Contamination Impact of Station Brush Fire on Cleanroom Facilities

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ABSTRACT

Brush and forest fires, both naturally occurring and anthropogenic in origin, in proximity to space flight hardware processing facilities raise concerns about the threat of contamination resulting from airborne particulate and molecular components of smoke. Perceptions of the severity of the threat are possibly heightened by the high sensitivity of the human sense of smell to some components present in the smoke of burning vegetation.

On August 26th, 2009, a brushfire broke out north of Pasadena, California, two miles from the Jet Propulsion Laboratory. The *Station Fire* destroyed over 160,000 acres, coming within a few hundred yards of JPL. Smoke concentrations on Lab were very heavy over several days. All Lab operations were halted, and measures were taken to protect personnel, critical hardware, and facilities. Evaluation of real-time cleanroom monitoring data, visual inspection of facilities, filter systems, and analysis of surface cleanliness samples revealed facility environments and hardware were minimally effected.

Outside air quality easily exceeded Class Ten Million. Prefilters captured most large ash and soot; multi-stage filtration greatly minimized the impact on the HEPA/ULPA filters. Air quality in HEPA filtered spacecraft assembly cleanrooms remained within Class 10,000 specification throughout. Surface cleanliness was minimally affected, as large particles were effectively removed from the airstream, and sub-micron particles have extremely long settling rates. Approximate particulate fallout within facilities was 0.00011% area coverage/day compared to 0.00038% area coverage/day during normal operations. Deposition of condensable airborne components, as measured in real time, peaked at approximately1.0 ng/cm2/day compared to 0.05 ng/cm2/day nominal.

Keywords: Cleanrooms, brushfire, smoke, ash, airborne contamination, airborne particulate contamination

Background

The Jet Propulsion Laboratory (JPL), a Federally Funded Research and Development Center, funded by NASA and maintained by the California Institute of Technology, sits at the base of the San Gabriel Mountains north of Pasadena, California. JPL has over 100 separate cleanrooms, varying from Class 10 (ISO Class 4) semiconductor fabrication facilities to Class 10,000 (ISO Class 7) Integration and Test High & Low Bays, Class 100,000 (ISO Class 8) Laboratory Cleanrooms and Class 300,000 (ISO Class 8.5) Controlled Environments.[i] Facilities vary significantly in age, design features and environmental control capabilities, and are spread across more than two dozen buildings on the 177 acre site.

JPL cleanroom facilities use a number of methods to effectively control the entry of solid and gaseous contaminants:

HEPA/ULPA filtration – High efficiency air filters are extremely effective at capturing more than 99.99% of all airborne particulate entering the cleanroom, including particles smaller than 0.1 micron in diameter. By count 99% of all particles are smaller than 1.0 micron in diameter. Typical outdoor air may have millions of particles per cubic foot, several orders of magnitude greater than can be allowed into a typical critical cleanroom environment. A HEPA/ULPA filter, installed at the last point where the air supply enters the cleanroom, insures that all the supply air entering the cleanroom is extremely low in airborne particle numbers. HEPA/ULPA filters typically have a useful life of over five years, however effective prefiltration is necessary to minimize media loading from very large particles, which can dramatically shorten their useful life.

Prefiltration – Intended to capture relatively large debris, various types of prefilters are used to capture gross contaminants before they reach the more critical, expensive carbon and HEPA/ULPA filters. A fraction of the cost of the critical filters, the prefilters remove large particles that would otherwise block the face of critical filters.

Airborne Molecular Contamination (AMC) filters – Non-particle gases will pass through HEPA/ULPA filters, so another type of filtration is required to capture AMC's. Granular filter media are used either to target specific AMC types (e.g. acids or bases) or to adsorb a broad spectrum of general AMC's (e.g. hydrocarbons). Granulated charcoal is a common broad-spectrum adsorbent, often used in cleanroom air handling systems to minimize the influx of outdoor chemicals and gases. Granulated charcoal, aka carbon, filters are expensive to maintain and add considerably to a facility's maintenance and utility costs. AMC filters must be included in the initial fan system design, because carbon filters require a significant amount of fan horsepower to force the air through and are very difficult to retrofit in later on. For that reason AMC filters are not widely used in smaller cleanroom installations. Typically used in granular form, AMC filters tend to shed small particles over time, so they are always installed ahead of the HEPA/ULPA filters.

Positive pressurization – Cleanrooms are pressurized slightly, to prevent the ingress of airborne particulate through doorways, wall seams, service chases and other openings. Typically only 0.05 to 0.08 inches w.g. of static pressure more than the surrounding area, it is sufficient to minimize the influx of particulate.

Increased air exchanges – The volume of supply air entering a typical office environment displaces all of the office air roughly every 15 minutes, producing an air exchange rate of 4 air changes per hour (ACH). Cleanrooms increase that volume of air significantly, from 20 to 500 ACH, to keep particles airborne as they migrate toward the air return grilles. This increases the particle removal efficiency of the air system, and keeps surfaces cleaner long-term by slowing the settling rate of airborne particles.

Recirculation airflow – Typically offices and cleanrooms bring in some outside air to prevent the indoor air from becoming stagnant. Typically 5% of the total room air supply is fresh outside air, while the remaining 95% of the air is being recirculated within the cleanroom or office area. With the increased air exchange rate cleanroom experience, this recirculation air passes through a HEPA/ULPA filter every few minutes, "scrubbing" the air more often and making it cleaner with each pass.

