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**Analysis of Vapor Samples Collected from the Center
Wing Tank of a Boeing 747-100 Aircraft during Ground
Tests**

(33 Pages)

Analysis of Vapor Samples Collected from the Center Wing Tank of a Boeing 747-100 Aircraft during Ground Tests

Final Report

Prepared By:

John C. Sagebiel, Ph.D.
Atmospheric Sciences Division
Desert Research Institute
2215 Raggio Parkway
Reno, Nevada 89512

Prepared For:

National Transportation Safety Board
Office of Research and Engineering
490 L'Enfant Plaza East, S.W.
Washington, DC 20594

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EXECUTIVE SUMMARY

This report describes the involvement of the Desert Research Institute (DRI) of the University of Nevada in assisting the National Transportation Safety Board (NTSB) with collection and analysis of vapor samples from a 747 aircraft during ground operations in Marana, Arizona. The objective of this work was to collect vapor/air samples from each bay of the Center Wing Tank (CWT) and analyze the samples for Jet-A fuel components.

The vapor samples were collected near the center of each of the six bays in the CWT. In bay 2, the third bay back from the front spar, three sampling ports were installed: one 17.5 inches up from the bottom of the tank, one near the center (35 inches up from the bottom), similar to the other bays, and a third near the top (52 inches up from the bottom). In the first test with approximately 50 gallons of fuel in the CWT, vapor/air samples were collected at one, two and three hours from the start of a test. This test was to simulate the nominally "empty" tank condition. In the second test with approximately 1800 gallons in the CWT, vapor/air samples were collected after three hours from the start of the test. No modifications were made to the environmental control systems for these tests. Sample collections were on May 29 and 31, 1998.

The samples were returned to DRI's laboratories via commercial courier. Analysis followed a modified EPA Method TO-14 for C2 to C12 hydrocarbons. Calibration was performed with a certified standard of benzene in nitrogen.

The analysis of the vapor samples showed amounts of approximately 59 to 92 parts per thousand of carbon (ppthC) of total fuel components. These calculate to fuel-to-air mass ratios of 0.028 to 0.045 at the conditions where these samples were taken, and

would be approximately from 0.045 to 0.071 at 14,000'. Some differences in carbon group distribution were noted between the two tests, with the 1800-gallon test having a slightly lighter average composition.

The tank as a whole is apparently well mixed as evidenced by the generally similar results overall and the similar temperatures and fuel concentrations in the lower, middle, and upper samples taken in bay 2.

The addition of approximately 1800 gallons of Jet A to the tank resulted in overall lower temperatures as compared to the 50-gallon test, but did not significantly lower fuel-to-air mass ratios. In four of the six bays, the fuel-to-air mass ratio was higher with the greater amount of fuel. This is most likely due to the change in mass loading in the tank at the greater fuel amount.

Comparisons of these data with laboratory-determined Jet A vapor pressure vs. temperature showed that the fuel partial pressure was generally correlated with temperature for the 1800 gallon test, but not well correlated for the 50 gallon test, despite the partial pressures being in the same range. This may be due to the non-uniformity in the fuel distribution during the 50-gallon test.

1.0 INTRODUCTION

1.1 Background and Objectives

As part of the investigation of accident DCA96MA070 (the crash of a 747-131, N93119, operated as TWA Flight 800), the Boeing Aircraft Company in cooperation with the National Transportation Safety Board (NTSB) conducted a series of ground tests using a Boeing 747-100 series aircraft. The Safety Board's objective in performing these tests, conducted in Marana, Arizona on May 29 through 31, 1998, was to learn more about the temperatures and fuel vapor conditions inside the center wing tank under various operating conditions and different fuel loads. Multiple temperature measurements were made and multiple vapor samples were collected inside the tank. This report covers the analysis and results of the vapor sampling effort.

The Marana tests were continuations of the flight tests conducted by NTSB in July 1997. In the July 1997 flight tests, multiple temperatures were measured in the center wing tank. However, vapor samples were collected from only one location in the tank during flight operations (both taxi and climb) and analyzed for fuel vapors. These ground tests provided the opportunity to study vapor concentration gradients in the tank by collecting vapor samples from each of the six bays of the tank and by collecting vapor samples at 3 different elevations within a given bay. In addition, most of the tests conducted in July 1997 flight tests used approximately 350 pounds of fuel in the CWT. One series was conducted with 12,000 pounds of fuel in the center tank; however, no vapor samples were collected from the tank during this flight test. Thus there was interest in measuring CWT ullage space vapor concentrations with the greater amount of fuel, which was done in the present experiment. One other goal was the measurement of

tank vapors over a period of time. During one test, vapor samples were collected at one, two and three hours into the test, to provide information about the vapor concentration as a function of time.

The Desert Research Institute (DRI) was involved in these tests primarily due to our experience in collecting and analyzing jet fuel vapors from work conducted for NTSB in support of the July 1997 test flights (Sagebiel, 1997). DRI also has extensive experience in the use of pre-evacuated stainless-steel canisters for sample collection from various sources. DRI has used this technology for samples of ambient air, automobile and diesel truck exhaust, fireplace smoke, soil-gas vapors, and other locations where representative samples of air containing compounds of interest are needed. Once the sample is preserved in the canister, it can be safely transported back to DRI's laboratory in Reno, Nevada, for analysis. The fuel vapors targeted here were hydrocarbon species in the range of approximately 4 to 12 carbon atoms, which is the same range normally targeted in ambient air sampling for photochemical smog precursors. This is the exact range that DRI's laboratories have extensive experience in determining and quantifying.

