Particle and Smoke Detection on ISS for Next Generation Smoke Detectors

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Rapid fire detection requires the ability to differentiate fire signatures from background conditions and nuisance sources. Proper design of a fire detector requires detailed knowledge of all of these signal sources so that a discriminating detector can be designed. Owing to the absence of microgravity smoke data, all current spacecraft smoke detectors were designed based upon normal-g conditions. The removal of buoyancy reduces the velocities in the high temperature zones in flames, increasing the residence time of smoke particles and consequently allowing longer growth time for the particles. Recent space shuttle experiments confirmed that, in some cases, increased particles sizes are seen in low-gravity and that the relative performance of the ISS (International Space Station) and space-shuttle smoke-detectors changes in low-gravity; however, sufficient particle size information to design new detectors was not obtained. To address this issue, the SAME (Smoke Aerosol Measurement Experiment) experiment is manifested to fly on the ISS in 2007. The SAME experiment will make measurements of the particle size distribution of the smoke particulate from several typical spacecraft materials providing quantitative design data for spacecraft smoke detectors. A precursor experiment (DAFT: Dust Aerosol measurement Feasibility Test) flew recently on the ISS and provided the first measurement of the background smoke particulate levels on the ISS. These background levels are critical to the design of future smoke detectors. The ISS cabin was found to be a very clean environment with particulate levels substantially below the space shuttle and typical ground-based environments.

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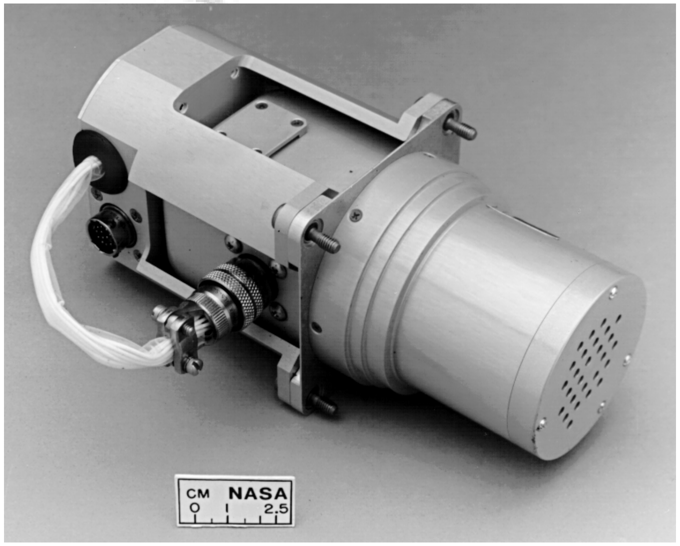
Background: Spacecraft Fire Detection

- Fire detection strategies for spacecraft have largely been based upon 1-g understanding.
- Soot particle size distributions are larger in μ-g flames.
  (work of Ku, Faeth and Choi)
- Results from a limited data set of μ-g smoke particulate suggest that smoke particle sizes are substantially larger for both solid and liquid smoke aerosols (McKinnon and Apostalakis)
- Proper design of spacecraft fire detection systems will require measurements of the particle size distributions of typical μ-g smoke sources.

Background: Spacecraft Fire Detection



STS Detector: sensitive < 1 micron

•dual-chamber ionization detector

•vane pump provides inertial separation system

•designed to make the detector insensitive to particulate larger than 1 to 2μm

•fairly large power consumption (9 Watts)

•fan noise and limited life due to the moving parts

•Installed in avionics air returns (possible reason for fan)

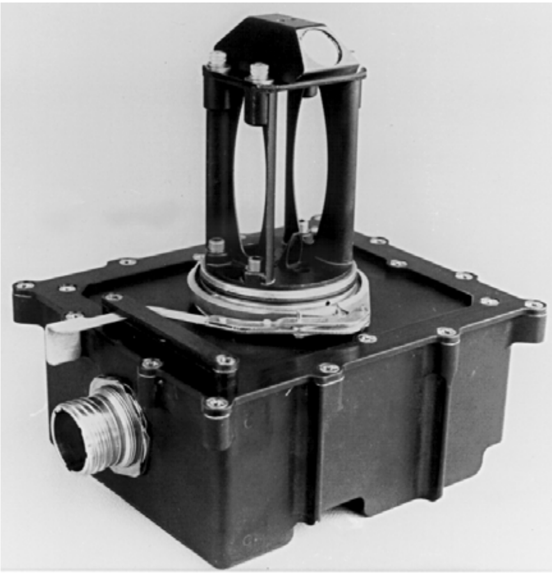
• Developed in the late 70’s when Ionization detectors were prevalent

•Limited 1-g testing supported small particle size distribution for incipient fires

•Detector was designed to reject particles with aerodynamic diameters greater than 1-2 microns.

• Decades of service with very few false alarms and no alarms.

Background: Spacecraft Fire Detection



ISS detector: most sensitive to particles larger than 1 micron

- **2-pass IR laser diode forward scattered light (30 degrees).**
- **minimum reported sensitivity is 0.3 μm**
- **Low power (1.5 W)**
- **Silent**
- **Installed in air ducts and in cabin area (with light shroud)**

Developed in the 90's and took advantage of the availability of stable diode light sources.

Years of continuous ISS service with some false alarms and no alarms.

Background: Spacecraft Atmosphere

- **Both the ISS and the Shuttle have air filtration systems to remove dust and other suspended particulate.**
- **Airborne particulate has previously only been measured once (STS 32 in 1990) by Liu et al.**

  Two cascade impactors

  Light scattering device.

  Impactors reported a bimodal particle size distribution with ~ 40% of the particles in each of the 2.5 to10 µm and >100 µm ranges.

  Light Scattering device showed higher particulate concentrations than typical 1-g environment.

