Washington Group International
Integrated Engineering, Construction, and Management Solutions

Fire Severity and Fire Source Term Modeling

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Why is understanding fire important?

Fire can be a dominate risk contributor for nuclear facilities.

Why fire is a significant event?

- Very energetic event
- Readily breach containment barriers (glove box, ventilation ductwork and building envelope)
- Severe smoke, excessive heat and large thermal gradients are common
- Significant thermal gradients, readily disperse radioactive material.

Objective and schedule

- Terminal Objective: Attendee's are able to judge the expected radiological consequences resulting from an accidental fire. This will include the ability to describe fire severity and estimate the five source-term equation factors (ST = MAR·DS·ARF·RF·LPF).
- Schedule
  - Start 1:00 PM
  - 2 Breaks (~2:15 and 3:30)
  - Complete 5:00 PM

Course Overview

- Fire Severity
  - Fire metrics
  - Pool fires
  - Fuel package behavior
  - Fire compartments
- Material at Risk
- Damage Ratio
  - Fire heat flux
  - Flashover
  - Container response
- Airborne Release Fraction
- Respirable Fraction
- Leakpath Factor
- Dose Estimate
- Others topics
  - Fire hazard analyses
  - Fire barriers
  - Fire frequency
  - Soot analysis

Source Term Formula

$$ST = MAR \cdot DR \cdot ARF \cdot RF \cdot LPF$$

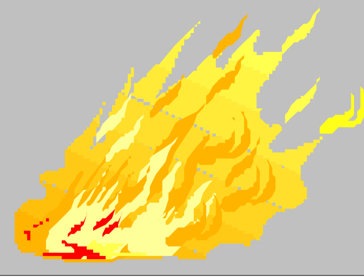
- MAR = Material-at-Risk
- DR = Damage Ratio
- ARF = Airborne Release Fraction
- RF = Respirable Fraction
- LPF = Leakpath Factor

[DOE-HDBK-3010-94]

Fire Severity

How bad will the fire be?

Fire Metrics



Heat of Combustion

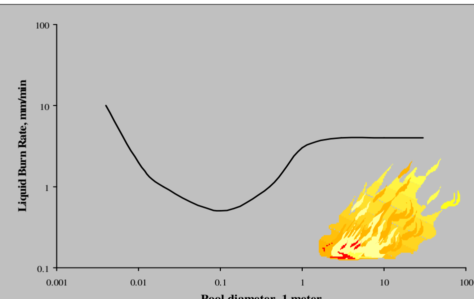
- Energy released per unit mass burned (MJ/kg)
- Gross or Net Heat of Combustion?
  - Gross Water is condensed
  - Net Water remains a vapor
- Example: kerosene
  - Gross heat of combustion 46.4 MJ/kg
  - Net heat of combustion 43.3 MJ/kg

Heat Release Rate

- Heat Release Rate (HRR) is the energy released by the fire.
- Units are usually kW
- It is the basic measure of fire behavior.
- It is typically an empirical value

Pool Fires

Pool Fire Behavior



Pool Fire Mass Loss Rate

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

$\dot{m}''$ = the is the mass loss rate per unit area [kg/s·m²]
D = the pool diameter [m]
k = is the extinction-absorption coefficient of the flame [m⁻¹]
β = the mean-beam-length correction

Typical Pool Fire Data

	Heat of combustion MJ/kg	Base mass loss rate $kg/m^2 \cdot s$	k β m^{-1}
Methanol	20.0	0.017	···
Gasoline	43.7	0.055	2.1
Kerosene	43.2	0.039	3.5
Oil	39.7	0.035	1.7

Pool Fires Heat Release Rate

$$\dot{Q} = \dot{m}'' A_{pool} \Delta H_c$$

$\dot{Q}$ = the heat release rate [kW]
$\dot{m}''$ = the mass loss rate per unit area [kg/s·m²]
A = the pool area [m²]
ΔH_c = heat of combustion [MJ/kg]

Kerosene Pool Fire Example

Spill size: 100 gallons (0.38 m³)
Diked area: 15 m²
Effective spill diameter: 4.4 m
Mass loss rate:

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

$$= \left(0.039 \frac{kg}{m^2 \cdot s}\right)\left(1 - e^{-(3.5\,m^{-1})(4.4\,m)}\right) = 0.039 \frac{kg}{m^2 \cdot s}$$

Heat Release Rate - Example

$$\dot{Q} = \dot{m}'' A_{pool} \Delta H_c$$

$$= \left(43.3 \frac{MJ}{kg}\right)\left(0.039 \frac{kg}{m^2 \cdot s}\right)\left(15\ m^2\right)$$

$$= 25\ MW$$

Pool Fire Duration

$$t = \frac{V}{A}\frac{\rho}{\dot{m}''} = h\frac{\rho}{\dot{m}''} = \frac{h}{\dot{y}}$$

Pool Fire Duration - Example

$$t = \frac{V}{A}\frac{\rho}{\dot{m}''} = \left(\frac{0.38\ m^3}{15\ m^2}\right)\left(\frac{820\ \frac{kg}{m^3}}{0.039\ \frac{kg}{m^2 \cdot s}}\right)$$

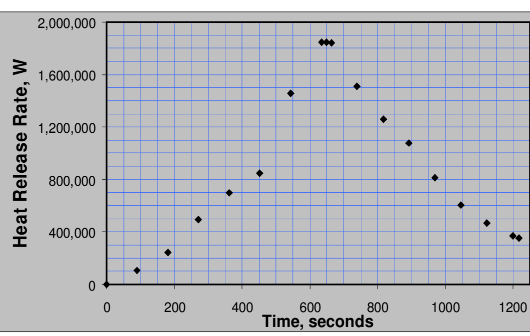
$$= 530\ s \approx 9\ minutes$$

Solid Fuel Package Behavior

NIST Pallet Test

NIST Pallet Test

Pallet Fire Test Results



t^2-Curves

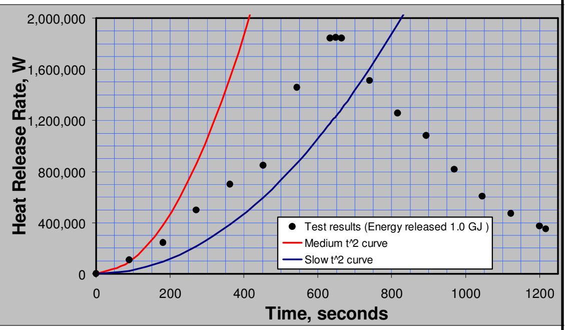
- **Standard FP practice is to approximate the growth period as:**

$$\dot{Q} = Kt^2$$

- **Constant is defined based on the time to reach 1,055 kW (1,000 Btu/s)**

	Time to reach 1,055 kW seconds	Constant K, kW/s^2
slow	600	0.00293
medium	300	0.0117
high	150	0.0469
ultra-fast	75	0.188

Pallet Fire Test Results



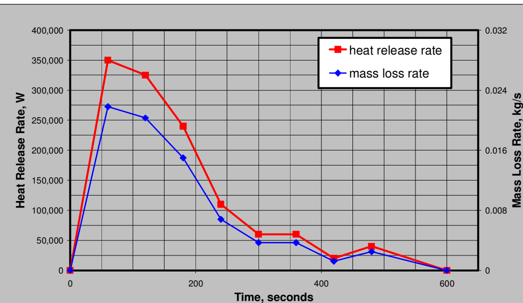
Typical Heat Release Rates (kW)

Trash	
1 or 2 bags	250
> 3 bags	500
Upholstered furnishings	
small (< 10 kg)	250
large (> 20 kg)	1000
Appliance housing	
plastic	250
Christmas tree	
fresh	250
dry	500

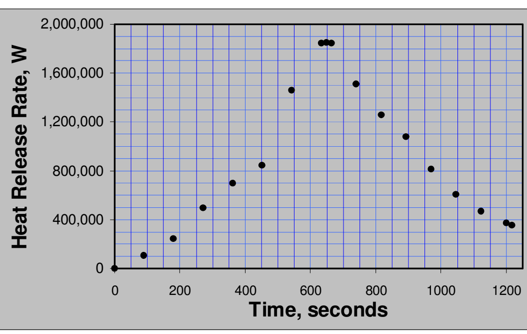
Heat Release Categories

	Energy emission range MW	Benchmark value MW
low	$P < 0.35$	0.25
medium	$0.35 \le P < 0.71$	0.5
high	$0.71 \le P$	1.0

HRR and Pyrolysis Rate – 3 Trash Bags



Scaling HRR Curves



Scaling HRR Data

Test Results		Design Fire	
Height	~0.6 m	Height	1.0 m
PHRR	1.8 MW	PHRR	?
Energy	1.0 GJ	Energy	?
ΔH_c	19 MJ/kg	ΔH_c	19 MJ/kg
Mass	54 kg	Mass	?