Using these methods effectively, a Class 10,000 (ISO Class 7) cleanroom are typically designed to meet or exceed the tighter air quality requirements of a Class 1,000 (ISO Class 6) cleanroom when no personnel are present.

The Brushfire Threat

Since brushfires have become a way of life in southern California, and drought conditions appear to be increasing in severity with time, the threat of a local or regional brushfire bringing heavy smoke onto the Lab is increasing. Several years ago a Brushfire Response Team was formed which created a plan that would protect critical hardware in JPL cleanrooms in the event of a severe outdoor air quality event.

A three-pronged approach was adopted to provide hardware protection from brushfire smoke contamination:

I. An early warning plan was created, intended to provide as much advance notice as possible of impending smoke arrival on Lab. This would allow hardware-protection measures to be implemented. This plan includes using:

- Continuous monitoring of outdoor air quality for elevated levels of smoke particles
- Monitoring of local outdoor conditions by our Security and Fire Department staff
- Notification by the LA County Fire Department dispatch system
- Notification by radio and television stations which, together with the LA County Fire and Sherriff's department, have a significant aerial presence in Los Angeles and surrounding Counties with helicopters and airplanes

II. Fire/Smoke Response Plans were developed for each building where critical hardware resides. Since buildings can vary significantly in design, construction and air conditioning requirements, each plan was tailored for that building. Hardware protection methodologies could include covering with clean bagging material with a clean gas purge, or storage in a vacuum chamber or shipping container.

III. Continuous facility monitoring during the event, and structured facility recovery efforts after the event to minimize recovery time. Facility monitoring equipment installed in several critical cleanroom facilities provide continuous data regarding airborne particulate concentrations and real-time molecular deposition rates on surfaces throughout the event. Particle fallout collection wafers located in those facilities provide post-event cumulative data regarding surface cleanliness levels for particle fallout as well as molecular deposition.

Housekeeping efforts are also increased to minimize the entry of ash fallout into the cleanrooms, and to address any potential particle/molecular deposition on surfaces. Facilities personnel immediately inspect and replace all building inlet air filters which have become plugged with ash fallout. HEPA filter performance and remaining life is also evaluated to determine the impact.

The Station Fire

The Station Fire started on August 26, 2009, and was the largest fire in the recorded history of Angeles National Forest (est. 1892) and the 10th largest fire in California since 1933. It started off the Angeles Crest Highway (SR 2), only four miles north of JPL, and resulted in the eventual destruction of 160,577 acres (250 square miles) of forest in the Angeles National Forest and the deaths of two firefighters. It burned for nearly seven weeks due to the heavily wooded, mountainous terrain, and was determined to have been caused by arson[ii].

Prevailing winds pushed the fire primarily northwest and east, along with the smoke, but during the first week the fire also moved gradually south, toward JPL and other heavily populated districts. The fire eventually came within ¼ mile of the Lab before its advance was halted.

Figure 1. Station Fire in hills above the Jet Propulsion Laboratory

Typically, southerly winds at night would bring brushfire smoke down over the Lab until a northerly wind shift in the late morning pushed the smoke away and air quality improved dramatically. As soon as the potential severity of the fire situation was understood by JPL management, the Brushfire Response Team activated the Fire/Smoke Response Plans for each building which contained critical or sensitive hardware. Cleanroom Managers and each Project Manager were notified of the potential severity of the smoke threat and were instructed to protect their facilities and hardware; the cognizant Contamination Control Engineer for each project was tasked with assessing the project-specific risk. JPL's Management Operating Committee (MOC) began having daily meetings to review the fire spread, weather patterns, wind predictions and real-time air quality data collected by JPL's BRushfire Airborne Hazards Monitoring System (BRAHMS) outdoor air quality monitor to decide whether closing the Lab would be necessary.

As the fire gradually moved south, air quality on Lab degraded more each day, reaching a peak on Sunday, August 30th, with airborne particle levels twenty times higher than normal, 126 million particles per cubic foot of air at 0.1 microns in diameter. While the immediate threat from the fire to the Lab gradually abated, visibility on Lab remained poor, and filter masks were necessary to protect security and fire personnel from airborne ash and smaller particulate. A decision was made to keep the Lab closed on Monday, August 31st to all but mission-critical staff and safety personnel.

On Monday, August 31st, a small team was permitted to visit the Lab to perform visual inspections of critical program cleanrooms. This effort was intended to assess cleanroom integrity, and to anticipate the effort necessary to resume flight hardware processing in the 120 cleanroom complexes scattered across the JPL campus.

Cleanrooms, by design, minimize the entry of contamination from external sources. Unfortunately, OSHA requirements and Good Manufacturing Practices stipulate that some outdoor air must be brought into the cleanroom to maintain healthy air for personnel, and to evacuate toxic process gases. Aerospace cleanrooms typically have between 5% and 30% outdoor, or makeup, air brought into the cleanroom continuously. Semiconductor cleanrooms often use 100% outside air to prevent the recirculation of dangerous processing chemical vapors. For any cleanroom that is located in a large urban area, the outside air surrounding the plant is typically heavily laden with airborne particulate, as well as a large variety of gases produced by regional and local industries, highways and environmental events (both local or global). Cleanrooms must be designed to minimize the impact on their internal environments by these changing outdoor conditions

During the Station Fire event, while there was a noticeable smoke odor in the cleanrooms, including those cleanrooms which use carbon filters in the air handling units that draw in outside air, there was no visible increase in particle deposition. This is in agreement with data provided by real-time in-situ particle counters and molecular deposition monitors within several cleanrooms.

