Soot Mitigation Strategies

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Abstract

- The Confinement Ventilation System (CVS) in facilities that house nuclear operations is relied upon to maintain a negative pressure within the various zones of the Confinement Building.
- The HEPA filters in the CVS are the last line of defense to contain the release of radioactive particulate.
- Soot generated during a fire event may build-up and block flow through HEPA filters thus compromising their ability to maintain negative pressure and control confinement.
- Should the HEPA filter rupture, contamination could be released to the public and the environment.
- This paper is based upon a Generic Nuclear Processing Facility (GNPF) discussing strategies to maintain the safety functional requirements of the CVS, its interfacing Fire Suppression System (FSS), and their interactions to control soot generation and mitigate risks due to a fire event.

Safety Terms

- SSCs – Structures, Systems and Components
- Safety Class (SC) – SSCs required to prevent or mitigate accidents whose consequences approach or exceed offsite evaluation guidelines during and after a design basis accident.
- Safety Significant (SS) – SSCs not designated as SC but whose preventative or mitigative function is a major contributor to defense-in-depth and/or worker safety as determined from hazard analysis.
- Defense-in-Depth (DID) – An approach to designing and operating nuclear facilities that prevents and mitigates accidents that release radiation or hazardous materials. The key is creating multiple independent and redundant layers of defense to compensate for potential human and mechanical failures so that no single layer, no matter how robust, is exclusively relied upon. Defense-in-depth includes the use of access controls, physical barriers, redundant and diverse key safety functions, and emergency response measures.

Mission and Objective

- Soot generated during a fire event in a process area, tertiary area, or glovebox could accumulate on the CVS HEPA filters to the point that:
  - The flow necessary to maintain a negative pressure in the confinement area cannot be maintained OR…
  - There is a breach in the HEPA filter due to a high pressure drop.
- The mission:
  - Develop a design solution that will minimize the amount of soot collected on the HEPA filter AND/OR…
  - Strengthen the HEPA filters to prevent a breach.
- The objective of this presentation is to provide some alternate technologies to achieve the mission and identify design analysis and testing deemed necessary to achieve safety class (SC) design.

Functional Requirements

Functional Requirements (CVS)

- Must maintain the facility process areas at negative pressure relative to atmosphere to control the spread of contamination by preventing the release of radioactive material to the public and environment during design basis accidents.
- Comply with DOE-HDBK-1169 and incorporate primary, secondary and tertiary confinement zones.
- Functionally classified as Safety Class (SC) that must remain functional during a Design Basis Accident (DBA)
- Safety functions
  - Provide confinement ventilation/filtration of airborne radioactive particulate releases
  - Provide a fire barrier function (ducts/dampers) to control fire propagation.

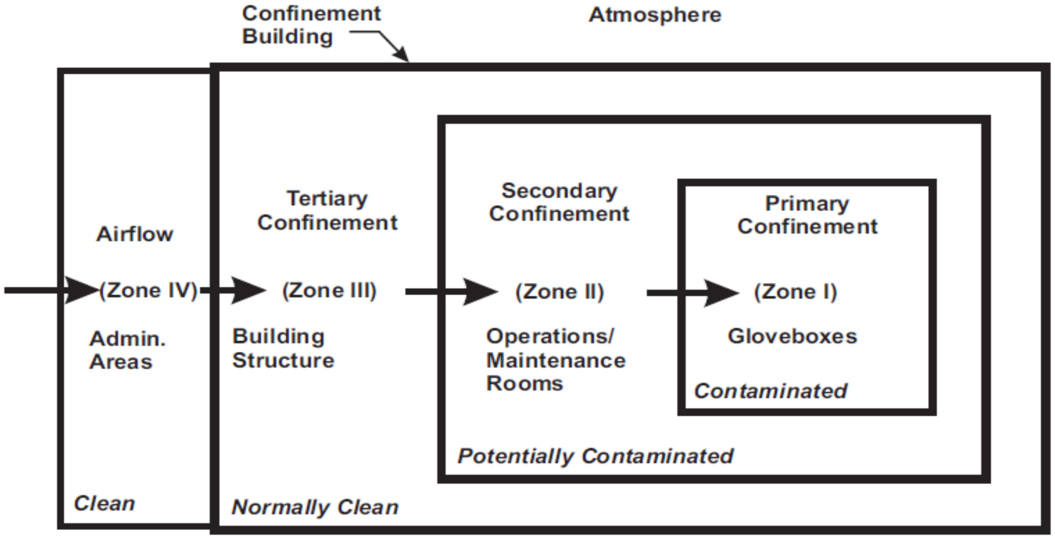
Functional Requirements for Fire Suppression

- Comply with DOE-STD-1066 and NFPA Standards
- Functionally classified as Safety Class (SC) and Safety Significant (SS) dependent upon Zone
- Safety functions
  - Extinguish postulated fires at an early stage (e.g., before it causes a glovebox fire) before HEPA filters are compromised from excessive soot or temperature.
  - Prevent re-ignition by reducing the oxygen level in the process rooms to less than 15% for a designated hold period.
  - The FSS must operate both during and after design basis accidents.

System Descriptions

System Description (CVS)