Scaling HRR Curves – Mass & Energy

$$m = 54\ \text{kg}\frac{1.0\ \text{m}}{0.6\ \text{m}} = 90\ \text{kg}$$

$$E = 1.0\ \text{GJ}\frac{1.0\ \text{m}}{0.6\ \text{m}} = 1.7\ \text{GJ}$$

Scaling HRR Data

Test Results		Design Fire	
Height	~0.6 m	Height	1.0 m
PHRR	1.8 MW	PHRR	?
Energy	1.0 GJ	Energy	1.7 GJ
ΔH_c	19 MJ/kg	ΔH_c	19 MJ/kg
Mass	54 kg	Mass	90 kg

Scaling HRR Curves – PHRR

$$PHRR_{pallet} = 1368\ (1 + 2.14H)(1 - 0.03M)$$

H is height of stack
M is moisture content

Scaling HRR Curves – PHRR

$$PHRR = 1368\ (1 + 2.14(0.6\text{m}))(1 - 0.03(12\%)) = 2{,}000\ \text{kW}$$

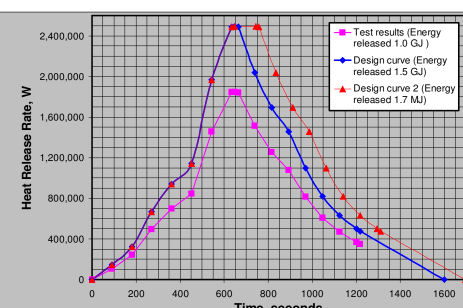
$$PHRR = 1368\ (1 + 2.14\ (1.0\text{m}))(1 - 0.03\ (12\%)) = 2{,}700\ \text{kW}$$

$$K_{PHRR} = \frac{2.7\ \text{MW}}{2.0\ \text{MW}} = 1.35$$

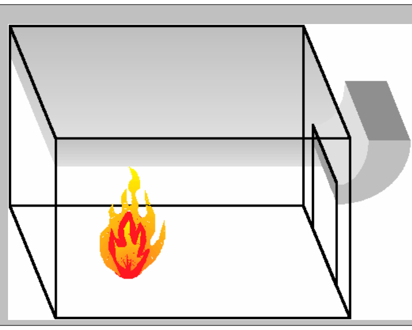
Scaling HRR Data

Test Results		Design Fire	
Height	~0.6 m	Height	1.0 m
PHRR	1.85 MW	PHRR	2.50 MW
Energy	1.0 GJ	Energy	1.7 GJ
ΔH_c	19 MJ/kg	ΔH_c	19 MJ/kg
Mass	54 kg	Mass	90 kg

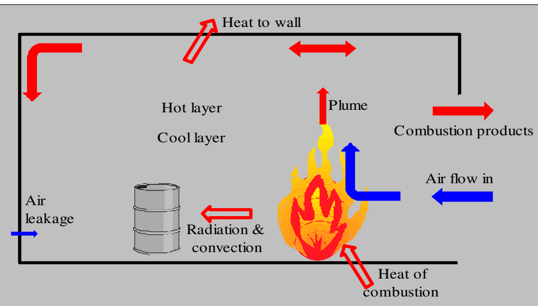
Pallet HRR Curve



Fire Compartment Behavior



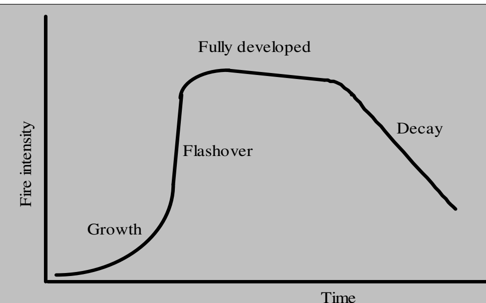
Fire Severity - The Engineering View



Energy Balance for Fire Compartment

- The laws of thermodynamics apply to Fire Protection Engineering
- Conservation of matter
  - Can't burn more than what's really there.
- Conservation of energy
  - The fire's energy must go somewhere
- Entropy always increases
  - Not all the energy goes to heating the containers, some must go out with the plume

Fire Severity - Heat Release Rate



Fire Severity - Lie's Correlation

Growth and fully developed burning phases:

$$T = 250\,(10F)^{\left(\frac{0.1}{F^{.3}}\right)} \exp\left\{-F^2 t\left[3\left(1-e^{-0.6t}\right)-\left(1-e^{-3t}\right)+4\left(1-e^{-12t}\right)\right]\right\} + C\left(\frac{600}{F}\right)^{0.5}$$

Decay phase:

$$T = -600\left(\frac{t}{\tau}-1\right)+T_{\tau} \quad \text{where: } \tau = \frac{Q}{330\,F} \quad \text{and} \quad F = \frac{A_v\sqrt{H_v}}{A_T}$$

Notes:

$$T = 20 \text{ if } T < 20°C \quad t = \frac{0.08}{F} \text{ if } t \le \frac{0.08}{F}+1$$

$$\text{Valid for: } 0.01 \le F < 0.15$$

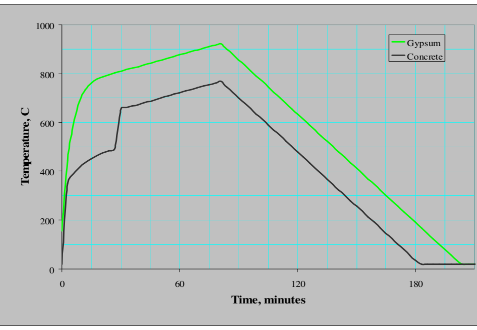
Lie's Correlation (con't)

- A_T = surface area of compartment [m²]
- A_v = area of ventilation opening(s) [m²]
- C = constant for wall (1 if ρ <1600 kg/m³ or 0 otherwise)
- H_v = height of ventilation opening(s) [m]
- Q = fuel load based on room surface area [kg/m²]
- t = time [hours]
- T = temperature [°C]
- τ = duration of fully developed burning [hours]

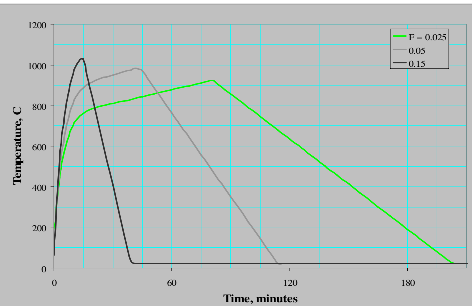
Energy Balance Correlation

- Combustible loading
  - L = 49 kg/m² (10 psf)
  - Q = 11 kg/m²
- Other data
  - A_o = 1.9 m²
  - H_o = 2.1 m
  - A_T = 110 m² (5 m x 5 m x 3 m high)
  - ρ = 700/2,100 kg/m³ (gypsum/concrete)

Composite Temperature Prediction



Ventilation Effect



Computer Model - CFAST

- Obtain from NIST at www.cfast.nist.gov
- Design
  - Zone model that solves Navier-Stokes equations for mass & energy transport
  - Separates a fire compartment into two layers
  - Each zone is assumed to be uniform (temperature, smoke concentrations, etc.)
  - Fire acts as a pump - moves energy and mass between layers - other mixing occurs at doors

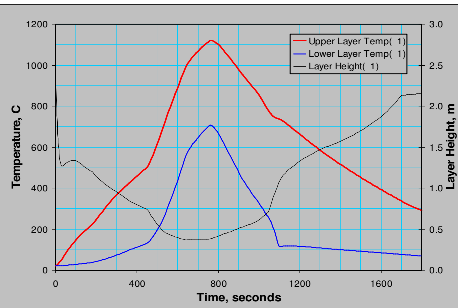
Capabilities

- Accounts for effect of oxygen depletion
- Tracks O_2, CO_2, CO, Soot, HCl, HCN
- Handles 30 fire compartments
- Main and object fires
- Models
  - Natural convection
  - Force convection
  - Changes in horizontal openings

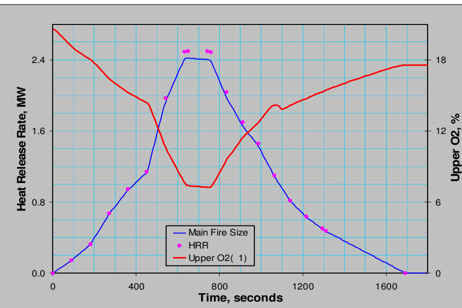
Principle Limitations

- CFAST does not evaluate fire behavior, rather it models the response of the building to a fire
- Neglects
  - Radiation feedback from walls that would increase pyrolysis rate
  - Wall flow
  - Radiation transfer through openings

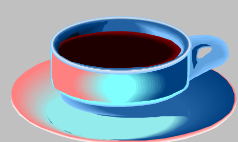
Typical CFAST Results



Typical CFAST Results (con't)



Break?



Course Overview

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  - Fire compartments
- Material at Risk
- Damage Ratio
  - Fire heat flux
  - Flashover
  - Container response
- Airborne Release Fraction
- Respirable Fraction
- Leakpath Factor
- Dose Estimate
- Others topics
  - Fire hazard analyses
  - Fire barriers
  - Fire frequency
  - Soot analysis

Material at Risk

What is available for release?

Definition - Material at Risk

- "The amount of radionuclides (in grams or curies of activity for each radionuclide) available to be acted on by a given physical stress."
- "Some analysts will exclude ... material from the MAR" if it is predetermined that the material would not be affected by the accident.