The Return to Normal Operations

On Tuesday, September 1st, a plan was activated which would put the most critical facilities back in operation as quickly as possible, followed by all remaining cleanrooms. This plan included:

- Restricting access until the cleanroom could be evaluated and cleaned
- Housekeeping staff assessment of each cleanroom, notifying cleanroom and project contamination control engineering if any unusual contamination is observed
- Place all cleanroom garments that were exposed prior to the resumption of operations in the used garment bins for laundering
- More frequent changes of tack mat surfaces
- Maintain/increase area housekeeping effort as necessary
- Limit the number of personnel entering and exiting clean areas
- Analysis of particle fallout wafers exposed throughout the brushfire event for particle size and concentration, as well as molecular deposition
- Cleanroom and hardware surface sampling and analysis for molecular deposition to assess the impact on surface cleanliness

- In parallel, the condition of HEPA filters and all building HVAC air filters were checked, replacing filters where needed

As the fires moved farther northwest and east, smoke levels on lab decreased significantly. As cleanrooms were inspected and cleaned, samples were analyzed for surface particle fallout and airborne molecular contaminant condensation on surfaces. Real-time air quality and surface molecular contamination data from critical cleanrooms was also analyzed to better understand the impact the fires had on the cleanrooms. By the end of the day Tuesday, September 1st, most critical facilities had been returned to normal operation. By Thursday, September 3rd, all facilities had returned to normal operation.

Station Fire impact on Cleanroom Facilities

Figure 2 shows the impact on outdoor air quality during the peak of the Station Fire. 0.1 micron diameter particle concentrations quickly rose from normal levels near five million particles per cubic foot of air to a peak of 126 million particles per cubic foot. The chart also shows the dramatic effect wind direction had on air quality, and how suddenly air quality can degrade/improve, making early fire detection and the implementation of building action plans crucial.

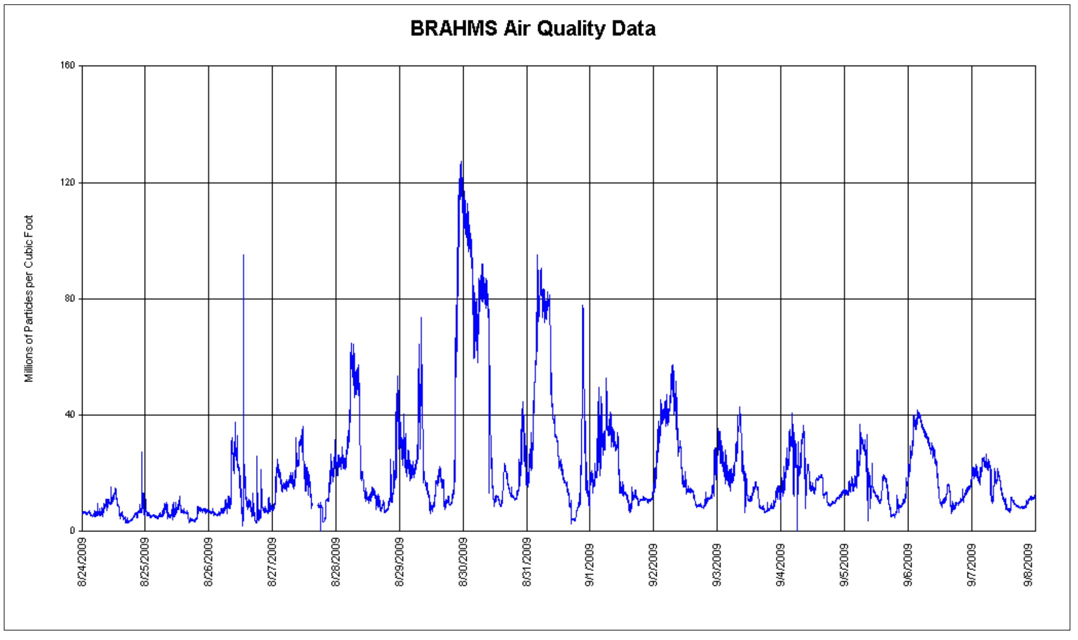


Figure 2. Outdoor air quality during the Station Fire

Figure 3 is an examination of particle size distribution in the outside air over a two-day period at the peak of the fire, showing more clearly the sudden, dramatic changes in air quality that can occur even a mile or less from a major brushfire. Monitoring of weather forecasts and projected wind patterns proved highly valuable in anticipating the potential impact on Lab air quality.