Background: Spacecraft Atmosphere

Comparison of STS-32 to Indoor Environments

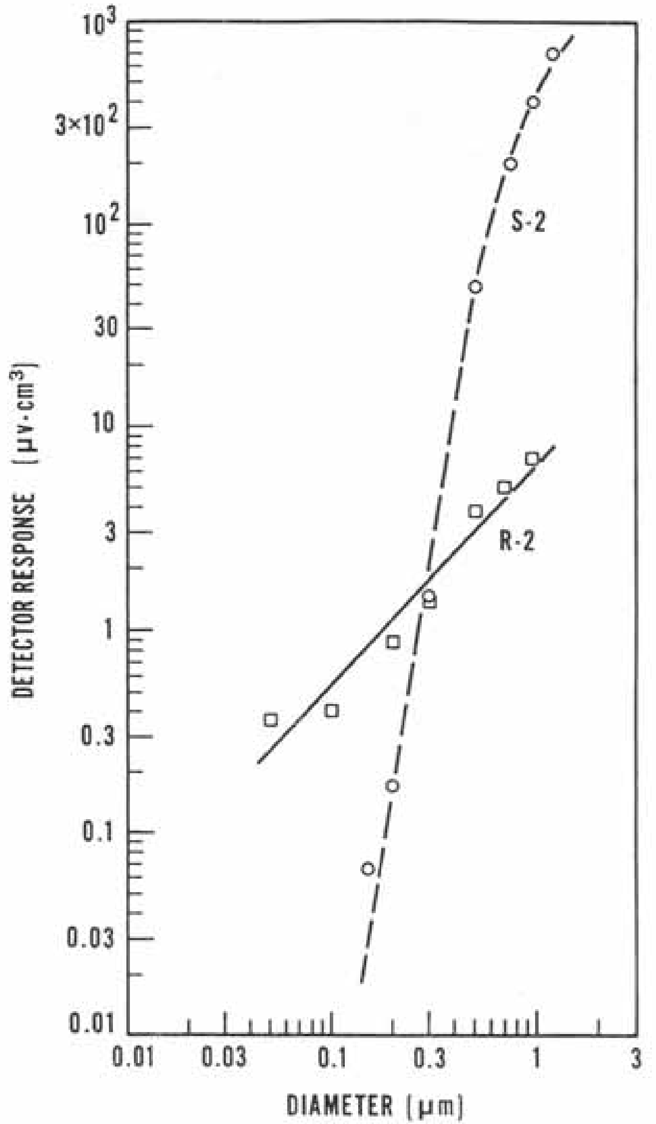
Sample	Particle Size Range				
Location	<2.5µm	2.5-10µm	10-100µm	>100µm	Total
	Mass Concentration, µg/m^3				
Shuttle	2.3	24.1	4.8	28.1	59.3
Shuttle	2.1	13.4	6.2	31.8	53.5
Home	3.0	3.0	1.0	1.5	8.5
Office	3.4	3.2	2.7	1.9	11.2
Laboratory	2.9	4.8	2.0	2.4	12.1
	Average Mass Concentration µg/m^3				
Ave. Shuttle	2.2	18.7	5.5	30.0	56.4
Ave. Indoor Environment	3.1	3.7	1.9	1.9	10.6
	Ratio of Mass Concentration				
Shuttle/Indoor	0.71	5.1	2.9	15.8	5.3

Residential (1-g) background

Well ventilated flames and established fires emit smaller particulate with sizes readily detected by ionization detectors

- Smoldering fires and over-heated (pyrolyzing) materials produce larger particulate favoring scattering detectors.
- Ionization detectors were favored in the 1970's though the mid 1990's due to the difficulty of producing light sources that would remain stable for several years.
- The advent of improvements in light emitting diode and diode laser technology has reduced the cost and increased the stability of photoelectric fire detectors.

Detector sensitivity



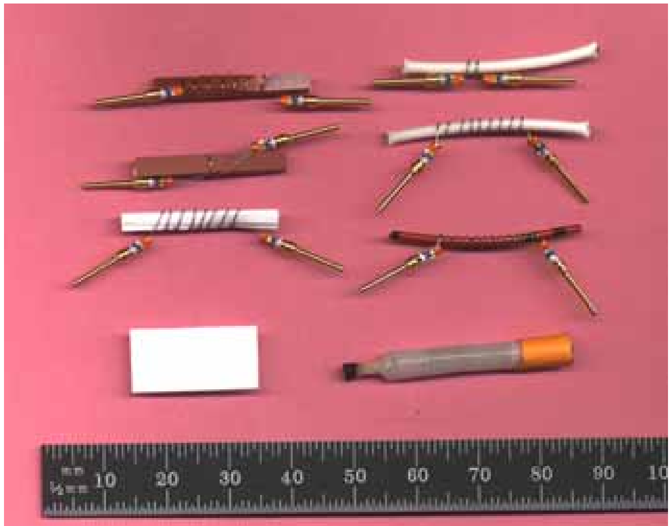
Ionization and scattering detector response ((detector output –background)/ particle concentration) versus diameter for light scattering (S-2) and ionization (R-2) detectors (Mulholland and Liu, 1980).

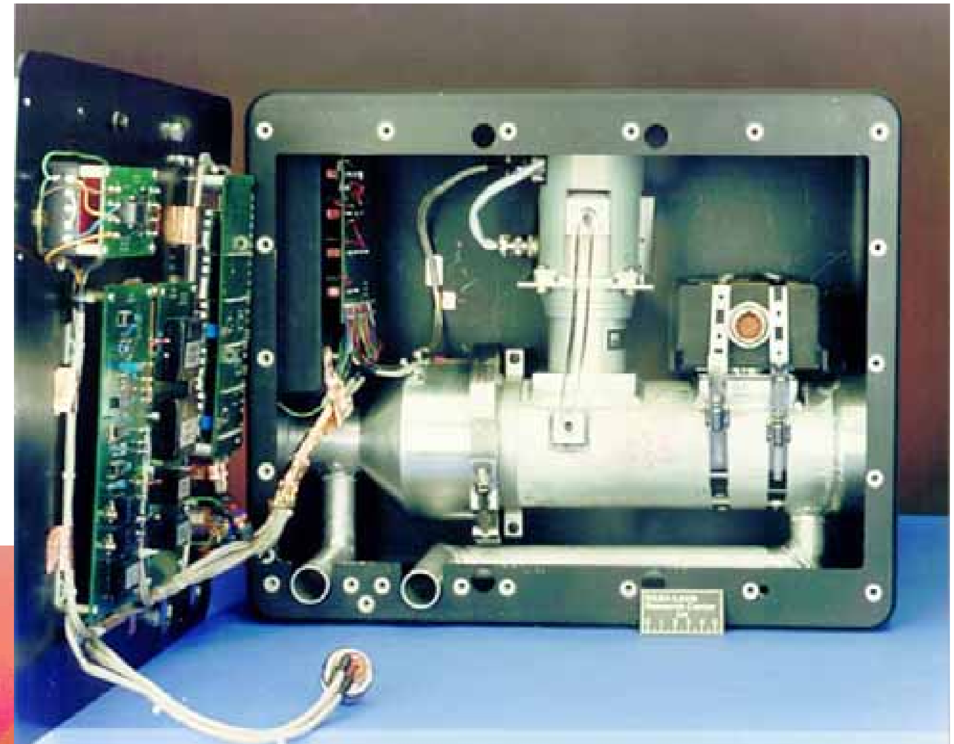
Effect is amplified by decrease in number concentration as particle size increases