1.2 Guide to Report

This section has provided some background as to the nature and origins of the project. Section 2 details the experimental methods used in both the field and laboratory phases of the project. The results are summarized in Section 3 and some conclusions and recommendations are provided in Section 4.

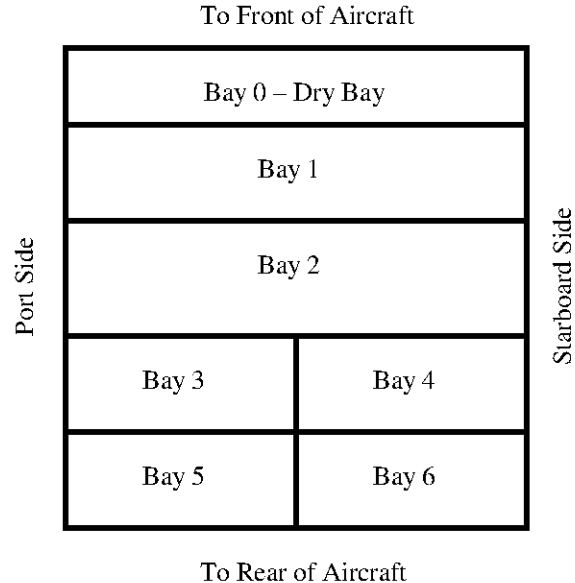
2.0 EXPERIMENTAL METHODS

This section describes both the field and laboratory methods used in this project. It also contains a description of the quality control measures.

2.1 Experimental Design

The vapor samples reported on here came from two different tests. In each of the two tests one sample was collected from each of bays 1 through 6, except for bay 2, where three samples were taken to determine whether or not vertical stratification of vapor concentration occurs in that bay. Thus a total of eight sample ports were installed. The bays are numbered as indicated on Figure 2-1.

Figure 2-1. Top view of the center wing tank showing numbering system for bays.



The vapor sampling probes were located in the approximate center of each bay and approximately midway from floor to ceiling. In bay 2, the sample probes were

centered and approximately 17.5, 35 and 52 inches up from the floor of the bay. These are referred to as the lower, middle and upper probes. Sampling probes and sampling line were 1/8" (outside diameter) copper and were heated to maintain a temperature between 140 and 160° F. This temperature is higher than the temperature in the tank to prevent any condensation in the lines. The samples were taken by allowing the vacuum in the canister to draw a sample from the tank. Prior to sampling, the heated sample lines were purged for five-seconds by a pump.

2.2 Test Matrix

Three tests were conducted as part of the overall program, but vapor samples were collected from only two of these tests, as summarized in Table 2-1. In both tests in which vapor samples were collected, all three air conditioning packs of the environmental control system (ECS) located under the center sing tank were operated without any modifications. The auxiliary power unit of the aircraft powered the ECS.

In test Number 1 approximately 50 gallons of Jet A fuel was put in the CWT. Vapor samples were collected from each of the eight sampling locations at one, two and three hours into the test. This sampling provided a total of 24 vapor samples for this test.

The second test for which vapor samples were collected was test Number 3, which was a replicate of test Number 1 except approximately 1800 gallons of Jet A fuel was put in the CWT. For this test, vapor samples were collected from the eight sampling locations at only one time, three hours into the test.

Table 2-1. Summary of Tests Conducted, Marana, Arizona, May 1998.

Date	Test No.	Start Time (PST)	CWT Fuel Load (approx. gallons)	ECS Insulation	Vapor Samples ¹ (Hours from start)
5/29/98	1	14:46:00	50	None	1, 2 and 3
5/30/98	2	14:56:30	50	Installed	none
5/31/98	3	13:06:00	1800	None	3

¹ Each vapor sample represents a full eight-canister set of samples.

2.3 Canister Handling

This section briefly describes the canister handling practices before and after shipment of the canisters to the field site for the test flights.

2.3.1 Cleaning and Evacuation

Standard protocol for canister cleaning at the DRI laboratory is six cycles of repeated pressurization and evacuation using humidified zero air (an extremely clean blend of 20% oxygen and 80% nitrogen), while the can is heated in an oven at 140°C. Each pressure/vacuum cycle lasts approximately 40 minutes. Following the cleaning cycle, one canister out of each lot of six is filled with the humidified zero air, equilibrated for 24 hours and analyzed. For this project the standard for cleanliness was less than 100 parts per billion of carbon (ppbC) total in the canister. If the canister does not test clean, the whole lot is recleaned. Once the lot is certified clean, the canisters are evacuated to approximately -29"Hg, fitted with a sample tag and packed for shipment. Canisters were then shipped to Marana.

