Methodology for Assessing Fire Hazards to HEPA Filters from Embers in Nuclear Facilities

by

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30th Nuclear Air Cleaning Conference
August 25-27, 2008 Bellevue, WA

Overview

- No guidance was found in the literature for assessing fire hazards to HEPA filters from embers within buildings or for assessing the effectiveness of mitigating equipment like fire screens or spark arrestors.

- A methodology was developed for assessing fire hazards based on the following steps:
  1. Determine the ember transport time from the fire to the HEPA filters
  2. Determine the critical ember size having a “burn time” that equals the “transport time” using combustion studies of burn time v ember size
  3. Determine the Leak Path Factor for the critical ember size along the transport path. If LPF<10-6, then no hazard exits.

Overview Continued

- If an ember hazard exists then fire screens or spark arrestors are generally used.

- A methodology is developed for assessing the mitigative performance of ember screens/arrestors
  1. Compute the largest ember that penetrates the screens/arrestors
  2. Compute the burn time of this ember
  3. Compute the transport time of the ember to the HEPA filter. If the burn time is less than the transport time, no hazard exits.

- Both methodologies assume any size ember can ignite deposits on a HEPA filter. Further analysis is required to include the threshold energy (size, temperature) of the ember required to ignite the HEPA filter.

No guidance was found for determining fire hazards

- Literature search did not result in any papers that describe a methodology for determining fire hazards against embers or for determining the performance of spark arrestors or ember screens.

- DOE-STD-1066 is a prescriptive standard and provides no guidance for determining the performance of ember screens.

Methodology for determining the fire hazard from embers

The hazard analysis consists of the following steps:

1. Determine the ember transport time to the HEPA filter
2. Determine the critical ember size having a "burn time" that equals the "transport time" from particle combustion studies of burn time v ember size.
   - Smaller ember sizes burn up prior to reaching the HEPA filters.
   - Larger ember sizes are easier to settle out along the path.
3. Determine the Leak Path Factor (LPF) for the critical ember size. LPF is the fraction of embers, having the critical size, that complete (e.g., don't settle out) the defined transport path. If the LPF > 10^{-6}, then an ember hazard exists.

Methodology for Ember Hazard- (1) Determining transport time

The ember transport time along each path was calculated based on the length of each path and based on the velocity along each path.

$$\text{Ember transport time} = \Sigma\,(\text{time})_i = \Sigma[(\text{distance})_i/(\text{velocity})_i]$$

$$\text{velocity} = \text{total flow/area}$$

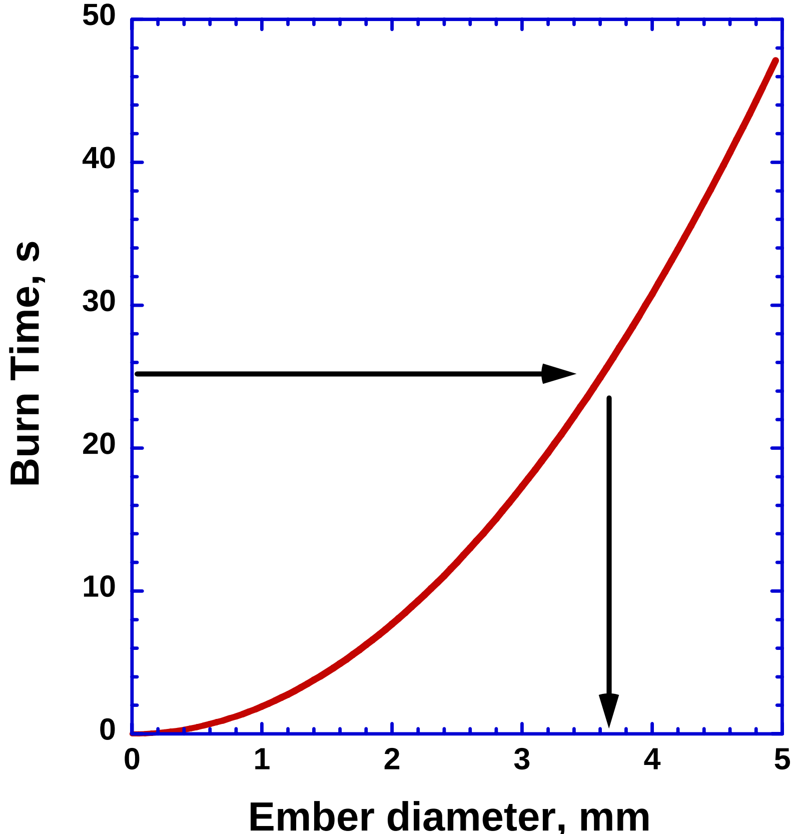
For ember transport in ducts, the duct length and air velocity was used.

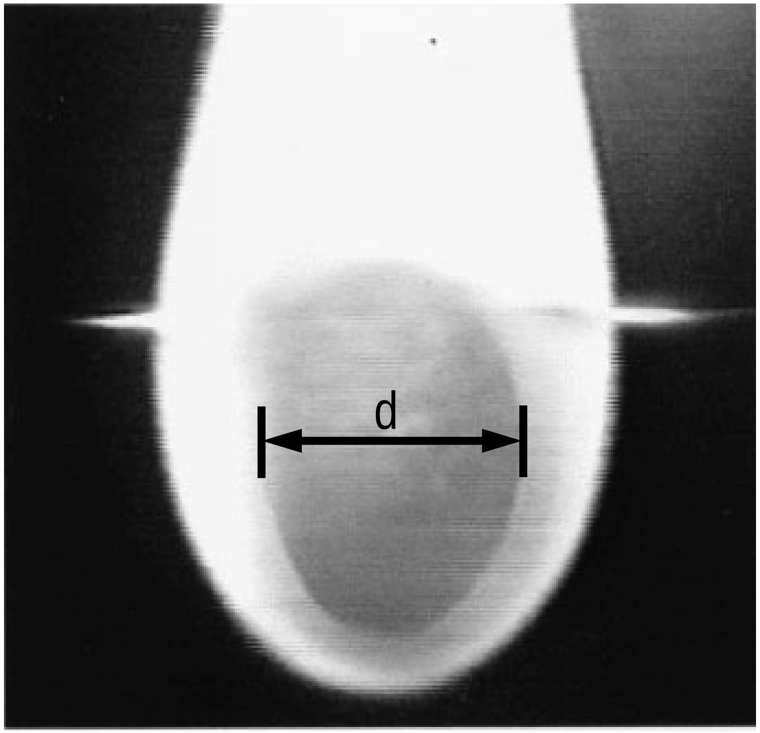
For ember transport in a room, the air velocity was estimated from the vector sum of the air flows along the path and the approximate area of the flow dispersion.

