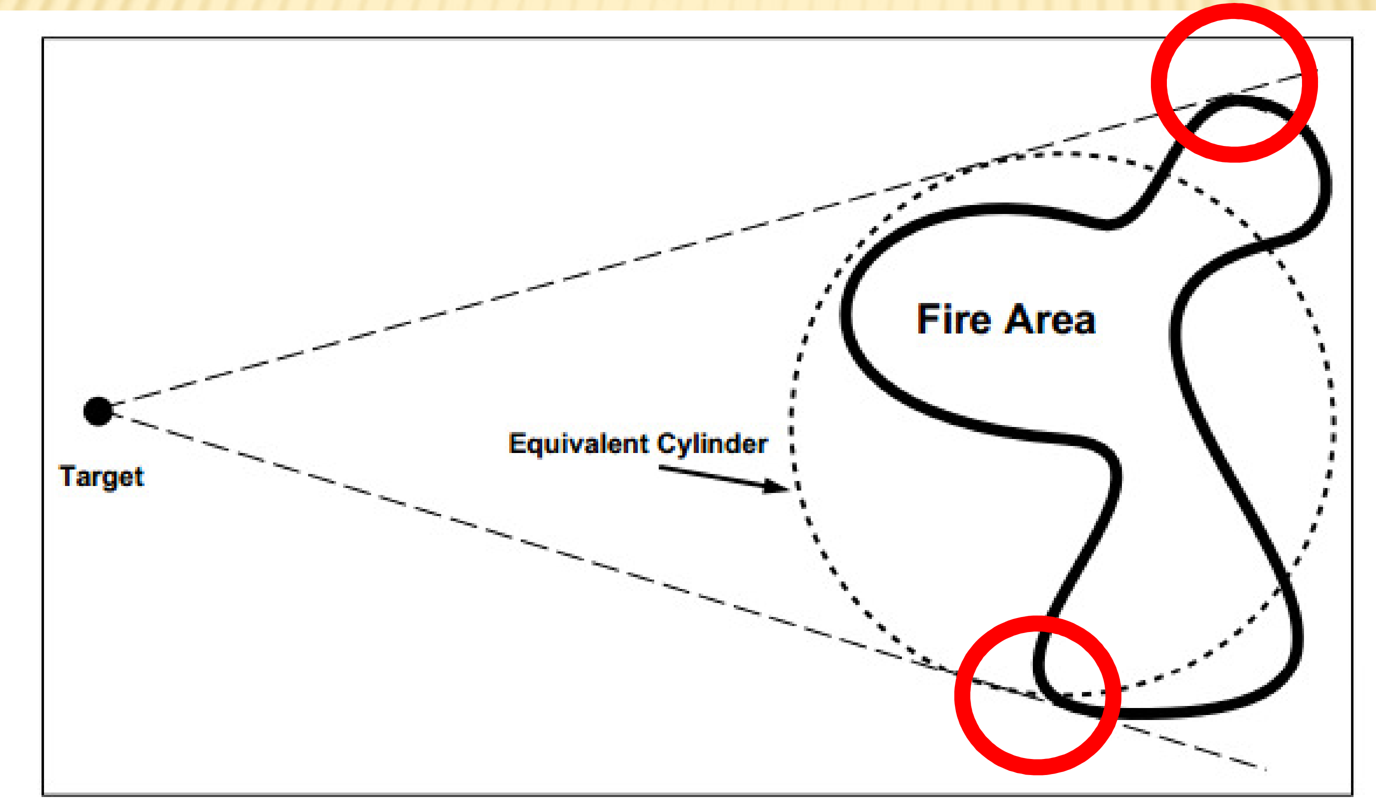
Distância Segura – Método Gráfico

O cálculo simplificado usa o diagrama do slide anterior, mas antes preciso do Diâmetro Equivalente da poça.

Diâmetro equivalente:



Usar a área visada pelo alvo.