2.3.2 Pressurization

Sample canisters were returned to DRI following sampling, and received on June 3, 1998. Once back at DRI, the canisters were pressurized to approximately +1 atm with dry zero air and allowed to equilibrate for 48 hours. This procedure served two purposes:

it diluted the sample slightly and it served to stabilize the samples. In addition, analysis is easier as one does not have to use vacuum to pull samples out of the canisters, which would make reading volumes more difficult. Pressurization is a standard practice and is performed with a test-gauge and an inlet for controlling the pressurization flow. The test-gauge is a certified compound gauge that reads both vacuum and pressure. The initial vacuum in the canister is read, flow is started and run until a desired pressure is reached and then the final pressure is read. The initial and final pressures (gauge readings) are converted to absolute pressure by subtracting the atmospheric pressure (commonly 25" Hg at DRI's altitude). This gives the dilution factor. For these canisters, which arrived with indicating pressures between 0 and +1 psi, the dilution factors were approximately 3x. Pressurization was conducted on June 4, 1998. Once pressurized, the canisters were equilibrated for approximately 48 hours before analysis.

2.4 Canister Analysis

The analysis of whole air samples for speciated hydrocarbons is not a routine analysis. Our prior experience in collecting and analyzing samples of ambient air and samples specifically resulting from motor-vehicle emissions (in tunnels and from dynamometer exhaust) has identified several significant challenges that we have worked to overcome. These include the analytical column selection and performance, and the inlet system and recovery of the higher molecular weight compounds. This section will address these challenges and present the technical approach to the analysis of speciated hydrocarbons for this project.

For the specific challenges of this study, we selected a standard column which met all the needs of this project. For the C2-C12 range we used a DB-1 column (60 m long 0.32 mm i.d., 1 μ m film thickness polymethyl siloxane bonded phase). An oven

program of -65 to 220 °C with an initial 2-min. hold and a 6 °C/min. program resolves most compounds in this range. The gas chromatograph is a Hewlett-Packard 5890 Series II, equipped with FID detector and an ECD (electron capture detector) with the column effluent split 9 parts to the FID and 1 part to the ECD. This allows us to monitor halogenated compounds on the ECD at the same time as the FID detects hydrocarbons.

The method we employ for injecting the sample on the DB-1 column involves a multi-port valve switching system that collects a small (ca. 0.09 ml) sample in a stainless steel loop and, upon switching, puts the sample loop in-line with the carrier gas which forces the sample onto the column. Our inlet system has been modified to have an absolute minimum number of transfer lines and valves for getting the sample from the sample loop to the column. In addition, the entire inlet is heated to prevent any condensation of compounds during the transfer.

Gas chromatography with flame ionization detector is the established technique for monitoring volatile hydrocarbons, ozone precursors, in ambient air. The DRI analytical procedure for analysis of C2-C12 hydrocarbons is consistent with the EPA document "Technical Assistance Document for Sampling and Analysis of Ozone Precursors" (October 1991, EPA/600-8-91/215).

2.4.1 Calibration

The GC/FID response is calibrated in ppmC, using primary calibration standards traceable to the National Institute of Standards and Technology (NIST) Standard Reference Materials (SRM). The NIST SRM 1805 (254 ppb of benzene in nitrogen) is generally used for calibrating the analytical system for C2-C12 hydrocarbon analysis, however, for this project a special standard of 100 ppm benzene in nitrogen was used

because of the much higher concentrations in these samples. This standard was purchased from AGA gas, Cleveland, OH. Based on the uniform carbon response of the FID to hydrocarbons, the response factors determined from these calibration standards are used to convert area counts into concentration units (ppbC or ppmC) for every peak in the chromatogram.

Identification of individual compounds in an air sample is based on the comparison of linear retention indices (RI) with those RI values of authentic standard compounds, as well as with the RI values obtained by other laboratories performing the same type of analysis using the same chromatographic conditions (Auto/Oil Program, Atmospheric Research and Exposure Assessment Laboratory, EPA). The DRI laboratory calibration table currently contains approximately 150 species, including all 55 target compounds listed in the EPA document "Technical Assistance Document for Sampling and Analysis of Ozone Precursors" (October 1991, EPA/600-8-91/215).

All of the gas chromatographs are connected to a data acquisition system (ChromPerfect, designed and marketed by Justice Innovation, Inc.). The software performs data acquisition, peak integration and identification, hardcopy output, post-run calculations, calibrations, peak re-integration, and user program interfacing. Acquired data are automatically stored on a hard disk. A custom-designed database management system is used to confirm all peak identifications. This step is described in section 2.4.3.

2.4.2 Quality Assurance

Quality assurance activities include canister cleaning and certification, calibration, blank system checks, daily calibration checks and replicate analyses of canister samples.

Canisters are cleaned as described above. Once a lot has been certified as clean the chromatograms of lot certification are stored in the laboratory's permanent files. Any lot that fails is sent back and re-cleaned and re-certified.

The instrument was calibrated at the beginning of this project and then single point calibration checks were run each day immediately after running a system blank. These steps confirm the cleanliness of the system and the accuracy of the calibrations.

The replicate analyses confirm the analytical system performance and serve as a secondary check on calibration. Standard procedures call for 10% of samples to be replicated; however, it was decided to run extra replicates on this project to confirm the equilibration of the higher molecular weight compounds. The results are shown in Table 2-2.

Table 2-2. Results of Replicate Analyses.

