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EXPERIMENTAL INVESTIGATION OF OPTIMAL PARTICULATE SENSOR LOCATION IN AN AIRCRAFT CABIN

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ABSTRACT

The primary objective of this research was to develop a reliable method to monitor and control air quality within a wide-body aircraft cabin. To achieve this objective, a long-term systematic experimental and computational research plan is developed. This paper deals with the description and results from an experimental study conducted to determine the best sensor placement locations within the aircraft cabin to detect particulates, and identify the minimum number of sensors necessary to accurately track air quality incidents. An 11-row mockup cabin, intended to be representative of a typical wide-body aircraft, was used for the research. The mockup interior is based on the actual dimensions of the Boeing 767 aircraft cabin. Inside the mockup cabin, actual aircraft equipment including seats and air diffusers are used. Each row has seven passenger seats.

Particulates were released from different locations in the second row of the mockup cabin. The transported particles were then collected at six different locations in the lateral direction. The best location to place a sensor was defined as the location having the strongest signal detection (maximum number of particles collected) and the fastest detection time. For the six locations examined, it was found that the best location for the placement of a sensor in the 11-row mockup cabin, in the lateral direction, was on the center-line near the cabin floor. Subsequently, particles were collected at the corresponding longitudinal locations from rows 1, 3, 4, and 5 to determine the signal strength and the detection time for each row. Furthermore, particles were released from row 6 and detection characteristics were examined by collecting particles from row 6 and adjacent rows, i.e., row 5 and row 7. Based on the results from above two-series of tests, it was concluded that a properly placed sensor can accurately detect particles from the corresponding release-row as well as one adjacent row ahead and behind the release-row.

INTRODUCTION

Each year millions of people travel by commercial aircraft. The Bureau of Transportation Statistics indicates that about 600 million passengers fly each year in the United States and, of those, roughly 350,000 are international travelers. This number of travelers leaves commercial airliners potentially vulnerable to biological contamination and makes the transmission of diseases a serious threat. The spread of SARS (Severe Acute Respiratory Syndrome) and H1N1 (swine flu) are examples of documented cases. Consequently, considerable research has been and continues to be conducted to study and understand particulate transport mechanisms and dispersion behavior inside aircraft cabins to develop means for detecting, controlling, and removing contaminants from aircraft cabins and to find methods for preventing the aircraft from being used for intentional contaminant deployment.

Aircraft cabin environmental health is clearly an important national need. In 2002, the National Research Council (NRC) committee included issues in the report entitled, "The Airliner Cabin Environment and the Health of Passengers and Crew," [14] related to the effects of low humidity inside the aircraft cabins, elevated cabin altitude, contamination from engine oil and hydraulic fluid, and disease transmission.

In 2002, during a flight from Hong Kong to Beijing, it was thought that at least 22 passengers may have been infected by SARS due to possible release of the SARS viruses from infected passenger/s. Furthermore, after the use of the nerve agent to attack the Tokyo subway in 1995 and the anthrax cases in Florida and Washington, D.C. in 2001, there have been concerns expressed of possible terrorist attacks by releasing chemical / biological agents in commercial airplanes.

In the recent years, disease transmission has become a major concern for the aircraft industry and a lot of effort is being spent to prevent the spread of the diseases and viruses inside aircrafts cabin.

EXPERIMENTAL SETUP

Description of the Mockup Aircraft Cabin

All of the tests were conducted in the 11-row mockup Boeing 767 aircraft cabin housed within the Airliner Cabin Environment Research (ACER) Laboratory at Kansas State University. The geometric shape and the dimensions of the mockup cabin are the same as an actual 767 Boeing aircraft cabin. The mockup cabin seats, the air supply duct, and the diffusers are parts from a salvaged Boeing 767 aircraft. This mockup cabin is 9.41 meters long and 4.72 meters wide and is one of the larger research mockup cabins in its class. The mockup cabin contains 11 rows with each row consisting of 7 seats as shown in Figure 1. Each seat in the cabin is occupied by an inflatable manikin which was instrumented with wire heater elements to generate approximately 100 Watts which is equivalent to the average heat gain from a resting adult [21]. There are two outboard and two centered simulated stowage bins installed along the length of the cabin. The air diffusers are located between the two centered stowage bins.

The remaining space between the upper parts of the inside and the outside of the mockup aircraft cabin is occupied by the air conditioning and the lightening systems components. Two access doors to the cabin are provided in the north end which is considered the rear of the cabin. Two hallways in the eastern and the western sides of the cabin were used to store the data acquisition system and the cabin control system. The chamber was supplied with 100% outside air conditioned to approximately 16 ˚C at the upstream section of the cabin main supply duct.

