# SRM Primary Particulate Ground Cloud Model Verification

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**Small, inexpensive IOT PM2.5 sensors were placed downrange of a recent Northrop Grumman Omega second stage (CBS C300 QM-1) static test to measure particulates in the motors exhaust plume in an attempt to verify a general use motor exhaust particulate model proposed by Robert Bennett [1] for NASA solid rocket boosters. Six PA-II-SD sensors were purchased for near-field particle detection and the PurpleAir sensor network was used for far field detection. A step change in particles was detected at the sensors 1.5 and 5.5 miles downrange, but the increase was within EPA defined limits for safe air and dispersed quickly. No significant difference in particle counts were detected by far field detectors. The Bennett model appears to significantly underestimate PM2.5 in motor exhaust, though the actual particle counts detected were small.**

## I. Nomenclature

| | | |
|---|---|---|
| $\sigma_g$ | = | geometric standard deviation of particle sizes in motor exhaust |
| $D$ | = | particle diameter |
| $\tau$ | = | average chamber residence time |
| $P_c$ | = | chamber pressure |
| $\xi_c$ | = | $AL_2O_3$ concentration in the chamber |
| $Dt$ | = | nozzle throat diameter |
| $D43$ | = | mass weighted average diameter |

## II. Introduction

Particulate Matter 2.5 microns in diameter, referred to as PM2.5, are fine particles which can be inhaled into the lungs and cause health effects like aggravated asthma, decreased lung function and respiratory problems for sensitive groups. In high enough concentrations, these particles are a significant contributor to winter smog in the Salt Lake Valley. Regulators have continued to drop acceptable particulate matter limits, and there has been increased interest internally in quantifying the amount of PM2.5 emitted during large static tests.

Significant work has previously been focused towards defining the PM10 contribution of motor exhaust, but few attempts have been made to measure the dispersal of the ground cloud significantly downrange of the Promontory, UT test site or to quantitatively measure the impact to surrounding communities.

## III. Previous Work

SRM exhaust cloud effluent has been extensively studied by NGC precursor companies and NASA [1] [2] [3] [4]. Much of this work has been focused on characterizing the average particle size and weight percent of PM 10 in rocket motor exhaust. Hermsen's paper discussing an empirically derived equation for estimating the average particle size ($D_{43}$) of solid rocket motor exhaust [5] is often cited as the most complete correlation. Hermsen used data from 66 separate studies on a wide range of rocket motors to show that the mean diameter of alumina ejecta in motor exhaust varies with the size of the nozzle throat. He then created 17 different correlations before settling on Equation 1.

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$$D_{43} = 3.6304 {D_t}^{0.2932}(1 - e^{-0.0008163\xi_c P_c \tau}) \quad (1)$$

Where D43 is the mass-weighted average diameter in μm, Dt is the nozzle throat diameter in inches, ξc is the AL2O3 concentration in the chamber in g-mol/100g, Pc is the chamber pressure in psia and τ is the average chamber residence time in msec.

NASA's Sambamurthi tested this correlation by firing darts equipped with sticky tape for capturing plume particles through an RSRM plume and counting the resulting particle sizes [6]. His investigation found experimental data from the RSRM motor to agree with the Hermsen equation on mean particle diameter and with the theoretical distribution predicted by Salita [7]. Sambamurthi found that a log normal curve best fit diameter data, though it slightly under-predicts small diameter particles (less than 10 micron).

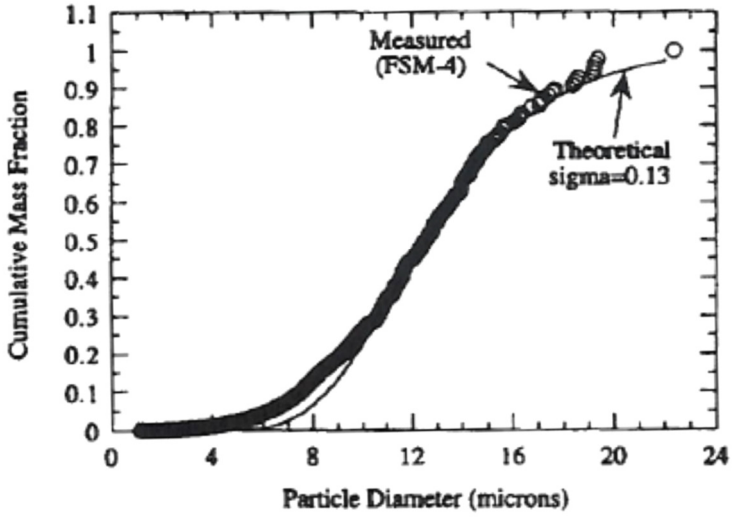


**Table 1: Cumulative mass fraction of particles from FSM-4. Log Normal Fit can slightly under-predict small particles [6]**