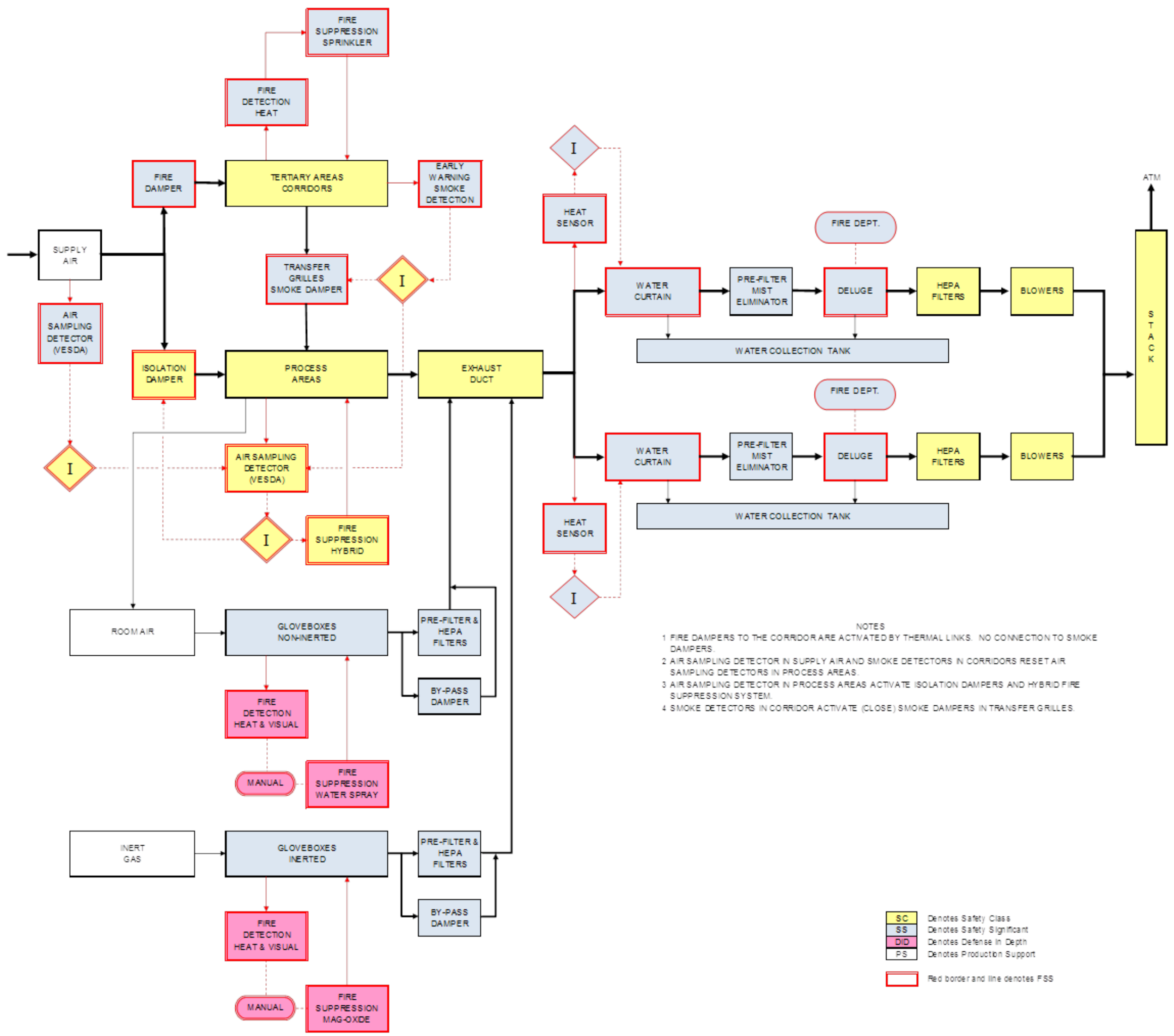
- The CVS SSCs are SC
- Once through system with no recirculation
- Redundant Blowers and HEPA Filter Trains
- Outside air is conditioned in the air handlers or dehumidifiers to meet and maintain temperature and humidity conditions
- Utilizes HEPA filters to filter the air prior to exhausting to the atmosphere
- Confinement zones



Fire Suppression Systems (FSS)

- Different fire detection and suppression technologies are applied to the following CVS zones
  - Zone III – Tertiary Area, Corridors and Airlocks
    - Photoelectric smoke detectors with wet pipe sprinklers
  - Zone II – Process Areas
    - Air sampling detectors with hybrid fire suppression systems with
  - Zone I – Gloveboxes
    - Inerted using argon blanket
      - Visual detection and heat detectors with Magnesium oxide ($MgOH_2$)
    - Non-inerted
      - Visual detection and heat detectors with manual water spray

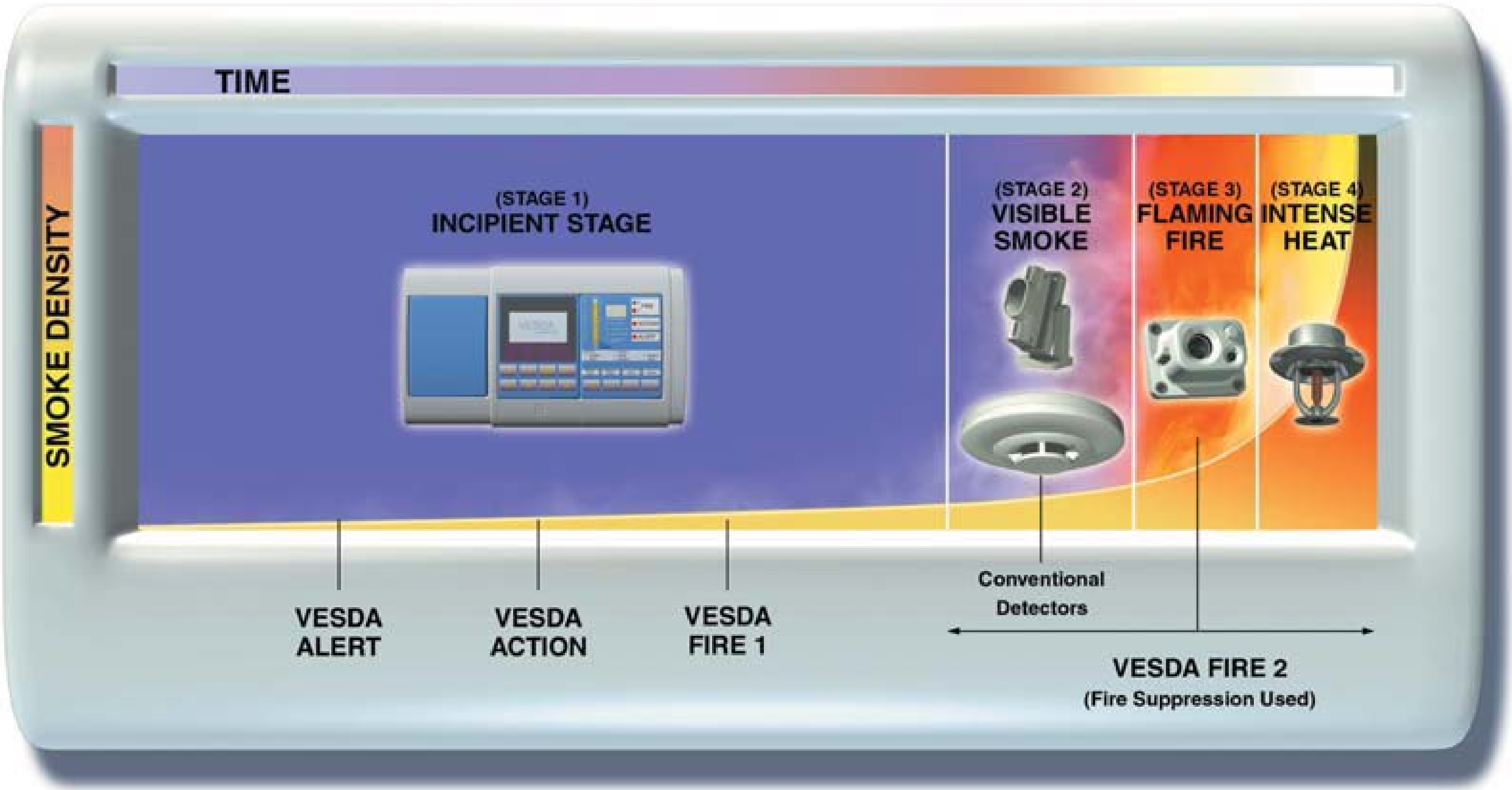
CVS and FSS Block Flow Diagram



Soot Generation

Four Stages of Fire Growth

Detectors and the Four Stages of Fire



Soot Generation

- Combustible material
  - Quantity
  - Properties
  - Combustion efficiency
  - Environmental conditions
    - Radiant heat
    - Oxygen concentration
    - Ventilation conditions
- Soot yield factor
  - Range of 1.5% to 10%
  - CETL test for MOX Fuel Fabrication Facility (5.08%)