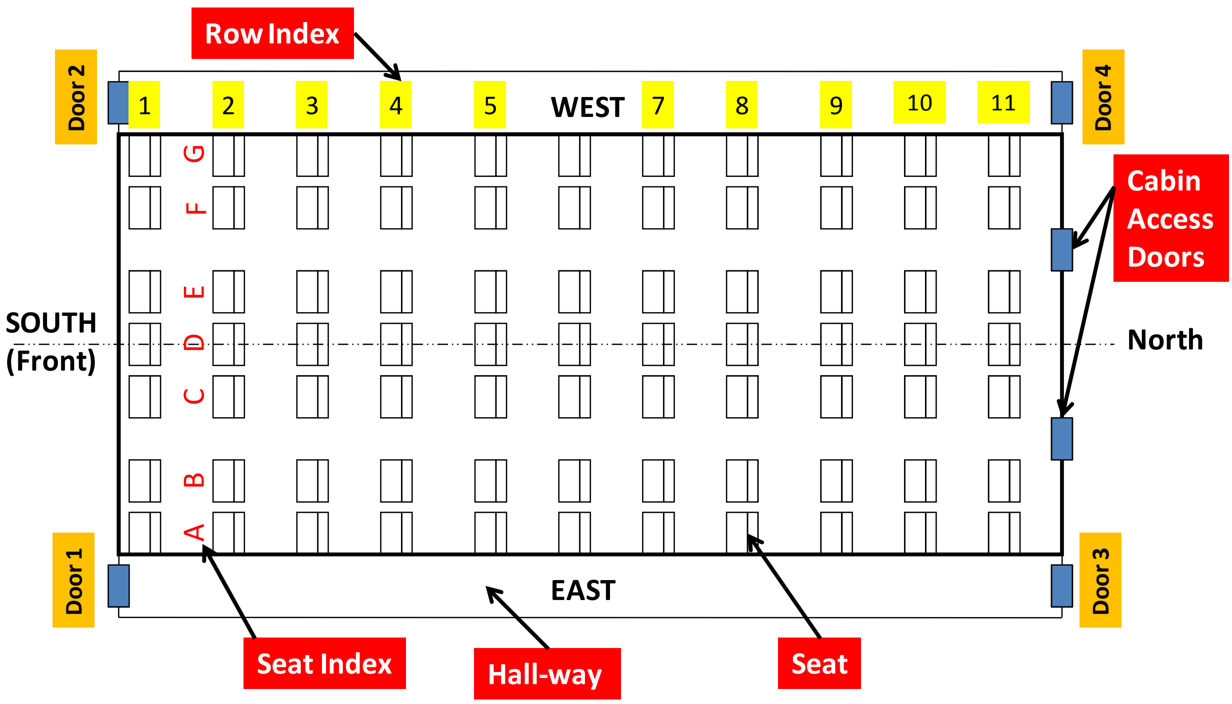

FIGURE 1 – SCHEMATIC DIAGRAM OF THE MOCKUP CABIN

Particulate Release and Data Collection Setup

During the tests, talcum powder was used to generate aerosolized fine particulates. The talc powder has a density of approximately 950 kg/m^3. For this study, focus was on the particles in the size range of aerodynamic diameters of 0.5 to 5 micro-meters which will follow the airflow motion [13]. An injection system was built having 7 injection ports and a fixed amount of powder was placed in plastic cups under each port. Pressurized air was released from each injection port into the cups filled with powder causing the powder to spread out forming an approximately 25 cm high powder cloud, as shown in Figure 2.

An Aerodynamic Particle Sizer (APS) unit was used to collect and categorize the particles, based on their diameters, at different selected locations inside the cabin.

Investigation of Particle Distribution in the Lateral Direction

The first task of the project was to determine the best location for the placement of the particulate detecting sensor in the lateral (side-to-side) direction. To achieve this task, powder was released separately from each seat of Row 2 (A through G). The transported particles were collected, using the APS unit, in 6 different locations in the lateral direction of the same row as shown in Figure 3.

For every injection in each seat, the tests were repeated 3-times for statistical consistency. The duration of each test was 15 minutes. A ten minute waiting period was used before each test to allow the particulates from the previous test to exhaust out from the cabin and thus forming zero particle count by the APS unit. Two criteria were used in determining the best location of the sensor. The first one was the maximum total exposure (maximum total number of particles collected), while the second criterion was the fastest detection time which is the time period required by the APS to start detecting and counting the particles, at a given location, after their release. The location with maximum exposure and minimum detection times was considered as the best location for a sensor placement.