Distância Segura – Método Gráfico

Distância "sempre" segura:

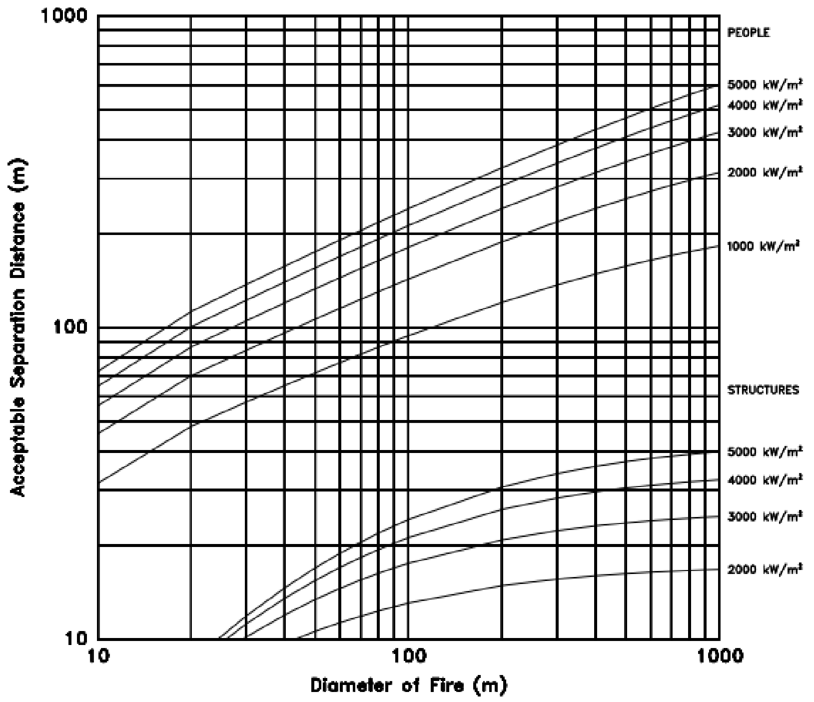


Figure 10: Acceptable Separation Distance (ASD) from nearly cylindrical fires resulting from spills of hazardous liquids, metric units. The upper curves are ASDs for people, the lower curves for combustible structures. The numbers associated with each curve are heat release rates per unit area of burning surface, $\dot{q}''_f$, in units of kW/m^2. These values for various fuels are obtained from Table 1.

A partir da tendência das curvas é possível observar que, a partir de um certo diâmetro, a distância segura não aumenta. Ou seja, existe uma distância que é sempre segura para um determinado combustível, independente do tamanho da poça.

Essa distância para D infinito é apresentada na tabela seguinte.

Liquid	Mass Burning Rate, $\dot{m}''$	Heat of Combustion	HRR Per Unit Area, $\dot{q}''_f$	Screen ASD Struct.	Screen ASD People	Reference
	kg/m²/s	kJ/kg	kW/m²	m	m	
Acetic Acid	0.033	13,100	400	10	90	Ref. [10]
Acetone	0.041	25,800	1,100	10	250	Ref. [9]
Acrylonitrile	0.052	31,900	1,700	15	390	Ref. [10]
Amyl Acetate	0.102	32,400	3,300	30	750	Ref. [10]
Amyl Alcohol	0.069	34,500	2,400	20	550	Ref. [10]
Benzene	0.048	44,700	2,100	20	480	Ref. [9]
Butyl Acetate	0.100	37,700	3,800	35	860	Ref. [10]
Butyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
m-Cresol	0.082	32,600	2,700	25	620	Ref. [10]
Crude Oil	0.045	42,600	1,900	15	430	Ref. [9]
Cumene	0.132	41,200	5,400	50	1220	Ref. [10]
Cyclohexane	0.122	43,500	5,300	45	1200	Ref. [10]
No. 2 Diesel Fuel	0.035	39,700	1,400	12	320	Ref. [9]
Ethyl Acetate	0.064	23,400	1,500	15	340	Ref. [10]
Ethyl Acrylate	0.089	25,700	2,300	20	530	Ref. [10]
Ethyl Alcohol	0.015	26,800	400	10	90	Ref. [9]
Ethyl Benzene	0.121	40,900	4,900	40	1100	Ref. [10]
Ethyl Ether	0.094	33,800	3,200	30	730	Ref. [10]
Gasoline	0.055	43,700	2,400	20	550	Ref. [9]
Hexane	0.074	44,700	3,300	30	750	Ref. [9]
Heptane	0.101	44,600	4,500	40	1000	Ref. [9]
Isobutyl Alcohol	0.054	35,900	1,900	15	430	Ref. [10]
Isopropyl Acetate	0.073	27,200	2,000	20	460	Ref. [10]
Isopropyl Alcohol	0.046	30,500	1,400	15	320	Ref. [10]
JP-4	0.051	43,500	2,200	20	500	Ref. [9]
JP-5	0.054	43,000	2,300	20	530	Ref. [9]
Kerosene	0.039	43,200	1,700	15	400	Ref. [9]
Methyl Alcohol	0.017	20,000	340	10	80	Ref. [9]
Methyl Ethyl Ketone	0.072	31,500	2,300	20	530	Ref. [10]
Pentane	0.126	45,000	5,700	50	1300	Ref. [10]
Toluene	0.112	40,500	4,500	40	1000	Ref. [10]
Vinyl Acetate	0.136	22,700	3,100	25	700	Ref. [10]
Xylene	0.090	40,800	3,700	30	850	Ref. [9]