Methodology for Ember Hazard- (2) Determining the burn time

The critical ember size having a "burn time" equal to the transport time was determined.

- "Smaller" embers tend to burn-up prior to completing the path.
- "Larger" embers tend to settle-out along the path.





Polymethyl Methacrylate (PMMA) Ember

Methodology for Ember Hazard- (2) Determining the burn time

A spherical shaped ember was used to calculate burn time because it takes longer to burn-out compared to other shaped embers.

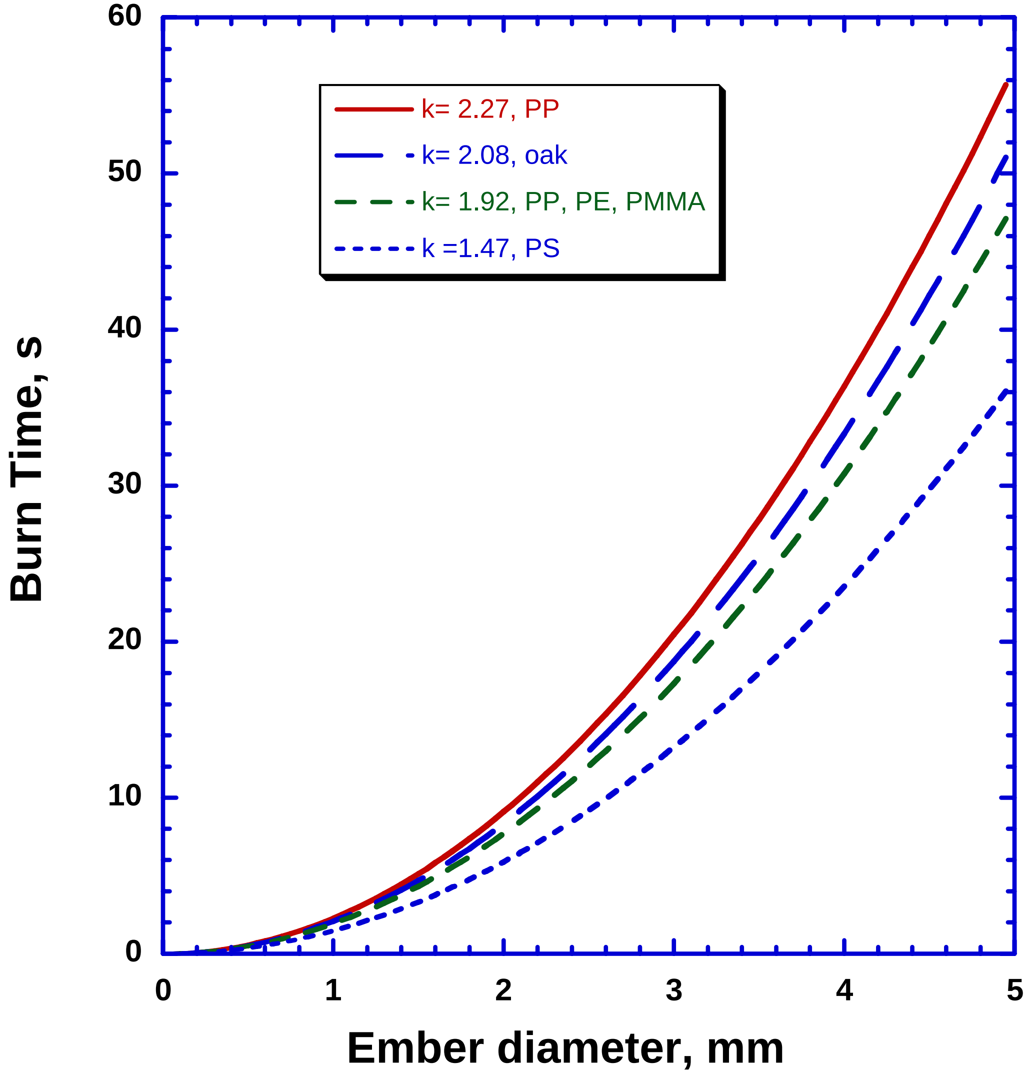
Burn time varies with materials

$$t_b = k\, d^2$$

t_b = burn time, s

d = ember diameter, mm

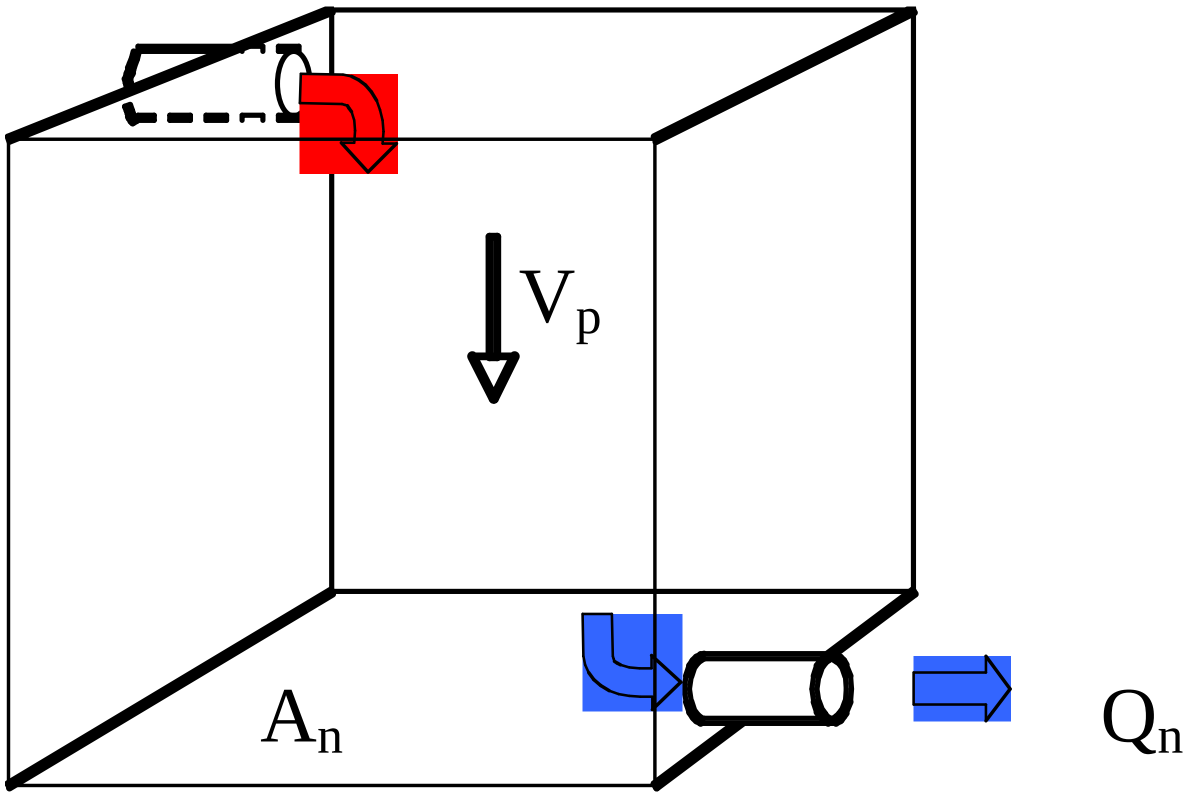
k = constant



Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

$$LPF_n = \frac{1}{m_n\,[(1+V_p/(Q_n/A_n)]} = \text{Leak Path Factor for Rooms}$$

V_p = settling velocity
Q_n = flow rate
A_n = floor area



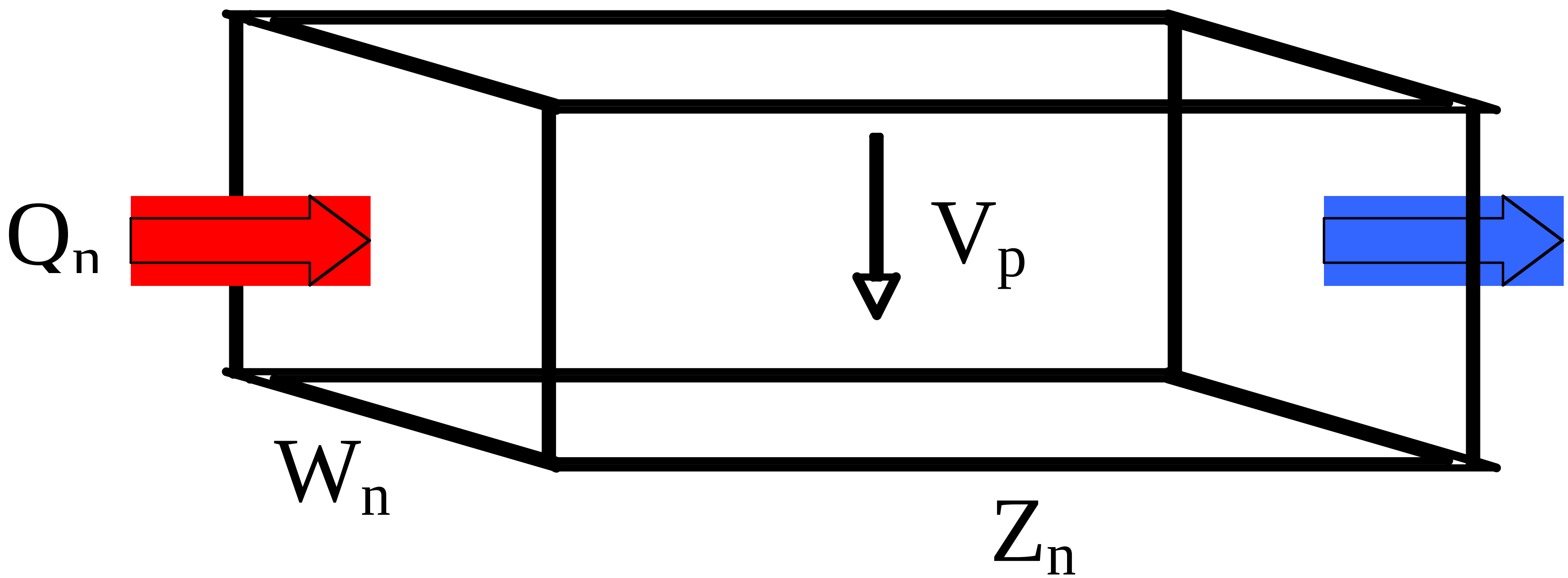
Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

$$LPF_n = e^{-\frac{W_n Z_n V_p}{Q_n}} = \text{Leak Path Factor for Ducts}$$

V_p = settling velocity

Q_n = flow rate

$W_n Z_n$ = floor area



Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

The ember settling velocity is used to determine the Leak Path Factor (LPF). Larger settling velocities yield smaller LPF.

$$V_P = \left(\frac{4\ \rho_p\ d_s\ g}{3\ C_n\ \rho} \right)^{1/2} \left(\frac{3}{2} E \right)^{1/3}$$