Canister	Date Pressurized	1st Anal. Date	Replicate Date	1st Anal. Amount	Replicate Amount	% Difference
379166	4-Jun	10-Jun	13-Jun	68.1	68.7	0.9%
379121	4-Jun	11-Jun	13-Jun	59.5	57.9	2.7%
379094	4-Jun	11-Jun	14-Jun	90.8	95.2	4.7%

2.4.3 Data Processing

The goal of our data processing is to provide accurate data combined into a single database for each analysis. A raw data signal is collected from the detector and stored as a digitized signal by the computer system. This signal is translated into a chromatogram by the chromatography software and integrated to give peaks and areas of those peaks. Using the appropriate response factors, area counts are converted to the calibration

parameter. The laboratory technician reviews this information and adjusts integration as necessary. A report is generated by the chromatography system.

For canister measurements, the report is imported into a custom-designed database program that has the user identify up to 12 reference peaks that are then used by a matching algorithm to compare them with a lookup table of all our identified compounds. This program also flags peaks it cannot uniquely identify and the user must then resolve any identification problems. A report can then be printed, and the individual sample data can be merged into a master database of identified compounds for the project.

The primary functions of data management are to have data stored in a consistent fashion that is both secure and available. To serve this need we have established a file server system that provides a central storage area for all laboratory and field data. The databases have defined structures that are maintained in one area so that all field names will be consistent, which permits easy merging and comparison of the various databases. Locating all data on a central file server prevents the problems associated with having multiple copies of the same data set, and allows the individuals charged with data processing, security, validation, and QA access to the same databases.

For security, all data are backed up on tape cartridges at regular intervals, depending on the sample load. Redundant backups of critical data are maintained to prevent loss due to failure of the backup media. The network that connects the organic analysis laboratory computers is an isolated local area network (LAN) that cannot be accessed by outside computers. There are no Internet or modem connections to this LAN, thus security cannot be breached from outside. Internal security is maintained by

locking of offices and by password-protected accounts on the LAN that record each individual's log-ins and what data were accessed. Other security procedures include a history file in the data collection system for the canister gas chromatographs that records the date, time, and name of the individual making changes to any file. The chromatogram files generated by this system also bind the calibrations with the file, preventing accidental changes in the data by changes in calibrations.

Data from the field, laboratory, and various quality control activities must be unified prior to reporting in a measurement database. Values must be accepted, corrected, flagged as suspect, or removed from this database after they are evaluated against validation criteria. Precision estimates associated with each value must be calculated from performance test data. The relational database FoxPro for Windows has been selected for this database management task.

Data validation is the most important function of data processing. Sample validation consists of procedures which identify deviations from measurement assumptions. Three levels of validation are applied which will result in the assignment to each measurement of one of the following ratings: 1) valid; 2) valid but suspect; or 3) invalid.

Level I sample validation takes place in the field or in the laboratory and consists of: 1) flagging samples when significant deviations from measurement assumptions have occurred; 2) verifying computer file entries against data sheets; 3) eliminating values for measurements which are known to be invalid because of instrument malfunctions; and 4) adjustment of measurement values for quantifiable calibration or interference biases. Each gas chromatogram is examined immediately after the run to verify that peak

integrations have been performed properly. The peak integration, retention times, and peak identifications assigned by the ChromPerfect software are stored to disk as an ASCII file. The files are then read into a FoxPro data file for additional processing and verification of peak identifications. The peak assignments for the major constituents (typically about a dozen peaks) in the chromatogram are manually verified, and retention times are recalculated for all detectable peaks based upon regression between sample and reference retention times for the manually identified peaks. The adjusted retention times are used to assign peak identifications for all detectable peaks (the reference file currently contains approximately 150 identified compounds). The retention time adjustments and peak assignments are executed automatically by a FoxPro program. The ChromPerfect and subsequent confirmatory peak identifications are then compared and discrepancies are resolved by the analyst based on peak patterns or confirmatory identification by GC/MS. In the final step, the Level I validated data are appended to the master database. Each sample appears as a record within the database and is identified by a unique sample identification, site, date, and time and as a primary, collocated, blank, spiked, or replicate sample.

When all data for a record have been assembled, the FoxPro programs perform Level II validation checks. Level II validation applies a consistency test based on known physical relationships between variables to the assembled data. Examples include range checks (both single species and ratios of species) and examination of scatterplots and time-series plots for outliers.

2.4.4 Reporting

Data are initially reported in units of volume ratio of carbon. For example the total hydrocarbon results are given in parts-per-thousand of carbon (ppthC). This is just a scale adjustment from parts-per-million of carbon (ppmC) or parts-per-billion of carbon (ppbC). For an individual compound this is equivalent to the parts-per-thousand by volume multiplied by the number of carbon atoms in the compound. This value is most useful because it can be summed over many different compounds easily and the calibration in ppmC allows for the maximum information to be obtained about unknown compounds. For this project, data will also be reported as the total mass per cubic meter of air and as mass-based fuel-to-air ratios.