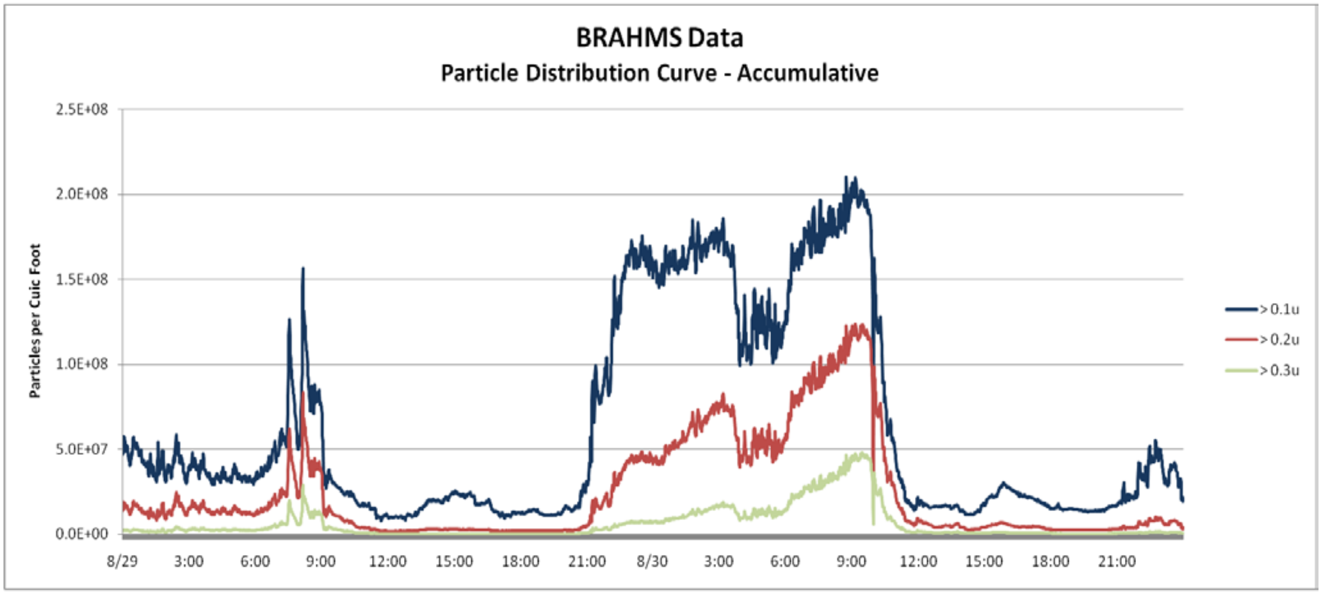


Figure 3. Outdoor air particle distribution curve

One of JPL's most closely monitored cleanrooms is a Class 10,000 (ISO Class 7) Integration and Test High Bay. This cleanroom provides a carefully controlled environment for final integration and test activities for major flight projects.

Air quality in the High Bay during the worst period of the fire is documented in Figure 4, a log-scale presentation of particle concentrations in sizes of ≥0.3 microns and ≥ 0.5 microns in diameter. The High Bay cleanroom remained well within the maximum limits of a Class 10,000 (ISO Class 7) cleanroom throughout the fire, due primarily to the effective use of HEPA filters and maintaining positive pressure in the cleanroom. Other certified cleanrooms also maintained their classification levels when they maintained airflow and positive static pressure. Another facility that suffers from low positive static pressure did experience an influx of visible ash and smaller particulate at an emergency exit door that wasn't sealed tightly.

A week after the peak of the Station Fire, after outdoor air quality had returned to near-normal levels, the High Bay cleanroom experienced a failure of the main air supply fans. Corrective actions were taken, but the fans remained off for several hours. While the High Bay was not occupied during this event, airflow and positive pressure were lost.

As Figure 5 clearly illustrates, the impact on the cleanroom was much more dramatic than the impact from the Station Fire. Airborne particle levels gradually rose to more than 1 million particles per cubic foot of air for ≥ 0.3 micron particles. Large particle levels remained low, as expec ted. While very small particles remain airborne for very long periods and will migrate freely between areas, larger particles tend to settle out quickly and remain stationary until sufficient energy is applied to move them. Thus, the urgency to remove large-particle generators (e.g., people) from a suddenly stagnant cleanroom is well justified.