Soot Generation Areas

- Outdoor (wildland) fire
- Tertiary, corridor and airlocks
- Process areas
- Inside gloveboxes

Inside Gloveboxes

- Depends upon…
  - Type of material inside glovebox
  - Components that are part of the glovebox
  - Inerted and ventilation
- Soot generated

Glovebox Condition	Soot Generated
Without involvement of PMMA	12 to 53 lbs.
With involvement of PMMA	87 to 250 lbs.
Ventilation limited case	0.12 to 0.8 lbs.

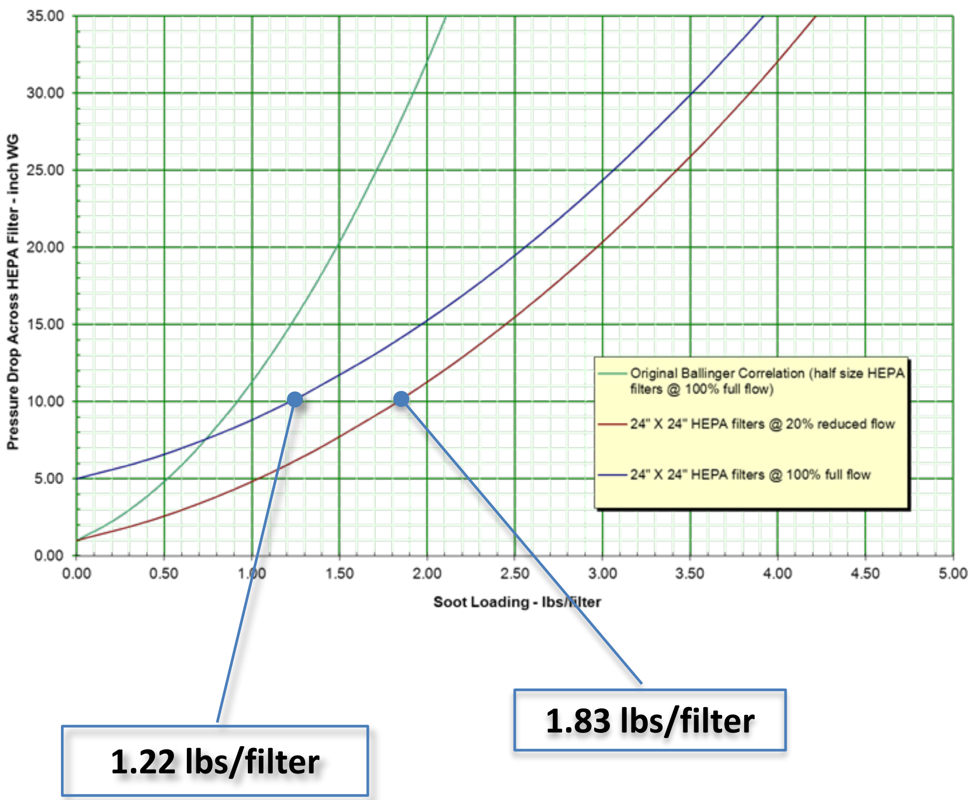
Soot Loading Capacity

HEPA Filter Soot Loading Capacity

- Ballinger correlation

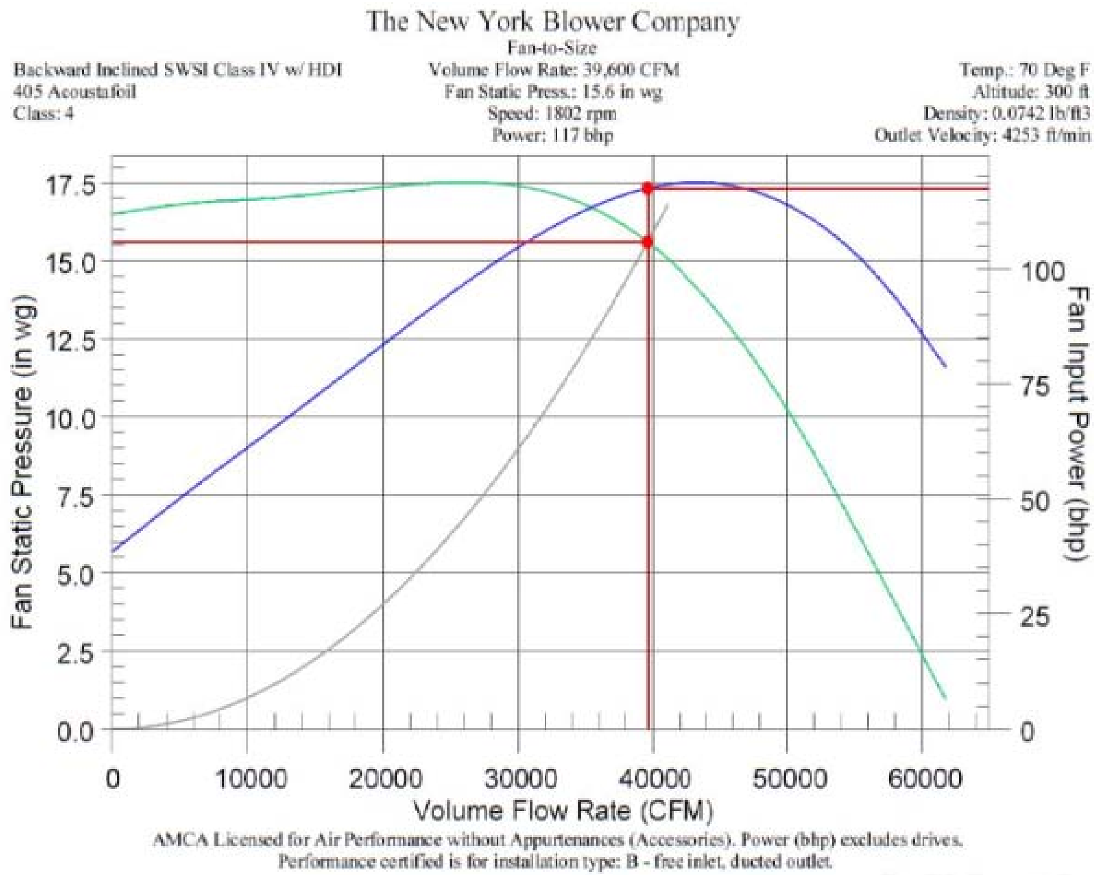
$$\Delta P = 6.5\times10^{-4} L_s^2 + 0.28 L_s + 22.6$$