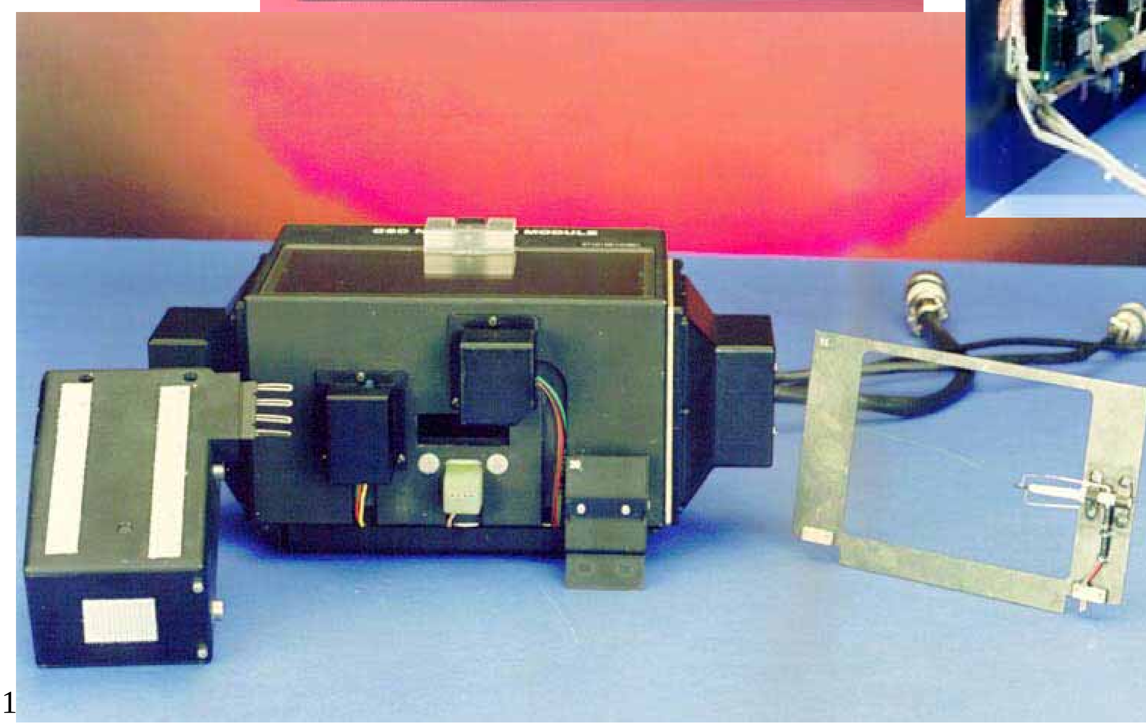
CSD Experiment (STS-75)

- **Mid-deck Glovebox experiment on STS-75**
- **Low cost comparison of existing detector performance for several smoke types**
- **Limited diagnostics:**
  - **Smoke detectors**
  - **Thermophoretic particle capture**
  - **Light extinction**

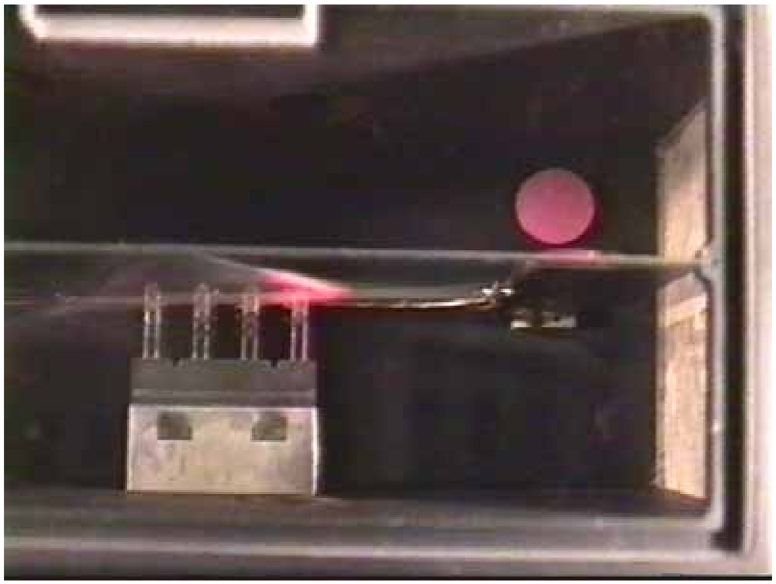
CSD Experiment Hardware



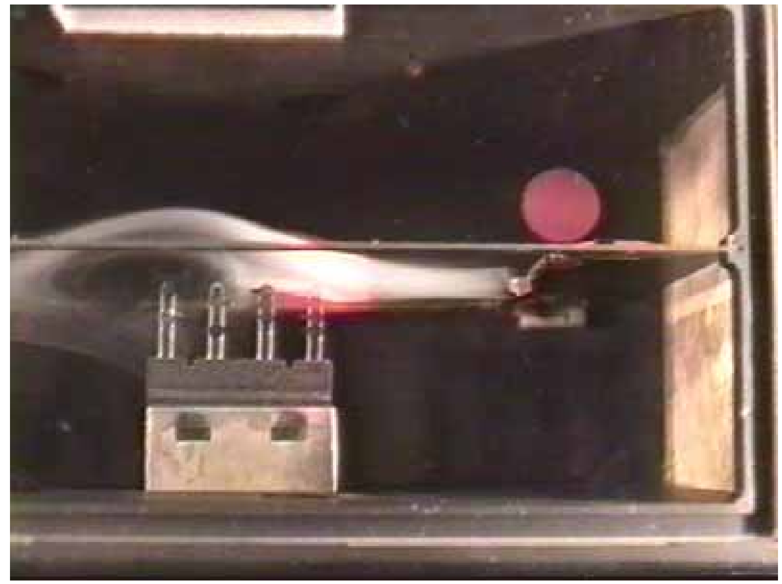




CSD results

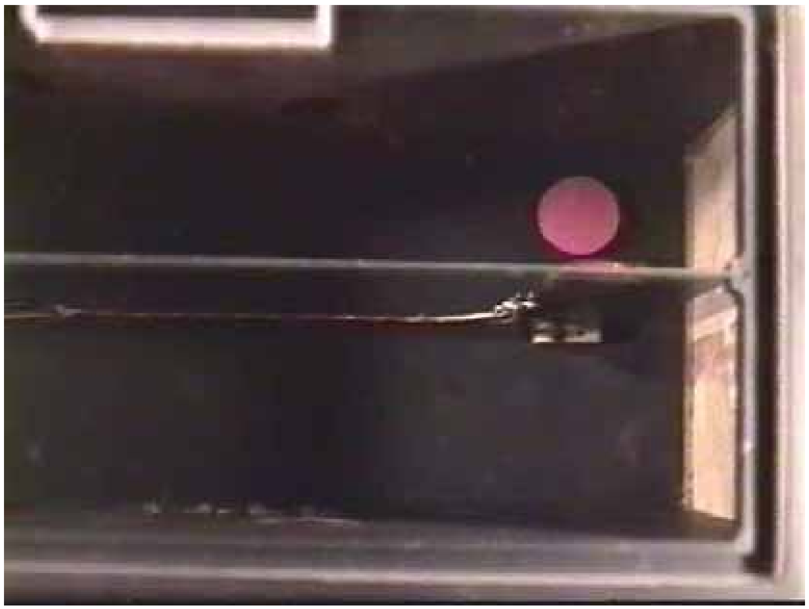


0-g results for Kapton.