Distância Segura – Método Gráfico

"Apagar incêndios em tanques de álcool é bem mais fácil que apagar tanques de óleo cru ou gasolina"

Liquid	Mass Burning Rate, $\dot{m}''$	Heat of Combustion	HRR Per Unit Area, $\dot{q}''_f$	Screen ASD Struct.	Screen ASD People	Reference
	$kg/m^2/s$	kJ/kg	kW/m^2	m	m	
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Gasoline	0.055	43,700	2,400	20	550	Ref. [9]
Hexane	0.074	44,700	3,300	30	750	Ref. [9]

Ver a apostila para entender as particularidades da modelagem de piscinas de gases liquefeitos.

http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

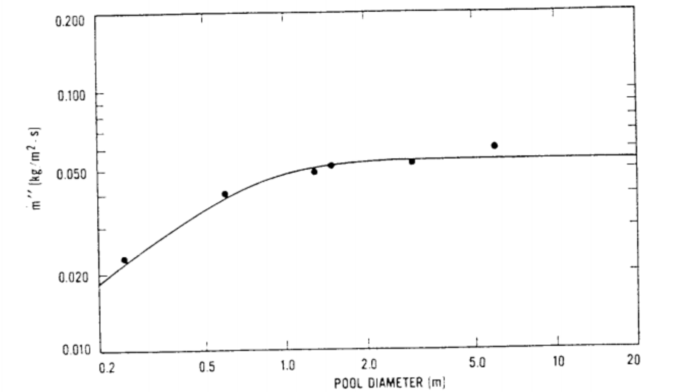


Figure 1. Pool burning rates for gasoline.