3.0 RESULTS AND DISCUSSION

3.1 Overview of Results

This section describes the results of the analysis of the samples collected for the fuel vapor hydrocarbons. Both total hydrocarbons and carbon fractions are presented along with the vapor temperatures at the time of sampling. The results are also presented as fuel-to-air ratios for comparison with the flammability data. Comparisons are also made to laboratory-determined vapor pressures at various temperatures and fuel loadings.

3.2 Summary of Results as Total Hydrocarbons

This section presents the total hydrocarbon results along with the conditions at the time of sampling. Table 3-1 shows a summary of the data. To identify the samples, an identifier column is presented along with the bay and test number and time. The identifier was written on the canisters and was used initially to identify the sample in the laboratory and thus was kept as a unique identifier for each canister. The bays are numbered following the system shown in Figure 2-1 and for bay 2, the three samples are identified as lower, middle and upper for the three samples. The test numbers are those listed in Table 2-1. The total hydrocarbons measured in the canister are reported in units of ppthC or parts-per-thousand of carbon, as described in Section 2.4.4. Also shown in Table 3-1 is the temperature of the thermocouple located at the sample collection point, in Celsius degrees. The temperature data were provided by Boeing to the NTSB, and are the vapor temperature at the time of sampling. It is noted that the temperature of the thermocouple nearest the sample collection point is not the same as the temperature of the liquid fuel. For this reason, we also present a set of bottom or fuel temperature data on Table 3-1. These temperatures are the bottom interior surface at the center of each bay

for test 1. Since with only 50 gallons in the tank fuel does not completely cover the floor, thus fuel may or may not be present at the thermocouple. For Test 3 the reported temperatures were taken 3 inches above the bottom interior surface of the center of each bay. These should represent the fuel temperature since with 1800 gallons, the fuel depth is approximately 12 inches at spanwise beam 3 and 6 inches at the rear spar.

Table 3-1. Summary of Results as ppthC and Fuel-to-Air Ratios.

Identifier	Bay	Test - time	Total ppthC	FAR ¹	Vapor Temp, °C	Bottom or Fuel ² Temp, °C
6170482-1	1	1 - 1hour	75.52	0.037	38.2	47.5
6170483-1	2 - Lower	1 - 1hour	67.51	0.033	39.7	59.3
6170484-1	2 - Middle	1 - 1hour	72.74	0.035	39.4	59.3
6170485-1	2 - Upper	1 - 1hour	68.08	0.033	40.1	59.3
6170486-1	3	1 - 1hour	58.92	0.028	40.2	56.8
6170487-1	4	1 - 1hour	59.52	0.029	37.2	52.1
6170488-1	5	1 - 1hour	63.45	0.031	41.1	60.2
6170489-1	6	1 - 1hour	87.06	0.042	38.8	49.7
6170482-2	1	1 - 2 hours	90.81	0.044	42.6	58.0
6170483-2	2 - Lower	1 - 2 hours	75.97	0.037	43.2	68.1
6170484-2	2 - Middle	1 - 2 hours	74.37	0.036	42.9	68.1
6170485-2	2 - Upper	1 - 2 hours	74.04	0.036	43.1	68.1
6170486-2	3	1 - 2 hours	63.74	0.031	44.2	63.2
6170487-2	4	1 - 2 hours	61.44	0.030	41.1	59.1
6170488-2	5	1 - 2 hours	65.83	0.032	43.8	67.0
6170489-2	6	1 - 2 hours	66.29	0.032	No data	56.6
6170482-3	1	1 - 3 hours	92.12	0.045	44.6	61.3
6170483-3	2 - Lower	1 - 3 hours	84.27	0.041	44.9	70.1
6170484-3	2 - Middle	1 - 3 hours	81.97	0.040	44.2	70.1
6170485-3	2 - Upper	1 - 3 hours	80.81	0.039	44.7	70.1
6170486-3	3	1 - 3 hours	68.20	0.033	45.0	64.8
6170487-3	4	1 - 3 hours	71.85	0.035	42.3	60.9
6170488-3	5	1 - 3 hours	68.70	0.033	44.6	67.9
6170489-3	6	1 - 3 hours	82.66	0.040	42.4	58.9
6170482-4	1	3 - 3 hours	69.46	0.034	33.3	39.9
6170483-4	2 - Lower	3 - 3 hours	72.26	0.035	29.2	41.7
6170484-4	2 - Middle	3 - 3 hours	66.32	0.032	29.2	41.7
6170485-4	2 - Upper	3 - 3 hours	69.68	0.034	29.1	41.7
6170486-4	3	3 - 3 hours	80.32	0.039	32.1	46.2
6170487-4	4	3 - 3 hours	74.65	0.036	30.1	43.7
6170488-4	5	3 - 3 hours	87.85	0.043	36.1	49.0
6170489-4	6	3 - 3 hours	84.32	0.041	33.7	46.1

¹ Mass-based Fuel to Air Ratio at Marana test conditions

² Bottom temperature is inner surface temperature for Test 1 and fuel temperature for Test 3.

Since the bottom or fuel temperatures most likely represent the temperature near where the fuel is evaporating, these temperatures will be used along with the vapor temperatures in this report to compare with measured fuel vapor quantities.