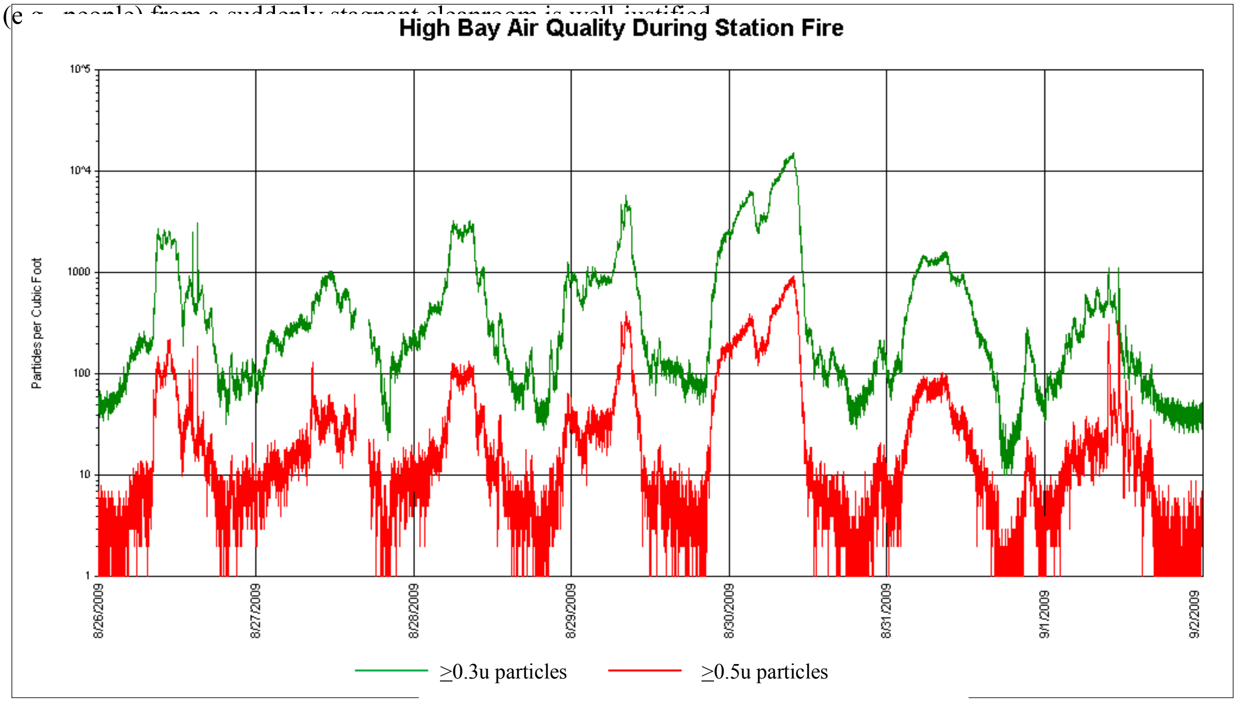


Figure 4. High Bay air quality during the peak of the Station Fire

Particle fallout wafers that were exposed in the cleanroom during both the brushfire and fan failure events were analyzed and found to have remained very clean. Again, the large number of very small particles was fairly irrelevant, because they have settling rates of many hours or even days and are more likely to stay airborne than to settle on surfaces (assuming there is no electrostatic potential on that surface to attract particulate). Large particle levels will remain low as long as particle sources are kept out of the cleanroom and doors remain closed.

Particle fallout accumulations during one month exposure intervals are charted in Figure 6. Large spikes indicate extended periods of intense program activities. The Station Fire and fan failure both occurred during a period of slow work activities, so particle fallout levels were very low. During this time, the Station Fire and fan failure also did not increase particle fallout rates by any significant amount.

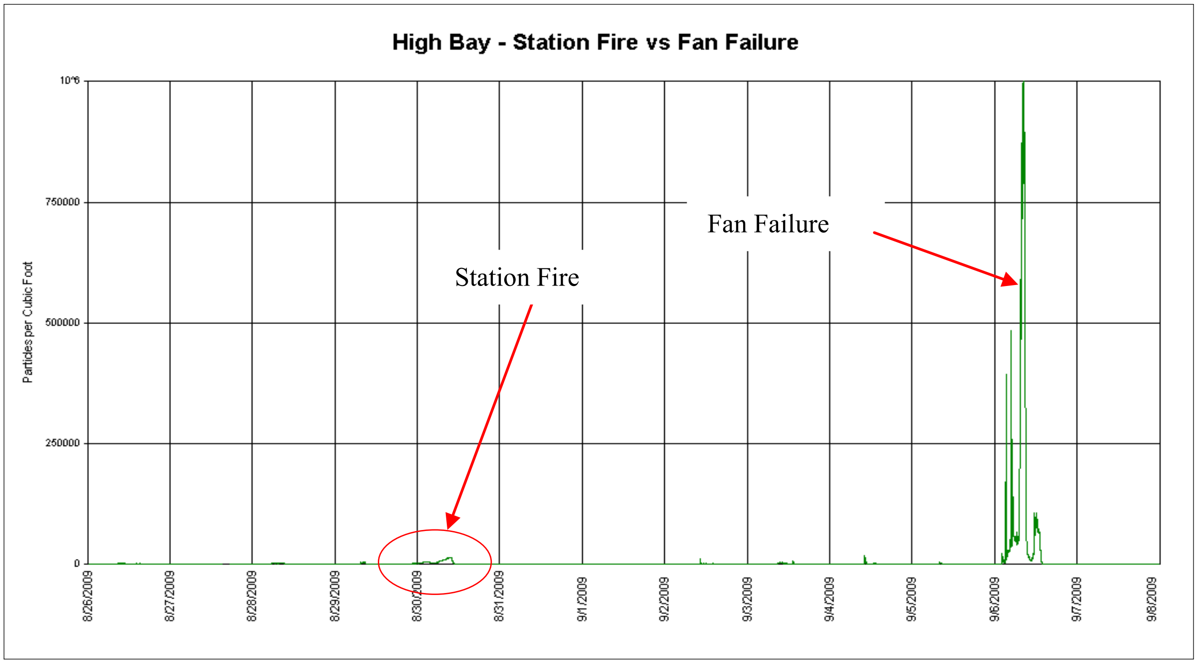
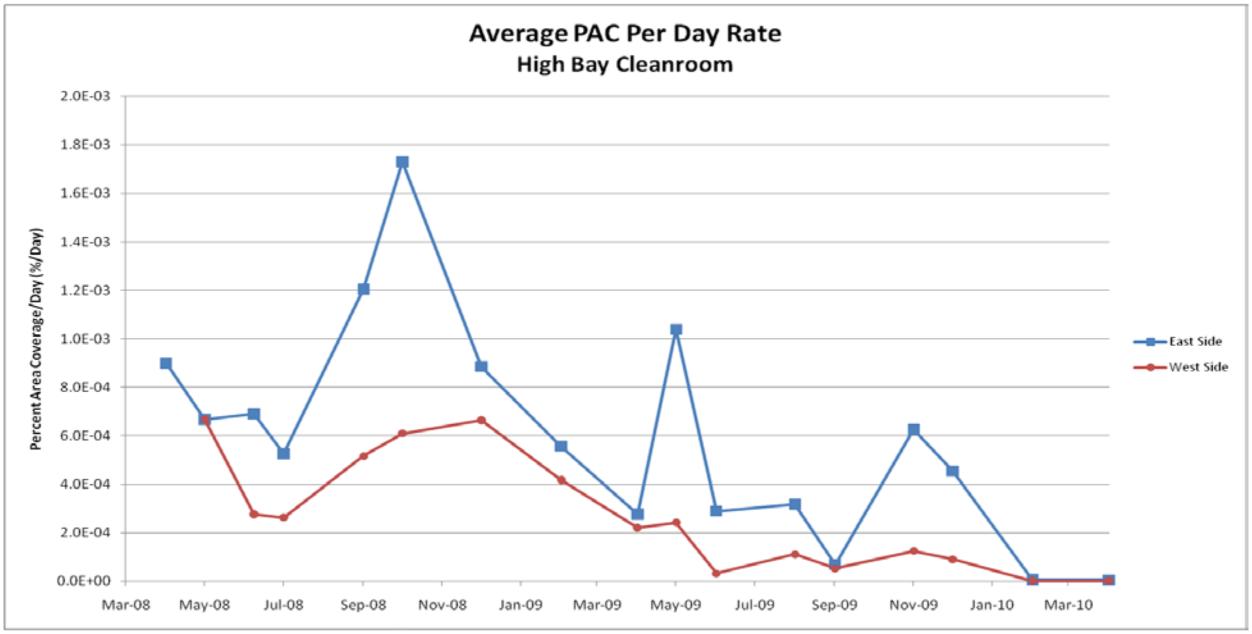


