Advanced Exploration Systems Program

Fire Detection Tradeoffs as a Function of Vehicle Parameters

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Background

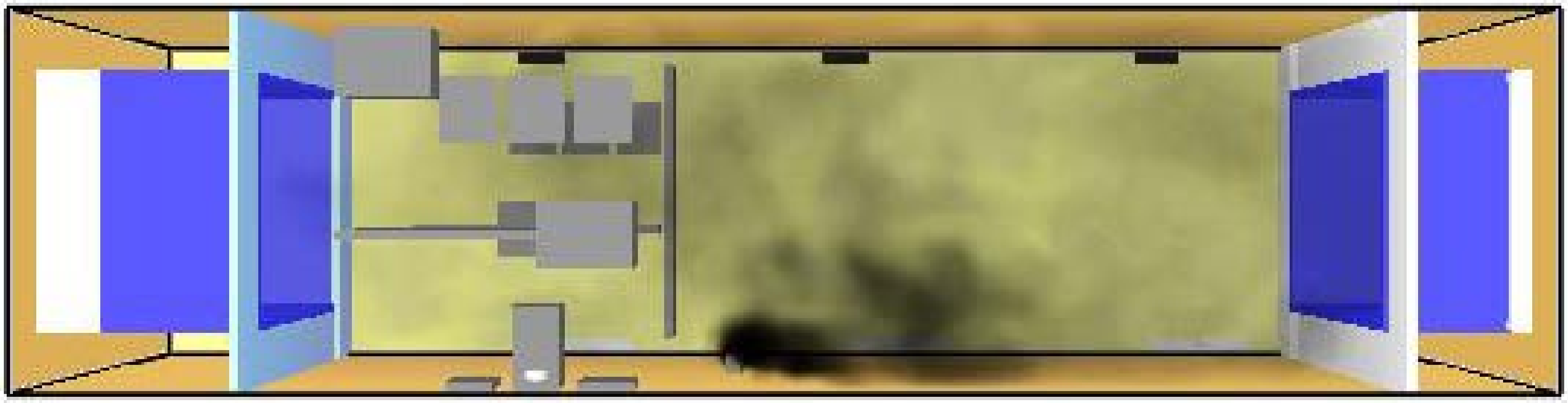
- **Since Skylab, NASA and other countries have included fire detection in all inhabited vehicles.**
- **The predominant technique has been smoke aerosol detectors**
  - This is based on the understanding that aerosol production is a prompt, distinct, and rapid product of overheat and fire of virtually all materials
  - Species production has been seen to be less universal, and less distinct
- **There is an increasing trend toward higher levels of air filtration.**
  - Increases crew comfort
  - Also filters the smoke potentially delaying the alarm
- **This work examines the interaction between the smoke detector and the air filtration system**

Detector Performance Requirements

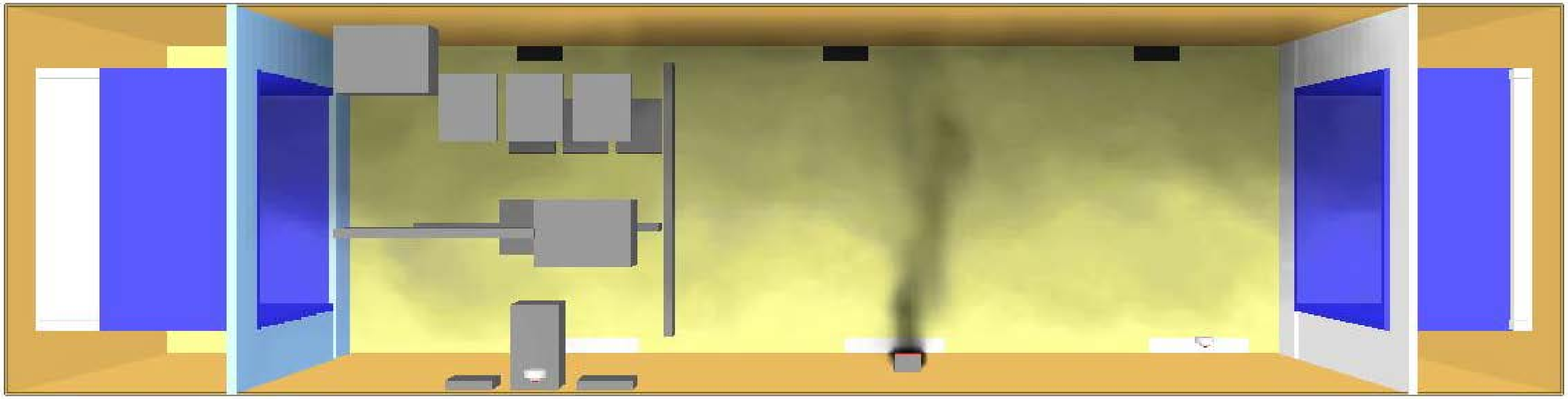
System	Detector Performance Basis	Technology
Residential	Minimum Sensitivity 1.6 to 13.2 % obscuration/m plus required response to reference test fires	Light Scattering or Ionization
FAA Cargo Bay	Emphasis on sampling the cargo area and false alarm avoidance, typical range is up to 13.2 % obscuration/m	Predominantly Light Scattering
Space Shuttle	2 mg/m^3	Ionization
ISS	3.3 % obscuration/m	Light Scattering
Orion	Current concept is rate of rise detection (light scattering)	Light Scattering

- No clear precedent from ground-based or space systems. Each have been defined empirically with limited traceability to definable.