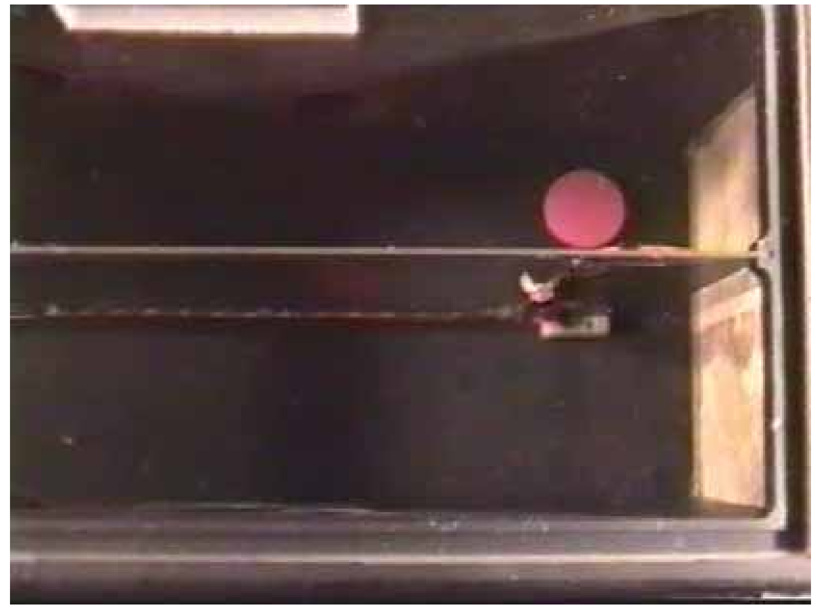


0-g results for silicone rubber.

CSD results

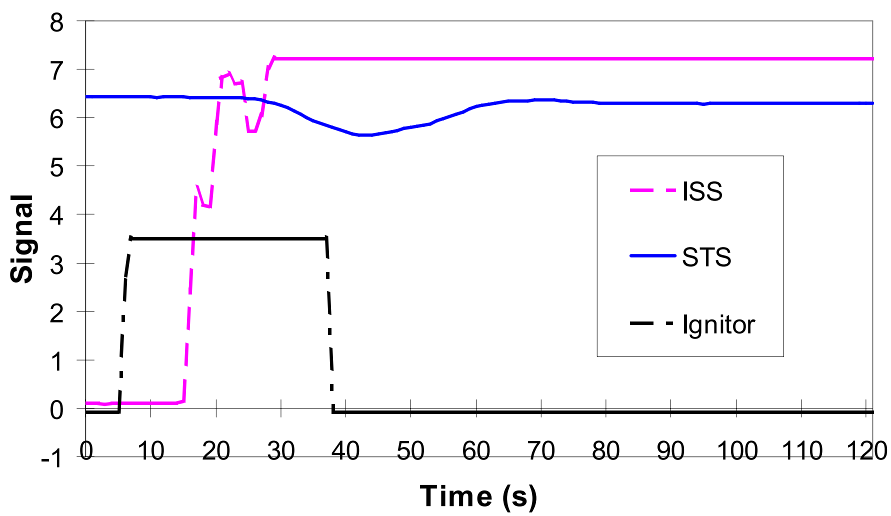


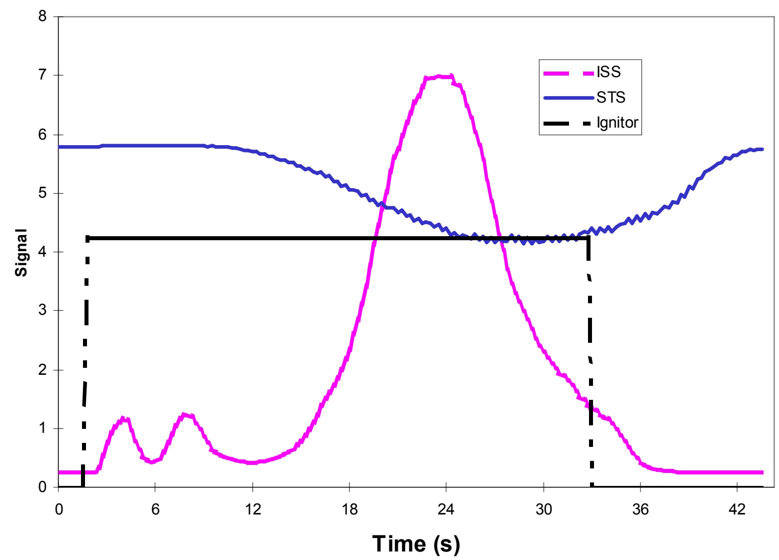
0-g results for Kapton.



0-g results for silicone rubber.