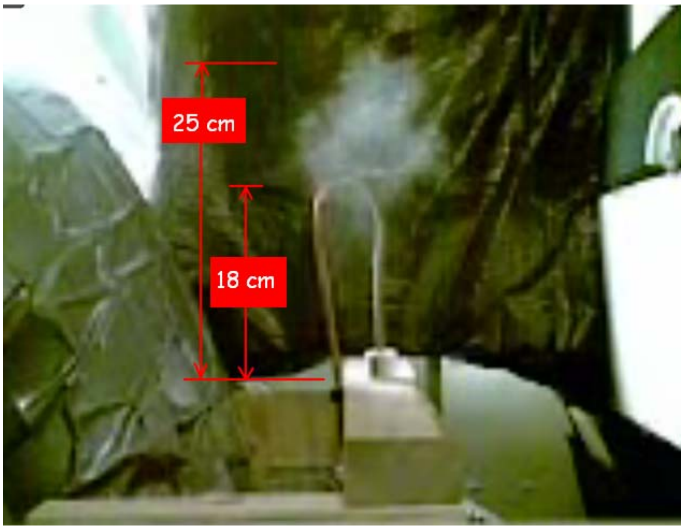

FIGURE 2 – POWDER CLOUD

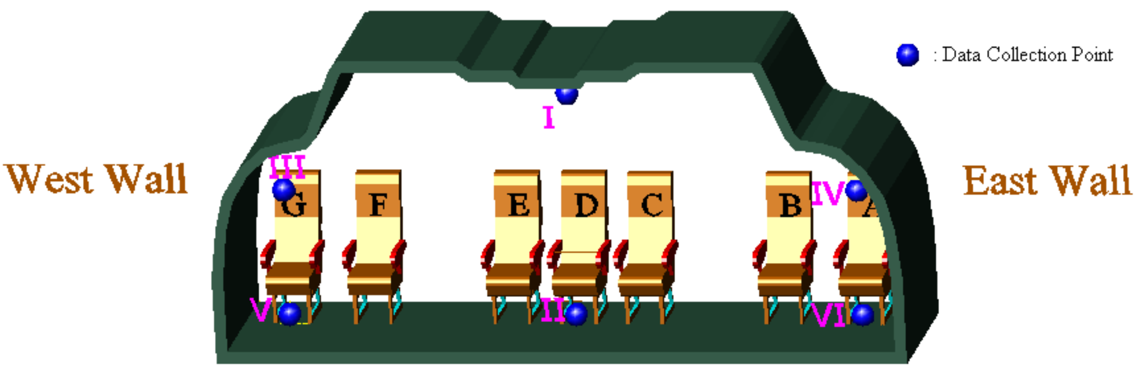

FIGURE 3 – MOCKUP CROSS SECTION SHOWING THE SENSORS LOCATIONS IN THE LATERAL DIRECTION

Investigation of Particles Distribution in the Longitudinal Direction

After determining the best location for the sensor in the lateral direction, the differences in the "total exposure" and the "detection time" between different locations in the longitudinal (front-to-back) direction were examined. The same testing procedures, as in the lateral study discussed above, were repeated here where the powder was released separately from each seat of "Row 2" and then the APS was used to collect the particles in row 1, 2, 3, 4, and 5 as shown in Figure 4.

Furthermore, powder was released in the middle section of the cabin (Row 6) and the particles were collected in Row 5, Row 6, and Row 7, consecutively (Figure 5).