Smoke Detection Background: Destiny Smoke Detection Simulation-25% Soot: effect of gravity

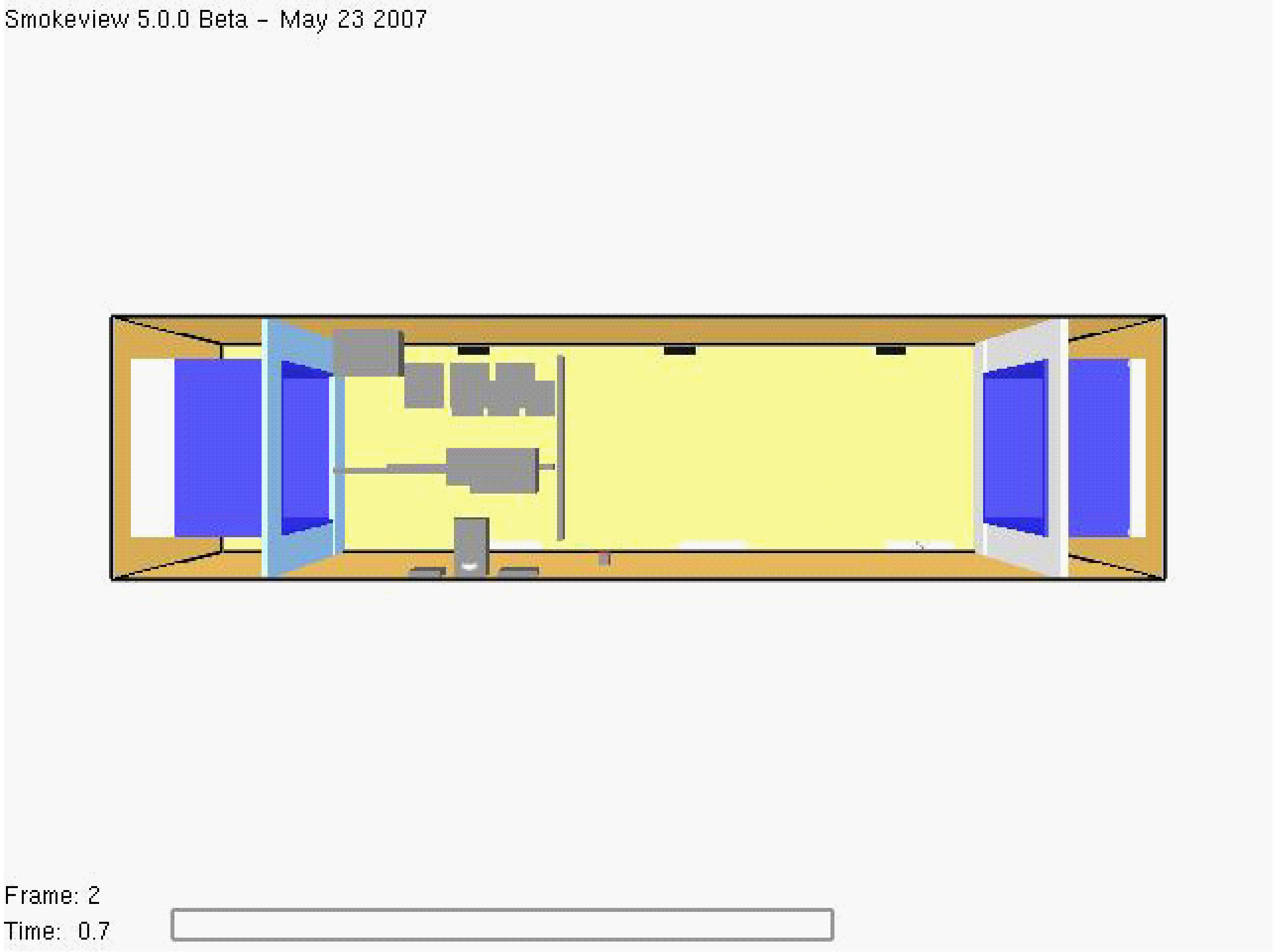


Low-gravity



Normal-gravity

Destiny Simulation: 5%soot



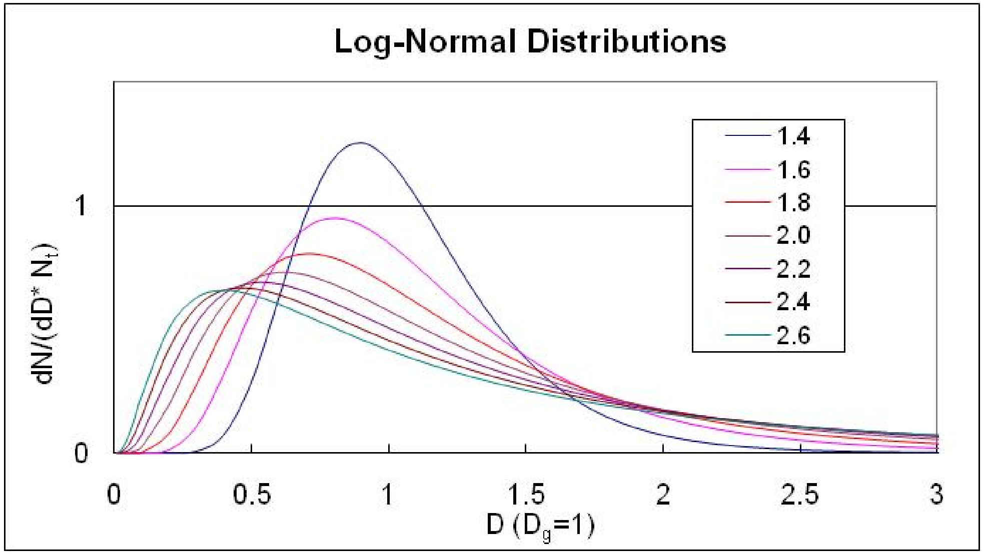
Using NIST Fire Dynamics Simulator
Detection times 118 and 206 s