Figure 5. Air quality data – Station Fire verses fan failure



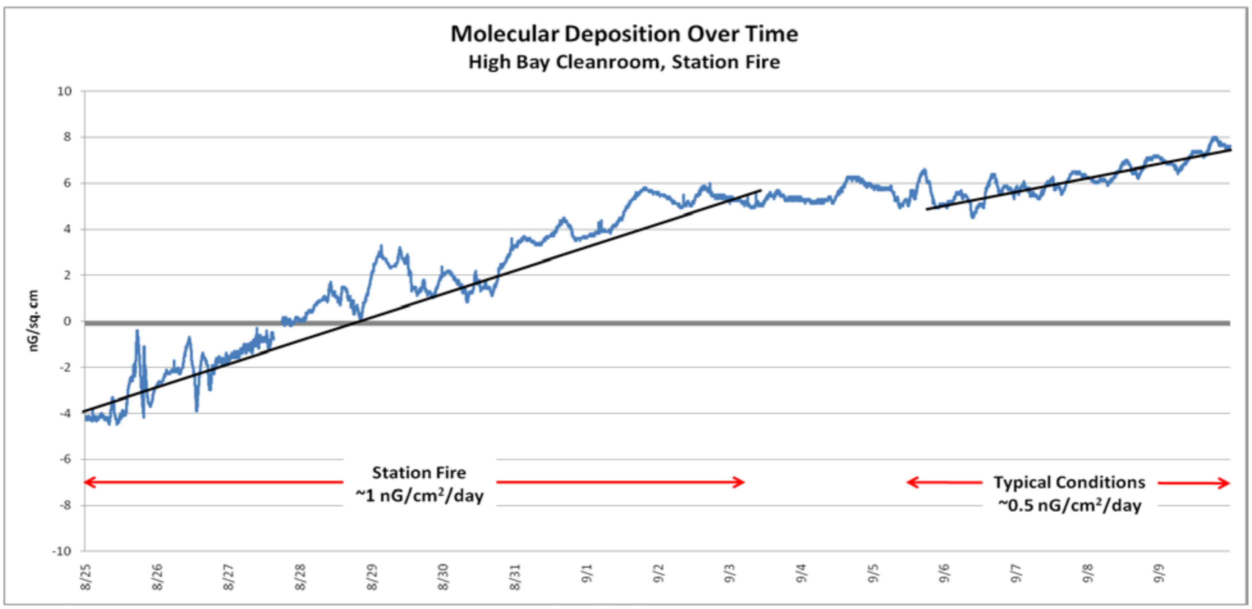


Figure 6. Particle fallout data for a High Bay Cleanroom

Figure 7. Molecular deposition data for a High Bay Cleanroom

In addition to measuring airborne particulate levels, instruments are also installed in several cleanrooms which measure real-time Airborne Molecular Contamination (AMC) deposition rates. Using SAW (Surface Acoustic

Wave) devices, molecular contamination that condenses on a vibrating crystal surface is detected and reported as a mass measurement in nanograms per square centimeter (ng/sq.cm). These devices are optimized for the detection of hydrocarbon-based AMC's.

Under normal operating and environmental conditions, the molecular accumulation rate is always fairly steady, averaging ~0.5 ng/sq.cm/day in the High Bay cleanroom. However, during the Station Fire, as shown in Figure 7, while there are always short-period variations typically caused by humidity changes which affect the instrument sensor, the overall the upward trend was steady, averaging ~1 ng/sq.cm/day, or .33 mg/sq.ft/year (Level A/3 per year, per IEST-STD-CC1246D).