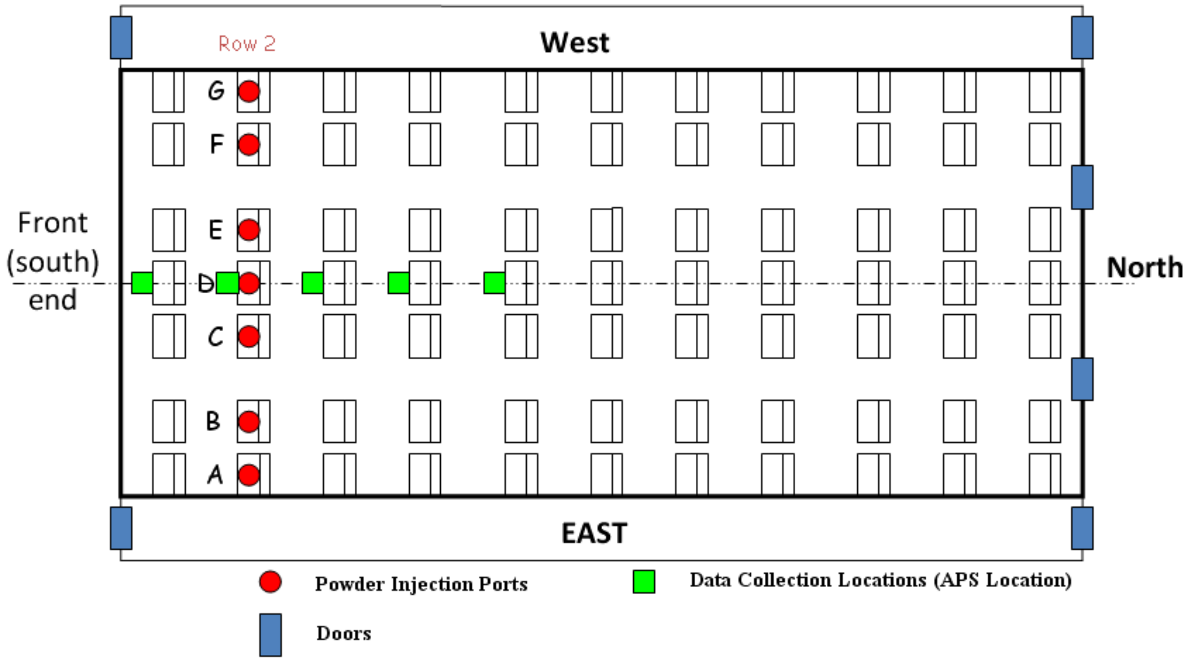

FIGURE 4 – LONGITUDINAL DATA COLLECTION LOCATIONS WHEN INJECTING IN ROW 2

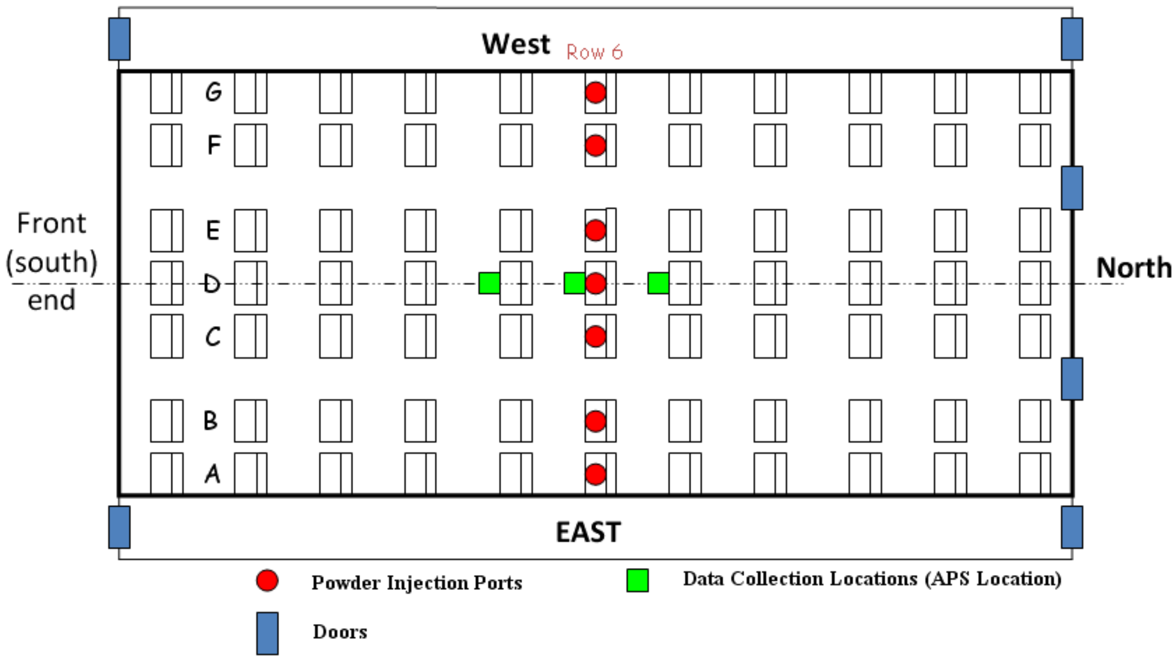

FIGURE 5 – LONGITUDINAL DATA COLLECTION WHEN INJECTING IN ROW 6

RESULTS AND DISCUSSION

Optimized Sensor Location in the Lateral Direction of Row 2

The total number of particles, collected from each measurement at the 6 different locations in the lateral direction, was normalized as a ratio of the total number of particles collected at the source. The average detection times of the three tests and the average of the normalized particle counts for each seat and in every location in the lateral tests are presented in Figure 6 and in Figure 7, respectively.
Results from Figure 6 show that Location IV and Location VI have almost the longest detection times, thus, these two locations are eliminated from further consideration as compared to other locations. Location I and Location II curves are the lowest two curves representing the lowest detection times when injection was in seats A, B, C, and D. For the case of injection in seats E and F, Location II and Location III have the lowest detection times. For injection in seat G, Location III is classified as the lowest record followed by Location I, Location V and then Location II. Note that Location V can also be eliminated from the comparisons when compared with Location III, because the detection times for Location III are lower than those for Location V at all points except at F where both of them are very close to each other. Consequently, if one chooses locations based on the detection time only, Location I, Location II, and Location III are recommended.

Analyzing Figure 7, which summarizes the normalized total counts at each location in the lateral direction of Row 2, it is noticed that Location I has much lower counts than Location II, for all seats (A through G), and lower than Location III for injection in seats C, D, E, F, and G. As a result, Location I is eliminated from the comparison of the lateral locations. This elimination yields Location II and Location III as the best locations for placing a sensor inside the cabin in the lateral direction.

Therefore, if a combination of sensors is to be used, then Location II and Location III are recommended, while if only one location is to be selected, then Location II is to be recommended due to the following reasons:

- Location II has lower detection times when releasing particles in seats A through D and higher particle counts when releasing in seats A through C.
- Location II and Location III have almost the same average detection times when releasing particles from seat E and seat F.
- Location II and Location III have almost the same average particle counts when releasing from seat D.

It is important to point out that a noticeable asymmetry is seen in the particle distribution behavior in the lateral direction although the geometry of the cabin is symmetrical. This asymmetry was investigated as part of the study and shown to be a naturally occurring phenomenon in ventilation systems of the nature employed in the cabin and is not a result of geometric asymmetry in the mockup cabin. [13]