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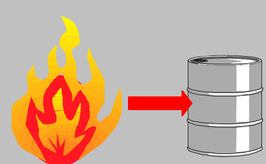
Damage Ratio

What fraction is realistically available for release

Damage Ratio

- Fire Stress
  - Heat flux predictions
- Compartment Fire Severity
  - Flashover
  - Temperature correlations
- Container Response

Fire Heat Flux



Emissive Power

$$q'' = \sigma T_f^4$$

q'' = emissive power [W/m^2]

σ = Stefan-Boltzmann constant [5.669E-11 kW/m^2·K^4]

T_f = flame temperature [K]

Flame Temperatures

- 10 CFR 71.73, Hypothetical Accident (Transportation)
  - 800°C for 30 minutes
- Empirical flame temperatures
  - Pool fires 770 to 1200°C (Babrauskus / Craig)
  - Non-pool fires 1000 to 1500°C (Tien)
- Recommended evaluation values (Babrauskus)
  - Small open pool fires (<1 meter) 900°C
  - Large open pool fires 1100 to 1200°C
  - Compartment fire ~1200°C

Emissive Power

$q'' = \sigma T_f^4$	Flame temperature °C	Flame temperature K	Power kW/m^2
Gasoline	967	1240	134
Methane	1016	1289	157
Polystyrene	1213	1486	276
Plexiglas	1265	1538	317
Kerosene	1327	1600	372
Wood	1459	1732	510

Pool Fire Emissive Power

$$E_{ave} = E_m e^{-SD} + E_s\left(1 - e^{-SD}\right)$$

E_m = maximum emissive power of the luminous spots [140 kW/m^2]

E_s = emissive power of smoke [20 kW/m^2]

S = empirical constant [0.12 m^{-1}]

D = pool diameter [m]

Design Heat Fluxes - Flammable Liquid

Observations

- Measured range in fires: 20 to 150 kW/m^2
- Practical range in fires: 10 to 80 kW/m^2

NFPA 30

- Design heat flux: Wetted area < 19 m^2 63 kW/m^2

Assumptions

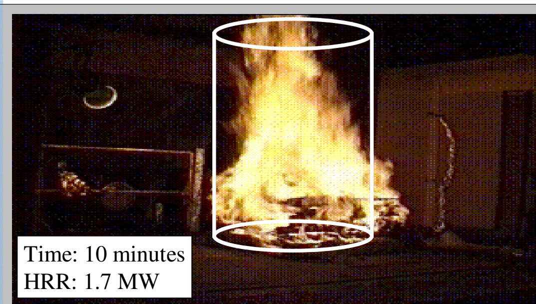
- Probable maximum heat transfer rate
- Likely area to be exposed
- Time required to bring to boil
- Time required to overheat unwetted metal

Heat Transfer

$$q_r'' = \sigma F_v F_e\left(T_f^{\,4} - T_o^{\,4}\right)$$

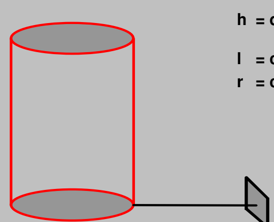
q_r'' = heat flux [kW/m^2]
σ = Stefan-Boltzmann constant
T_f = flame temperature [K]
F_v = view factor [unitless]
F_e = emissivity function [unitless]
T_o = object temperature [K]

Modeling Flame Geometry



View Factor

$$F = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left\{\left(\frac{X-2H}{H\sqrt{XY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right)\right\}$$



h = distance from the object to cylinder centerline
l = cylinder height
r = cylinder radius

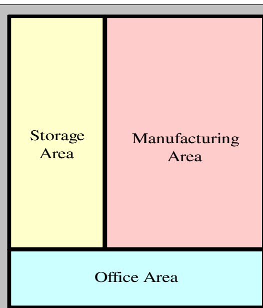
H = h/r
L = l/r
X = (1+H)^2+L^2
Y = (1-H)^2+L^2

Sample Problem

Required Separation in a Vault

Required Separation Problem

- Multi-use building
- Vault is in storage area
- Inventory
  - Foodpack-style welded cans
- Container size
  - height 0.3 m
  - diameter 0.2 m
- Failure criteria limit:
  - 15 MJ absorbed energy



What is Required Standoff?

- Exposure: Stack of pallets
  - Foot print: 1.49 m^2
  - Stack height: 0.5 m
  - Peak HRR: 1,850 kW
- Question
  - What is the required standoff between a stack of pallets and a foodpack can to prevent loss of containment?
- Start by assuming 0.5 meters is OK

Estimate the Heat Flux

$$q_r'' = \sigma F_v F_e \left(T_f^4 - T_o^4\right)$$

- Predict fire geometry
  - Effective diameter
  - Flame height
- Establish view factor
- Estimate flame temperature
- Work the math

Establish an Effective Diameter

- Foot print: 1.49 m^2

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4\left(1.49\ m^2\right)}{\pi}} = 1.38\ m$$

Flame geometry (NFPA 555)

For small fires, the flame can be modeled as cylinder

$$H = 0.235Q^{2/5} - 1.02D$$

H = Flame height (m)
Q = Heat release rate (kW)
D = Fire diameter (m)
E = Emissive power (kW/m^2)

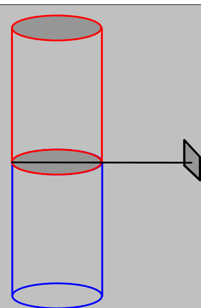
Estimate the Flame Height

- Diameter: 1.38 meters
- Peak HRR: 1,850 kW

$$H = 0.235\ \dot{Q}^{2/5} - 1.02\ D$$
$$= 0.235(1{,}850\ MW)^{2/5} - 1.02(1.38\ m)$$
$$= 3.4\ m$$

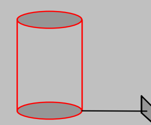
Calculate the View Factor

l = (3.4 m)/2 =1.7 m
r = (1.38 m)/2 = 0.69 m
h = 0.5 + 0.69 = 1.19 m
H = 1.72
L = 2.46
X = $(1+H)^2 + L^2$ = 13.5
Y = $(1-H)^2 + L^2$ = 6.57

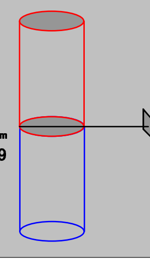


View Factor

$$F_{top} = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left\{\left(\frac{X-2H}{H\sqrt{XY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right)\right\}$$
$$= 0.29$$



$$F_{total} = F_{top} + F_{bottom} = 0.29 + 0.29 = 0.58$$



Estimate the Heat Flux

$$q_r'' = \sigma F_v F_e \left(T_f^{\,4} - T_o^{\,4}\right)$$
$$= \left(5.669E-11 \frac{kW}{m^2 \cdot K}\right)(0.58)(1.0)\left[(1{,}732\ K)^4 - (373\ K)^4\right]$$
$$= 300 \frac{kW}{m^2}$$

T_{flame}		Flux
K	°C	kW/m^2
1200	927	68
1486	1213	160
1732	1459	300

Estimate the Energy Transfer to the Can

- Container size
  - height 0.3 m
  - diameter 0.2 m
- Fire conditions
  - Incident heat flux: 300. kW/m^2
  - Duration: 12. minutes
- Container properties
  - failure criteria limit 15. MJ

Energy Transfer (con't)

Exposed container surface area:

$$A = (0.2\ m)(0.3\ m) = 0.06\ m^2$$

Energy absorbed:

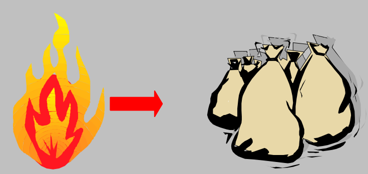
$$E = A\dot{q}''t = (0.06\ m^2)\left(300\frac{kW}{m^2}\right)(720\ s) = 13{,}000\ kJ = 13\ MJ$$

15 MJ > 13 MJ, thus no failure @ 0.5 meters

Vault Area Controls

- Container
  - Size: 0.3 by 0.2 meters
  - Energy absorption capability: 15 MJ
- Combustible loading limit
  - Fuel packages limited to 1,850 kW
  - If more than one package, credible combination must be less than 1,850 kW
- Standoff
  - Standoff from fuel packages to can is 0.5 meters

Secondary Ignition



Thresholds - Secondary Ignition

- Primary heat transfer modes
  - Radiation
  - Convection
- Complexities
  - Target surface finish
  - Target thermal mass
  - Ambient environment
  - Chemical kinetics
  - Exposure duration
- Tests for solids don't match real world

Thresholds - Ignition for Wood

	Spontaneous ignition	Piloted ignition
Radiation	600°C	300 – 410°C
Convection	490°C	450°C

Fire Temperatures

- Room Temperature
  - Range 300 to 1200 C
- Flame Temperatures
  - Small open pool fires (<1 meter) 900°C
  - Large open pool fires 1100 to 1200°C
  - Compartment fire ~1200°C
- Wood Ignition Temperature
  - Previous slide 300 to 600 C

Secondary Ignition Criterion

	Piloted Ignition		Spontaneous Ignition	
Material	T_{ig} (°C)	$\dot{q}''_{crit}$ & $\dot{q}''_{min}$ (kW/m^2)	T_{ig} (°C)	$\dot{q}''_{crit}$ & $\dot{q}''_{min}$ (kW/m^2)
Wood	180 - 497	6 - 20	192 - 730	20 - 53
Plastics	250 - 580	5 - 28	328 - 700	
Textiles	230 - 600	8 - 18	280 - 600	
Electrical cables		6 - 36	263	

Fire Heat Fluxes

- Practical range in fires:
  - 10 to 80 kW/m^2
- Range for ignition (previous slide)
  - 5 to 53 kW/m^2
- Cautions
  - Differentiate between net and gross flux
  - Computer codes often report net flux
  - Evaluation thresholds are usually gross heat flux

Flashover

- Consider as an instability, which occurs during a compartment fire, between the expanding phase and the fully developed phase.
- Accept that if flashover occurs, conditions are extreme.