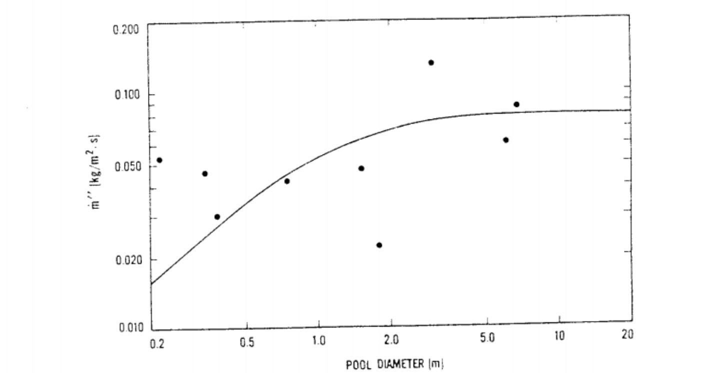


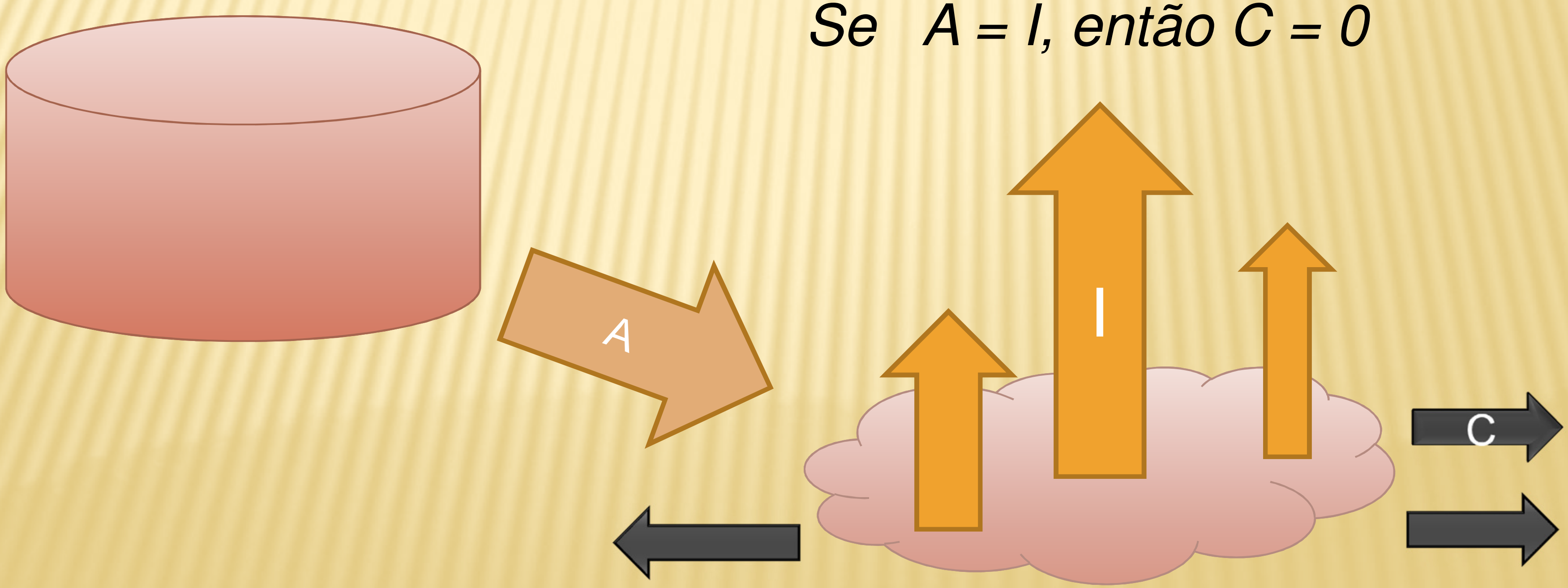
Figure 2. Pool burning rates for LNG, shown as an example of a fuel where experimental data show large variations.

Unconfined Pool Fire

As equações anteriores são função do diâmetro, o que funciona bem para Confined Pool.

Para Unconfined Pool o líquido se alastra até que a perda de material pelo fogo se iguale a vazão de vazamento.

Se A = I, então C = 0



Unconfined Pool Fire

Diâmetro máximo de poça atingido pelo líquido para vazamento **contínuo e constante, com ignição no tempo t = 0**:

Volumetric spill rate (m3/s)

$$D_{max} = 2\left(\frac{V_s}{\pi\, y}\right)^{\frac{1}{2}}$$

Eq 9

maximum pool diameter

Liquid pool fire regression rate (m/s)
(ver próximo slide)

http://www.wpi.edu/Pubs/ETD/Available/etd-0501102-221341/unrestricted/leblanc.pdf

Unconfined Pool Fire

Liquid pool fire regression rate (m/s)

Regression rates are dependent upon the fire configuration and thus are difficult to calculate in a general fashion. However, for most hydrocarbon pool fires, regression rates are on the order of 0.1 mm/sec (0.0393in/sec).

Converter antes de usar este valor!

Fire Environments Typical of Navy Ships

by David LeBlanc

A Thesis
Submitted to the Faculty
of the
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Master of Science
in
Fire Protection Engineering

May 1998

http://www.wpi.edu/Pubs/ETD/Available/etd-0501102-221341/unrestricted/leblanc.pdf

Unconfined Pool Fire

Liquid pool fire regression rate (m/s)

FIGURE 1 shows scale dependency of burning rate (Fuel level regression rate) and flame height on pan diameter, obtained by Blinov and Khudyakov[1], which is of very classical data but still useful.