Bennett proposed a model of exhaust particle mass distribution based on deviation around the mean diameter of alumina D43 using a geometric mean with Equations 2 and 3 [8].

$$f(D) = \frac{m(0 \to D)}{m(0 \to \infty)} = 0.5\left[1 + \mathrm{erf}\left(\frac{Z}{2^{0.5}}\right)\right] \quad (2)$$

$$Z = \left[\frac{\ln\left(\frac{D}{D_m}\right)}{\ln(\sigma_g)}\right] \quad (3)$$

Here D is the diameter of the particle of interest, $D_m$ is the mean particle diameter, and $\sigma_g$ is the geometric standard deviation of particle sizes in motor exhaust. $\sigma_g$ was found to be 1.35 for RSRM motors and is the number quoted by Bennett for permitting PM10 emissions for previous motor tests. These three generally accepted equations were used as the basis for the attempted prediction of PM2.5 in a recent CBS test.

### A. Particle size predictions

When Equations 1 and 2 are applied to both the RSRM (Reusable solid rocket motor) based subscale static test MNASA motor and full scale RSRM static test FSM-4 motor using data from Sambamurthi, a clear difference is apparent in both the mean particle diameter and the size distribution of particles (Figure 1). These equations can then

be used to estimate what particle distribution would be expected for a CBS C300 motor with a 22 inch diameter throat. The mean particle size falls predictably between the small, 10" nozzle throat of the MNASA and 54" throat of the FSM-4.

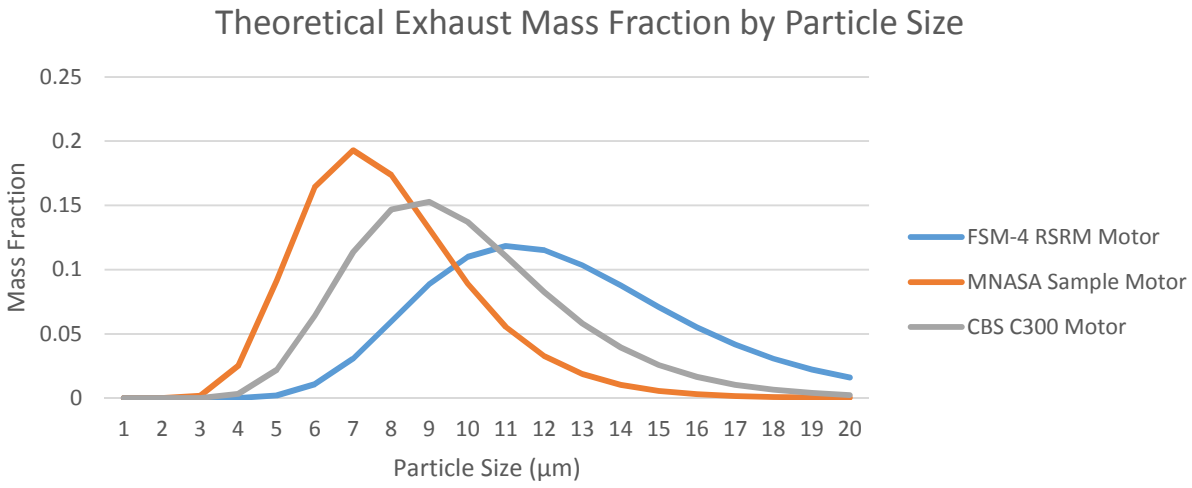


**Figure 1: Mass Fraction by Particle Size**

This relationship shows there should be very few particles PM 2.5 or smaller emitted by the CBS C300 motor, and that 15% of the particles by mass should be around the mean alumina diameter of 9 microns. The number of particles of each size can be determined by taking the molecular weight of alumina (3.987 g/cm3) and dividing the mass of propellant in the motor, leading to Figure 2.