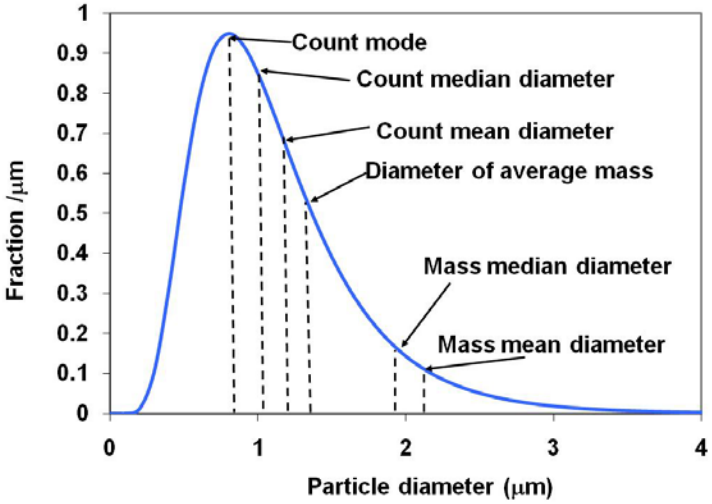
Log-Normal Distribution

$$f_N(D) = \frac{N_t}{(2\pi)^{1/2} D \ln \sigma_g} \exp\left(-\frac{(\ln D - \ln D_g)^2}{2 \ln^2 \sigma_g} \right)$$

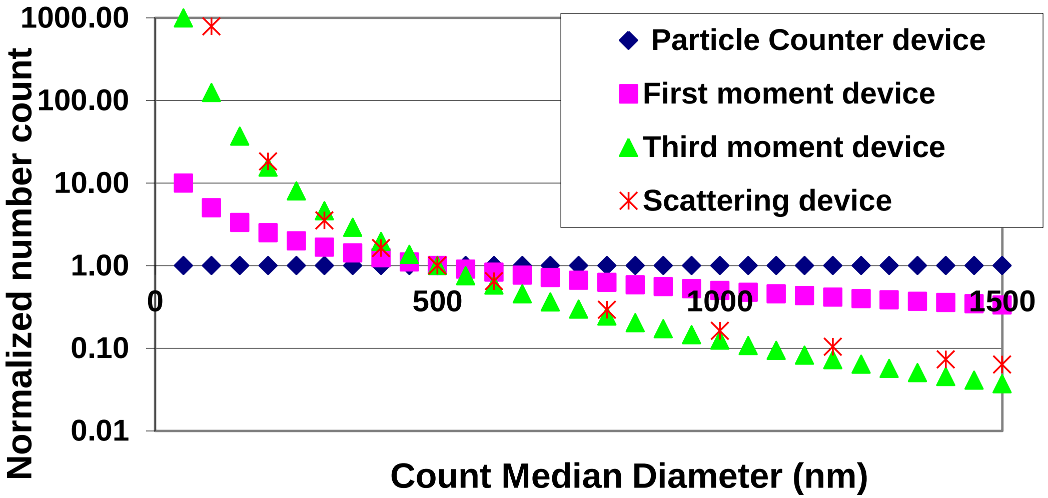
Number is dominated by the smaller particles

Mass is dominated by the larger particles (tail)