To verify the results of the real-time AMC monitor data, swabs were taken of cleanroom and hardware surfaces for molecular films, and silicon wafers exposed in cleanrooms throughout the event were analyzed for condensable molecular contamination. Every sample tested found that there was no significant increase in molecular buildup on surfaces beyond typical trace quantities of generic aliphatic hydrocarbons and esters (≤ 0.02 µg/cm^2). While there may have been trace quantities of gaseous contaminants entering the cleanrooms during the Station Fire, either the gases were insufficient to condense in significant amounts, or they were sufficiently volatile that they were unable to condense and remain on surfaces at room temperature. Some of the short-term variations in Figure 7 may have been condensation of AMC's on the sensor, with gradual re-vaporization over time.

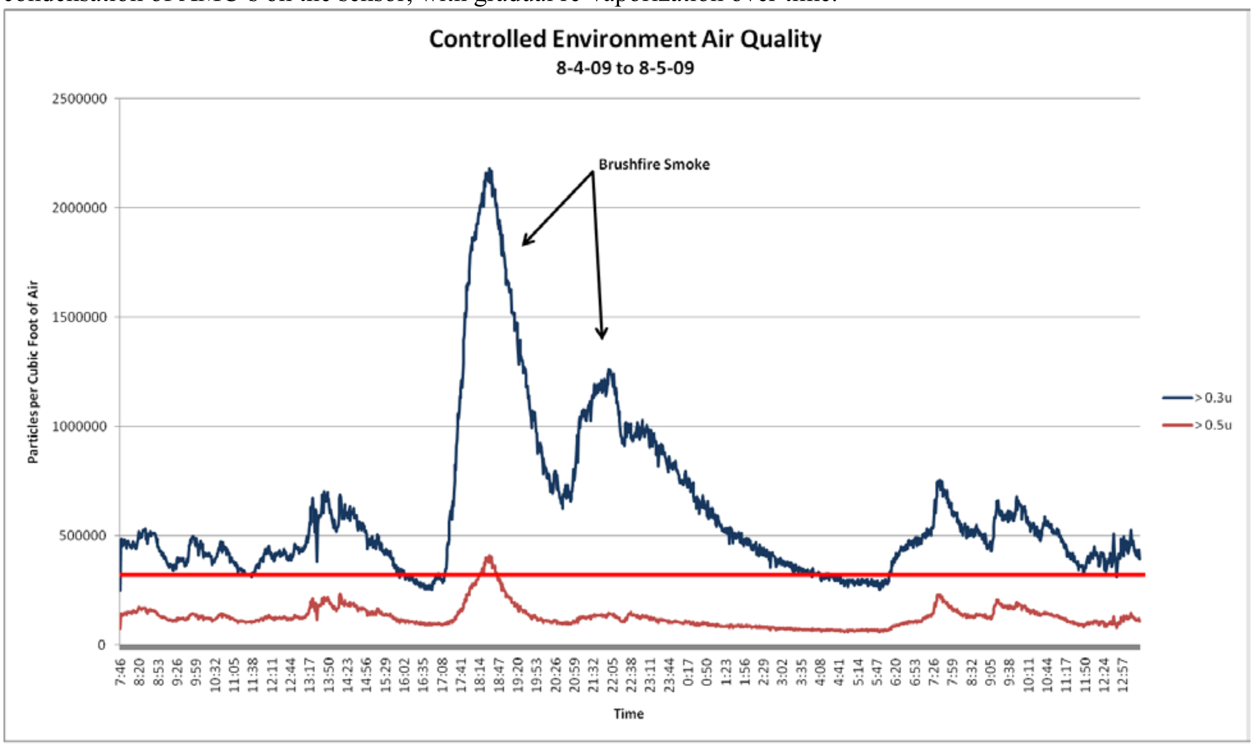
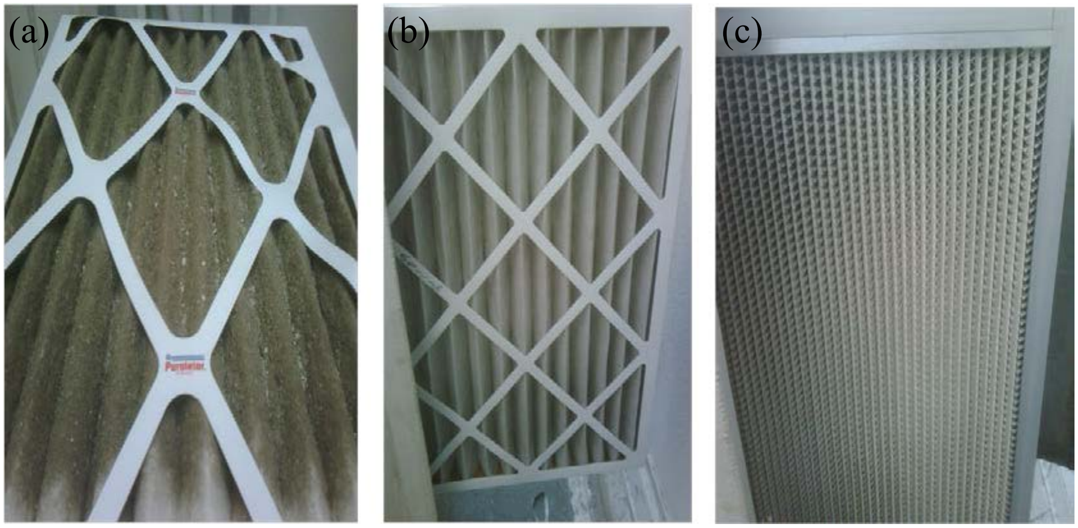