Flashover Predictions

- Heat flux at the floor
  - Nominal value: 20 kW/m²
- Heat release rate
  - Smaller rooms: 1,000 kW (1,000 Btu/s)
- Temperature near the ceiling
  - Nominal value: 600°C
  - Typical values: 500 to 600°C
  - Extreme values: 300 to 650°C

Flashover (NFPA 555)

$$\dot{Q} = 7.8A_T + 378A_o\sqrt{H_o}$$

$\dot{Q}$ = critical heat release rate (kW)
A_T = room surface area (m^2)
A_o = opening area (m^2)
H_o = opening height (m)

T_{flash} is assumed to be 577°C

Sample Problem - Flashover

- Room Details
  - Door area, A_o = 1.9 m^2
  - Door height, H_o = 2.1 m
  - Surface area, A_T = 110 m^2 (5 m x 5 m x 3 m high)
- Heat Release Rate to cause flashover

$$\dot{Q} = 7.8A_T + 378A_o\sqrt{H_o}$$
$$= 7.8(110\ m^2) + 378(1.9\ m^2)\sqrt{2.1\ m}$$
$$= 1900\ kW$$

Sample Problem - Flashover

$$\dot{Q} = 7.8A_T + 378A_o\sqrt{H_o}$$
$$= 1900\ kW$$

Heat Release Rate for short pallet stack: 1850 kW

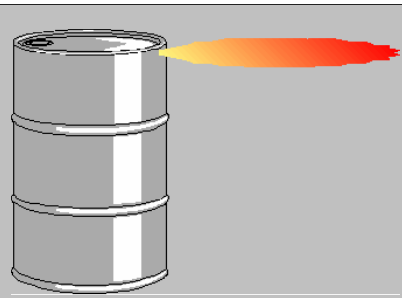
1850 kW < 1900 kW

- Conclusion 1: Flashover won't occur
- Conclusion 2: Results too close to call
- Analytical approach: Assume flashover occurs

Review

- Fuel Package Heat Release Rates
- Flashover Predictions
- Room Temperature Models

Container Response

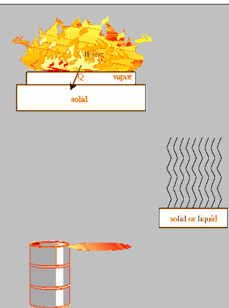


Container Failure Mechanisms

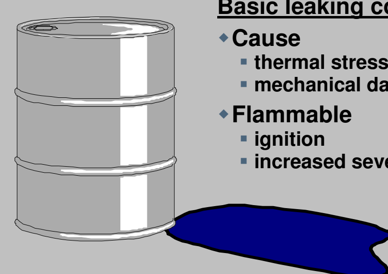
- Venting
  - Most likely in light duty containers
  - Gases, liquids or solids
- Spills
  - Liquids or solids
  - Melting
- Rapid releases (bursting)
  - More likely in sealed containers with moderate to significant strength

Venting

- Pyrolysis for solids
- Offgassing vapors
  - Model as vaporization
- Vapor jet
  - Requires pressure build-up
  - Backflash is possible



Spills



Basic leaking container

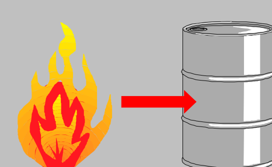
- Cause
  - thermal stresses
  - mechanical damage
- Flammable
  - ignition
  - increased severity

Rapid Releases

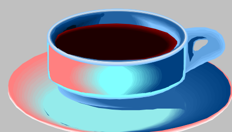
- Burst - Occurs for slow increase in pressure
- Explode
  - Deflagration
  - Detonation
  - BLEVE (Boiling Liquid Expanding Vapor Explosion)
    - Container fails rapidly
    - Liquid above flashpoint
    - Liquid flashes to vapor and ignites

Container Failure Discussion

- The major variables
  - Fire temperature
  - Fire duration
  - Container rating
    - pressure
    - temperature
    - weak points
- Other variables
  - Proximity of fire and container
  - Structural damage



Break?



Course Overview

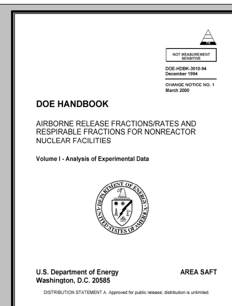
- Fire Severity
  - Fire metrics
  - Pool fires
  - Fuel package behavior
  - Fire compartments
- Material at Risk
- Damage Ratio
  - Fire heat flux
  - Sample problem
  - Flashover
  - Container response
- Airborne Release Fraction
- Respirable Fraction
- Leakpath Factor
- Dose Estimate
- Others topics
  - Fire hazard analyses
  - Fire barriers
  - Fire frequency
  - Soot analysis

Airborne Release Fraction & Respirable Fraction

How much gets lofted into the room?

How big are the released particles?

Source Reference



DOE-HDBK-3010-94
December 1994

CHANGE NOTICE NO. 1
March 2000

DOE HANDBOOK

AIRBORNE RELEASE FRACTIONS/RATES AND RESPIRABLE FRACTIONS FOR NONREACTOR NUCLEAR FACILITIES

Volume I - Analysis of Experimental Data

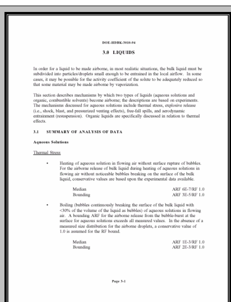
U.S. Department of Energy
Washington, D.C. 20585

AREA SAFT

1.0 Introduction
2.0 Materials in the Gaseous State
3.0 Liquids
4.0 Solids
5.0 Surface Contamination
6.0 Inadvertent Nuclear Criticality
7.0 Application Examples

The change notice only affected a single page (HEPA filters)

Typical Page



3.0 Liquids
- 3.1 Summary of Analysis of Data
- 3.2 Aqueous Solutions
- 3.3 Organic, Combustible Liquids

Typical Page Details

Aqueous Solutions

Thermal Stress

- Heating of aqueous solution in flowing air without surface rupture of bubbles. For the airborne release of bulk liquid during heating of aqueous solutions in flowing air without noticeable bubbles breaking on the surface of the bulk liquid, conservative values are based upon the experimental data available.

Median	ARF 6E-7/RF 1.0
Bounding	ARF 3E-5/RF 1.0

- Boiling (bubbles continuously breaking the surface of the bulk liquid with <30% of the volume of the liquid as bubbles) of aqueous solutions in flowing air. A bounding ARF for the airborne release from the bubble-burst at the surface for aqueous solutions exceeds all measured values. In the absence of a measured size distribution for the airborne droplets, a conservative value of 1.0 is assumed for the RF bound.

Median	ARF 1E-3/RF 1.0
Bounding	ARF 2E-3/RF 1.0

Interpretation for Aqueous Solutions

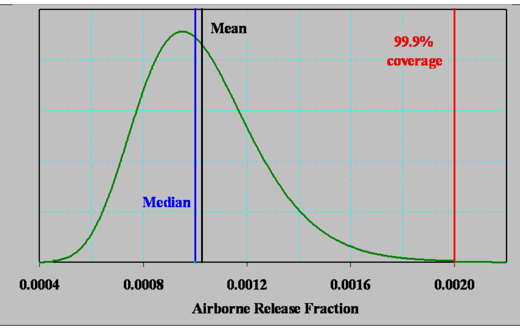
- **Heating in flowing air** (no bubbles break surface)

	ARF	RF
Median	6E-7	1.0
Bounding	3E-5	1.0

- **Vigorous boiling** (Void fraction < 0.3)

	ARF	RF
Median	1E-3	1.0
Bounding	2E-3	1.0

ARF for Vigorous Boiling



Benefits of Bounding Method

- The more detailed the model, the more controls that need to be supplied
  - Safety class items
  - TSR controls and specific administrative controls
- Detailed models make facility changes more difficult
- Uncertainty in inventories especially for waste containers make detailed analysis difficult

Release Fraction Considerations

- Material Form
  - Liquid
  - Solid
    - Powder
    - Metallic
    - Composites
  - Contaminated solids
- Accident progression
  - Container integrity
  - Building integrity
- Container type
  - Drum/steel boxes
  - Cardboard/wood boxes
  - Pressure vessels
- Stress Type
  - Thermal
  - Combustion
  - Spill
  - Entrainment
  - Blasts and Explosion
  - Vibration