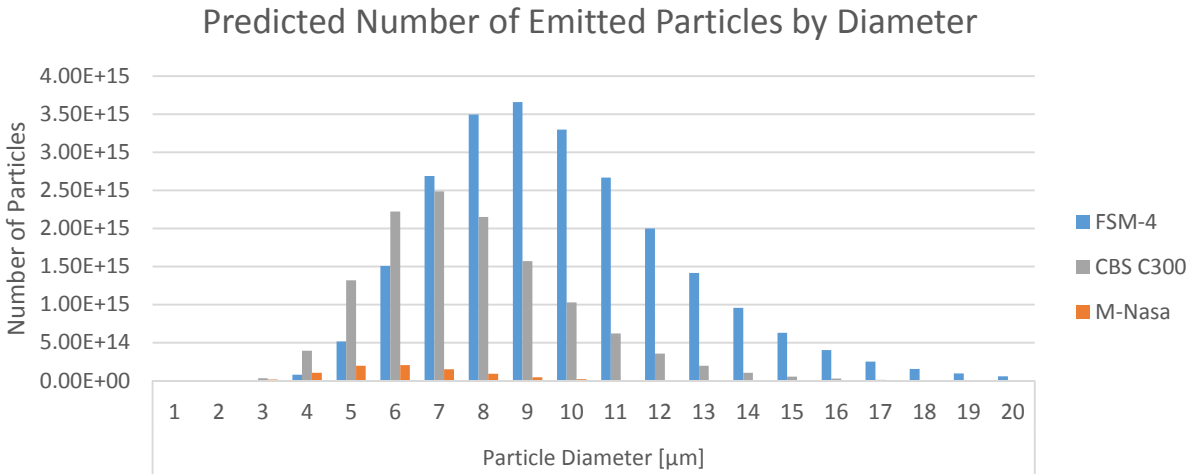


**Figure 2: Number of particles of each diameter**

This data implies that very small amounts of PM 2.5 should be present in a potential ground cloud post fire.

## IV. Measuring the ground cloud at Promontory

### B. Sensor Selection

Much of the previous work around particle emissions in rocket exhaust has been centered around PM10, but with the increasing regulatory interest in PM 2.5, a small testing program was started around sensing PM 2.5 from motor testing at Northrop Grumman's Promontory, UT facility.

Testing was performed using Purple Air PA-II-SD sensors, an inexpensive and readily available IOT based sensor [9]. PA-II sensors use PMS5003 and PMS1003 laser particle counters, along with a proprietary algorithm to calculate PM1, PM2.5, and PM10 counts. The SD version of the sensor can store data locally, which was useful for distributing sensors downstream of the expected plume path with battery packs for remote operation. A second benefit of using a PA sensor is widely available community data. Data from a large number of community sensors in the Tremonton, Brigham City, Logan, and Ogden areas is freely available on the Purple Air website (Figure 3). A full picture of possible PM2.5 emissions in the nearby community can be constructed by combining near-field data recorded on NG sensors with far field data available through the PA sensor network.

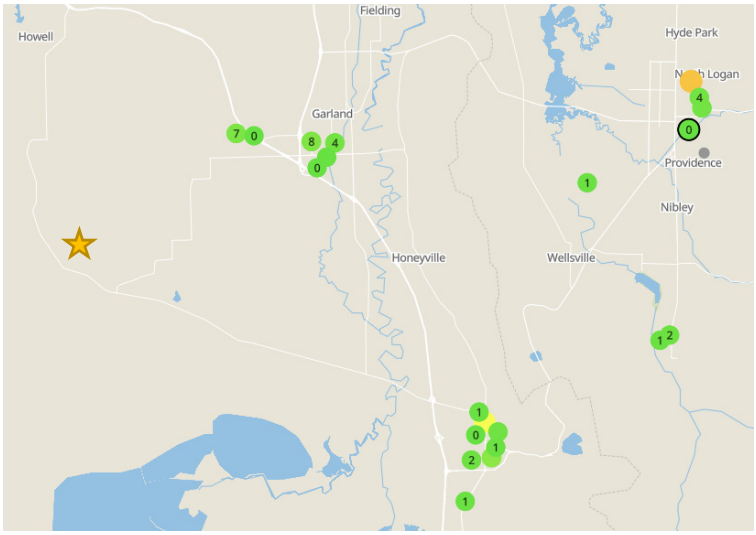


**Figure 3: Location of nearby community PA-II sensors [9]. Star indicates Promontory test facility**

PA-II sensors have been found to precisely measure small airborne particulates by multiple testing agencies (See section C for more details). For the purposes of this exploratory test, these sensors provide a reasonably accurate way to correlate near and far field data at an affordable price.

Six PA-II-SD sensors were purchased along with six 6000mAh batteries and watertight boxes for remote operation (Figure 4). The sensors were function tested in a lab bench test prior to the first deployment during a C600 static test.