3.3 Adjustment of Fuel-to-Air Ratios to 14,000'

The fuel-to-air ratios presented above are for the samples as they were collected on the ground in Marana, Arizona. To compare the vapor concentrations measured during the ground tests (1850 feet) to the flight test data at 14,000 feet, the ground test vapor concentrations were converted to an equivalent pressure altitude of 14,000 feet, where we assume the pressure is 0.587 standard atmospheres. The results of this calculation are presented in Table 3-2.

If we take a fuel-to-air ratio of 0.030 as the lower flammability limit for jet fuel, at least some of the bays are not flammable at sea level, but all bays are flammable at 14,000'. This is an approximation since the calculation does not take into account the different temperatures that might exist at higher altitude. During the July 1997 flight tests, the temperatures in the CWT were observed to decrease as the aircraft climbed and the tank vented. Thus the values in Table 3-2 should be considered an upper bound for the fuel-to-air ratio at 14,000', based on these conditions.

Table 3-2. Estimation of Fuel-to-Air Ratios at 14,000', Based on Differences in Air Density from Marana to 14,000'

Bay	Test	FAR	FAR at 14,000'	Vapor Temp, °C	Bottom or fuel ¹ Temp, °C
1	1 - 1hour	0.037	0.058	38.2	47.5
2 - Lower	1 - 1hour	0.033	0.052	39.7	59.3
2 - Middle	1 - 1hour	0.035	0.056	39.4	59.3
2 - Upper	1 - 1hour	0.033	0.052	40.1	59.3
3	1 - 1hour	0.028	0.045	40.2	56.8
4	1 - 1hour	0.029	0.046	37.2	52.1
5	1 - 1hour	0.031	0.049	41.1	60.2
6	1 - 1hour	0.042	0.067	38.8	49.7
1	1 - 2 hours	0.044	0.070	42.6	58.0
2 - Lower	1 - 2 hours	0.037	0.059	43.2	68.1
2 - Middle	1 - 2 hours	0.036	0.057	42.9	68.1
2 - Upper	1 - 2 hours	0.036	0.057	43.1	68.1
3	1 - 2 hours	0.031	0.049	44.2	63.2
4	1 - 2 hours	0.030	0.047	41.1	59.1
5	1 - 2 hours	0.032	0.051	43.8	67.0
6	1 - 2 hours	0.032	0.051	No data	56.6
1	1 - 3 hours	0.045	0.071	44.6	61.3
2 - Lower	1 - 3 hours	0.041	0.065	44.9	70.1
2 - Middle	1 - 3 hours	0.040	0.063	44.2	70.1
2 - Upper	1 - 3 hours	0.039	0.062	44.7	70.1
3	1 - 3 hours	0.033	0.052	45.0	64.8
4	1 - 3 hours	0.035	0.055	42.3	60.9
5	1 - 3 hours	0.033	0.053	44.6	67.9
6	1 - 3 hours	0.040	0.064	42.4	58.9
1	3 - 3 hours	0.034	0.053	33.3	39.9
2 - Lower	3 - 3 hours	0.035	0.056	29.2	41.7
2 - Middle	3 - 3 hours	0.032	0.051	29.2	41.7
2 - Upper	3 - 3 hours	0.034	0.054	29.1	41.7
3	3 - 3 hours	0.039	0.062	32.1	46.2
4	3 - 3 hours	0.036	0.057	30.1	43.7
5	3 - 3 hours	0.043	0.068	36.1	49.0
6	3 - 3 hours	0.041	0.065	33.7	46.1

¹ Bottom or fuel temperature is inner surface temperature for Test 1 and fuel temperature for Test 3.

3.4 Summary of Carbon Groups

The total amount of fuel vapor in each carbon group for each sample is presented in Table 3-3. These carbon distributions were used to estimate the average composition of the fuel vapor. For all samples, the average carbon number is 9.03, slightly less than the 9.58 found previously in the vapor samples taken from the CWT of the test aircraft in New York in 1997. Since additional fuel was added between Tests 1 and 3 in the current

study, we compared the average composition in these two tests. All samples taken for Test 1 showed an average carbon number of 9.10 and those from Test 3 showed an average of carbon number of 8.82. The distribution of the carbon groups is presented in Figure 3-1 for the average of all Test 1 samples and the average of all Test 3 samples. As can be seen from Figure 3-1, Test 3 had slightly more light carbon fractions (C3-C8) while Test 1 had slightly more heavier components, but this difference is quite small since the average carbon composition changed by only 3% between the two tests.