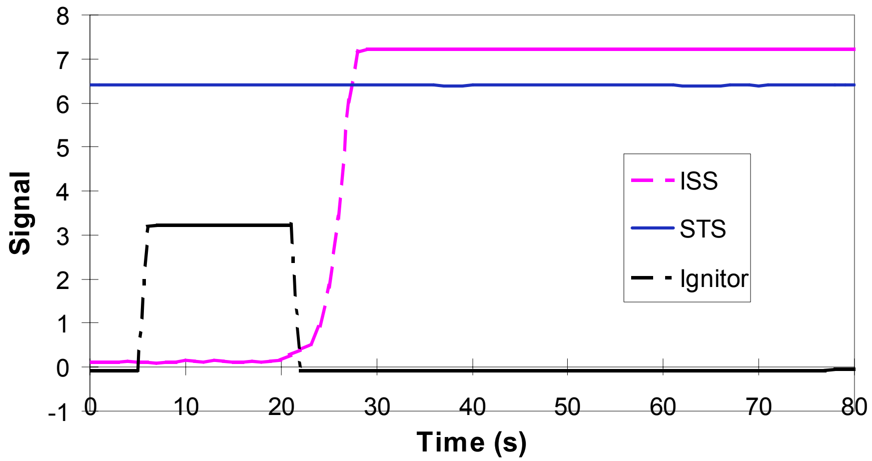
CSD results: detector signals: Kapton



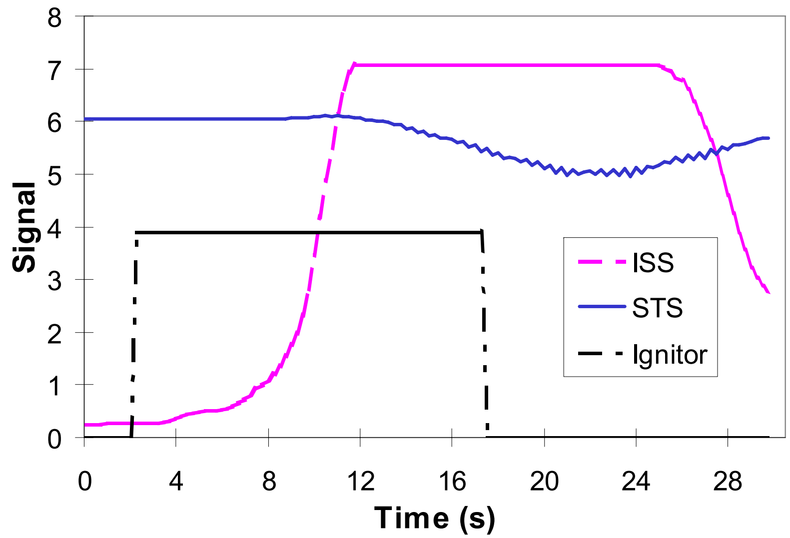


0-g **1-g**

CSD results: detector signals: Silicone Rubber

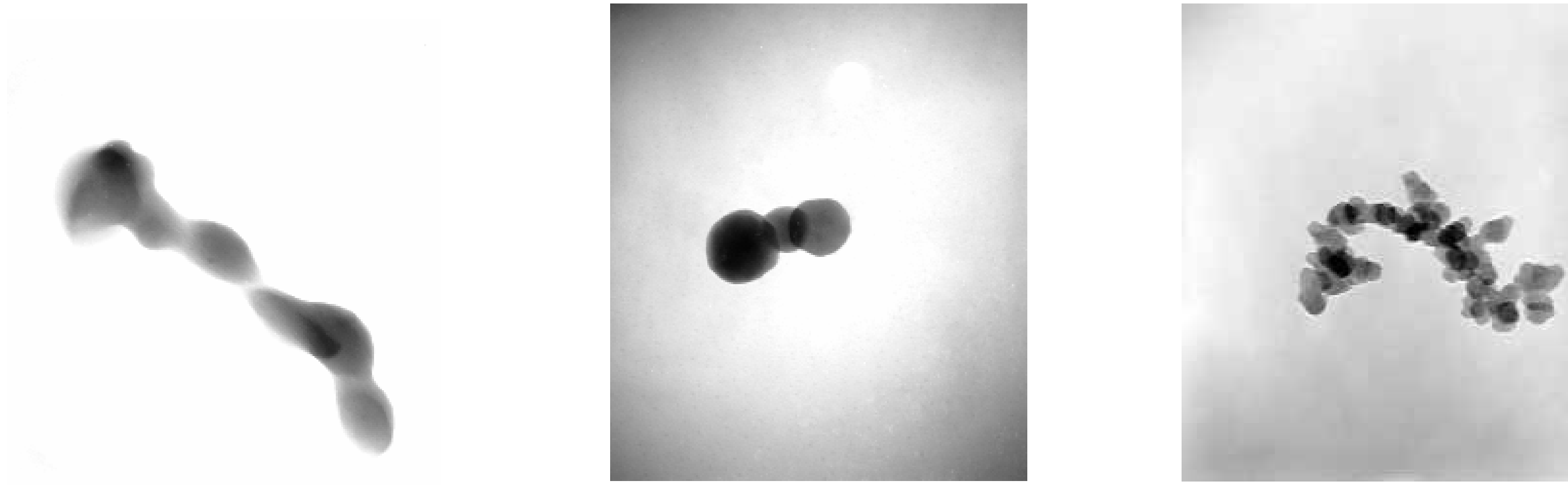


0-g



1-g

CSD results:
smoke particle dimensions



From left to right images of microgravity particulate from overheated Teflon and Kapton and candle soot. Images are at the same magnification. Average particle dimensions are shown below.

Material	Low-g Primary Diameter (nm)	1-g Primary Diameter (nm)	Low-g Aggregate Length (nm)	1-g Aggregate Length (nm)
Kapton	**76**	**35**	**223**	N/A
Candle	**34**	**17**	**976**	**265**
Teflon	**136**	**75**	**662**	**277**

CSD results:
smoke detector performance

	Test Runs		
Material	Total	Detected by ISS detector	Detected by STS detector
Paper	5	2	1
Candle	4	3	2
Silicone Rubber	5	5	0
Teflon	6	3	2
Kapton	5	4	4

SAME Experiment

- **CSD demonstrated**
  - **Smoke detector design must be based on low-g data**
  - **Liquid smoke aerosols require on-orbit measurement of smoke particulate size distribution**

- **Power and mass limitations prevent direct measurement of the smoke particle size distribution**

- **Integral measures (moments) of the particle size distribution were chosen as the best approach**

- **SAME (Smoke Aerosol Measurement Experiment) Shipped and ready for launch this summer**

SAME

Smoke Aerosol Measurement Experiment

Motivation

- **Droplet size for liquid-smoke aerosols are essentially unknown.**
- **Particulate dimensions for solid-particulate smoke have been measured for a small number of particles.**

Despite its demonstrated effectiveness, smoke detection has remaining challenges for spacecraft:

- **Increased importance on longer missions**
- **The current state of knowledge is insufficient to truly assure system effectiveness.**
- **Rational design and implementation require better smoke particulate size distribution information.**

This research will directly improve crew safety and mission assurance by providing data necessary to ensure reliable detection of incipient spacecraft fires, ensuring the safety of future crews and missions.

Moment Analysis

For a particle size distribution $$f_N(D) = \frac{dN}{dD}$$

The moments are: $$M_i = \int D^i f_N(D)\, dD$$

Where

i =0 : Number Concentration Moment

i = 1 : Diameter Concentration Moment, Proportional to the ionization detector moment

i = 3 : Mass Concentration Moment

Moment Analysis (Cont'd)

From these measurements, it is possible to calculate:

Arithmetic mean diameter, (D_{10}): M_1/M_0

Diameter of average mass, (D_{30}) : $(M_3/M_0)^{1/3}$.

Assuming a log-normal distribution:

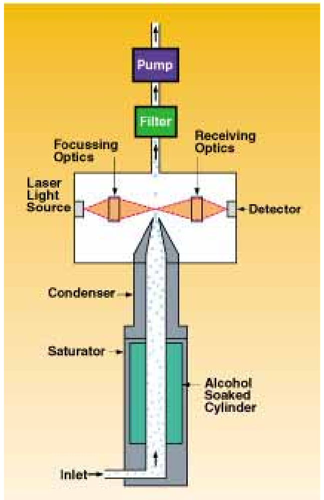
the geometric mean number diameter D_g can be found by:

$$D_{qp} = D_g \exp((q + p/2)\ln^2 \sigma_g)$$

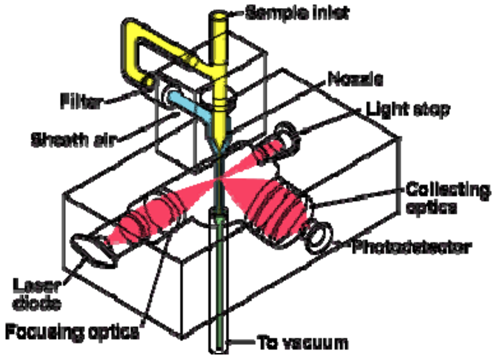
and the geometric standard deviation σ_g is:

$$\sigma_g = \exp\left(\ln(D_{30}/D_{10})\right)^{1/2}$$

SAME: Moment Instruments:



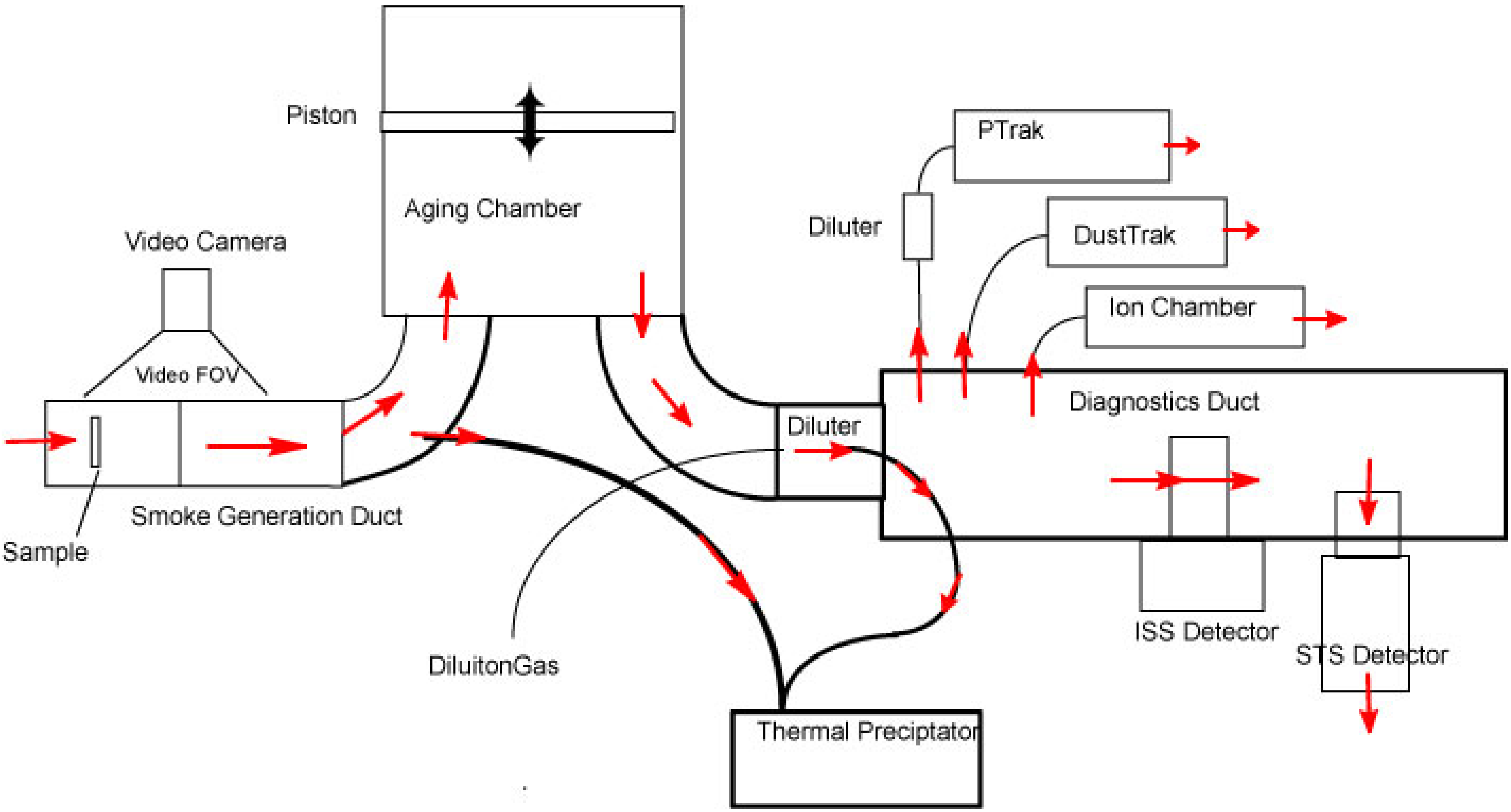
First Moment:
First Alert™
Smoke Detector