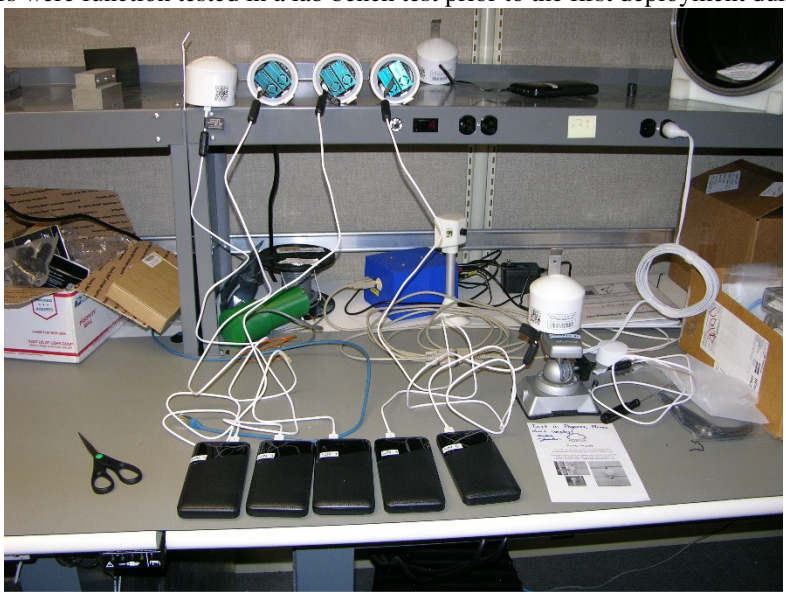

**Figure 4: Sensors and batteries under test**

The first deployment during the Northrop Grumman Omega first stage (C600 QM-1) test showed there to be little PM2.5 in the area surrounding the test or in the nearby community sensors, but the PA-II-SD sensors deployed in the path of the plume did not record data during the optimal time due to a logistics error. A second deployment during a subsequent Omega second stage (C300) test managed to get active sensors in the path of the plume during the test (Figure 5), delivering a more complete data set.

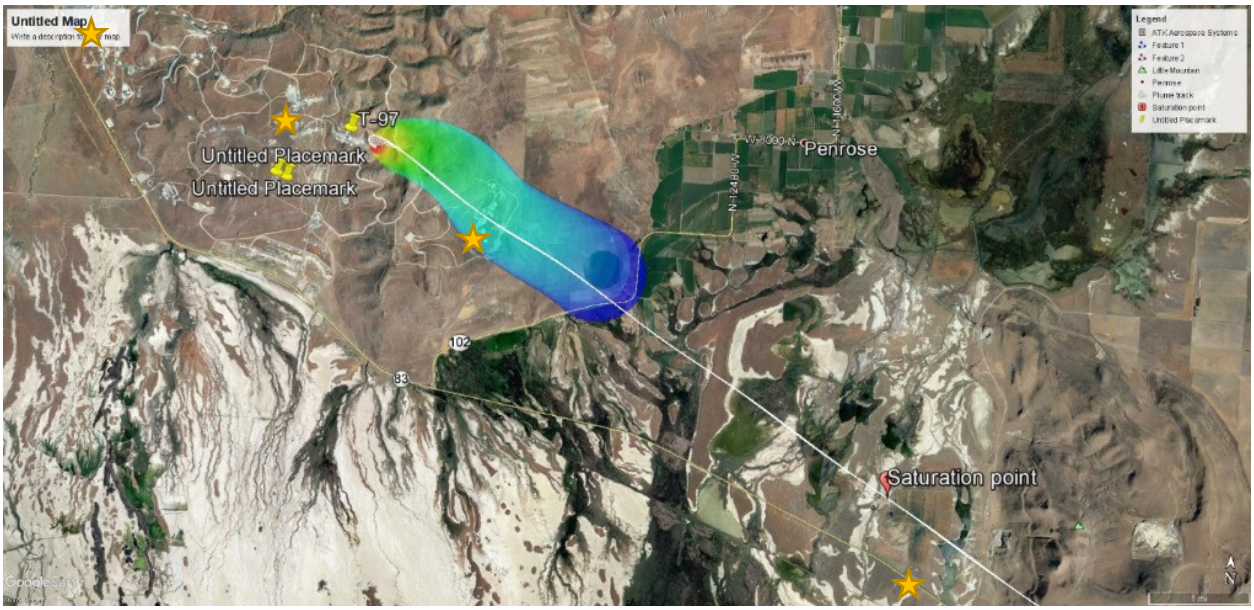


**Figure 5: Model of the track of the exhaust plume for the CBS C300 Static Test. Gold stars indicate sensor locations. Model courtesy of Northrop Grumman and NASA [10]**

### C. Sensor Accuracy and Calibration

PA-II sensors have been found by other researchers to be precise at measuring PM 1 and PM 2.5 in field and laboratory environments [11] [12]. Analysis by the Puget Sound Clean Air Agency found the sensors could be classified as an EPA class III sensor, useful for supplemental monitoring with a precision between 7 and 15% and bias of less than 12% [12] when calibrated.

A similar analysis by AQ-SPEC found the sensors to have strong correlations with much more expensive reference equipment in both a field setting ($PM_{1.0}$ $R^2 > 0.96$, $PM_{2.5}$ $R^2 > 0.93$), and a laboratory setting ($PM_{1.0}$ $R^2 > 0.99$, $PM_{2.5}$ $R^2 > 0.99$). The sensors are not as capable of detecting accurate levels of $PM_{10}$ ($PM_{10}$ $R^2 > 0.66$) due to the much larger particle's size [11]. The larger particles may impact the walls of the measuring device and are not pulled into the measuring chamber as readily as smaller, lower mass particles. As a result $PM_{10}$ counts are underestimated by PA-II sensors and were not heavily relied upon in this analysis.