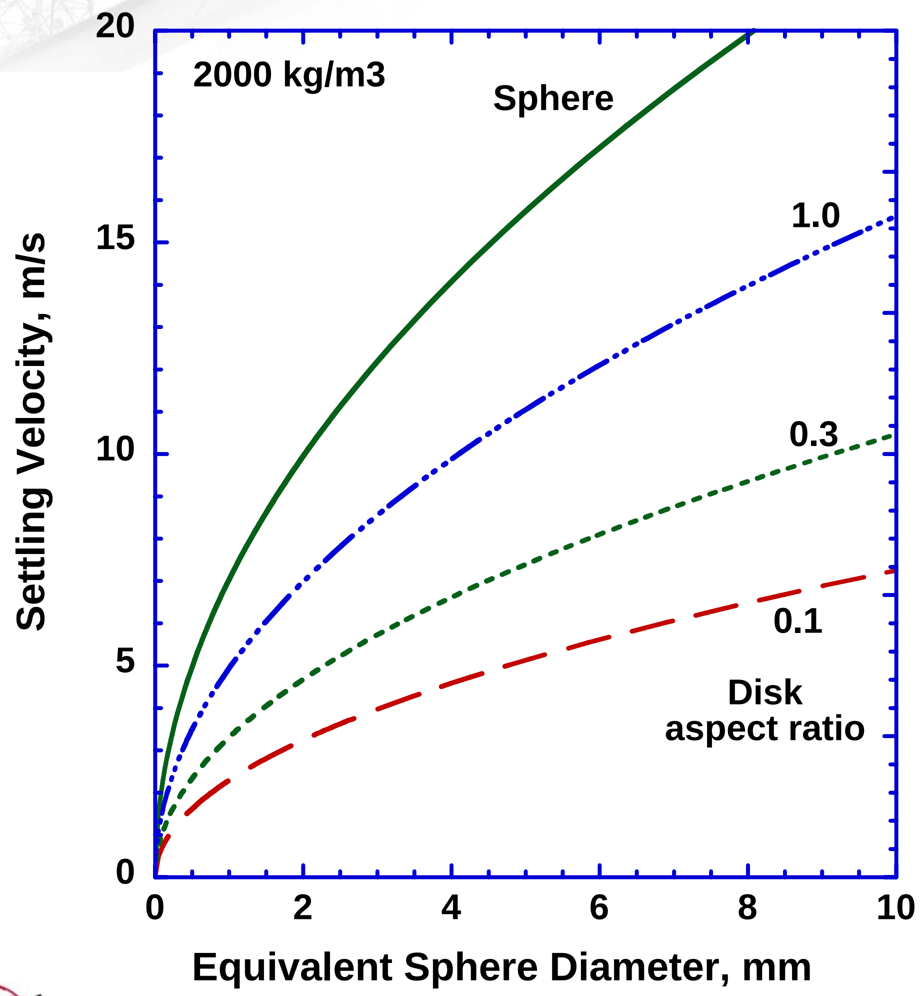
$$V_P = \text{Settling Velocity for Disc Shaped Embers, (m/sec)}$$

$$E = 1 \text{ for spheres}$$

ρ_p = Ember Density, kg/m^3
d_s = Ember Equivalent Sphere Diameter, m
g = Gravity Acceleration, 9.81 m/sec^2
C_n = Coefficient of Drag on Disc = 1.17
ρ = Air Density, 1.2 kg/m^3
E = Disk Aspect Ratio = h/D (Assumed E = 0.1)
h = Disc Thickness
D = Disc Diameter

Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

Assuming embers are discs yield much lower settling velocities and consequently larger LPF.



E = Disc Aspect Ratio
E = h / D
h = Disc Thickness
D = Disc Diameter

20 m/sec = 65.6 feet/sec
15 m/sec = 49.2 feet/sec
10 m/sec = 32.8 feet/sec
5 m/sec = 16.4 feet/sec

Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

At high velocities particles are kept in suspension and do not settle out, and LPF = 1. The critical velocity is called the pick-up velocity.

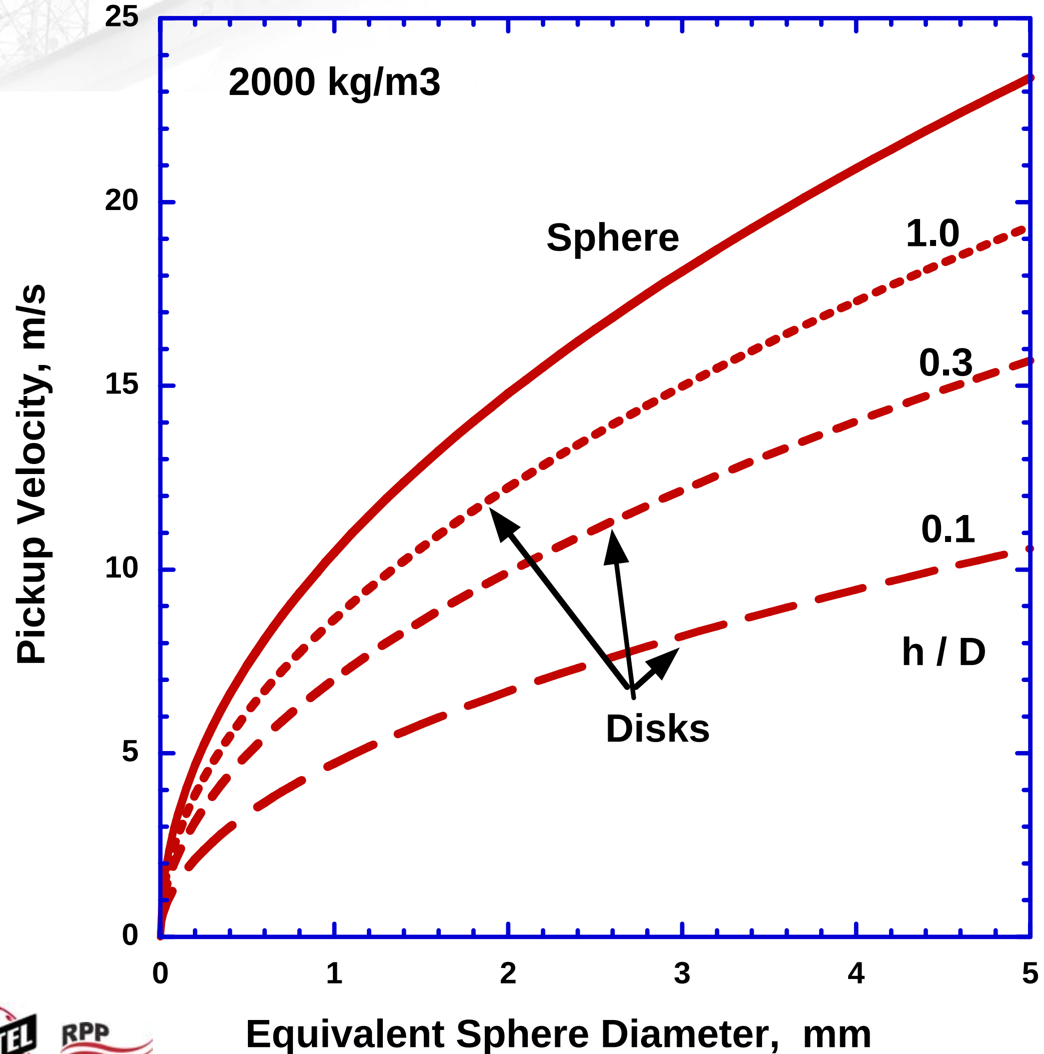
$$U_{pu} = 1.65 \left(d_s \, \rho_p \right)^{1/2} e^{[1.97 (E)^{2/3} / (0.5 + E)]}$$