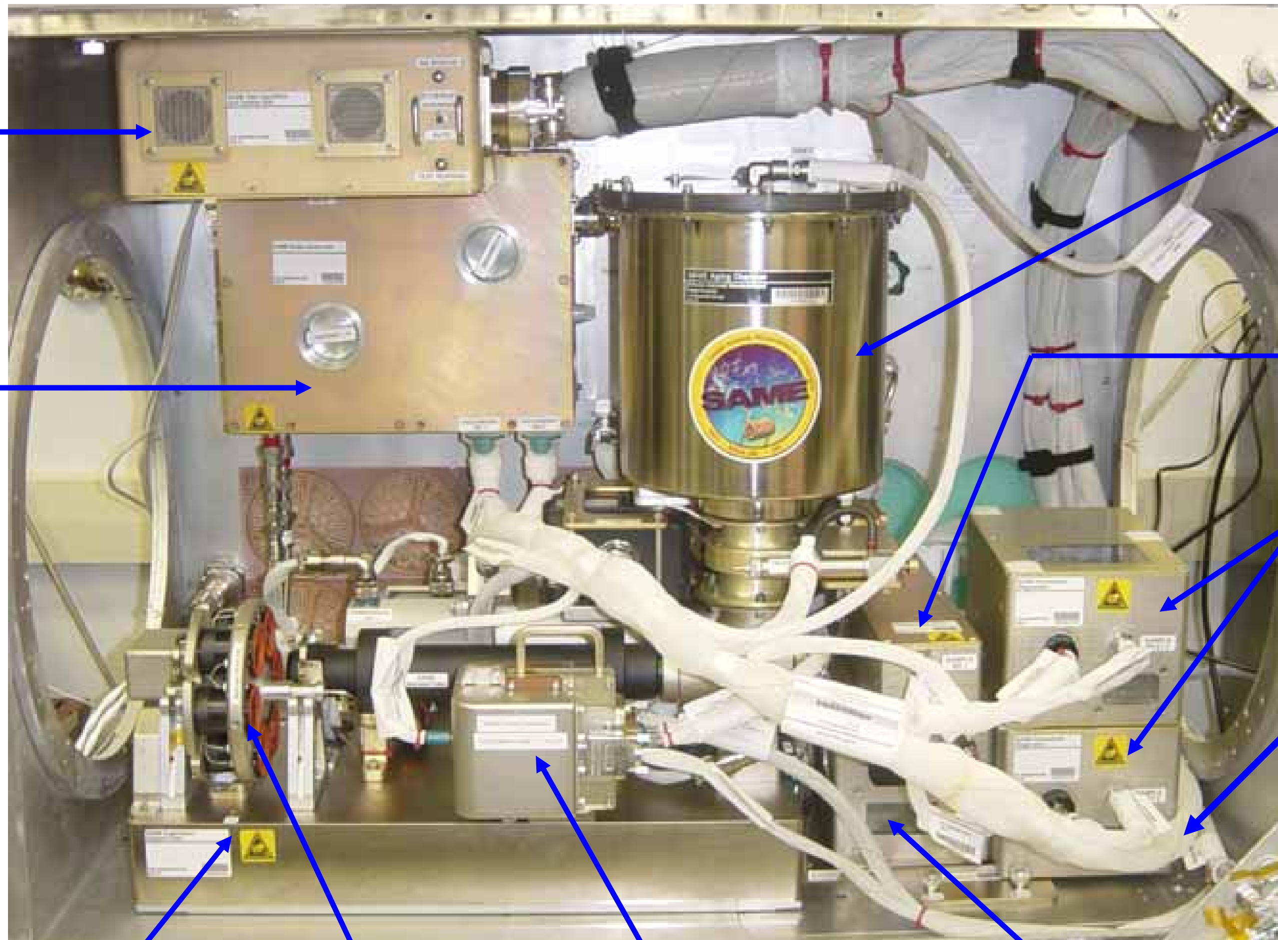
Zeroth Moment:
TSI PTrak™

Third Moment:
TSI Dust Trak™

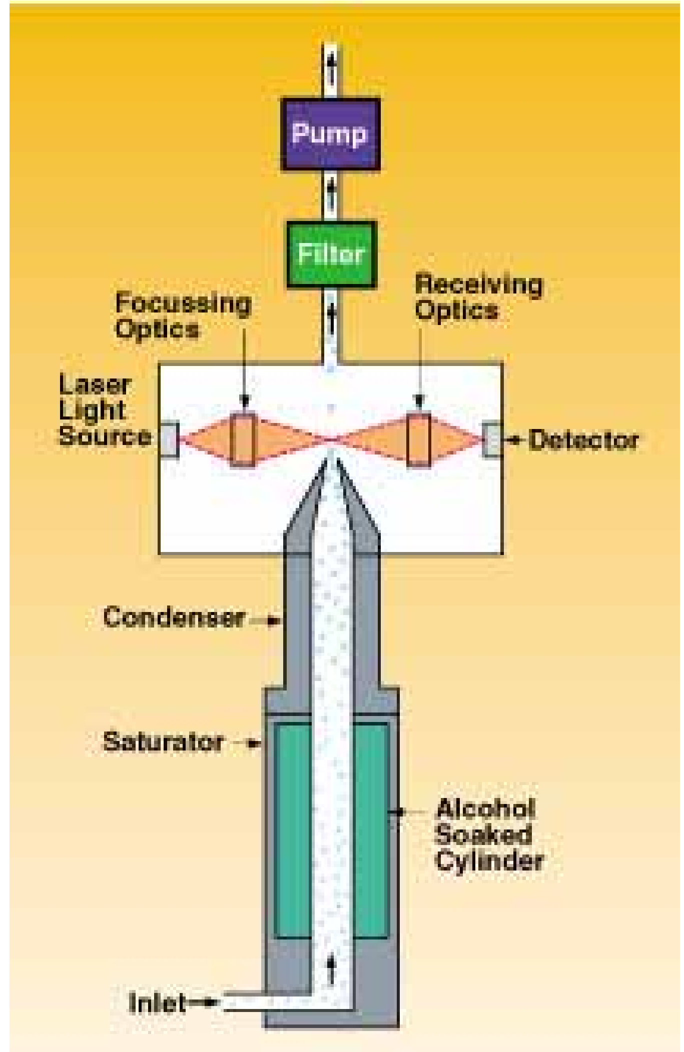
Experimental Layout



SAME in MSG (mockup)



DAFT Motivation: low-g operation of the PTrak



Control of the condensate in the condenser was not assured in low-gravity so a rapid turn around experiment was proposed
DAFT:
Dust Aerosol Measurement Feasibility Test

DAFT:

Dust Aerosol Measurement Feasibility Test

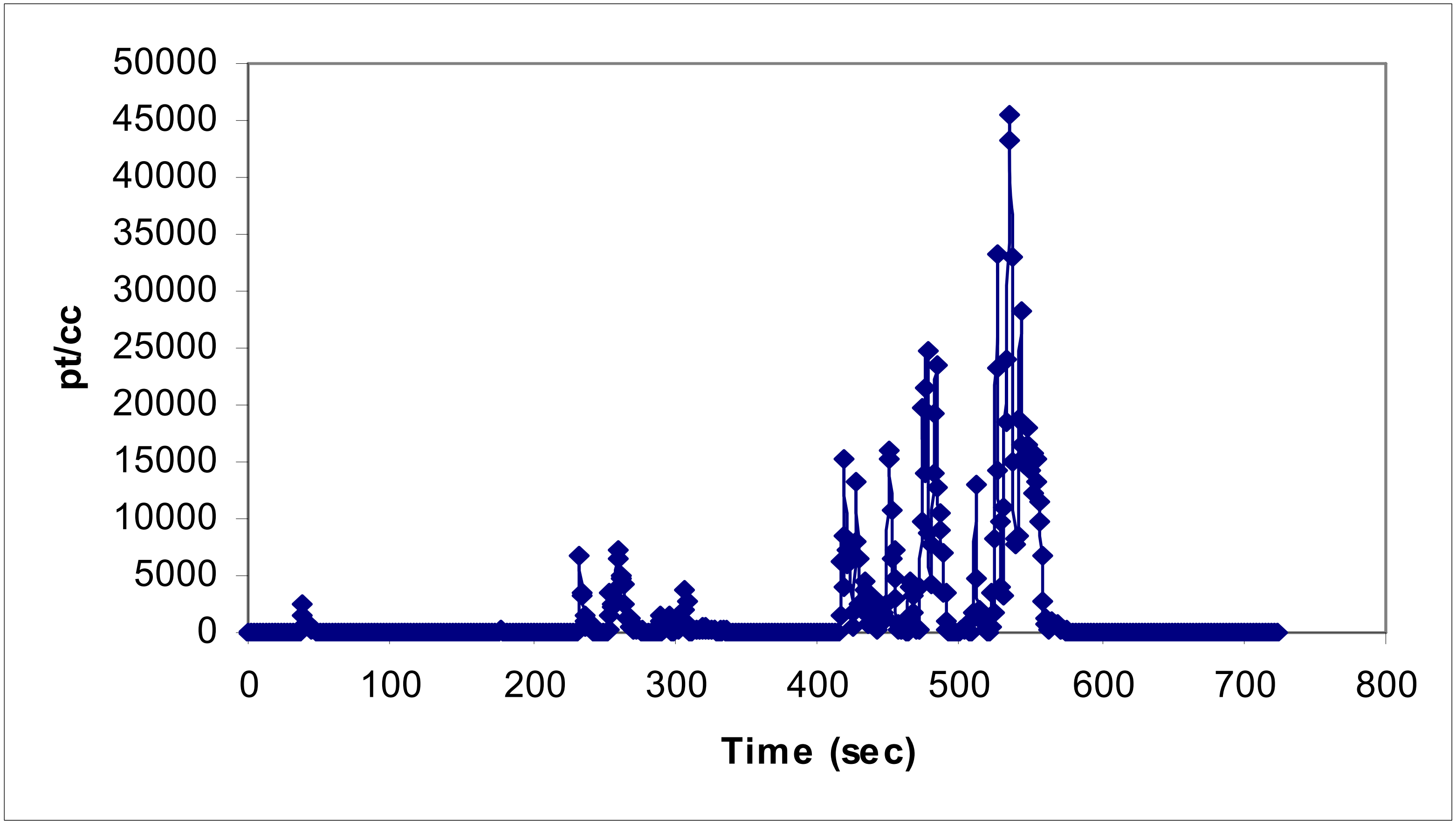
- Flew a P-Trak and Dust Trak on Expedition 10
- And then a reference source on Expedition 13