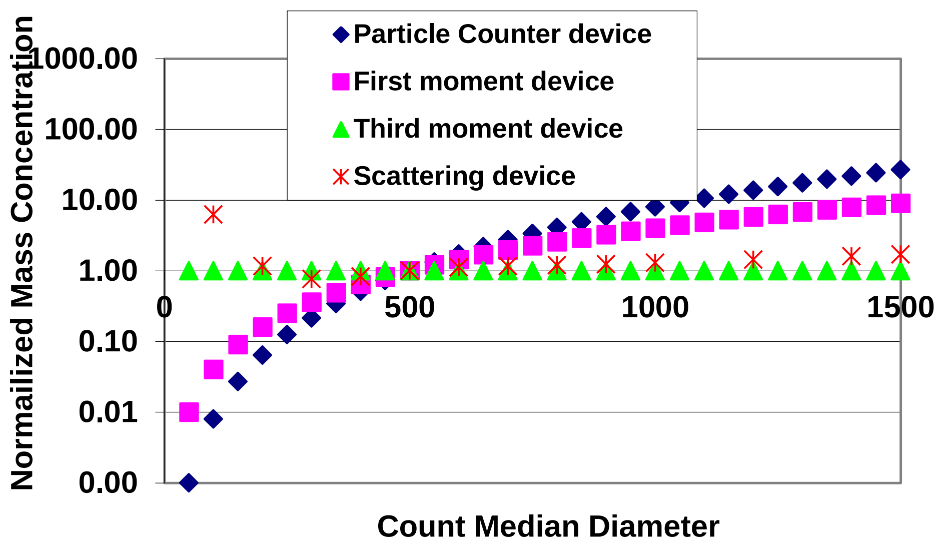
Detector Design - Issues



Normalized Number Concentration to alarm for each device type

Alarm level: 2 mg/m^3 (500 nm CMD and a σ_g of 1.3)

22 x 10^6 particles/cc



Normalized Mass Concentration at alarm for each device type

Spacecraft Smoke Particulate

Smoke Source		Geometric Mean Diameter (Dg) (µm)	Count Mean Diameter (M_1/M_0) (µm)	Diameter of Average Mass (M_3/M_0) (µm)	σ_g
Kapton	Unaged	0.042	0.056	0.101	2.154
	Aged 720 s	0.089	0.109	0.161	1.872
Lampwick	Unaged	0.090	0.128	0.258	2.312
	Aged 720 s	0.229	0.276	0.398	1.834
Silicone	Unaged	0.128	0.196	0.465	2.530
	Aged 720 s	0.269	0.355	0.619	2.108
Teflon	Unaged	0.081	0.101	0.170	2.198
	Aged 720 s	0.070	0.105	0.232	2.442
Pyrell	Unaged	0.149	0.204	0.384	2.211
	Aged 720 s	0.293	0.359	0.539	1.892

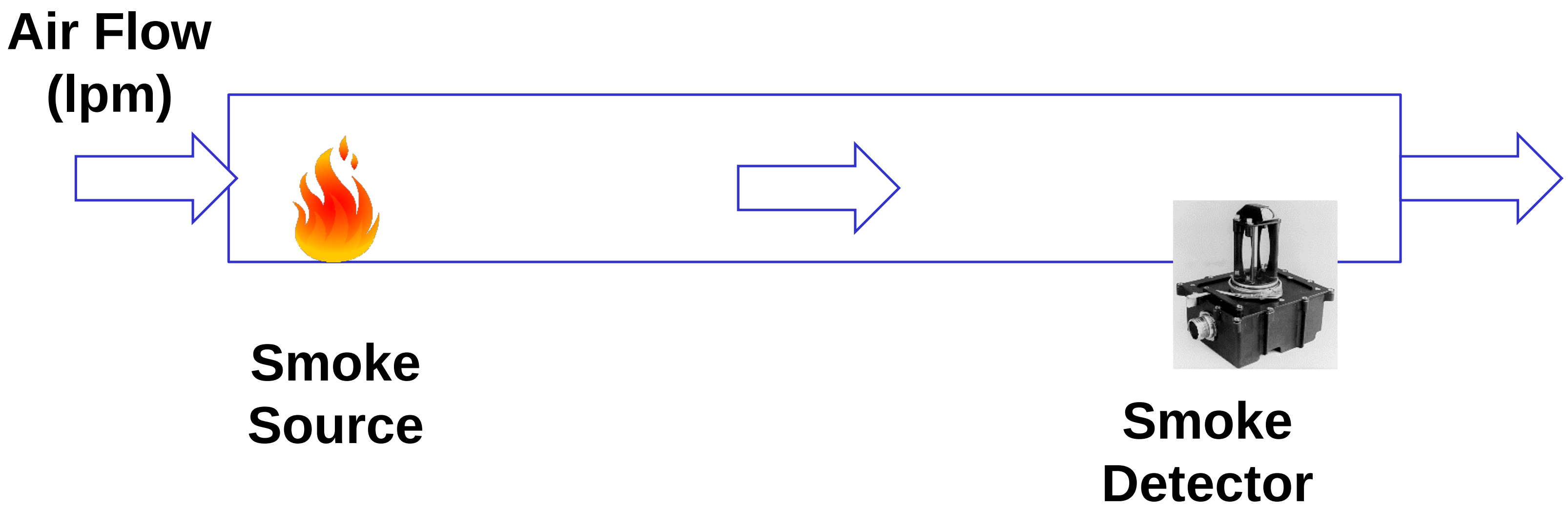
Species Production From Pyrolysis of Spacecraft Materials