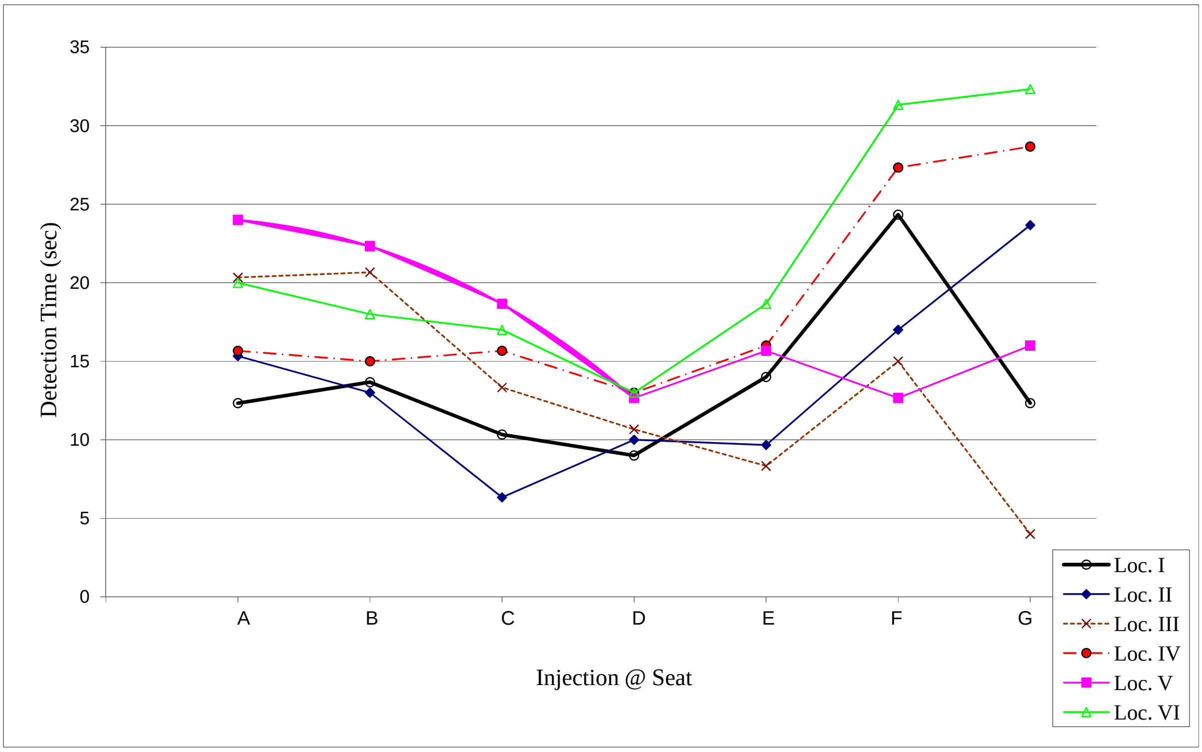

FIGURE 6 – DETECTION TIMES FOR ALL LOCATIONS IN THE LATERAL DIRECTION OF ROW 2 (INJECTION IN ROW 2)

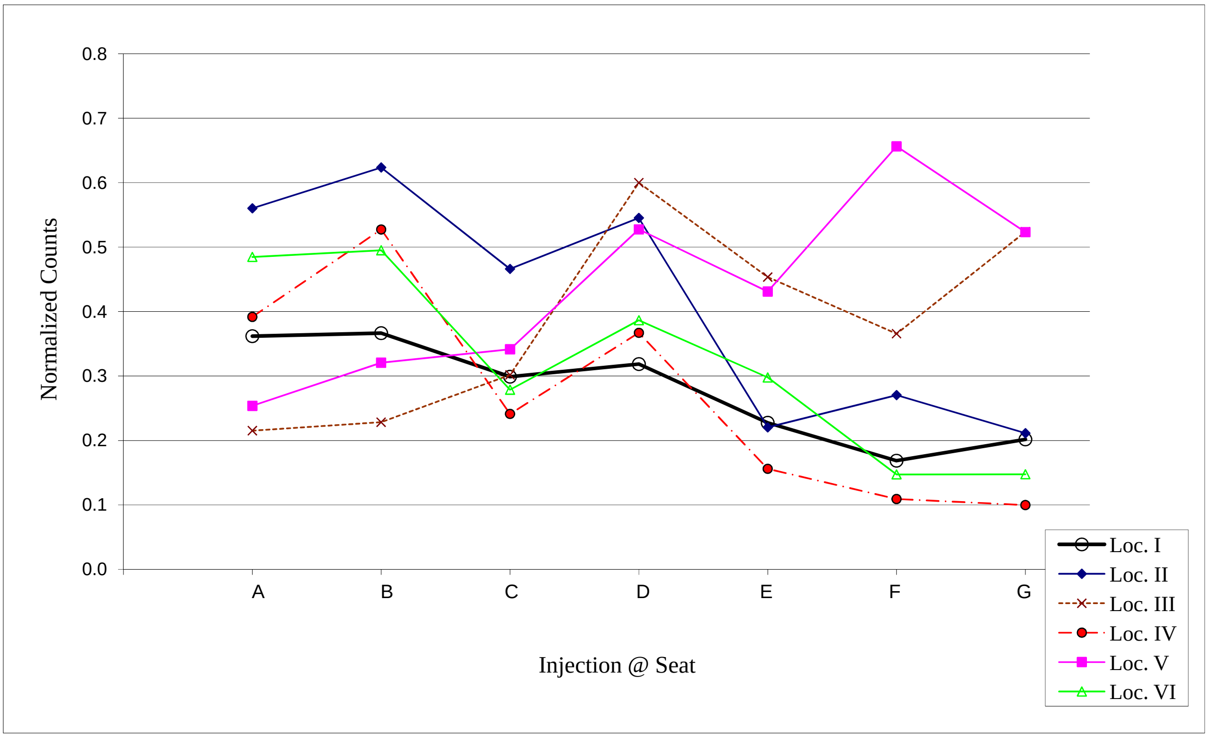

FIGURE 7 – NORMALIZED COUNTS FOR ALL LOCATION IN THE LATERAL DIRECTION OF ROW 2 (INJECTION IN ROW 2)

Optimum Distance between Two Consecutive Locations in the Longitudinal Direction

Figures 8, 9, 10, and 11 show the results of the detection times and the normalized counts for the longitudinal tests when powder was released in Row 2 and in Row 6.

Starting with the results in Figure 8, which summarizes the detection times obtained at Location II in rows 1, 2, 3, 4, and 5, it is noticed that there is a strong overlapping in the results obtained for Row 1, Row 2, and Row 3. Row 5 is far above the results of 1, 2, and 3 and Row 4 as well, except for point G. Therefore, when releasing particles in Row 2 we have almost the same results or at least acceptable results obtained in Rows 1, 2, and 3.