Specific Topics

- Section 3, Liquids
  - Combustible
  - Non-combustibles
- Section 4, Solids
- Section 5, Surface Contamination
  - Combustible waste
  - Non-combustible solids
  - HEPAs
- Plutonium-Iron

Other Values for Liquids

- Covered in Section 3 of DOE-HDBK-3010
- Liquid Type
  - Aqueous solutions
  - Organic & combustible solvents
- Release mechanism
  - Boiling & heating
  - Venting under pressure
  - Spill
  - Combustion of flammable liquids
  - Aerodynamic Entrainment & Resuspension

Venting of Pressurized Liquid

	ARF	RF
◆ Failure under liquid surface	1E-4	1.0
◆ Failure above interface/total vessel failures		
▪ Below or at boiling point	ARF	RF
• Low pressure (<0.35 MPa, 50 psig)	5E-5	0.8
• High pressure (0.35 MPa to 3.45 MPa, 500 psig)		
– Aqueous solution	2E-3	1.0
– Concentrated heavy metal solution	1E-3	0.4
▪ Depressurization above boiling point		
– <50°C superheat	1E-2	0.6
– 50 to 100°C superheat	1E-1	0.7

bounding ARF & RF values

Spill of Liquids

◆ **Aqueous solutions** (density ~ 1.0 g/cm^3)

	ARF	RF
▪ Median	4E-5	0.7
▪ Bounding	2E-4	0.5

◆ **Heavy metal solutions** (density ~ 1.2 g/cm^3)

	ARF	RF
▪ Median	1E-6	0.3
▪ Bounding	2E-5	1.0

Combustion of Liquids

- Volatiles (i.e., iodine) ARF = 1.0 RF = 1.0
- Burning intensity
  - Quiescent burning ARF = 1E-2 RF = 1.0
  - Vigorous burning
- Burning surface
  - Above aqueous layer
  - Porous or absorbing surface
  - Heat absorbing surface (e.g., metal)

bounding ARF & RF values

Vigorous Combustion of Liquids

	ARF	RF
◆ Large pool over aqueous layer		
▪ Turbulence affects aqueous layer	3E-2	1.0
▪ Burn to complete dryness	1E-1	1.0
◆ Aqueous solution or air dried salts under gasoline fire		
▪ On porous surface	5E-3	0.4
▪ On heat conducting surface	2E-1	0.3

bounding ARF & RF values

Liquid Entrainment & Resuspension

◆ ARR - Airborne Release Rate

	ARR	RF
▪ Indoors		
• low airspeeds	4E-7/hr	1.0
• covered with debris	4E-8/hr	1.0
▪ Outdoors		
• large pool (windspeed < 30 mph)	4E-6/hr	1.0
• absorbed on soil (windspeed < 50 mph)	9E-5/hr	1.0

bounding ARF & RF values

Solids

- Covered in Section 4 of DOE-HDBK-3010
- Metals
- Nonmetallics and Composites
- Powders

Solids - Metals

	ARF	RF
Thermal stress - Plutonium		
Self sustained combustion	5E-4	0.5
Flowing metal during combustion	1E-2	1.0
Oxidation without ignition	3E-5	0.04
Thermal stress - Uranium		
Free-falling molten metal	1E-2	1.0
Oxidation (T > 500°C)	1E-3	1.0

bounding ARF & RF values

Solids - Nonmetalic or Composites

	ARF	RF
Thermal stress (e.g., concrete, cement)		
Tritium present (T < 200°C)	5E-1	1.0
Tritium present (T < 600 °C)	1.0	1.0
Suspendible powder	6E-3	0.01

bounding ARF & RF values

Solids - Powders

	ARF	RF
Thermal stress		
Non-reactive compounds	6E-3	0.01
PuF_4	1E-3	0.001
Other reactive compounds	1E-2	0.001
Venting		
< 0.17 MPa (25 psig)	5E-3	0.4
0.18 - 3.5 MPa (25 - 500 psig)	1E-1	0.7
Spill (fall 0.3 meters)	2E-3	0.3

bounding ARF & RF values

Powder Entrainment & Resuspension

	ARR	RF
Indoors		
low airspeeds	4E-5/hr	1.0
covered with debris	4E-6/hr	1.0
Outdoors		
road surface with vehicles	1E-2/pass	1.0

bounding ARF & RF values

Surface Contamination

- Covered in Section 5 of DOE-HDBK-3010
- Combustible solids
- Non-combustible solids
- HEPA filters

Contamination - Combustibles

	ARF	RF
Thermal stress		
Packaged mixed waste	5E-4	1.0
Uncontained cellulosics	1E-2	1.0
Uncontained polystyrene	1E-2	1.0
Other uncontained plastics	5E-2	1.0
Fall or impaction stress		
Unpackaged or lightly packaged	1E-3	1.0
Packaged in metal container	1E-3	1.0

bounding ARF & RF values

Contamination - Non Combustibles

	ARF	RF
Thermal stress	6E-3	0.01
Fall or impaction stress		
Non-brittle materials	1E-3	1.0
Brittle materials	(See Section 4.3.3)	

Contamination - HEPA Filters

	ARF	RF
Thermal stress	1E-4	1.0
Explosive stress		
momentary pressure pulse	2E-6	1.0
passage of high velocity air	1E-2	1.0
Fall or impaction stress		
Enclosed	5E-4	1.0
Unenclosed	1E-2	1.0

bounding ARF & RF values

Rev. Summary: DOE-HDBK-3010-94

- Section 5.4.1 - Deleted 1 paragraph on HEPA Filters subject to thermal stress
  - Filters OK for >825 °C for > 10 minutes
  - Efficiency OK for 500 °C for 45 minutes
  - Release rate very low < 400°C

Retained Information on HEPAs

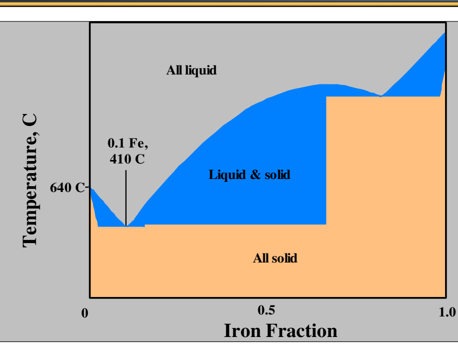
- No releases for < 150°C
- Limited releases for 175 to 190°C
- Bounding values
  - ARF 1E-4
  - RF 1.0

Contamination Entrainment/Resuspension

	ARR	RF
Combustibles		
low airspeeds	4E-5/hr	1.0
covered with debris	4E-6/hr	1.0
Non-combustibles		
low airspeeds	4E-5/hr	1.0
covered with debris	4E-6/hr	1.0

bounding ARF & RF values

Plutonium-Iron Interaction

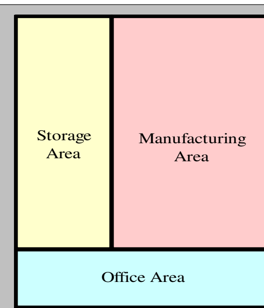


Sample Problem

Release Fraction

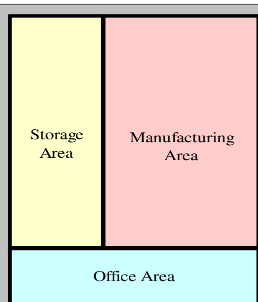
Release Fraction Problem

- Multi-use building
- Vault is in storage area
- Inventory
  - Foodpack-style welded cans
- Container size
  - height 0.3 m
  - diameter 0.2 m
- Failure criteria limit:
  - 15 MJ absorbed energy



Release Fraction Problem

- Multi-use building
  - Office
  - Manufacturing
  - Storage
- Inventory
  - Manufacturing
    - 10 kg Pu_{239}
    - 1 kg Pu_{238}
  - Storage
    - 1000 containers
    - 3 kg Pu_{239}/container



Damage Fraction & Release Mode

- Manufacturing
  - all containers released as loose powder
  - 10 kg Pu_{239}
  - 1 kg Pu_{238}
- Storage
  - 0.5 meter standoff
  - 1 can permitted within standoff region
  - single can fails by bursting
  - 3 kg Pu_{239}

ARF and RF Selection

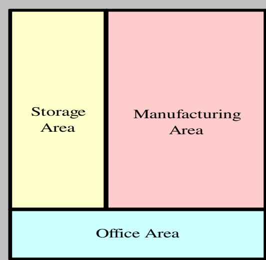
Release mode	ARF	RF
Manufacturing		
Thermal	6E-3	0.01
Spill	2E-3	0.3
Storage		
Burst container	1E-1	0.7
Resuspension (24 hours)	1E-3	1.0

Multiple Fire Area (con't)

Release mode	MAR (kg)	DS	ARF	RF	Release (kg)
Manufacturing area					
Thermal	11	1.0	6.00E-03	0.01	0.00066
Spill	11	0.5	2.00E-03	0.3	0.0033
Storage area					
Burst container	3000	0.001	1.00E-01	0.7	0.21
Resuspension					
(24 hours)	41	1.0	1.00E-03	1.0	0.04
					0.25

Release Estimate for Example

- Manufacturing
  - 0.00363 kg Pu_{239}
  - 0.00033 kg Pu_{238}
- Storage
  - 0.21 kg Pu_{239}
- Resuspension
  - 0.04 kg



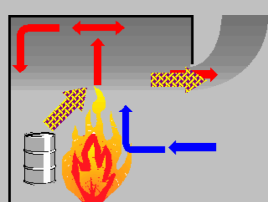
Leakpath Factor

What gets out of the building?