$$d_s = D \left(\frac{3}{2} E \right)^{1/3}$$

U_{pu} = Minimum Pickup Air Velocity, m/sec
d_s = Ember Equivalent Sphere Diameter, m
ρ_p = Ember Density, kg/m^3
E = Disk Aspect Ratio = h/D (Assumed = 0.1)
h = Thickness of Disk, m
D = Diameter of Disk, m

Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

Disc shaped embers are easier to pick-up (lower pickup velocities) compared to spherical shaped embers and will yield larger LPF than spheres of the same equivalent size.



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20 m/sec = 65.6 feet/sec
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Methodology for Ember Hazard- (3) Determining the LPF for critical ember size

Compute the total Leak Path Factor for the selected path including rooms and ducts using the calculated LPF for each path segment.

$$LPF_{Parallel\ Path} = \sum_i f_i LPF_i = f_1 LPF_1 + f_2 LPF_2 + \ldots\ f_n LPF_n$$

$$LPF_{Series\ Path} = \prod_i LPF_i = LPF_1\ x\ LPF_2\ x\ \ldots\ LPF_n$$

If the Leak Path Factor is greater than 10^{-6}, then:

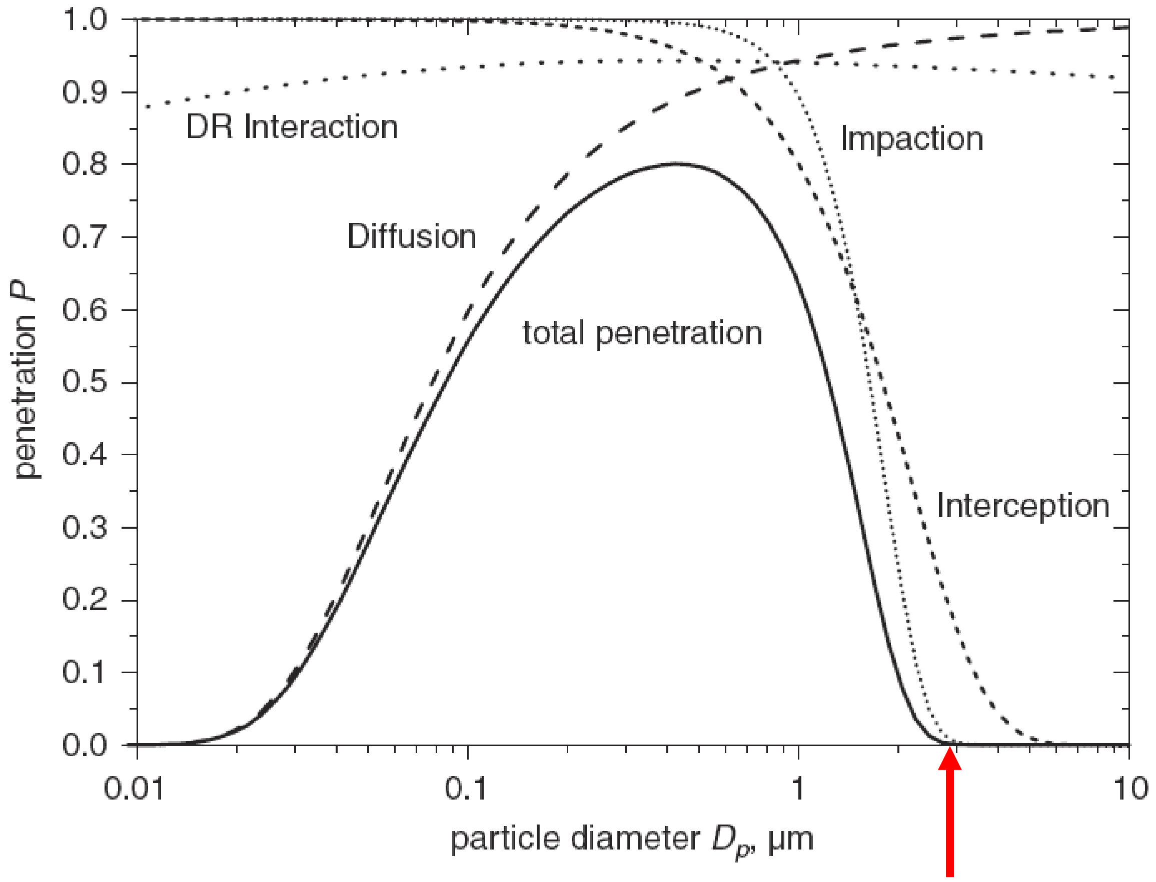
- The ember does not settle out
- The ember hazard exists
- Counter measures like fire screens or spark arrestors are needed

Methodology for assessing hazard mitigation for ember screens and spark arrestors

1. Compute the largest ember that penetrates the screens/arrestors
   – Treat the ember screen and spark arrestor as a particle removal device and determine the particle penetration theoretically or empirically as a function of particle size and density.
2. Compute the burn time of this ember (described before)
   – Determine the burn time of the largest particle that penetrates the ember screen or spark arrestor using empirical burn data or theory such as burning droplet model.
3. Compute the transport time for the ember from the ember screen or spark arrestor to the nearest HEPA filter (described before)
   – If the burn time is shorter than the transit time, then the ember screen or spark arrestor is properly designed. If not, then the ember screen or spark arrestor must be redesigned.