  - $\Delta P:\ mm\ Aq$
  - $Ls: smoke\ loading\ on\ filter\ (\frac{g}{unit})$
  - Based upon half size HEPA filter (12" X 12" X 11.5") at 445 cfm
- Modified to full size HEPA filter (24" X 24" X 11.5") at 1180 cfm
- In the event of a fire, the flow will be reduced to 20% of full flow
  - Full flow = 1500 cfm
  - 20% reduced flow = 300 cfm
- Assume dirty filter: ΔP_o = 5 inch WG
- Maximum: ΔP = 10 inch WG
- 48 HEPA filters per train…
  - Full flow: 59 lbs/train capacity
  - 20% flow: 88 lbs/train capacity



Exhaust Fan Capacity

- Rated condition is 39,600 @ 15.6 cfm (115 BHP)
- Fan curve based upon…
  - 34,434 cfm @ 12.0 in wg
  - 15% margin
  - 32% additional static pressure
- Normally two will be running



Soot Mitigation Strategies

Soot Mitigation Strategies

- Do nothing
- Minimize the amount of combustible materials in the area.
- Detect and suppress fires at an early stage.
- Prevent fires from re-igniting.
- Collect soot before it enters the CVS exhaust duct and before the HEPA filter
- Increase the strength of the HEPA filter to withstand an increase in pressure across the filter to increase the amount of soot the HEPA filter that can be deposited.

Minimize Combustibles

- Engineering controls
  - Identify materials of construction for the facility and equipment in the area. These are identified as fixed combustibles.
  - Provide fire barriers to divide the area into segregated compartments to limit the spread of any fire.
- Administrative controls
  - Procedural requirements that identify the type and amount of material that is permitted to enter and remain in the space.

Fire Detection Methods

- Very Early Warning Smoke Detection – VESDA air sampling detectors
- Early Warning Smoke Detectors – ceiling mounted detectors
- Heat Detectors - sprinklers
- Visual Detection – operators present to observe abnormal conditions

Fire Extinguishment Methods - GNPF

- Automatic total flooding suppression - Hybrid (SC)
- Automatic wet pipe sprinklers (SS)
- Manually activated suppression (DID)
  - Water spray
  - Dry chemical

Local Capture of Soot Before Exhaust Duct

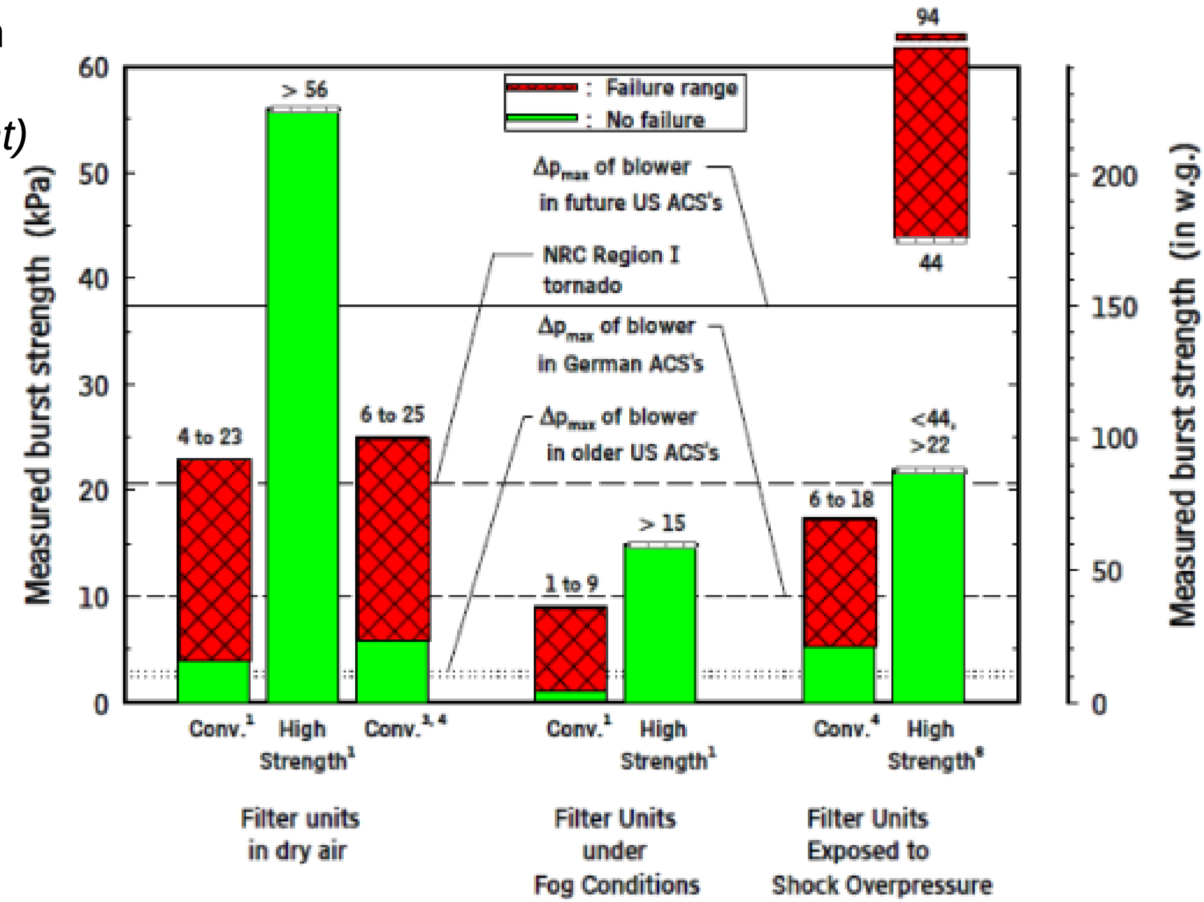
- "Smoke eater" device
  - Filter (mist eliminator)
  - ESP
- Normally in stand-by
  - Actuated by signal from fire detection device