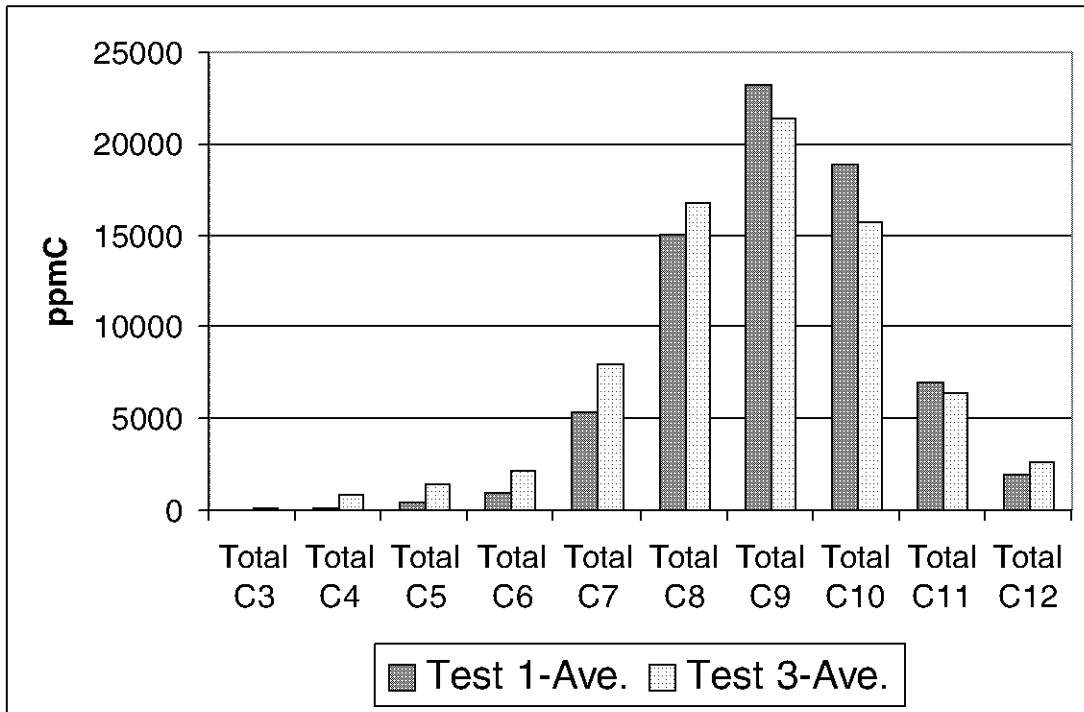
The average hydrogen to carbon ratio remained approximately 1.8:1 for the ground testing program. This resulted in an average composition of $C_{9.03}H_{16.25}$ and a molecular weight of 124.83 g/mol. This value was used in all calculations for this report. This value is compared to the measured average molecular weight of the vapors in the flight test of 132.4 g/mol.

The difference in the average carbon numbers and molecular weights in the ground tests and the flight tests are likely the result of 2 factors. First, the Jet fuels are from two different sources. Second, the Jet A fuel used in the flight tests was weathered by being transported from Athens, Greece to New York and was subject to further weathering during the flight test program. "Weathering" is known to preferentially remove the lower molecular weight species since the tank is vented to the atmosphere.

Table 3-3. Total Amount (in ppmC) of Fuel in Each Carbon Group for All Samples.

Bay	Test	Total C3	Total C4	Total C5	Total C6	Total C7	Total C8	Total C9	Total C10	Total C11	Total C12
1	1 - 1 hr	20	222	601	1471	7176	17721	24267	17112	5425	1502
2 - L	1 - 1 hr	15	147	355	815	4285	12569	20660	18394	7708	2562
2 - M	1 - 1 hr	15	149	377	880	4605	13605	22488	20027	8084	2506
2 - U	1 - 1 hr	15	151	371	853	4477	13093	21454	18601	7070	1995
3	1 - 1 hr	12	112	253	579	3282	10366	17943	16785	7260	2324
4	1 - 1 hr	12	108	244	573	3223	10312	17718	16493	7624	3215
5	1 - 1 hr	12	108	227	531	3279	11150	19603	18291	7769	2484
6	1 - 1 hr	18	152	332	728	4471	15038	26221	24436	11170	4490
1	1 - 2 hrs	18	207	605	1664	8935	23030	30956	19644	4851	907
2 - L	1 - 2 hrs	16	178	474	1186	6171	16432	24296	19139	6693	1381
2 - M	1 - 2 hrs	16	177	473	1178	6127	16265	23780	18337	6342	1678
2 - U	1 - 2 hrs	16	177	477	1195	6122	16245	23701	18187	6296	1622
3	1 - 2 hrs	14	142	328	793	4234	12361	19685	17075	6950	2156
4	1 - 2 hrs	12	125	294	697	3775	11344	18968	17203	6953	2063
5	1 - 2 hrs	14	118	255	612	3588	11950	21080	18967	7406	1840
6	1 - 2 hrs	13	119	258	600	3550	12003	21421	19166	7111	2043
1	1 - 3 hrs	16	193	566	1658	9316	24159	31574	18874	4640	1121
2 - L	1 - 3 hrs	16	185	507	1359	7295	19110	26947	20053	6930	1868
2 - M	1 - 3 hrs	16	183	505	1366	7329	19127	26321	18934	6392	1801
2 - U	1 - 3 hrs	16	186	529	1399	7459	19351	26563	18464	5628	1219
3	1 - 3 hrs	15	161	403	1006	5294	14460	21434	17087	6509	1831
4	1 - 3 hrs	15	159	397	992	5267	14671	22728	19055	6880	1692
5	1 - 3 hrs	13	134	301	711	4010	12567	21656	19578	7580	2153
6	1 - 3 hrs	15	157	372	862	4852	15387	27099	24216	8099	1600
1	3 - 3 hrs	132	808	1273	1909	6897	14612	19616	15881	6396	1936
2 - L	3 - 3 hrs	140	840	1363	2066	7387	14972	18282	14196	8315	4696
2 - M	3 - 3 hrs	136	826	1327	2005	7273	15164	19322	13876	4962	1428
2 - U	3 - 3 hrs	141	855	1360	2062	7468	15477	19462	13963	5770	3124
3	3 - 3 hrs	146	890	1469	2295	8509	18007	23178	17113	6281	2435
4	3 - 3 hrs	143	877	1410	2151	7876	16390	20822	15546	6460	2971
5	3 - 3 hrs	162	1000	1661	2630	9845	20746	26298	18079	5908	1525
6	3 - 3 hrs	151	933	1529	2402	8895	18769	23828	17403	7409	3004

Figure 3-1. Distribution of Carbon Groups in Tests 1 and 3.