Material	Mass of pyrolyzed material required to reach alarm level smoke concentrations (g)	Species Concentration increase due to overheat event in a 10 m^3 vehicle (ppm)				
		CO	HF	HCN	HCl	CO_2
Kapton snips	6.7	256	0.4	5.7	0.4	263
Bulk Teflon	53.7	104.	382	3.5	66.	2090
Orange PVC wire	0.89	2.2	0.1	0.1	12.8	42.1
Printed Circuit Board	2.25	9.0	0.1	0.0	0.6	44.6
Components	0.65	3.4	0.0	0.0	0.0	10.6
Lamp wick	1.34	24.3	0.1	0.1	0.1	26.3
Nomex	1.32	47.8	0.2	0.5	0.2	170.0
Pyrell	0.40	4.3	0.0	0.2	0.0	15.6
Bulk Kapton	16.81	931	1.1	13.1	1.1	1420
1 Hr SMAC (ppm)		55	2.5	8	5	13,000
24 Hr SMAC (ppm)		20	1	4	2	13,000

Detection concepts

- **Flow through system**
  - Air continually enters the system at one end and then is transported to the smoke detector at the other end e.g.
    - Space Shuttle avionics bays
    - Capsule with bulk air flow from one end to the other
- **Simple mixed volume**
  - System is largely closed with air being well circulated and the smoke detector at an arbitrary location (usually at an air intake)
    - Closest example is the shuttle mid-deck
- **Mixed system with filtration**
  - System is largely closed with air being well circulated with particulate filtration on the air recirculation system.
    - Smoke detector is usually located at the intake to the air filtration system
    - ISS modules
    - Orion and other new vehicles

Flow-through Systems (ducts)



Analysis is simply based on the smoke production rate diluted in the forced air flow. Since there is no storage, detection depends on the smoke pulse being long and strong enough to trigger the detector

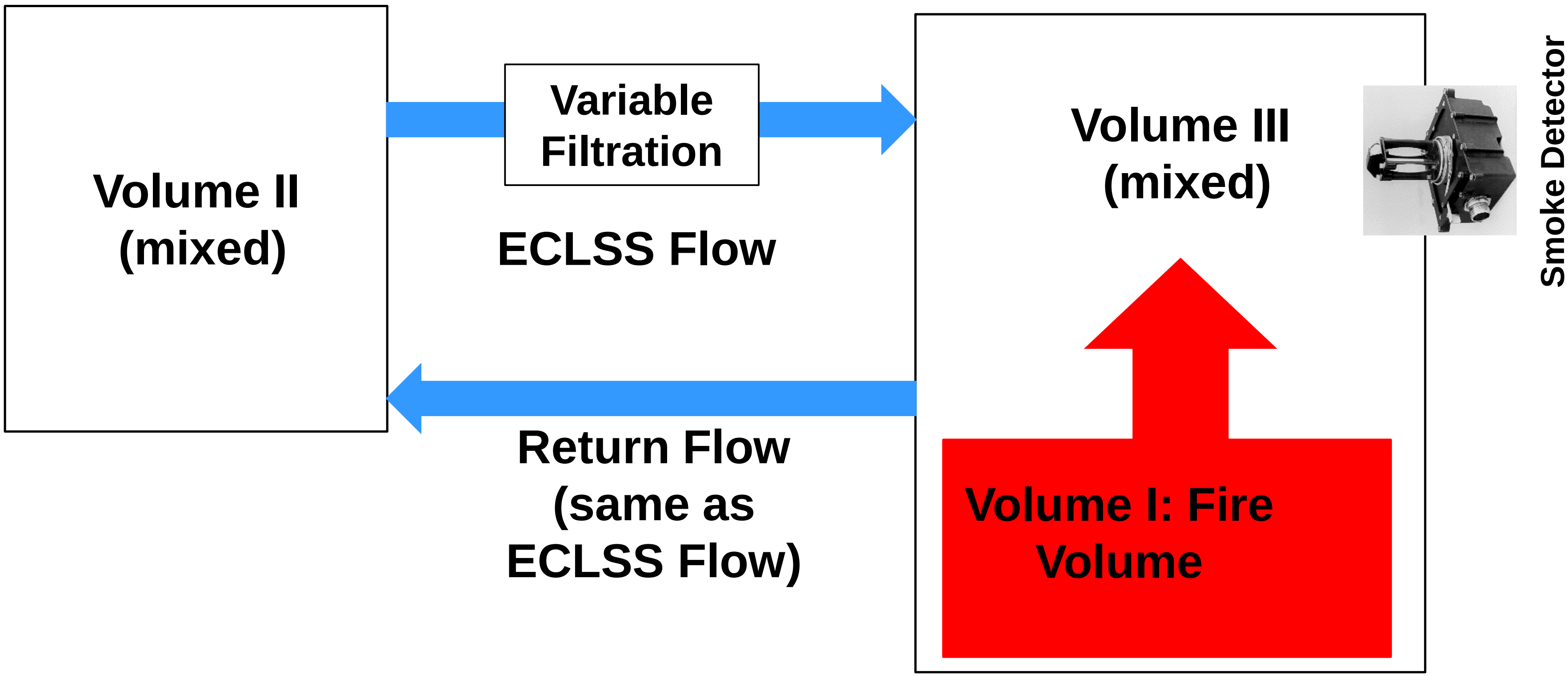
Flow-through Systems (ducts)