Overall Release Quantity Discussion

- Damage state
  - Fire temperature
  - Fire duration
  - Decay time/recovery
- ARF/RF
  - Material type & form
    - Liquid, solid or powder
    - Flammable/ noncombustible
  - Failure model

Leak path factor
- Filtration
- Deposition
- Conglomeration



HEPA Filter Effectiveness

	efficiency	LPF
Design requirement	99.97%	0.0003
Accident conditions (DOE-HDBK-1169-2003, Nuclear Air Cleaning Handbook)		
First stage	99.8	0.002
Subsequent stages	99.9 to 99.95	0.001
Composite value	99.99	0.0001

LPF Estimates

- Estimate number of air changes per hour
- Assume a normalized contaminate quantity
- Prepare a spread sheet to incrementally estimate the release
  - Calculate the leak quantity for the increment
  - Estimate the new concentration
  - Sum the leak quantities to estimate the LPF

LPF Estimates (con't)

- Calculate the leak quantity for the increment
- Estimate the new concentration
- Sum the leak quantities to estimate the LPF

$$L_k = C_k \frac{\dot{m}}{V_{room}} t_{increment}$$

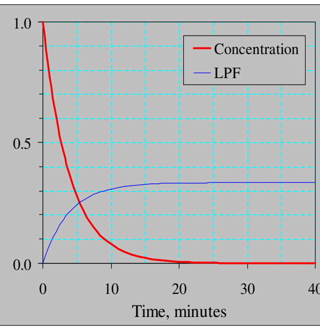
$$C_{k+1} = C_k - L_k$$

$$LPF_{k+1} = \sum_{i=1}^{k+1} L_i$$

	t	L	C	LPF
1	0	0.0000	1.0000	0.0000
2	10	0.0100	0.9900	0.0100
3	20	0.0099	0.9801	0.0199
4	30	0.0098	0.9703	0.0297
5	40	0.0097	0.9606	0.0394
6	50	0.0096	0.9510	0.0490

Leak Path Factor Example

- Room size
  - 1000 m³
- Ventilation flow
  - 10 changes/hr
  - HEPA filtered
  - LPF = 0.0001
- Door flow
  - 5 changes/hr
  - LPF = 1



Leak Path Factor Example

- Room size
  - 1000 m³
- Ventilation flow
  - 0 changes/hr
  - HEPA filtered
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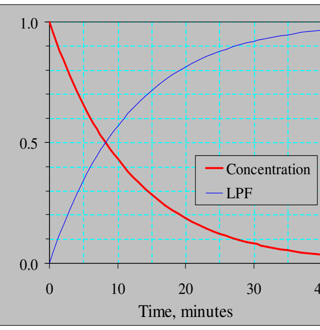

HEPA Filter LPF Considerations

- Ventilation system must operate
  - Filters must not plug (~27 kg wood/filter)
  - Fans must continue to run
    - Exhaust temperature limits
    - Power supply protection
- Doors must be closed
  - Building occupants evacuate
  - Fire department rescues trapped occupants
- Little redundancy in dampers

Sample Problem

Crediting Filtration

Source Term Estimate for Example

- Manufacturing
  - Assume unfiltered: LPF = 1.0
    - 0.0036 kg Pu_{239}
    - 0.00036 kg Pu_{238}
- Storage
  - Assume filtered: LPF = 0.0003

ST = MAR · DR · ARF · RF · LPF

ST = 3000 kg·0.001 ·0.1 ·0.7 ·0.0003 = 0.000063 kg

Dose Estimate

What is the effect of the release?

Contamination - Non Combustibles

	ARF	RF
◆ Thermal stress	6E-3	0.01
◆ Fall or impaction stress		
▪ Non-brittle materials	1E-3	1.0
▪ Brittle materials	(See Section 4.3.3)	

Contamination - HEPA Filters

	ARF	RF
◆ Thermal stress	1E-4	1.0
◆ Explosive stress		
▪ momentary pressure pulse	2E-6	1.0
▪ passage of high velocity air	1E-2	1.0
◆ Fall or impaction stress		
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bounding ARF & RF values

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	ARR	RF
◆ Combustibles		
▪ low airspeeds	4E-5/hr	1.0
▪ covered with debris	4E-6/hr	1.0
◆ Non-combustibles		
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bounding ARF & RF values

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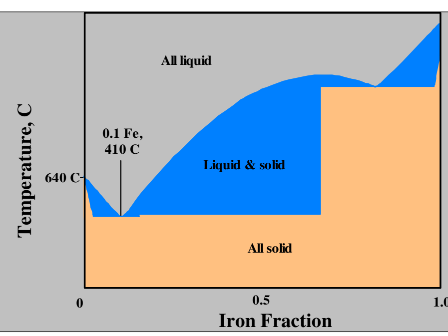

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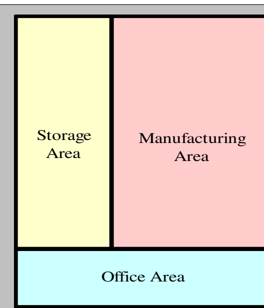

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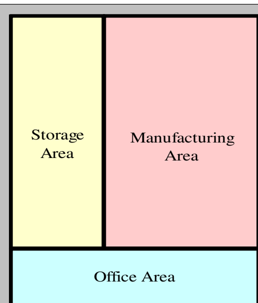

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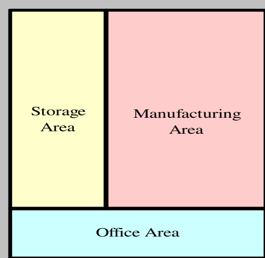
Resuspension (24 hours)	1E-3	1.0

Multiple Fire Area (con't)

Release mode	MAR (kg)	DS	ARF	RF	Release (kg)
Manufacturing area					
Thermal	11	1.0	6.00E-03	0.01	0.00066
Spill	11	0.5	2.00E-03	0.3	0.0033
Storage area					
Burst container	3000	0.001	1.00E-01	0.7	0.21
Resuspension					
(24 hours)	41	1.0	1.00E-03	1.0	0.04
					0.25

Release Estimate for Example

- Manufacturing
  - 0.00363 kg Pu_{239}
  - 0.00033 kg Pu_{238}
- Storage
  - 0.21 kg Pu_{239}
- Resuspension
  - 0.04 kg



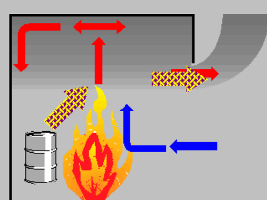
Leakpath Factor

What gets out of the building?

Overall Release Quantity Discussion

- Damage state
  - Fire temperature
  - Fire duration
  - Decay time/recovery
- ARF/RF
  - Material type & form
    - Liquid, solid or powder
    - Flammable/ noncombustible
  - Failure model

Leak path factor
- Filtration
- Deposition
- Conglomeration



HEPA Filter Effectiveness

	efficiency	LPF
Design requirement	99.97%	0.0003
Accident conditions (DOE-HDBK-1169-2003, Nuclear Air Cleaning Handbook)		
First stage	99.8	0.002
Subsequent stages	99.9 to 99.95	0.001
Composite value	99.99	0.0001

LPF Estimates

- Estimate number of air changes per hour
- Assume a normalized contaminate quantity
- Prepare a spread sheet to incrementally estimate the release
  - Calculate the leak quantity for the increment
  - Estimate the new concentration
  - Sum the leak quantities to estimate the LPF

LPF Estimates (con't)

- Calculate the leak quantity for the increment
- Estimate the new concentration
- Sum the leak quantities to estimate the LPF

$$L_k = C_k \frac{\dot{m}}{V_{room}} t_{increment}$$

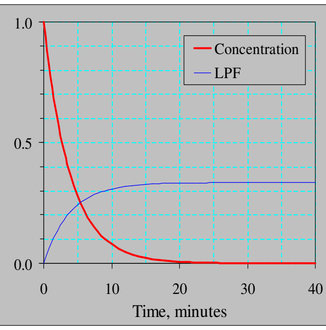
$$C_{k+1} = C_k - L_k$$

$$LPF_{k+1} = \sum_{i=1}^{k+1} L_i$$

	t	L	C	LPF
1	0	0.0000	1.0000	0.0000
2	10	0.0100	0.9900	0.0100
3	20	0.0099	0.9801	0.0199
4	30	0.0098	0.9703	0.0297
5	40	0.0097	0.9606	0.0394
6	50	0.0096	0.9510	0.0490

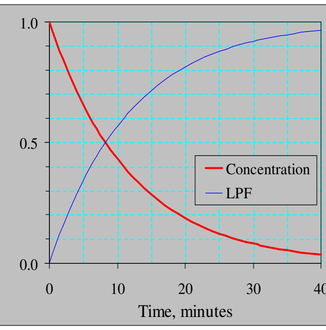
Leak Path Factor Example

- Room size
  - 1000 m^3
- Ventilation flow
  - 10 changes/hr
  - HEPA filtered
  - LPF = 0.0001
- Door flow
  - 5 changes/hr
  - LPF = 1



Leak Path Factor Example

- Room size
  - 1000 m^3
- Ventilation flow
  - 0 changes/hr
  - HEPA filtered
  - LPF = 0.0001
- Door flow
  - 5 changes/hr
  - LPF = 1



HEPA Filter LPF Considerations

- Ventilation system must operate
  - Filters must not plug (~27 kg wood/filter)
  - Fans must continue to run
    - Exhaust temperature limits
    - Power supply protection
- Doors must be closed
  - Building occupants evacuate
  - Fire department rescues trapped occupants
- Little redundancy in dampers

Sample Problem

Crediting Filtration

Source Term Estimate for Example

- Manufacturing
  - Assume unfiltered: LPF = 1.0
    - 0.0036 kg Pu_{239}
    - 0.00036 kg Pu_{238}
- Storage
  - Assume filtered: LPF = 0.0003

ST = MAR · DR · ARF · RF · LPF

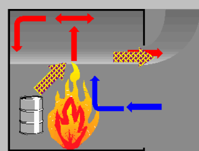
ST = 3000 kg·0.001 ·0.1 ·0.7 ·0.0003 = 0.000063 kg

Dose Estimate

What is the effect of the release?