Methodology for hazard mitigation: (1) determine the largest ember size

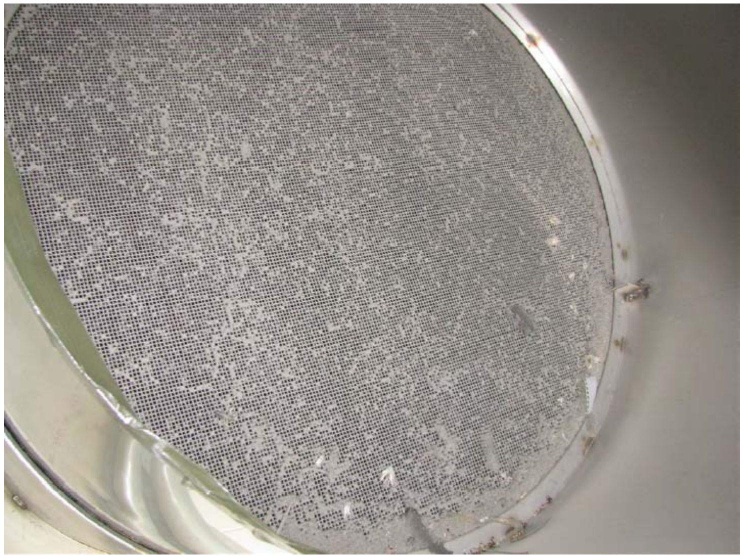
All porous material including screens have a characteristic particle removal or penetration curve.

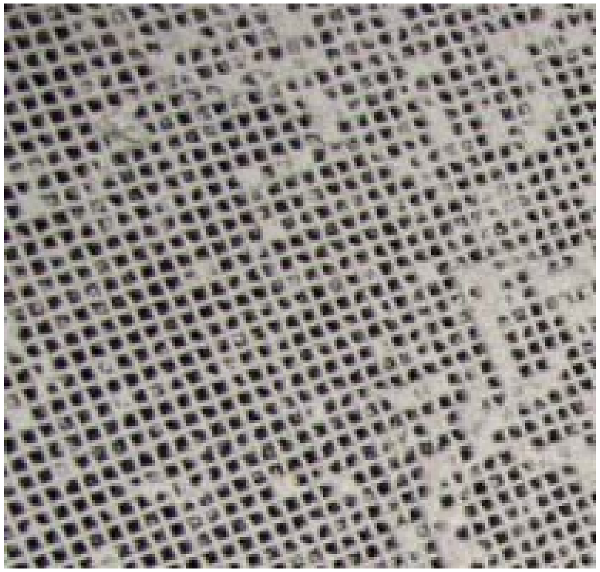


Maximum Ember Size

Methodology for hazard mitigation: (1) determine the largest ember size for screens

Example of fire screen installed in ventilation system for several years



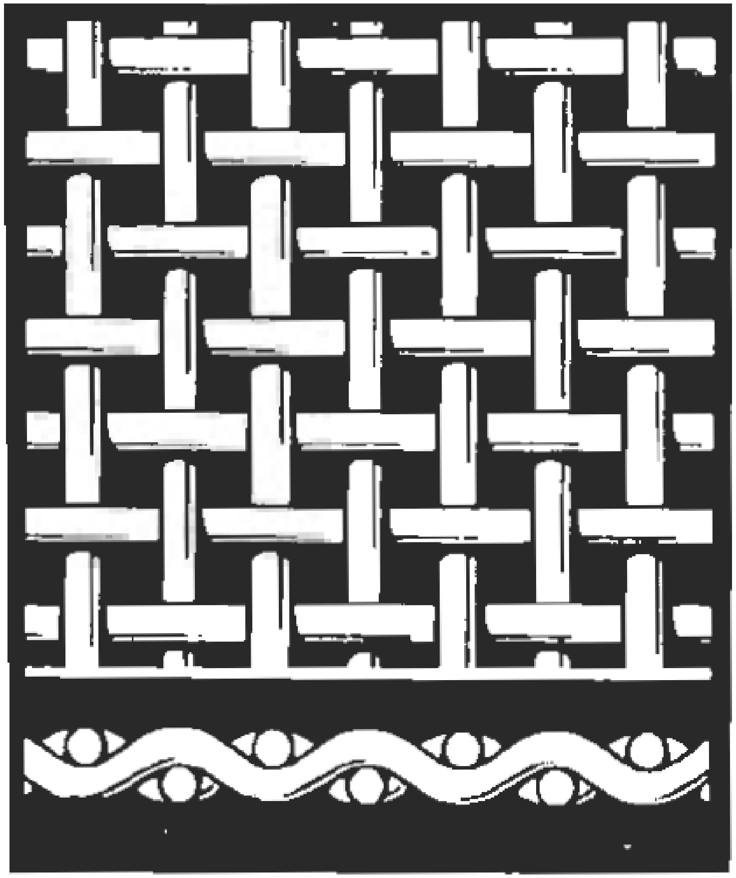


Methodology for hazard mitigation: (1) determine the largest ember size for screens

For ember screens with 8 to 16 openings per inch (mesh), the maximum particle size is determined from the opening dimensions