Capture Soot in Exhaust Duct

- Electrostatic Precipitator (ESP)
- Scrubber
- Fire screen
- Pre-filter
- Mist eliminator

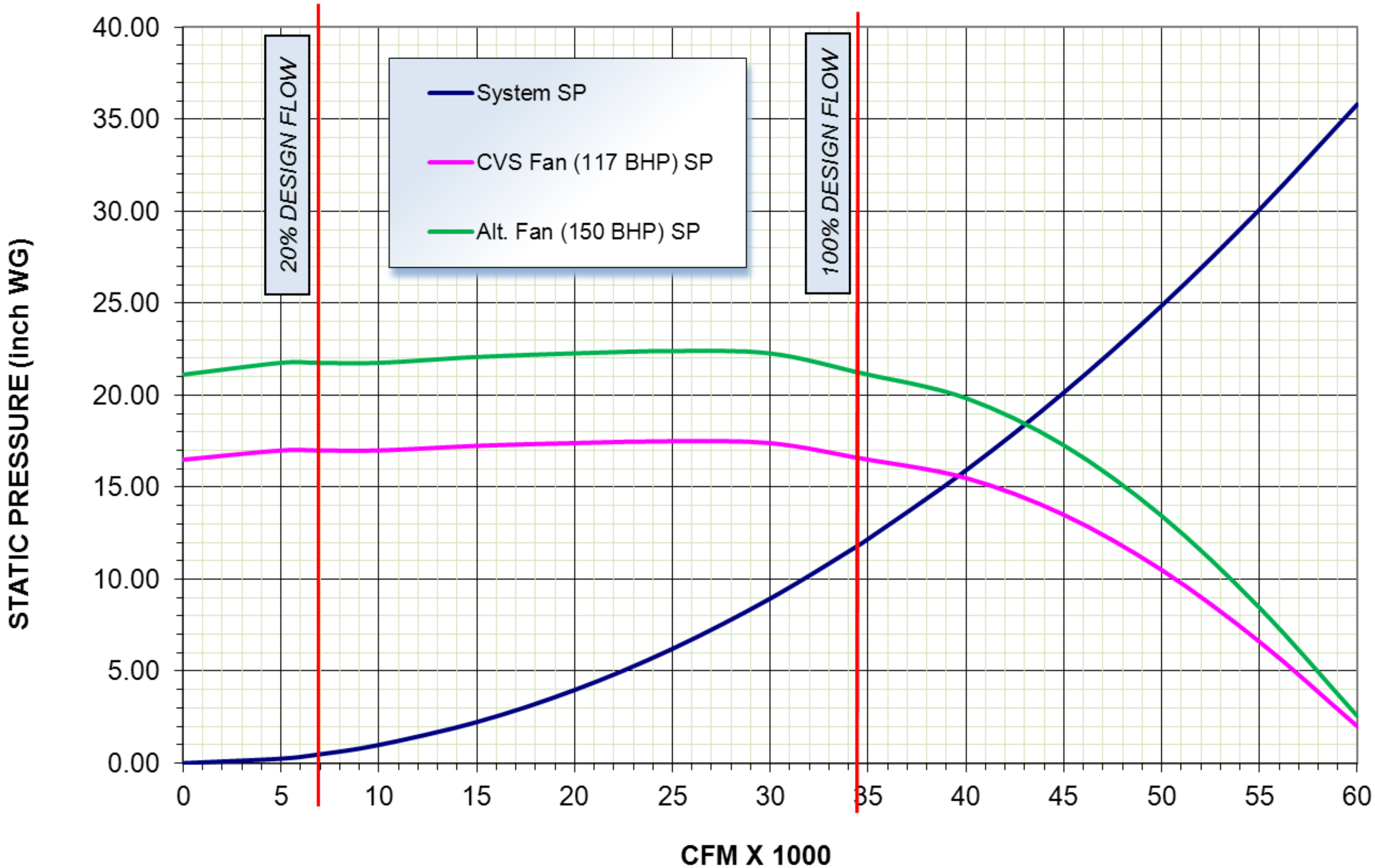
High Strength HEPA Filters

- Section FC – Conventional Nuclear Grade HEPA Filters
- Section FM – High Strength HEPA Filters *(NEW AG-1 Section Under Development)*

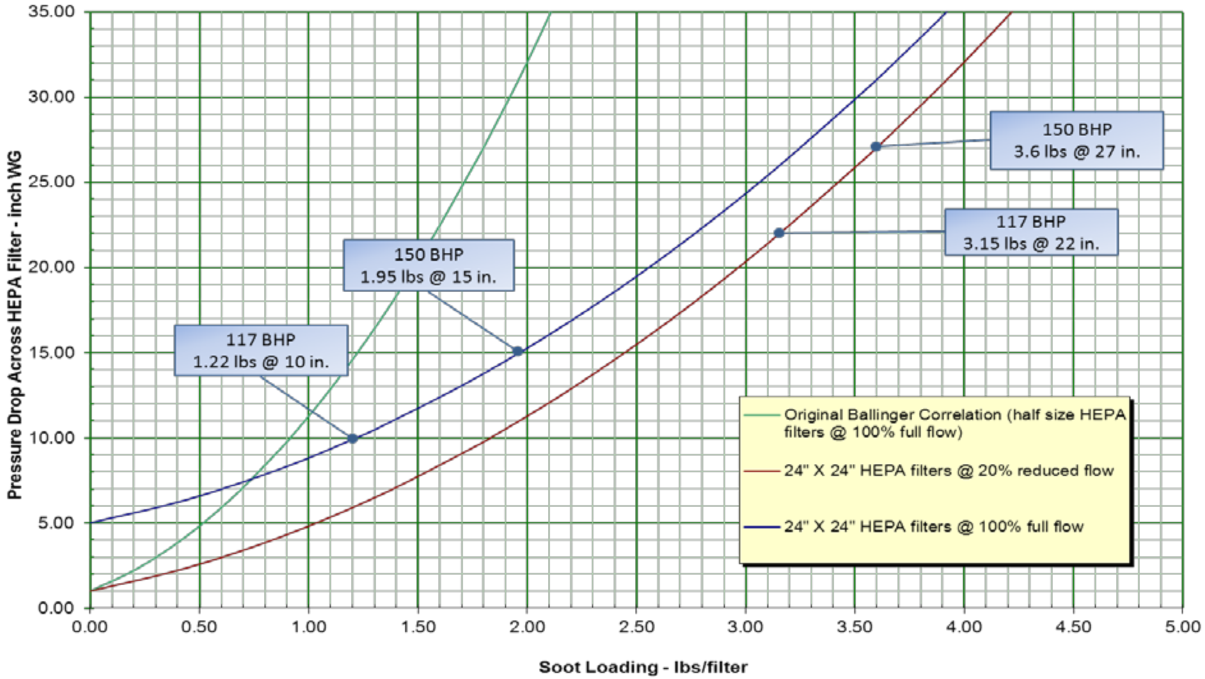


Fan Capacity for High Strength HEPA Filters

$$P_a = P_b \times \frac{HP_a}{HP_b} \times \frac{Q_b}{Q_a}$$



Fan Soot Loading Capacity



System Flow Rate	Conventional HEPA Filters		High-Strength HEPA Filters	
	117 BHP Fan	150 BHP Fan	117 BHP Fan	150 BHP Fan
Full Flow (34,434 CFM)	59 lbs.	59 lbs.	59 lbs.	94 lbs.
20% Reduced Flow (6,887 CFM)	88 lbs.	88 lbs.	151 lbs.	173 lbs.