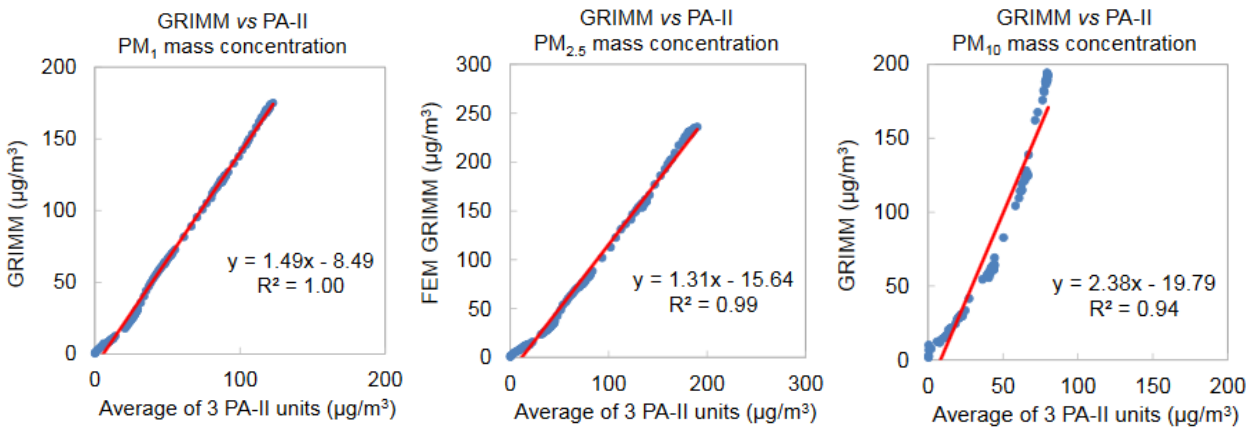


**Figure 6: PA-II Sensor agreement with a GRIMM optical particle counter [13]**

*1. Correlation with EPA sensors*

Funding was not available on this project for independent calibration of the six NG PA-II-SD sensors, so calibration was performed via a proxy PA-II sensor in Harrisville, 33 miles away from the test site. This sensor was within 500 feet of an EPA monitor which could be used for independent verification of PA-II results. PM2.5 readings from The EPA monitor was found to consistently read particle counts approximately 2.5x lower than those read by the PA-II sensors (Figure 7), showing the PA-II to be precise but not necessarily accurate. The other sensors in the sample set were calibrated off this Harrisville sensor.

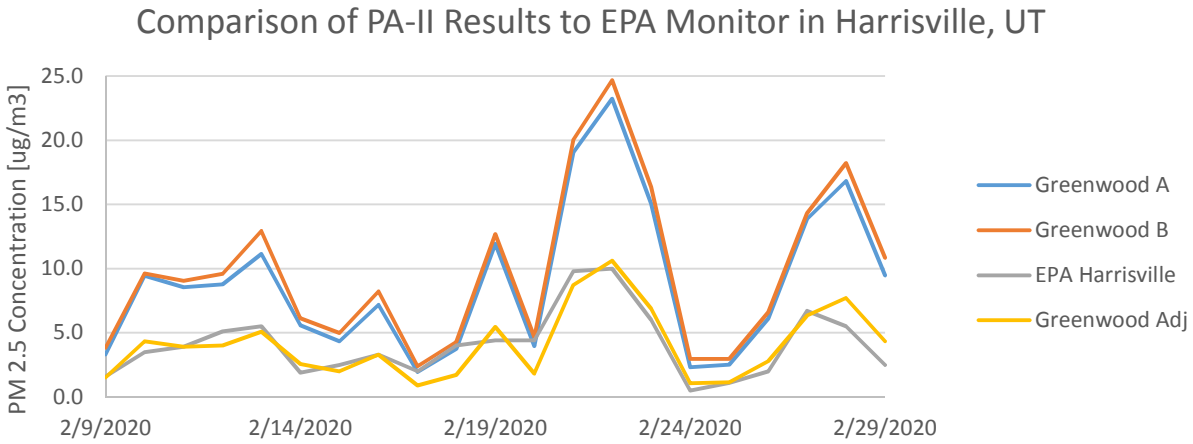


**Figure 7: EPA Harrisville, UT (49-057-1003) particle concentration sensor comparison to PA-II sensor**

The EPA sensor uses a filter to capture various particle sizes for later analysis instead of the instant laser based measurement of the PA-II sensor. As Figure 7 shows the different measurement type of the PA-II is still comparable to the EPA sensor, with an R value of the fit of PA-II calibrated data against the EPA sensor of 0.8.