Screen parameters

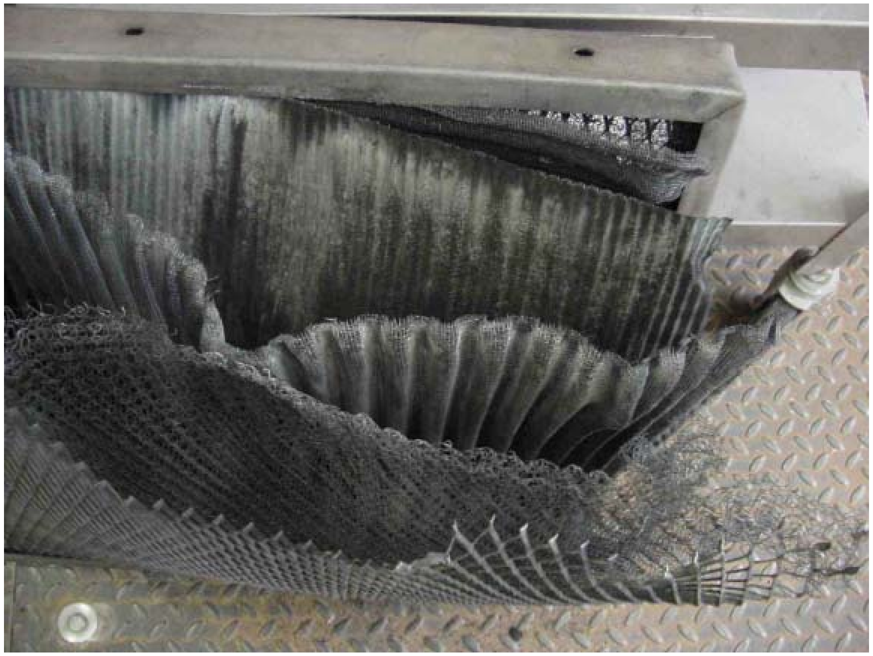
Mesh	Wire dia (In.)	Max.Particle Size (mm)
8	0.028	2.5
16	0.025	1.0



Methodology for hazard mitigation: (1) determine the largest ember size for spark arrestors

The potential spark arrestors are filters made from multiple layers of steel fiber mats and screens. The unit pictured here is used in the MOX facility.

Disassembled filter after fire test

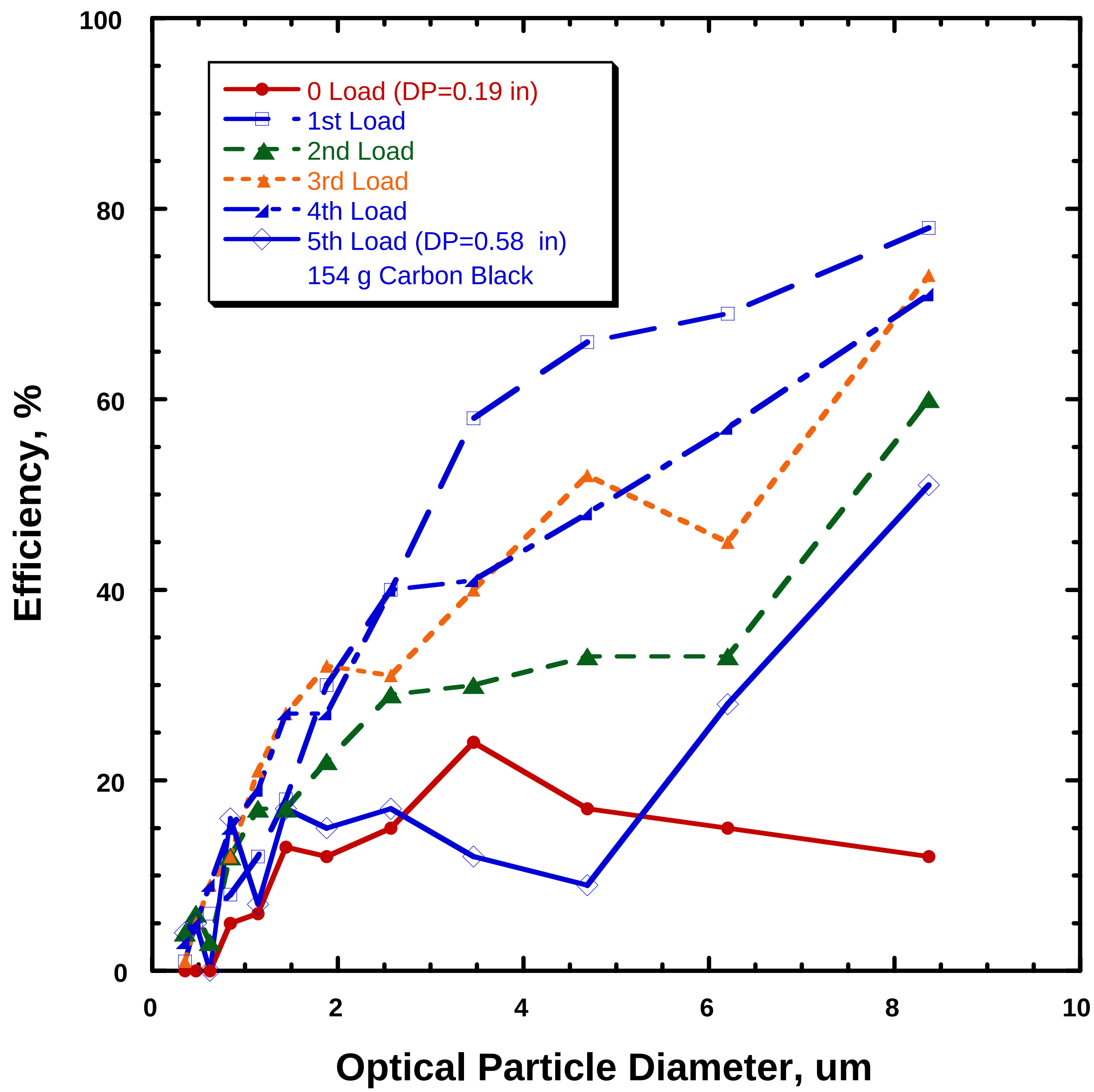


Clean rear side of filter

Methodology for hazard mitigation: (1) determine the largest ember size for spark arrestors

Efficiency test results using a modified ASHRAE 52.2 test in which carbon black was used for filter loading rather than ASHRAE dust.

Maximum particle size could not be established with ASHRAE 52.2 test.