Figure 8. Air quality in a Controlled Environment during a similar smoke event

JPL also has several Class 300,000 (ISO Class 8.5) Controlled Environments, many of which do not have HEPA filters in the incoming supply air. These rooms are typically used for R&D and research work, with HEPA filtered Class 100 (ISO Class 5) clean benches providing clean work areas. On August 4th/5th, another smaller local brushfire occurred which brought smoke over the Lab for several hours, with outdoor smoke concentrations approximately half that of the Station Fire.

One of these Controlled Environments was being continuously monitored for air quality overnight, (see Figure 8) and captured the smoke plume as it entered the Controlled Environment over several hours, peaking at more than 2.2 million particles per cubic foot $\geq$ 0.3 microns. This event clearly demonstrates the importance of using HEPA filters to capture the potentially huge number of small particles before they enter any cleanroom or controlled environment. No clean environment can really be considered controlled without the use of HEPA or ULPA filtration. A non-HEPA filtered Controlled Environment may be successfully certified at Class 300,000, but there is no guarantee that air quality will be maintained continuously. Without continuous monitoring in that facility, there can be no assurance that the facility is within specification at any given time.

Figure 9 is an excellent example of how effective the prefilters were in protecting the critical HEPA final filters. The two banks of pleated-panel prefilters in Figures 9a. and 9b., for instance, were placed in series, and were installed just weeks before the Station Fire. The HEPA filters in Figure 9c were also installed just before the Station Fire broke out. After the fire, filter conditions were evaluated across the Lab, with fairly universal results. The initial prefilters absorbed the majority of the large ash and soot fallout very well, several to the point of collapse. Secondary filters were fairly well protected, but many did capture some ash and debris that got around or through the initial prefilters. The HEPA filters remained in very good condition overall, absorbing large quantities of extremely small particulate. Analysis of filter media differential pressure verses face velocity measurements, a gauge of filter loading, found that the filters held up very well. Overall filter life wasn't affected more than 10%, worst case.



(a) Prefilters exposed to outdoor air were heavily loaded with large ash and soot, some to the point of collapse. (b) Secondary filters were in surprisingly good condition. (c) HEPA final filters were also in very good condition, having been protected from any large particulate.

Figure 9. Examples of filter loading during Station Fire

Conclusions

Brushfires release huge quantities of solid particulate, in the form of organic particles, carbon and a large number of trace chemical compounds and gases.[iii] Close to the fire's origin, large ash flakes are produced and carried intermediate distances by atmospheric convection. This material settles out quickly due to its relatively large mass. The vast majority of particles generated by brushfires are much smaller, averaging less than one micron in diameter.[iv] This small size allows the particles to remain airborne for several weeks, and travel much greater distances.

Equally significant are the chemical compounds and gases that are produced by brushfires, which are difficult to quantify, as there are several variables which affect the amount and proportions of released gaseous contaminants, including: Vegetation type, quantity, and moisture content; local and seasonal weather patterns weather; fire intensity and duration, among others.

It is difficult to clearly anticipate what types and quantities of gases and chemicals will be present in brushfire smoke. Several studies have identified more than 100 different chemicals and compounds in brushfire smoke. Some of the most common include carbon dioxide, carbon monoxide, methane and various other hydrocarbons, and also nitrous oxide, nitric oxide, and ammonia. Wood smoke also includes other highly undesirable materials, including acidic/hygroscopic particles, wood molds, dioxin, lead, cadmium and arsenic.[v]

Cleanrooms that use HEPA or ULPA filtration are inherently well prepared to deal with brushfire smoke. There are between two and four levels of air filtration used by cleanrooms to ensure requisite air quality in the cleanroom:

I. Prefilters (~40% ASHRAE) capture large contaminants (Pollen, insects, seed pods, dust, wood ash, etc.). Inexpensive to maintain and replace;

II. Intermediate filters (~80% - 95% ASHRAE) capture the smaller particles that penetrate the prefilters, (~10 to >100 microns).

III. Carbon filters – Adsorbs airborne molecular contamination (AMC) onto the surface of the granulated media. Can act as unintended particle traps, but can also release grains of carbon media.

IV. HEPA/ULPA filters are at least 99.99% efficient at removing even the smallest solid particles. Recirculation of the cleanroom air through these filters re-scrubs the air many times per hour.

One particularly important observation from the data collected during the Station Fire is that a fan failure (due to a power outage or mechanical failure) can have a more profound effect on cleanroom air quality than a major brush fire. It is important for Cleanroom Managers and Project staff to understand that in the event of a sudden power or fan failure it is much more important to get people out of the room than to have them stay inside and cover cleanliness-sensitive hardware. It is also important that personnel know that they should leave the cleanroom through the gowning area, while not stopping to disrobe. Leaving through the nearest emergency exit may bring huge quantities of large and small particulate directly into the cleanroom from outside. By leaving through the gowning area, particle ingress to the cleanroom is restricted by distance as well as by a second entry door.

Acknowledgement

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