Minimizing Soot Generation

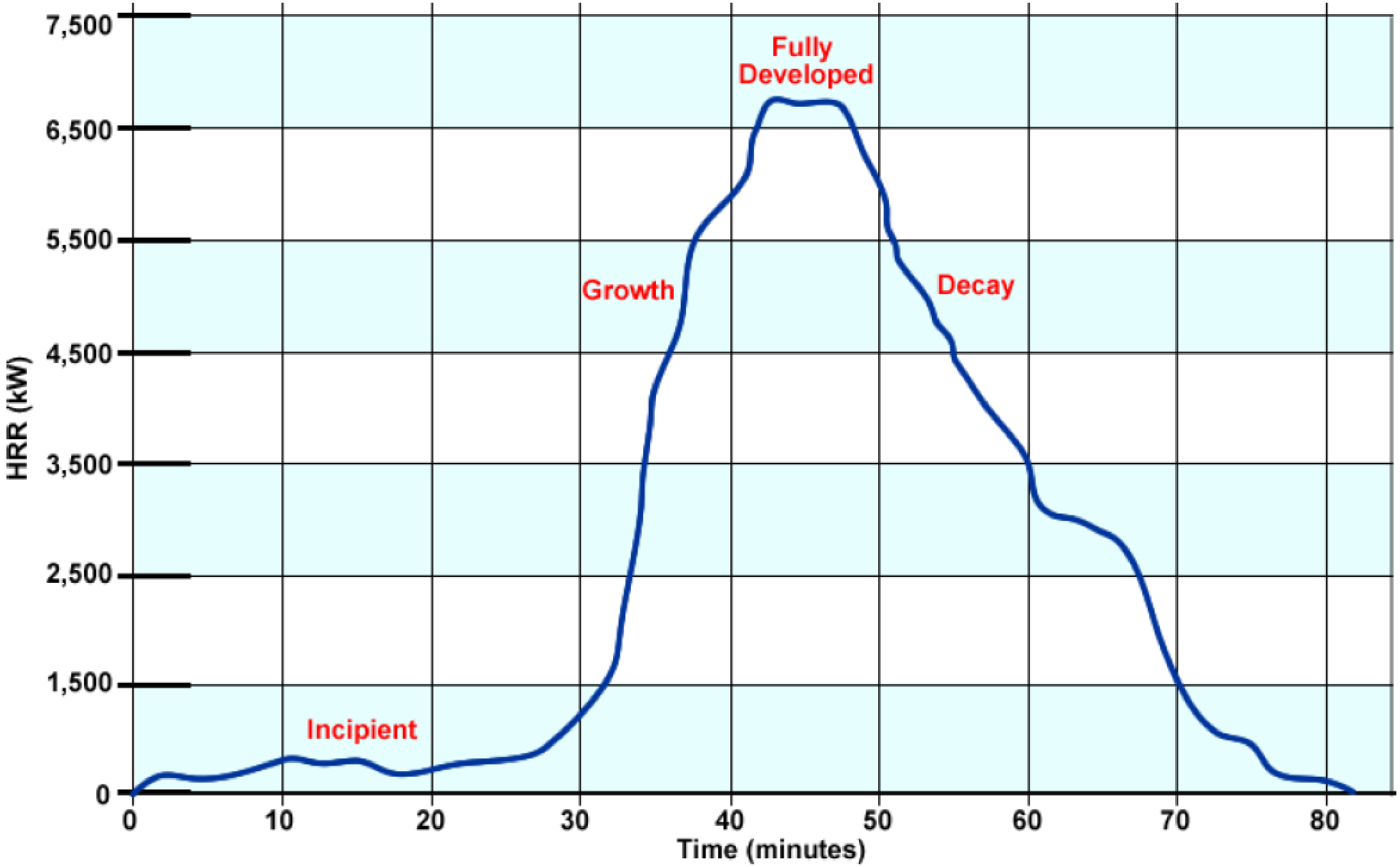
Minimize Combustibles in the Area

- The amount of combustible materials, either fixed or transient, in the various zones should be minimized.
- The size of the areas should be minimized; it is recommended that fire walls be provided to isolate different operations where possible.
- Testing should be performed to determine soot yield based upon the various materials and product mix anticipated for the respective areas.

Detection Fires at a Very Early Stage

- Early detection of a fire and activation of the fire suppression will reduce the amount of smoke an soot generated.
- Detection of a fire during the incipient stage allows early response, thus minimizing the amount of soot generated.
- Testing should be performed to determine the time to detect a fire and activate the fire suppression system.

Fire Curve



7,500
6,500
5,500
4,500
3,500
2,500
1,500
0
HRR (kW)
Fully
Developed
Growth
Decay
Incipient
0
10
20
30
40
50
60
70
80
Time (minutes)

Soot Collection Before Exhaust Duct

- Smoke-eater device
  - The strategy is the use of equipment such as filters or ESP in “smoke-eater” devices to capture generated soot in Zone I and Zone II areas before it enters the CVS exhaust duct.
    - This type of equipment has been used in industrial environments and restaurants to capture welding fumes and cigarette smoke.
    - It is proposed that a more robust design be developed for a nuclear application and only be actuated in the event of a fire.
  - This equipment would be located in the upper elevation of the area to capture smoke that rises. It is recognized that this type of equipment will not capture all generated soot.
- By-pass damper in glovebox vent
  - In regards to Zone III gloveboxes, pre-filters and HEPA filters are installed in-line in the exhaust duct from the glovebox to the CVS exhaust duct. In the event that negative pressure of the glovebox cannot be maintained due to filter blockage, a by-pass damper is open to allow flow directly into the CVS exhaust duct.