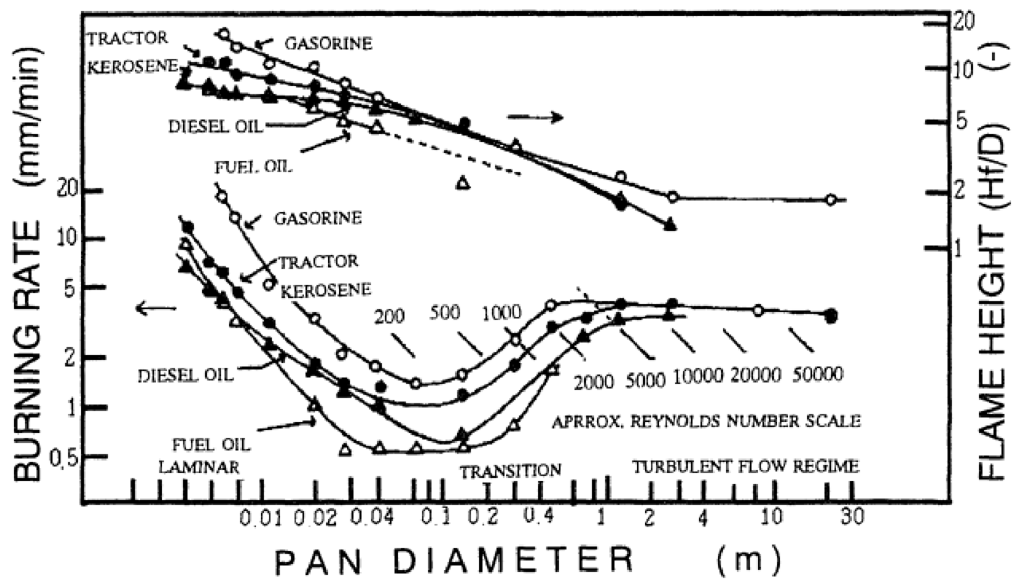


FIGURE 1 Scale dependency of burning rate, flame height with pan diameter[1]

http://www.iafss.org/publications/fss/6/115/view

Invited Lecture

Large Scale Pool Fires: Results of Recent Experiments

HIROSHI KOSEKI
National Research Institute of Fire and Disaster
Fire and Disaster Management Agency
Nakahara, Mitaka, Tokyo, 181-8633 Japan

Unconfined Pool Fire

Correção de Cline e Koening (experimental):

D max = 1,25 D max

(a baixa temperatura do solo reduz a velocidade da queima durante o início do processo)

Unconfined Pool Fire

Diâmetro de poça não confinada (Modelo NIST):

$$D = 10\sqrt{V}$$

Eq 10

Diâmetro (m)

Volume (m3)

Porém, a incerteza é tão elevada que pode ser melhor usar a distância segura para poça de diâmetro infinito (NIST).

http://www.fire.nist.gov/bfrlpubs/fire00/PDF/f00177.pdf

Unconfined Pool Fire

Diâmetro máximo de poça atingido pelo líquido para vazamento **contínuo e constante, com ignição no tempo t = 0**:

$$D_{max} = 2\left(\frac{V_s}{\pi\, y}\right)^{\frac{1}{2}}$$

Ou

$$D = 10\sqrt{V}$$

Agora posso aplicar a equação de Heat Release Rate (kW) de Confined Pool Fire.

Unconfined Pool Fire

Tempo para atingir o diâmetro máximo:

$$t_{max} = \frac{0.564\, D_{max}}{\left(gyD_{max}\right)^{\frac{1}{3}}}$$

Dmax is the maximum pool diameter (m)

g is the gravitational acceleration (9.81 m/sec2)

y is the pool regression rate (m/s)

http://www.wpi.edu/Pubs/ETD/Available/etd-0501102-221341/unrestricted/leblanc.pdf

Unconfined Pool Fire

Modelo de Cline e Koening
Relação D x t

(D / Dmax)^2 = 1 - e ^ (- t.Y/s)

Onde
s: espessura (em metros) (Exemplo: 0,5 mm)