	Flow rate lpm	Alarm level (mg/m^3)	Vehicle volume (m3)	Mass of pyrolyzed material to trigger alarm: Lamp wick (g)	Bulk Kapton (g)	Bulk Teflon	Polyvinyl Chloride (PVC)	Nomex	PPM increase due to fire at Alarm: CO (Bulk Kapton)	HF (Bulk Teflon)	HCN (Bulk Kapton)	HCl (PVC)	CO2 (Bulk Teflon)
Avionics Cooling duct STS Alarm level	9000	2	65.0	0.1	1.0	3.2	0.1	0.1	186	77	3	3	417
Avionics Cooling duct ISS Alarm level	9000	10	65.0	0.4	5.0	15.9	0.3	0.4	931	383	13	13	2087

Flow-through systems

- Due to the high flow rate, a significant amount of overheated material is required to trigger the alarm
- Despite the resulting high concentrations of hazardous species at alarm, the net concentraion in the spacecraft will not necessarily that large

Mixed (Stirred) Systems



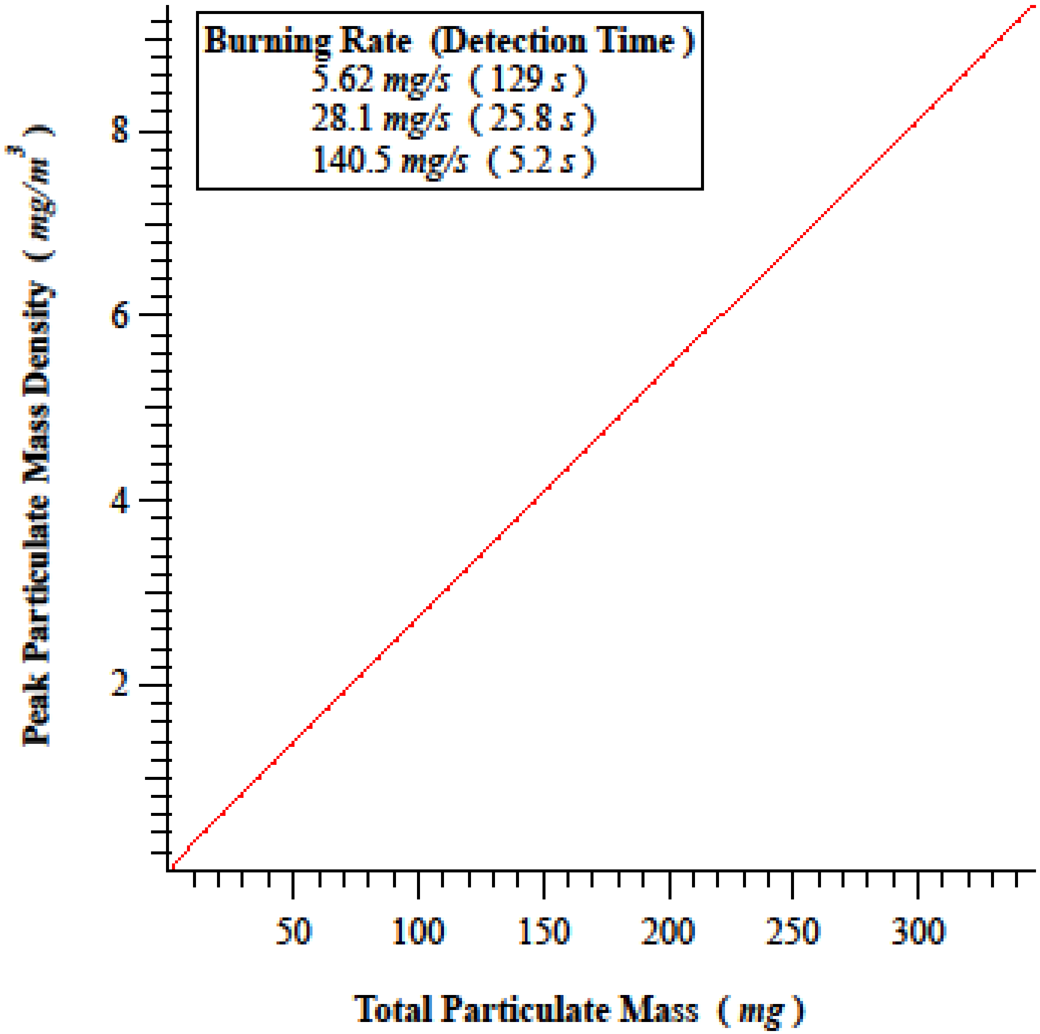
$$\frac{d}{dt}X_{i,III} = \dot{n}_{i,III} + (1-\alpha_i)\frac{\dot{V}_{ECLSS}}{V_{III}}X_{i,II} - \frac{\dot{V}_{ECLSS}}{V_{III}}X_{i,III}$$

Net Change of Species in Volume 3 as a result of the fire

Mixed Systems

- Since the system is well mixed, the entire volume needs to be raised to the detection threshold
- This is facilitated by the fact that the smoke can accumulate in the volume
- However the air filtration system also removes smoke particulate from the system delaying the triggering of the alarm
- This delay enables hazardous species to accumulate if they are not also filtered