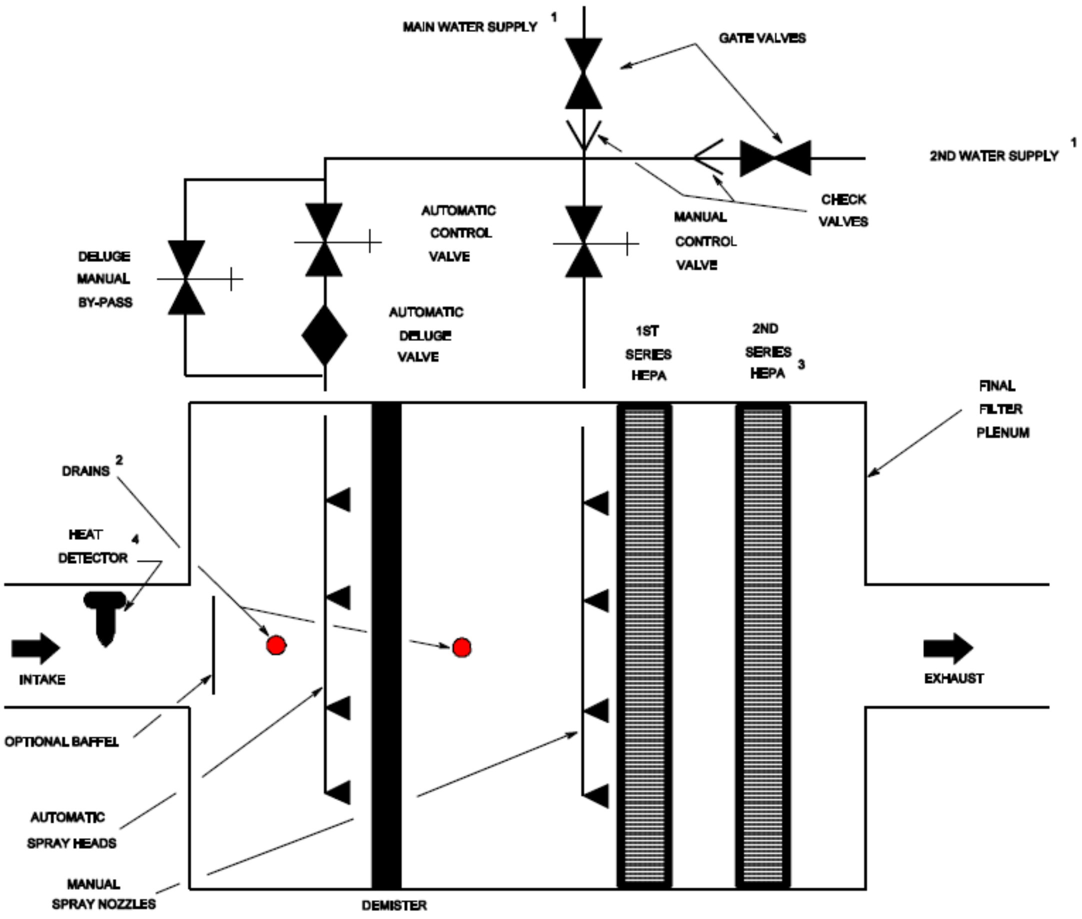
Soot Collection in Exhaust Duct Before HEPA Filter

- Electrostatic Precipitators
  - A DOE project evaluated the technical readiness of an ESP in this particular application and scored them as technical readiness level (TRL) of 3 which is low. DOE recommends a TRL ≥ 4 at CD-1 stage.
  - The parameters and data associated with the soot generation needs to be obtained and follow up testing of an ESP should be performed to verify that it can meet the performance criteria.
- Scrubbers
  - Per the requirements of DOE-STD-1066-99, the CVS exhaust design at the final HEPA filters, shall contain a water curtain that is automatically actuated upon high temperature to quench the air and a deluge system that is manually actuated by the fire department, if deemed necessary, to extinguish a fire on the HEPA filters. This equipment cannot be credited for removing soot.

Soot Collection in Exhaust Duct Before HEPA Filter

- Fire Screens and Pre-filters
  - Fire Screens and Pre-filters are to be provided per DOE-STD-1066-99 to protect the HEPA filters from larger size particulate and moisture.
  - Fire screens are to be located upstream of all pre-filters (4-5 ft.) and upstream of final filter plenums (20 ft.) and are typically used to collect any hot embers prior to them reaching the pre-filters.
  - Pre-filters are used to in the final filter plenum to protect the HEPA filters from dust and particulate loading.
  - Demisters must be installed between the automatic spray nozzles and the HEPA filters as depicted in Appendix C, Figure C-1 of DOE-STD-1066-99.
  - Results from testing performed for MFFF showed that these filters will collect some of the soot before it reaches the HEPA filters.

DOE-STD-1066-99 Figure C.1



[1] Water supply may be a limited water supply. Secondary supply may not be required.
[2] Pipe drains to either a process waste system or collection tanks.
[3] Minimum two stages of HEPA filters required. Additional stages of HEPAs are permitted.
[4] Pilot sprinkler heads may be used to activate deluge system. Heat de tection also required in final filter enclosure.

Increase Strength of HEPA Filter

- Collection of soot on conventional HEPA filters is limited to a maximum pressure drop of 10 inch WG. Reducing the flow through the CVS system will result in a lower pressure drop thus enabling the HEPA filter to collect more soot before reaching the 10 inch WG limit.
- ASME Committee on Nuclear Air and Gas Treatment is currently developing Code Section FM for high strength HEPA filters that will with stand a high pressure drop thus increasing the soot loading capacity.
- Larger blowers will be required to take advantage of this larger capacity.
- Testing of these HEPA filters should include gathering of data as to their soot loading capacity.