Dose Estimates

- Atmospheric modeling effort (rem/gram)
- MELCOR Accident Consequence Code System (MACCS2)
  - Suggested assumptions
    - 20 minute release
    - No plume rise
  - Complications
    - Plume rise
    - Touchdown
    - Multiple plumes

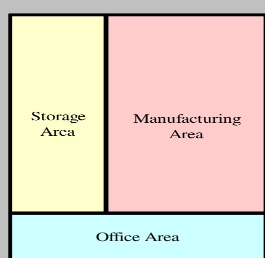


Sample Problem

Estimating the Facility Dose

Source Term Estimate for Example

- Manufacturing
  - 0.0036 kg Pu_{239}
  - 0.00036 kg Pu_{238}
- Storage
  - 0.000063 kg Pu_{239}
- Resuspension
  - 0.04 kg



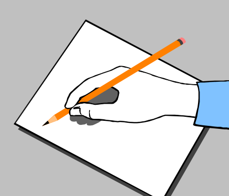
Example Closure

	MAR kg	ST kg	Ci/kg	rem/Ci	rem
Pu_{238}, power	1	3.6E-4	17100	0.261	1.6
Pu_{239}, power	10	3.6E-3	62.1	0.263	0.059
Pu_{239}, leak	3000	6.3E-5	62.1	0.263	0.001
					1.7

Remaining Time

- DSAs and FHAs – Confusion continues
- Fire Walls and Barriers
- Soot and Filters
- Fire Frequency
- Scaling HRR Curves

The DSA vs. the Fire Hazard Analysis



SARs and FHAs - Confusion continues

- Several things don't mix
  - Oil and water
  - Cats and dogs
  - DSAs and Fire Hazard Analyses (FHAs)
- Are the requirements incompatible?
- What are some of the misperceptions?
- How should they be coordinated?

Background Documents

- 10CFR830: Nuclear Safety Management
- 10 CFR851: Worker Safety and Health Program
- DOE Standard 3009-94: Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports
- DOE-HDBK-1163-2003: Integration of Multiple Hazard Analysis Requirements and Activities
- 420.1B: Facility Safety
- 440.1A: Worker Protection Management
- DOE G 440.1-8: Implementation Guide for use with 10 CFR Part 851 Worker Safety and Health Program
- DOE G 440.1-5: Implementation Guide for use with DOE Orders 420.1 and 440.1 Fire Safety Program

Required Protective Features

- Fire Protection controls and features can:
  - Reduce NS and fire risk
  - Reduce fire risk
- When a feature is not required for NS, but is for FP, the SAR and FHA are not necessarily inconsistent.

Basic Comparison

- DSA Purpose [10CFR830]
  - Identify and justify a set of hazard controls
  - Focus: environment, public and worker safety
- FHA Purpose
  - Identify the potential for fire loss
  - Justify the appropriate fire protection programs & systems
  - Focus: life, monetary & mission

DSA Preparation Steps

- Hazard identification - What hazards exist?
- Hazard analysis - How can a hazard effect the facility?
- Accident analysis - How bad can it get?
- Functional classification - What provides protection?
- Controls selection - What programs must exist?

FHA Preparation Steps

- Hazard identification
- Code compliance review
  - Demonstrate compliance with applicable codes & standards
  - Covers both engineered features and administrative programs

Codes & Standards Process

- Requirements are imposed based on the identified hazards
- Requirements are based on a process where:
  - Harm potential is identified - hazard analysis
  - Risk is evaluated - accident analysis
  - Engineered controls are identified - functional classification
  - Operating limits and program requirements are established - controls selection

When Results Conflict

- Just because the results conflict does not imply that DSA and FHA methodologies are incompatible
- Generic process considerations
  - Is generic analysis is applicable?
  - Generic controls are poor fit
  - Standard conduct of operations is not credited
- Was there any effort to coordinate the controls

Why More FHA Controls?

- DSA analyzed accidents
  - Very severe but low frequency
  - Bound consequence of other events
- FHA evaluates full spectrum of fire risk
  - Incipient fire frequency: 0.1 to 1/yr
  - Very severe fire frequency: 1.0E-6 to 1.0E-3/yr
  - Often overall fire risk is dominated by the high frequency fires
- Thus, FHA may require additional controls

Why More SAR Controls?

- Before DOE-STD-3009-94
  - Code compliance= adequately protected.
  - Thus, multi-room fires were Beyond Design Basis events & not analyzed.
- After DOE-STD-3009-94
  - Incredibility threshold become better defined (10^{-6}/yr for natural phenomena)
  - Multi-room fires in code compliant facilities are Extremely Unlikely (10^{-6}/yr to 10^{-4}yr per year) and sometimes higher.

Fire Walls and Barriers

Protecting by construction

Fire Wall Construction

- Fire wall
  - Structurally stable during fire (e.g., free standing)
  - Intended to survive fire
- Fire barrier wall
  - Very limited stability requirements
  - Intended to survive to allow building egress

[NFPA 221]

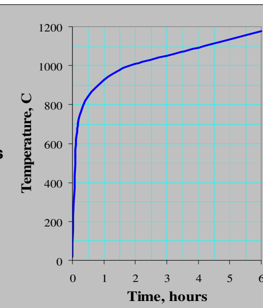
Fire Barriers and Separation

- Physical Space
  - Walls
  - Doors
  - Roofs
  - Floors
- Why put in
  - Occupancy protection (separate hazards)
  - Monetary and programmatic limitation
  - Risk Reduction

ASTM E 119 - "The Fire Curve"

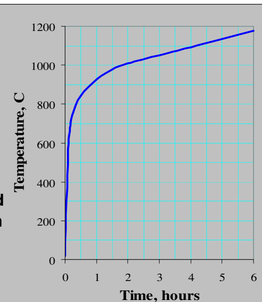
Fire Tests of Building Construction & Materials

- Defines furnace temperature during test
- Bounds the observed temperatures in Ingberg's tests
- Maximum temperatures
  - 1200°C at 6½ hours
  - 1260°C at 8 hours



Fire Ratings - What they mean

- Test Elements
  - Furnace temperature
  - Cold side temperature
  - Flame penetration
  - Hose stream test
- Failure criteria
  - $T_{cold\ side}$ < 139°C
  - Limited passage of flame and hot gases (can't ignite cotton waste)
  - Keep structural integrity



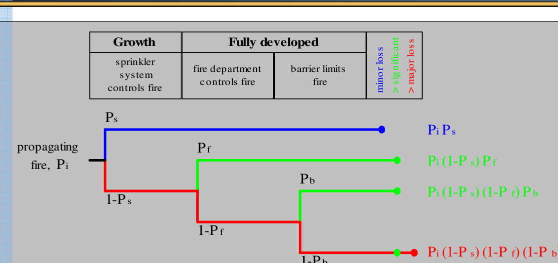
Test Results

- Results are presented in hours
- Rounded down to 0.5, 1, 2, 3, 4-hours, etc.
- Represent an equivalent fire severity (°C-hr)
- Does not imply survival for a specified duration

Fire Frequency

Fire Frequency

Fire Frequency

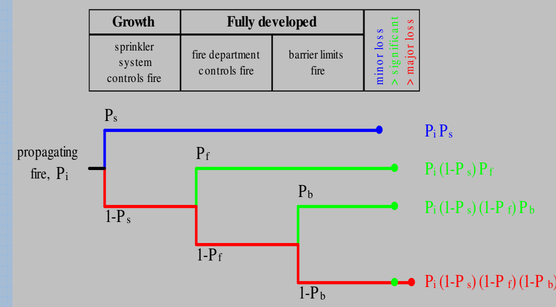


Incipient Fire Frequencies

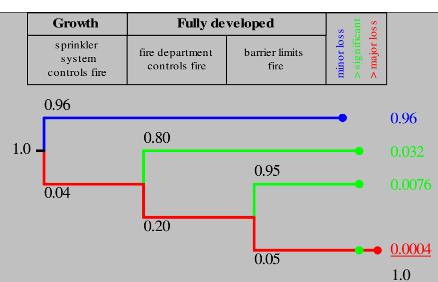
- Offices F = 1.0E-5 A
- General storage F = 3.3E-5 A
- Production and industrial facilities
  $F = 0.0017\ K\ A^{0.53}$
  - Low potential (vault storage, reactor operations) K = 0.8
  - Nominal potential (general industry, simple operations) 1.5
  - High potential (laboratories, material processing facilities) 3.0
- Other locations $F = 0.0027\ A^{0.52}$

where: F is fire frequency (fires/year) & A is the building area (m^2)