Methodology for hazard mitigation: (1) determine the largest ember size for spark arrestors

Potential methods for determining maximum ember size

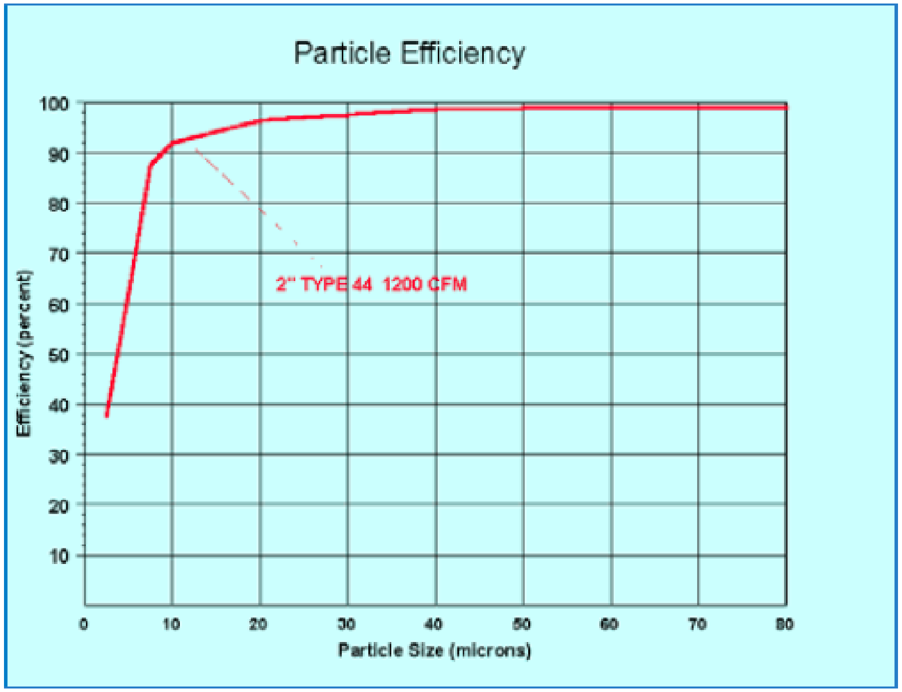
- For spark arrestors consisting of multiple screen layers, disassemble the filter and physically measure the openings

- For any spark arrestor consisting of random mat of steel fibers, the maximum physical opening can be computed based on fiber-fiber spacing.

- Experimental measurements of penetration for particles larger than 10 microns are not well established.

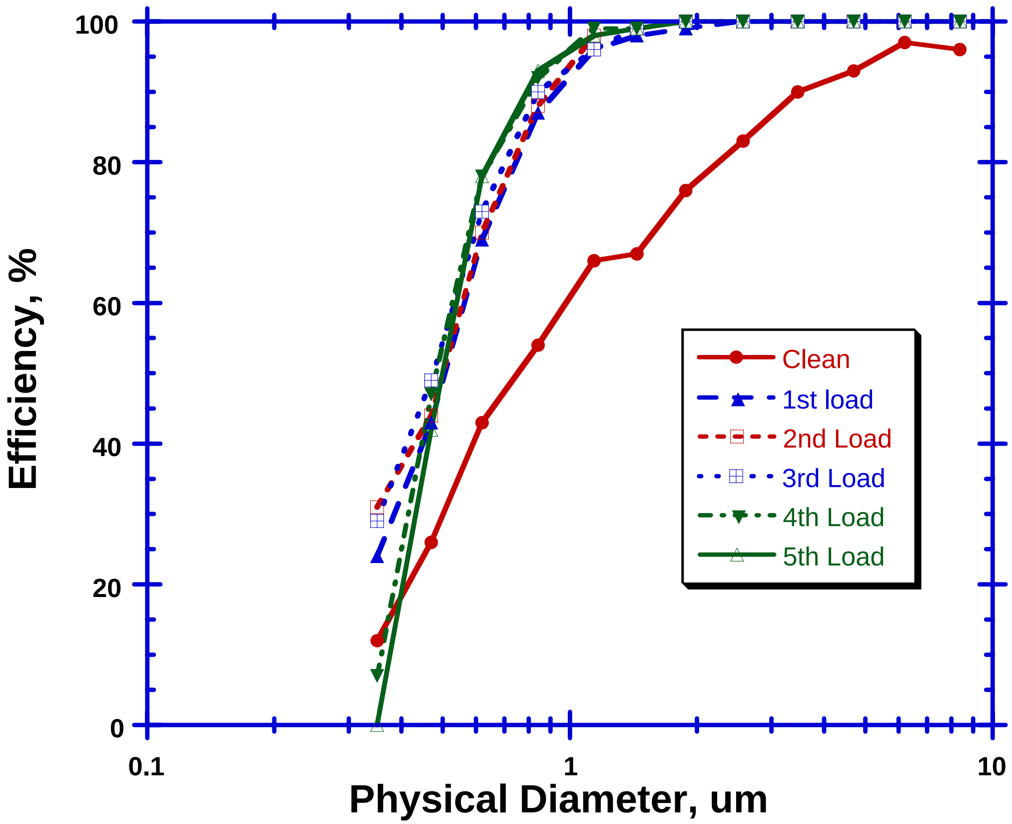
Other potential spark arrestors

Camfil Farr Type 44 Filter



Other potential spark arrestors

Layers of steel/glass fibers provide higher efficiency, high strength and fire/temperature resistance.



Conclusion

- No guidance was found in the literature for assessing fire hazards to HEPA filters from embers within buildings or for assessing the effectiveness of mitigating equipment like fire screens or spark arrestors.
- A methodology was developed for assessing fire hazards for embers based on determining (1) the ember transport time from the fire to the HEPA filters (2) the critical ember size having a “burn time” that equals the “transport time” and (3) the Leak Path Factor for the critical ember size along the transport path. If LPF<10-6, then no hazard exits.
- A methodology was developed for assessing the performance of ember screens/arrestors by (1) computing the largest particle that penetrates the screens/arrestors, (2) computing the burn time of this ember and (3) comparing the burn time to the transit time.
- Both methodologies assume any size ember can ignite deposits on a HEPA filter.