Evaluation

Evaluation

ESTIMATED SOOT MITIGATION VERSUS HEPA FILTER TRAIN CAPACITY	Estimated % of Soot Mitigation		Zone III Tertiary	Zone I Glovebox (non-inerted)			Zone I Glovebox (Inerted)			Zone II Process		
	Note 1		*Note 2*	*Note 3*	*Note 4*	*Note 5*	*Note 3*	*Note 4*	*Note 5*	*Note 6*	*Note 7*	*Note 8*
COMBUSTIBLE MATERIALS IN AREA			18.0 lbs	530.0 lbs	2500.0 lbs	80.0 lbs	530.0 lbs	2500.0 lbs	80.0 lbs	20700.0 lbs	20700.0 lbs	20700.0 lbs
Soot yield factor			10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	1.5%	5.0%	10.0%
Amount of Soot Generated (unmitigated)			1.8 lbs	53.0 lbs	250.0 lbs	0.8 lbs	53.0 lbs	250.0 lbs	0.8 lbs	310.5 lbs	1035.0 lbs	2070.0 lbs
FIRE DETECTION												
Very Early Detection (VESDA)	80%									248.4 lbs	828.0 lbs	1656.0 lbs
Early Warning Smoke Detectors	30%											
Heat Detectors	5%		0.1 lbs	2.7 lbs	12.5 lbs	0.0 lbs	2.7 lbs	12.5 lbs	0.0 lbs			
Visual Detection	20%			10.6 lbs	50.0 lbs	0.2 lbs	10.6 lbs	50.0 lbs	0.2 lbs			
	Soot Balance		1.7 lbs	39.8 lbs	187.5 lbs	0.6 lbs	39.8 lbs	187.5 lbs	0.6 lbs	62.1 lbs	207.0 lbs	414.0 lbs
FIRE EXTINGUISHMENT												
Hybrid - Rapid extinguishment of a fire	60%									37.3 lbs	124.2 lbs	248.4 lbs
Wet-Pipe Sprinkler	30%		0.5 lbs									
Water Spray or Dry Chemical	20%			8.0 lbs	37.5 lbs	0.1 lbs						
Mag Oxide	30%						11.9 lbs	56.3 lbs	0.2 lbs			
	Soot Balance		1.2 lbs	31.8 lbs	150.0 lbs	0.5 lbs	27.8 lbs	131.3 lbs	0.4 lbs	24.8 lbs	82.8 lbs	165.6 lbs
LOCAL COLLECTION BEFORE ENTERING EXHAUST DUCT												
Filter (limited to 1.8 lbs for gloveboxes)	30%		0.4 lbs	1.8 lbs	1.8 lbs	0.2 lbs	1.8 lbs	1.8 lbs	0.1 lbs	7.5 lbs	24.8 lbs	49.7 lbs
Reduction in flow (close transfer grilles)	50%		0.6 lbs									
ESP	20%											
	Soot Balance		0.2 lbs	30.0 lbs	148.2 lbs	0.3 lbs	26.0 lbs	129.5 lbs	0.3 lbs	17.4 lbs	58.0 lbs	115.9 lbs
COLLECTION IN EXHAUST DUCT BEFORE HEPA FILTER												
Pre-filter	30%		0.1 lbs	0.5 lbs	0.5 lbs	0.1 lbs	0.5 lbs	0.5 lbs	0.0 lbs	2.2 lbs	7.5 lbs	14.9 lbs
ESP	20%											
Wet Scrubber / water spray	10%											
	Soot Balance		0.2 lbs	29.5 lbs	147.7 lbs	0.3 lbs	25.5 lbs	128.9 lbs	0.3 lbs	15.2 lbs	50.5 lbs	101.0 lbs
SOOT LOADING CAPACITY OF HEPA FILTER TRAIN												
	Blower HP	*Capacity*	*Soot Loading Capacity minus Soot Generated*									
Capacity of Convention HEPA Filters												
Full Flow	117 BHP	59.0 lbs	58.8 lbs	29.5 lbs	(88.7) lbs	58.7 lbs	33.5 lbs	(69.9) lbs	58.7 lbs	43.8 lbs	8.5 lbs	(42.0) lbs
20% Reduced Flow	117 BHP	88.0 lbs	87.8 lbs	58.5 lbs	(59.7) lbs	87.7 lbs	62.5 lbs	(40.9) lbs	87.7 lbs	72.8 lbs	37.5 lbs	(13.0) lbs
Full Flow	150 BHP	59.0 lbs	58.8 lbs	29.5 lbs	(88.7) lbs	58.7 lbs	33.5 lbs	(69.9) lbs	58.7 lbs	43.8 lbs	8.5 lbs	(42.0) lbs
20% Reduced Flow	150 BHP	88.0 lbs	87.8 lbs	58.5 lbs	(59.7) lbs	87.7 lbs	62.5 lbs	(40.9) lbs	87.7 lbs	72.8 lbs	37.5 lbs	(13.0) lbs
Capacity of High Strength HEPA Filters												
Full Flow	117 BHP	59.0 lbs	58.8 lbs	29.5 lbs	(88.7) lbs	58.7 lbs	33.5 lbs	(69.9) lbs	58.7 lbs	43.8 lbs	8.5 lbs	(42.0) lbs
20% Reduced Flow	117 BHP	151.0 lbs	150.8 lbs	121.5 lbs	3.3 lbs	150.7 lbs	125.5 lbs	22.1 lbs	150.7 lbs	135.8 lbs	100.5 lbs	50.0 lbs
Full Flow	150 BHP	94.0 lbs	93.8 lbs	64.5 lbs	(53.7) lbs	93.7 lbs	68.5 lbs	(34.9) lbs	93.7 lbs	78.8 lbs	43.5 lbs	(7.0) lbs
20% Reduced Flow	150 BHP	173.0 lbs	172.8 lbs	143.5 lbs	25.3 lbs	172.7 lbs	147.5 lbs	44.1 lbs	172.7 lbs	157.8 lbs	122.5 lbs	72.0 lbs

NOTES

(1) The soot mitigation rates are best guess conservative estimates based upon engineering judgment. Testing should be undertaken to validate these amounts.

(2) Amount of combustible material in Zone III Tertiary & Corridor (Airlock) Area Area (pg. 6)

(3) Amount of soot generated based upon glovebox without involvement of PMMA (Ref. Table 2)

(4) Amount of soot generated based upon glovebox with involvement of PMMA (Ref. Table 2)

(5) Amount of soot generated based upon glovebox at ventoilation limited case (Ref. Table 2)

(6) Amount of soot generated based upon 2070 ft^2 Process Area (lower boundary)

(7) Amount of soot generated based upon 2070 ft^2 Process Area (MOX soot generation rate)

(8) Amount of soot generated based upon 2070 ft^2 Process Area (upper boundary)

(9) Plating out of soot in the exhaust ducts is not considered.

(10) HEPA Filter Train soot loading capacity per Table 3.

Conclusions

Risk Mitigation Strategies

- Minimizing the amount of combustible materials, either fixed or transient, in the various zones will reduce the potential amount of soot that can be generated.
- Reducing the size of the areas will limit the amount of combustibles that can be involved in a fire.
- Detecting fires at a very early stage is essential in limiting smoke and soot generation.
- Reducing the confinement ventilation airflow will reduce the amount of fire suppression agent required to maintain concentration required to prevent re-ignition.
- Additional testing should be performed to determine soot yield based upon the various materials and product mix anticipated for the respective areas.

Qualification Test Program

Qualification Test Program

- A significant amount of the evaluation presented is based upon engineering judgment.
- A proposed program to perform *Qualification Testing for SC Hybrid Fire Extinguishment System* is provided in Appendix G of the paper.