## V. Results of ground cloud measurements for C300 QM-1

The track of the motor exhaust plume verified by Nexrad appeared to pass just to the north of the predicted path (Figure 8).

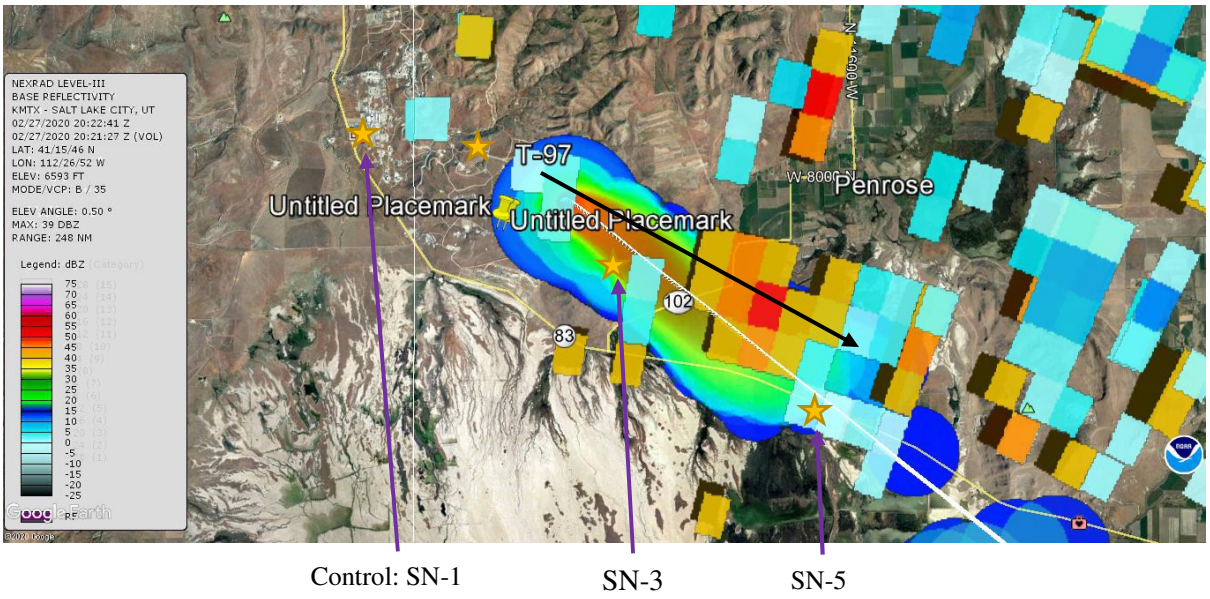


**Figure 8: Nexrad verification of the track of the exhaust plume for the CBS C300 QM-1 Static Test. Gold stars indicate approximate sensor locations. Nexrad data courtesy of NOAA [14].**

The results of both C300 and C600 tests confirm model predictions that very few PM 2.5 particles are emitted into a ground cloud during a large static fire test at T-97. However, appreciable amounts of PM2.5 were detected at the SN-3 sensor (Figure 9), approximately 1.5 miles downrange from the C300 motor nozzle.