Space Shuttle Flight Deck



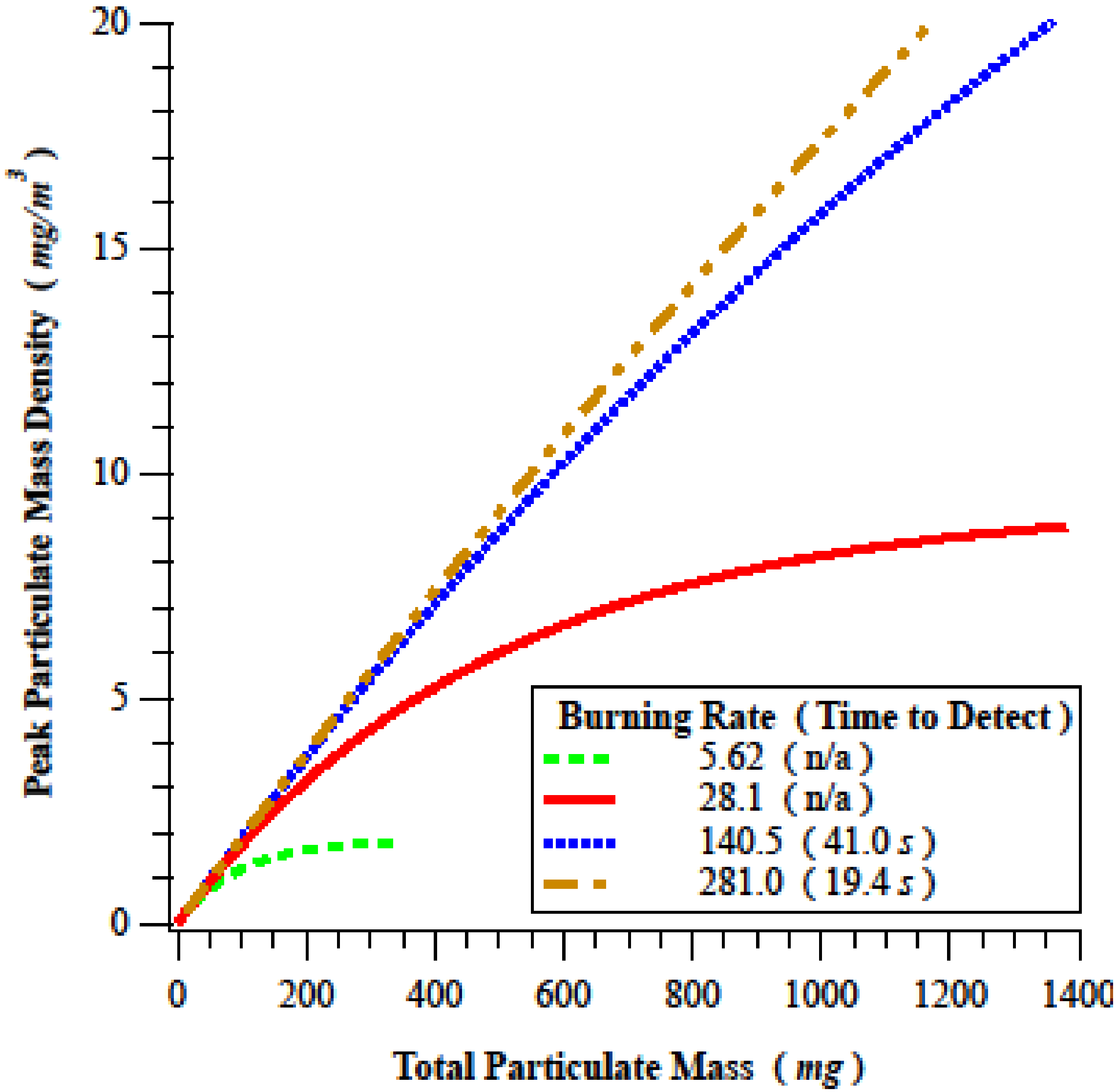
Assumes Shuttle Flight Deck well mixed before intake into the avionics
The detection threshold is ~ 2mg/m^3

Absence of filtration allows accumulation

Mixed Systems

						Mass of material pyrolyzed				PPM increase due to fire at alarm				
	Vehicle Habitable Volume	Air Flow Rate	HEPA Filtration	Smoke Alarm setting	Pyrolysis Rate	Total Mass Cellulose Pyrolyzed to alarm	Mass Kapton pyrolyzed to alarm	Mass Teflon pyrolyzed to alarm	Mass Polyvinyl Chloride pyrolyzed to alarm	CO (Bulk Kapton)	HF (Bulk Teflon)	HCN (Bulk Kapton)	HCl (Polyvinyl Chloride)	CO_2 (Bulk Teflon)
	m^3	m^3/h	%	mg/m^3	mg/s	g	g	g	g	ppm	ppm	ppm	ppm	ppm
Destiny	53	1100	100	10	140.5	7.9	98.4	314.0	5.2	1027	422	14	14	2304
Space Shuttle	37	521	0	2	NA	1.0	12.4	39.7	0.7	186	76	3	3	417
CEV / Commercial Crew Capsules	6	500	100	10	28.1	0.9	11.8	37.7	0.6	1089	448	15	15	2442

ISS Destiny Module



ISS detection threshold ~ (10 mg/m^3).

Total mass of smoke particulate at the alarm threshold for detection is 565 mg at 281mg/s and 586 mg at 140.5 mg/s.

Smoke production rate must exceed the filtration rate.