DAFT 1-2: Results

- Sampled undisturbed air at 2 locations in the lab and in the node
- One test deliberately generated aerosol by separating Velcro
- Average values of cabin air less than
  - 0.005 mg/m3 (Dust Trak)
  - 15 particles /cm3 (P-Trak)
- **Substantially cleaner than the shuttle or typical office environment**

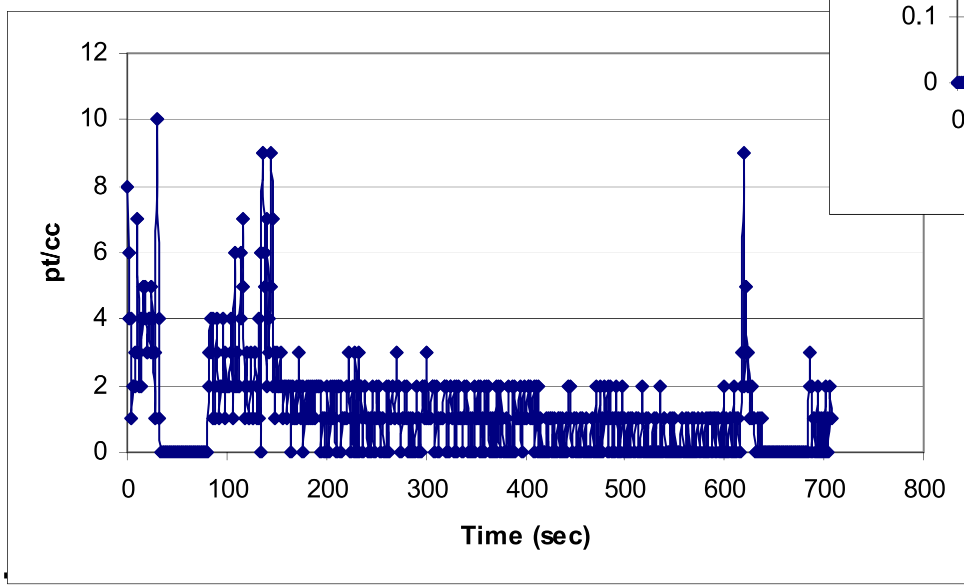
DAFT: Results

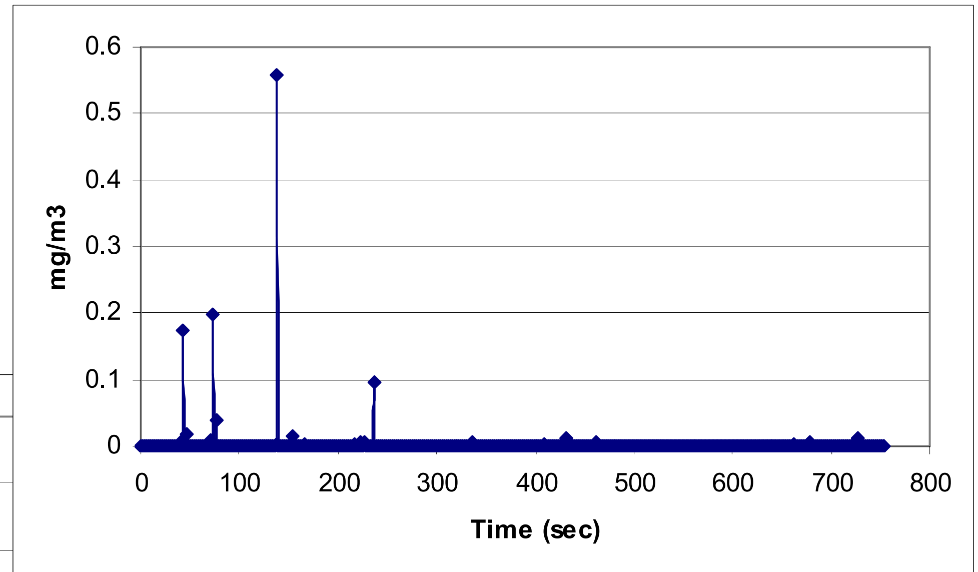
Velcro separation



DAFT: Results

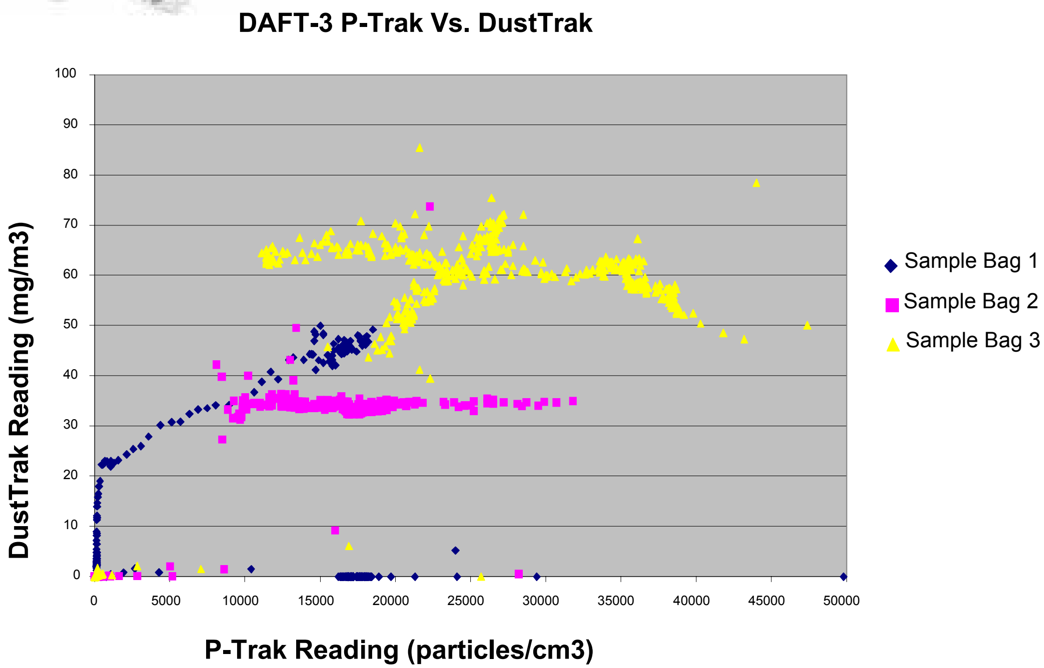
Measurements in the Lab





DAFT 3-4: Results

Comparison with reference dust



- **Sampled reference dust source for 3 runs. Data compared well for first run before effects of low alcohol became significant.**

- **Demonstrated the functionality of the modified P-Trak in low-g**

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