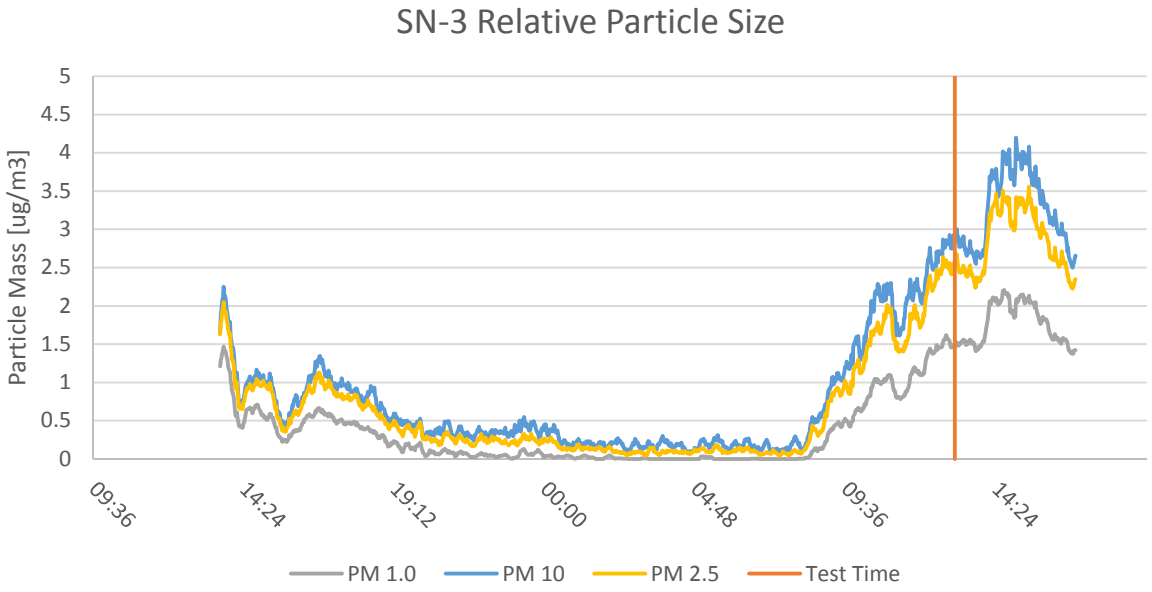


**Figure 9: PM2.5 and PM1 levels 1.5 miles downrange of the test site**

Similar to SN-3, a small concentration was also detectable at the SN-5 Salt Marsh sensor location, 5.5 miles downrange (Figure 10).

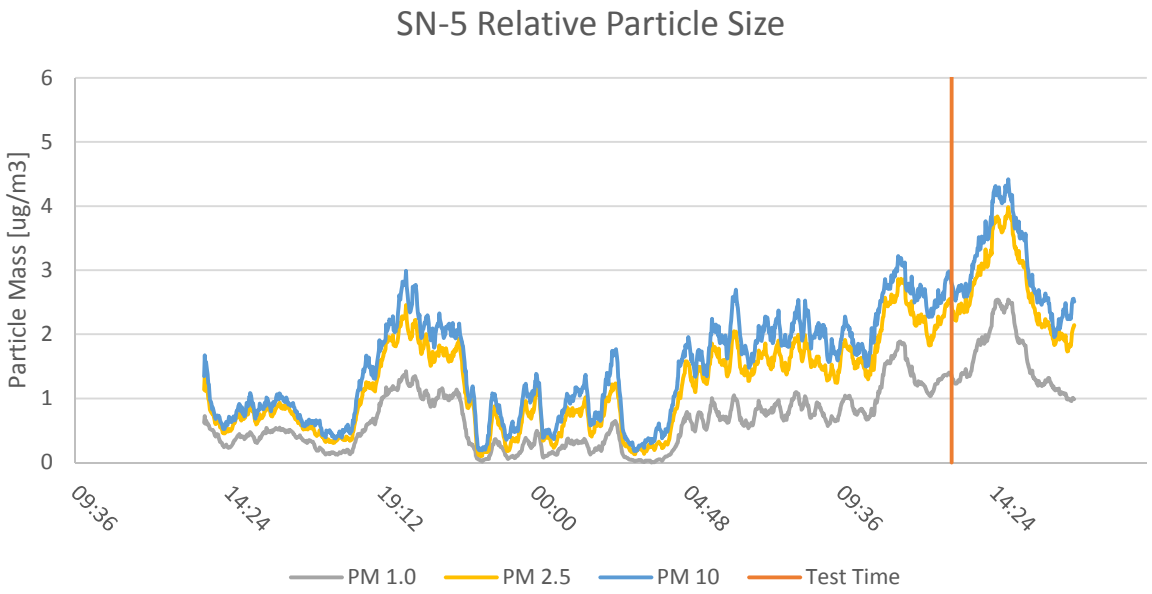


**Figure 10: PM2.5 and PM1 levels 5.5 miles downrange of the test site**

A step change in particles was not detected in sampled community sensors at other areas, or the other NG sensors scattered around the plant. There was an increase in particulate counts on a sensor close but upwind of the test site around an hour after the test time. It is unclear if that increase was associated with the C300 QM-1 test or a $CO_2$ cooling chamber in the vicinity.

While PM 2.5 did appear to increase after the static fire, the measured increase in PM 2.5 does not appear to be abnormal for the area. When the SN-3 sensor was measured for a week post-test to determine a baseline the PM 2.5 signal fluctuated lower and higher than the value measured after the static test (Figure 11).