Severe Fire Probability Estimates



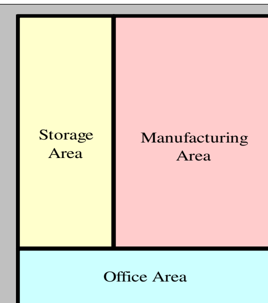
Event Tree with Numbers



$$F_{net} = F_i \cdot P_t = (0.005\ \text{fires/yr})(0.04) = 0.0002\ \text{severe fires/year}$$

Fire Risk Analysis for Building 323-Q

- Multi-use building
  - Office (20%)
  - Manufacturing (50%)
  - Storage (30%)
- Size
  - 120,000 m^2
  - 1,300,000 ft^2
- Fire Area Separation
  - 2 hours



Miscellaneous Details

- Construction
  - Concrete block w/ concrete panel roof.
  - Unprotected steel columns support the roof.
- Fire loads
  - Office 10 psf wood
  - Manufacturing 10 psf wood
  - Storage (very low) < 2.5 psf wood

Incipient Fire Frequency

- Production and industrial facilities
  - Building size 120,000 m^2
  - $F = 0.0017\ K\ A^{0.53}$ where K = 1.5
  - Incipient fire frequency 1.3 fire/year
- Split by area size
  - Storage 0.2 fires/year
  - Manufacturing 0.8
  - Office <u>0.3</u>

  1.3

Propagating Fire Frequency

Release mode	Fraction of area	Incipient frequency fires/yr	Propagation probability	Propagating fire frequency fires/yr
Office area	0.2	0.2	0.9	0.18
Manufacturing area	0.5	0.8	0.5	0.40
Storage area	0.3	0.3	0.05	0.015

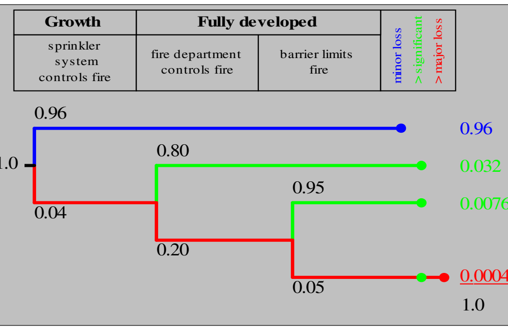
Credited Features

- Basic fire protection program
- Housekeeping program
- Limited combustibles in the vault

Conclusion

- A release resulting from a vault fire is anticipated
- The dose with no filtration would be 3.3 rem.

Severe Fire Probability



Frequency of Fire Exceeding 1.7 rem

Fire Path starts in	Fire Path goes to	Propagating fire frequency yr^{-1}	Probability severe fire with release	Frequency of fire with release yr^{-1}
office	manufacturing	0.18	0.0004	7.2E-5
manufacturing	manufacturing	0.40	0.008	3.2E-3
storage	manufacturing	0.015	0.0004	6.0E-6
				3.3E-3

What are the Credited Features?

Consequence

- Limited combustibles in the vault
- Container integrity (15 MJ absorbed energy)
- Standoff distance (~16") to limit vault release to 1 container
- Combustible fuel package PHRR in vault is limited to 1 MW
- Filtration and containment of vault release

Frequency

- Basic fire protection program
- SRS generic housekeeping program
- Limited combustibles in the vault
- Sprinkler system
- Fire Department
- Fire barriers
- Overall combustible loading

Soot and Filters

Soot Analysis Methodology

Soot Analysis Methodology

- Predict the Soot Demand
  - Establish the soot yield fraction for the material present (kg-soot per kg-fuel pyrolized)
  - Calculate the soot demand (product of soot fraction & combustible loading)
- Predict the System Capacity
  - Establish a specific HEPA filter soot capacity (kg-soot/filter)
  - Estimate the HEPA filter capacity for number of filters present (kg-soot)
- Is demand < capacity?
- Try and keep it simple

Smoke Yields for Flaming Combustion in Air

	Butler & Mulholland Table 1	Butler & Mulholland Table 2	Minimum	Maximum
Asphalt	...	0.14	0.14	0.14
Flexible polyurethane (PU) foam	0.131–0.227	0.034	0.034	0.227
Nylon	0.075	...	0.075	0.075
Polycarbonate (PC)	0.112	...	0.112	0.112
Polyester (PET)	0.089–0.091	...	0.089	0.091
Polyethylene (PE)	0.06	0.015–0.018	0.06	0.06
Polymethylmethacrylate (PMMA)	0.022	0.042	0.022	0.022
Polypropylene (PP)	0.059	0.041	0.059	0.059
Polystyrene (PS)	0.164	0.105–0.185	0.164	0.164
Polyvinylchloride (PVC)	0.172	...	0.172	0.172
Rigid polyurethane (PU) foam	0.104–0.130	0.012	0.012	0.13
Teflon (PTFE)	0.003	...	0.003	0.003
Wood (birch)	...	0.0035-0.053	0.0035	0.053
Wood (douglas fir)	...	0.0009-0.035	0.0009	0.035
Wood (red oak)	0.015	...	0.015	0.015
			0.0009	0.227

Fire Chemistry

- Complete combustion - theory

  $C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$

- Flaming combustion – empirically observed

  $C_2H_4 + 2.848O_2 = 1.836CO_2 + 2H_2O + 0.024CO + 0.06C$ (Soot)

- Ventilation-limited combustion

  $C_2H_4 + aO_2 = bCO_2 + cH_2O + dCO + eC + \text{other stuff}$ (Soot & tars)

Soot Yield Fraction (Design Value)

- Range for flaming combustion: 0.0009 to 0.227
- Increases in ventilation-controlled combustion
- Limited data on mixtures
- Analysis approach
  - Establish a single blended value for all materials
  - Select value representative of most likely fire (i.e., ventilation-limited)
  - Select value representative of most demanding fire (i.e., ventilation-limited)
  - Use more demanding of two values
- Range of reasonable values: 0.1 to 0.3 (kg/kg burned)

Soot Demand Value

Fire load (400 ft^2)			Soot produced (kg)		
psf	pounds	kg	0.1	0.2	0.3
0.5	200	91	9	18	27
2.5	1000	454	45	91	136
5	2000	907	91	181	272
10	4000	1814	181	363	544

Published Soot Capacity of HEPA Filters

	Low value (grams)	High value (grams)
Clemson Tests (filter train)	570	740
Alvares, Beason, Bergman, Ford, and Lipska	106	574
Gaskill and Magee (heated - small scale)	65	630
Fenton, Bunaji, Tang, and Martin	186	1256
Gregory, Martin, Smith, and Fenton (stearic acid with water)	500	8000

Filter Soot Capacity (Clean Design Value)

$$S_{plug}\Big|_{new} = N\, s_{filter} = (6\ \text{filters})\left(0.5\,\frac{\text{kg-soot}}{\text{filter}}\right) = 3\ \text{kg}$$

where:

- S_{plug} Soot necessary to plug a CSSC filter bank when the filters are new [kg]
- N Nominal face area of filter bank [number of filters]
- s_{filter} Soot necessary to plug a standard 2 foot x 2 foot filter [kg]

Comparison of Demand & Capacity (3 kg soot)

Fire load (400 ft²)			Soot produced (kg)		
psf	pounds	kg	0.1	0.2	0.3
0.5	200	91	? 9	18	27
2.5	1000	454	45	91	136
5	2000	907	91	181	272
10	4000	1814	181	363	544

Burn Quantity to Cause Pluggage

$$m_{burn} = \frac{N\, s_{filter}}{f_{soot}} = \frac{(6\ \text{filters})\left(0.5\,\frac{\text{kg-soot}}{\text{filter}}\right)}{0.2\,\frac{\text{kg-soot}}{\text{kg-burned}}} = 15\ \text{kg}$$

where:
- m_{burn} Mass burned to plug filters [kg]
- N Nominal face area of a CSSC filter bank [number of filters]
- s_{filter} Soot necessary to plug a standard 2 foot x 2 foot filter [kg]
- f_{soot} Soot fraction

Course Overview

- Fire Severity
  - Fire metrics
  - Pool fires
  - Fuel package behavior
  - Fire compartments
- Material at Risk
- Damage Ratio
  - Fire heat flux
  - Flashover
  - Container response
- Airborne Release Fraction
- Respirable Fraction
- Leakpath Factor
- Dose Estimate
- Others topics
  - Fire hazard analyses
  - Soot analysis
  - Fire barriers
  - Fire frequency
  - Scaling HRR curves

Closure