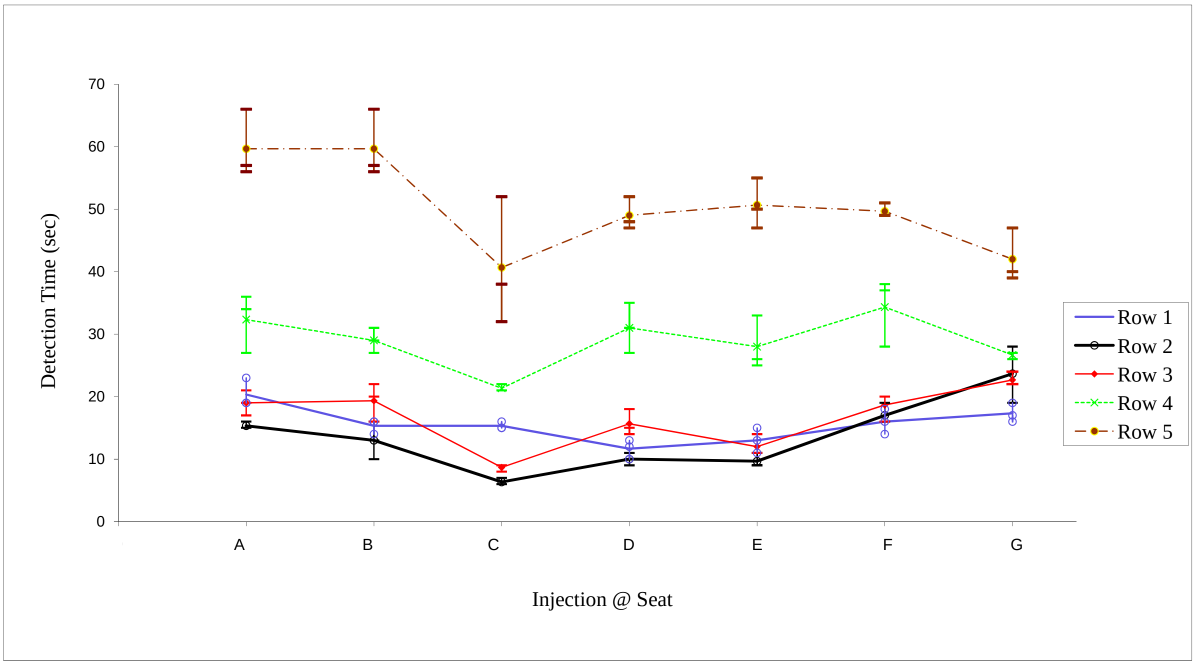

FIGURE 8 - DETECTION TIMES AT LOCATION II IN DIFFERENT LONGITUDINAL LOCATION (INJECTION IN ROW 2)

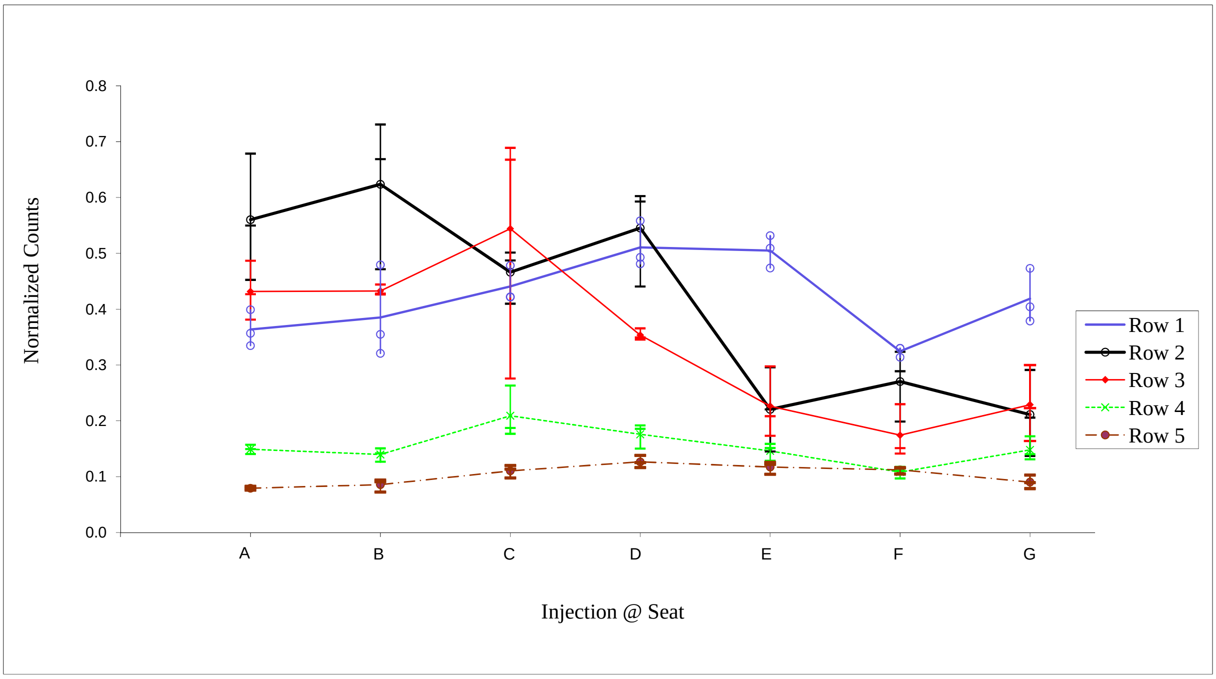

FIGURE 9 – NORMALIZED COUNTS AT LOCATION II IN DIFFERENT LONGITUDINAL LOCATIONS (INJECTION IN ROW 2)