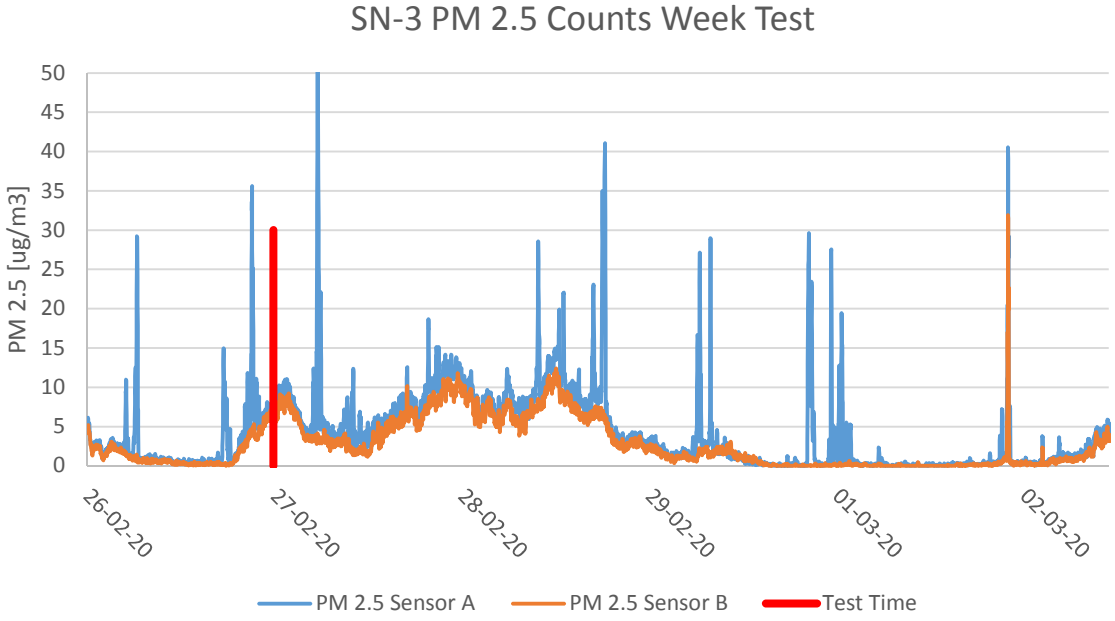


**Figure 11: Week long particle counts at SN-3**

## VI. Discussion

Particle loading of the two down range sensors (SN-3 and SN-5) were smaller, but in family with a similar analysis of a Titan III launch in Florida which found solids loading in the 5-10 $\mu g/m^3$ range [15]. The measured PM2.5 was far in excess of what would have been expected using the Bennett model. However, while this testing showed that particles in a ground cloud following the test are apparent, they are still well below the EPA's annual standard of 15 micrograms per cubic meter ($\mu g/m^3$).

The test equipment chosen was not capable of verifying the model presented in Section A. One way to verify the model would be to compare sampled PM1 levels to PM2.5 and PM10 and compare those ratios to values obtained from the model. However, the model suggests PM2.5 levels should be 99% higher than PM1 levels, and PM10 levels should be 99% higher than PM2.5 levels. This type of analysis is not realistic with the sensitivity level of the PA-II sensors, and also not reflected in the captured data. Even with the degraded ability of the PA-II to sense PM10 particles, PM 10 was only found in 10% greater abundance than PM2.5. The Bennett model predicts only .07lbs of PM2.5 material for a C300 motor, compared to 37,900lbs of PM10 material. This raises the question of whether the Bennett model is an accurate way to predict a potential ground cloud of particles from static testing.

## VII. Future Work

PA-II sensors are inexpensive, precise and widely available, features which make them excellent for conducting a wide area survey. However, the ability to compare PM 10 counts to PM 2.5 would be more useful for verifying the models proposed by Sambamurthi [6] and Hermsen [5] which predicted average particle sizes in the 9-11 micron range for the large diameter nozzles used at the T-97 test stand. This work was based on data from sensors which precisely monitor PM 1 and 2.5, but larger mass fractions are not recorded well by these sensors. Having the ability to monitor larger particles in real time would help in verifying the Bennett model or creating a new one for a ground cloud scenario.

The PA-II-SD sensors don't have the range required to verify if Sambamurthi's theoretical fit for RSRM motors is true as well for CBS motors. While a direct comparison of PM10 to PM 2.5 would have been ideal, at least in this test the Bennet model seems to have understated the mass contribution of sub 10 micron particles. As the EPA's attention turns to the emission of smaller and smaller particle sizes, a better understanding of emissions of small particles may be helpful for permitting purposes.

This work and much of the previous work on particulate effluent from rocket testing has focused on primary sources of particulate matter, meaning particles formed directly during the process and then ejected into the atmosphere. Much of the PM problem in the Salt Lake Valley stems from secondary sources, or chemical reactions in the atmosphere from emitted non-particulate chemicals. More work could be done to better understand the chemistry interactions in the exhaust cloud and how they affect secondary particle formation.

## VIII. Conclusion

Sensors were placed downrange of a C300 motor in an attempt to quantify PM2.5 in a ground cloud from rocket emissions and compare to Robert Bennet's prevailing model of emission particle sizes. PM2.5 was detected at sensors 1.5 and 5.5 miles downrange from the motor, but in quantities which are not hazardous for human health. No spike in PM2.5 emissions was detected in the nearby communities. The takeaway from this testing is there is more PM2.5 emitted by the motor than the Bennett model would suggest, but the total detected particulates were still well within EPA guidelines for clean air and quickly dispersed.

## IX. References


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