Mixed Systems

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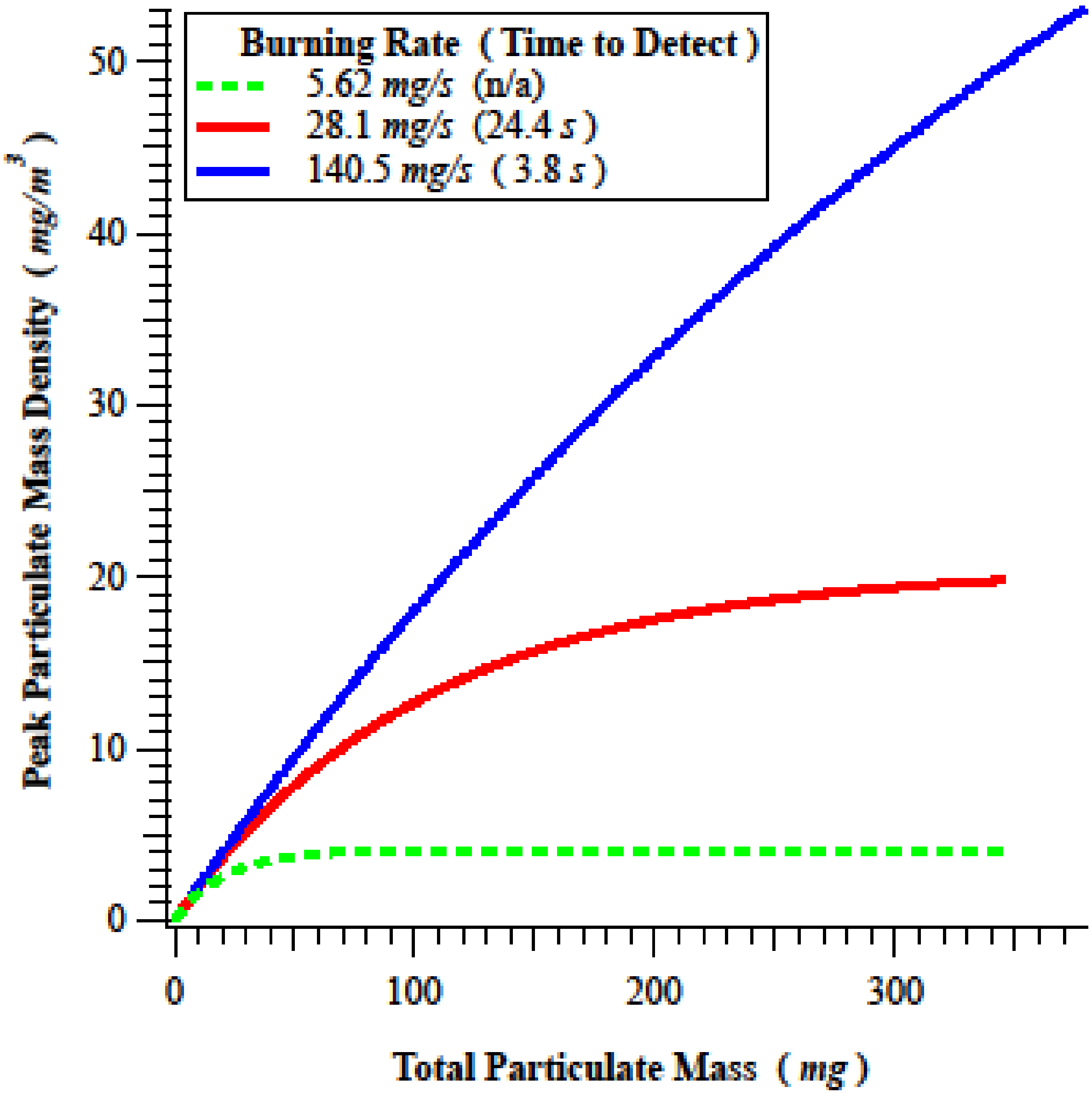
CEV



CEV detection threshold ~(10 mg/m³).

The total mass of smoke particulate at the alarm threshold for detection is 55 mg at 140.5 mg/s and 70.3 mg at 28.1 mg

Smaller volume facilitates detection.

Mixed Systems

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	Vehicle Habitable Volume	Air Flow Rate	HEPA Filtration	Smoke Alarm setting	Pyrolysis Rate	Total Mass Cellulose Pyrolyzed to alarm	Mass Kapton pyrolyzed to alarm	Mass Teflon pyrolyzed to alarm	Mass Polyvinyl Chloride pyrolyzed to alarm	CO (Bulk Kapton)	HF (Bulk Teflon)	HCN (Bulk Kapton)	HCl (Polyvinyl Chloride)	CO_2 (Bulk Teflon)
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Conclusions

- Effectiveness of smoke detection is strongly affected by the vehicle ventilation system
- High flow rates can lead to large dilution rates in flow-through systems
- Air filtration competes with smoke production in mixed systems
- This can lead to:
  - Non-detection
  - Buildup of undesirable components that are not filtered.
- It may be possible to filter at a lower rate which enables crew comfort while still fostering rapid detection
- Spacecraft fire detection systems (measured parameter, locations, thresholds) should be designed in tandem with the air filtration system

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