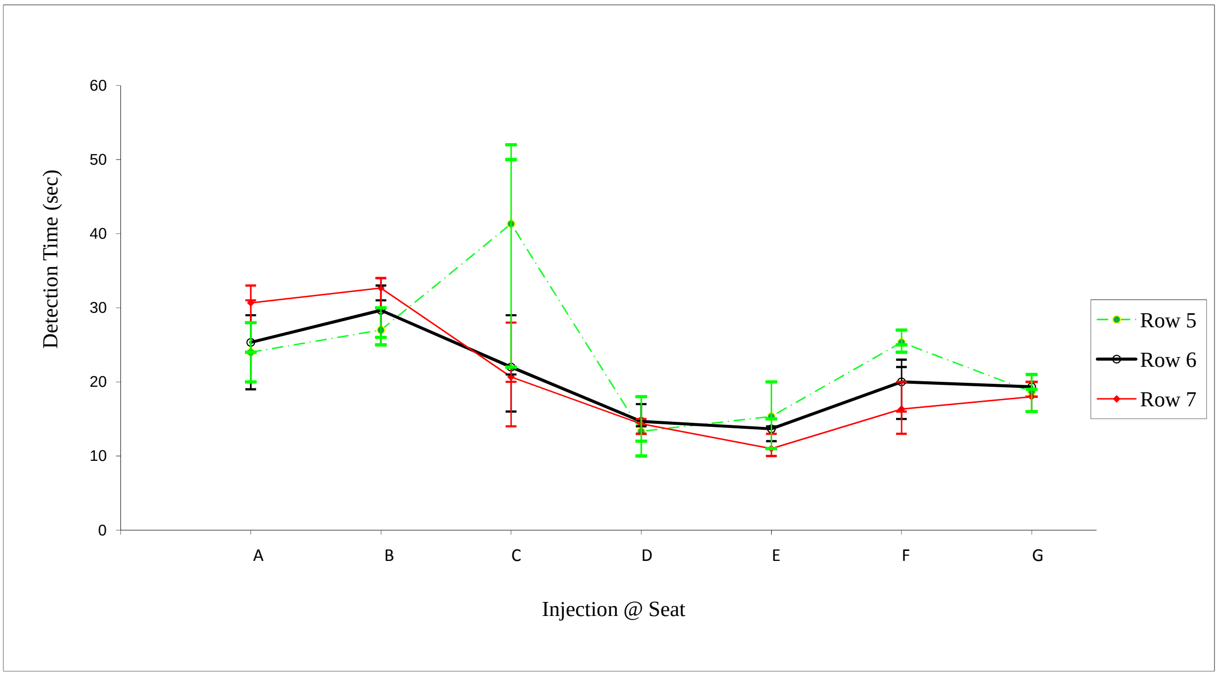

FIGURE 10 – DETECTION TIMES AT LOCATION II IN DIFFERENT LONGITUDINAL LOCATION (INJECTION IN ROW 6)

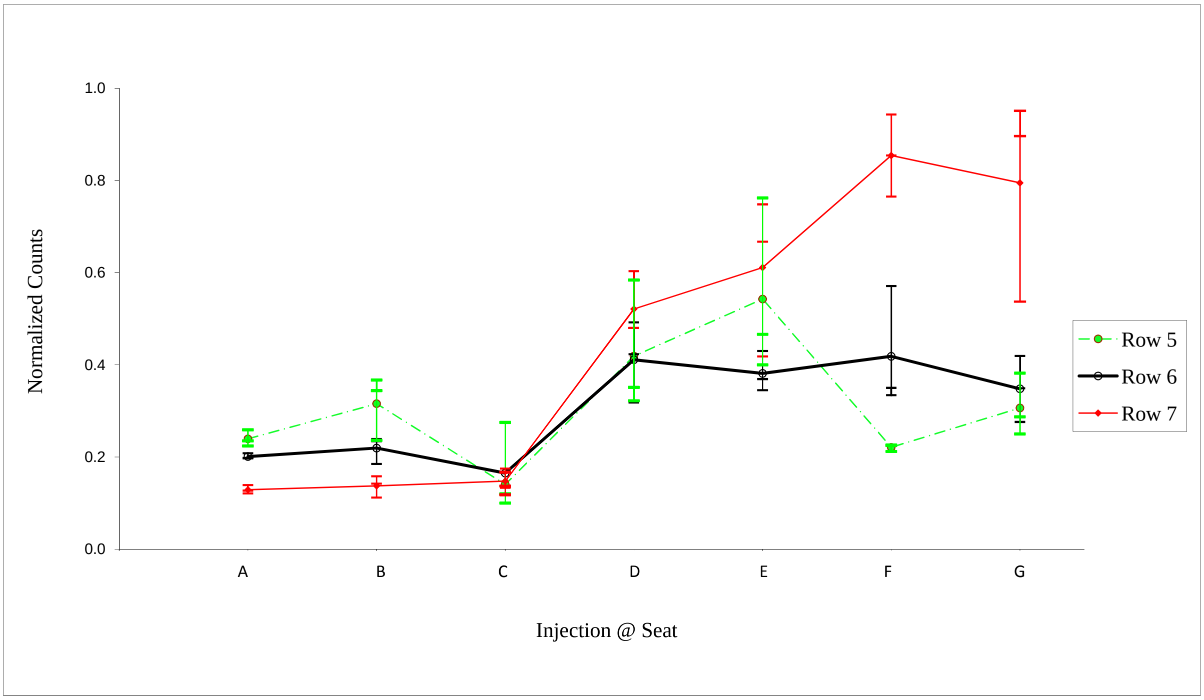

FIGURE 11–NORMALIZED COUNTS AT LOCATION II IN DIFFERENT LONGITUDINAL LOCATIONS (INJECTION IN ROW 6)

Again, the normalized particle counts (Figure 9) shows that both Row 4 and Row 5 are out of the range of the other results except at point E, where they're close to Row 2 and Row 3 results. Row 4 curve has another overlapping point at G. Row 1, 2, and 3 overlap in the cases when releasing in A through D and beyond that Row 2 and Row 3 continue overlapping, while Row 1 records higher counts.

Figure 10 and 11 also confirms the results obtained above, but when releasing the powder in the middle section of the cabin in Row 6, with some exceptions at some points.

As a result, we conclude that a sensor can be used to reasonably monitor particles release in the same row it is placed in, the row in front, and the row in back of the release (±1 row).

CONCLUSIONS

An experimental analysis of the best location for placing a particulate detecting sensor in the lateral direction and the optimum separating distance between two consecutive sensors locations in the longitudinal direction were described in this study. The objective of the project was to collect fine particles at several locations inside an 11-row mockup Boeing 767 aircraft cabin in order to determine the optimum location for placement of a particulate detecting sensor based on the total number of particles collected and the fastest detection time.

Multiple steps and procedures were taken in order to meet the project objective. First, fine particles were released in each seat of the second row of the mockup cabin and an aerodynamic particle sizer (APS) was used to collect the particles in several locations in the lateral direction of row 2. Of the six locations examined, two locations were selected as acceptable locations in the lateral direction, but one of the two locations appeared more suitable for sensor placement and selected as the best representative location if only one sensor per row was to be used. This location was on the centerline near the cabin floor. An uncertainty analysis was performed to check the variability of the measurements and it showed that there was no major differences in the measurement uncertainty for the above two locations. The total uncertainty for all locations considered in the lateral direction ranged between ±26% to ±48%, knowing that the APS alone has ±10% uncertainty.

After selecting the best location in the lateral direction of row 2, fine particles were released in two different rows during the longitudinal tests. The front and the middle regions of the cabin showed that particulates could be detected faithfully by a sensor if they were released in the same row as the sensor location, a row in front, and a row in back of the release. The uncertainty of the measurements taken in the middle of the cabin was approximately ±56% as compared to about ±42% in the front part of the cabin. As a result, a total of four sensors was recommended to be used in the 11 row mockup cabin and their locations were on the center line near the cabin floor in each of row 2, 5, 8, and 11 as shown in Figure 12.

It should be mentioned that the high relative uncertainties obtained were mainly due to the small sample sizes considered and due to the high disturbance inside the cabin. Also a value of ±10% for the APS affects the results. To lower the uncertainty level, enough tests should be conducted in order to reasonably represent each location with low variability levels. Also due to some of the assumptions in the "root mean squared" method, which was used to estimate the relative uncertainties, this method may not be the best method to use for the calculation of the relative uncertainty in this project.

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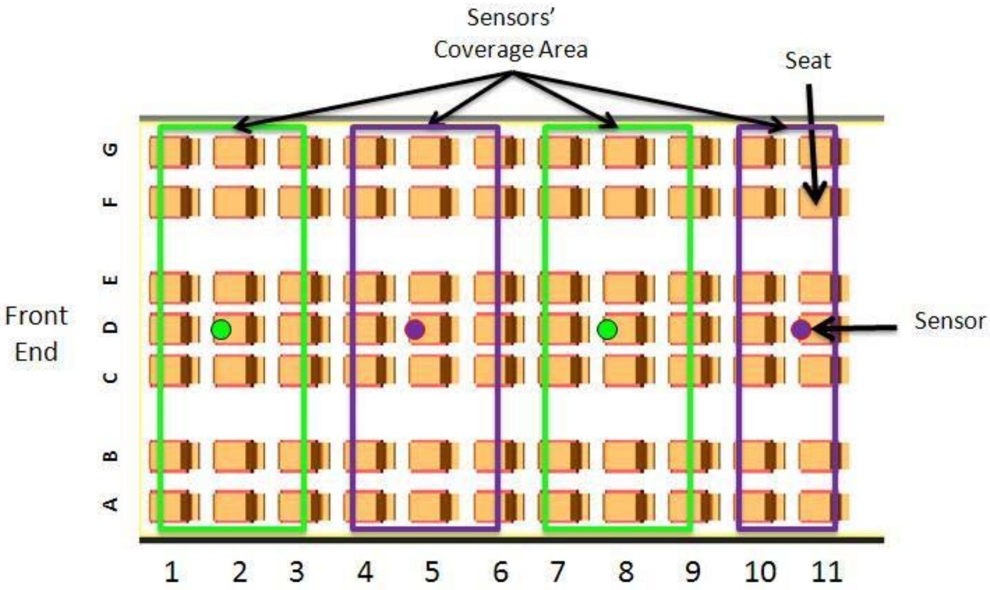

FIGURE 12 – SENSOR'S COVERAGE AREA IN THE 11-ROW CABIN MOCKUP

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