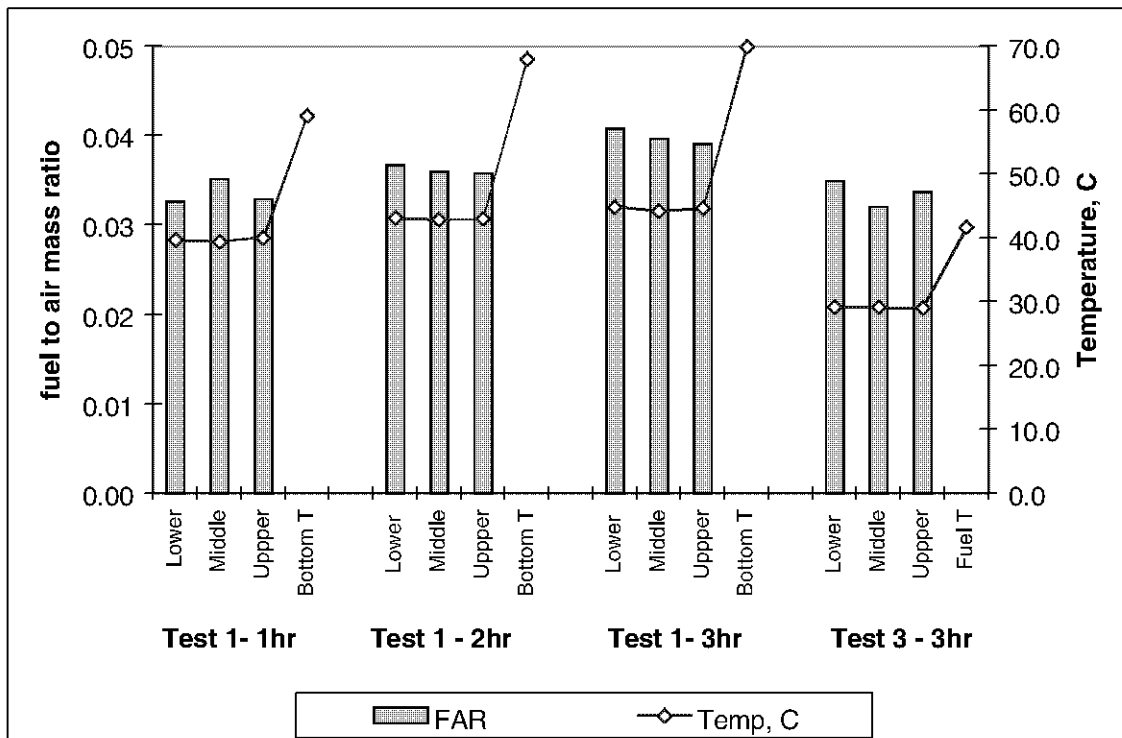


3.5 Assessment of Uniformity in Bay 2

The multiple sampling in bay 2 allows us to look at the vertical distribution of fuel vapors in the bay since samples were taken at approximately 17.5, 35 and 52 inches up from the floor of the bay (lower, middle and upper probes, respectively). The results of this sampling in 2 tests are presented in Figure 3-2 along with the temperatures at the sampling points. These results show that the vertical profile of the tank is fairly uniform, with relative standard deviations (the standard deviation divided by the average) all less than 4.5%. The specific values for the tests were 4.1% for Test 1 – 1 hour, 1.4% for Test 1 – 2 hours, 2.1% for Test 1 – 3 hours, and 4.3% for Test 3 – 3 hours. In addition, the air temperatures at the sampling points are very uniform with less than 0.5 °C difference between the sample points. Since the heat sources from the environmental control systems are below the tank and the upper skin of the tank is cooler, it might be expected

that the concentration would be higher at the lower point and lower at the upper sample points. The similarity of these values suggests that the tank is well mixed, but we must consider the possibility that these sample probes were not close enough to either the upper or lower surface to see the effect of the cooler or hotter surfaces. Seen in Figure 3-2 is the change of temperature with time of sampling. For Test 1, the temperatures generally increase with time, as does the vapor concentration, however, for Test 3, the vapor samples are much higher than the temperatures would suggest, based on the Test 1 results. Also on Figure 3-2 is the bottom or fuel temperature, and it can be seen that in all cases these temperatures were higher than the corresponding vapor temperatures.

Figure 3-2. Bay 2: Results of Samples at Various Heights with Fuel-to-Air Mass Ratios and both Vapor and Bottom or Fuel Temperatures.

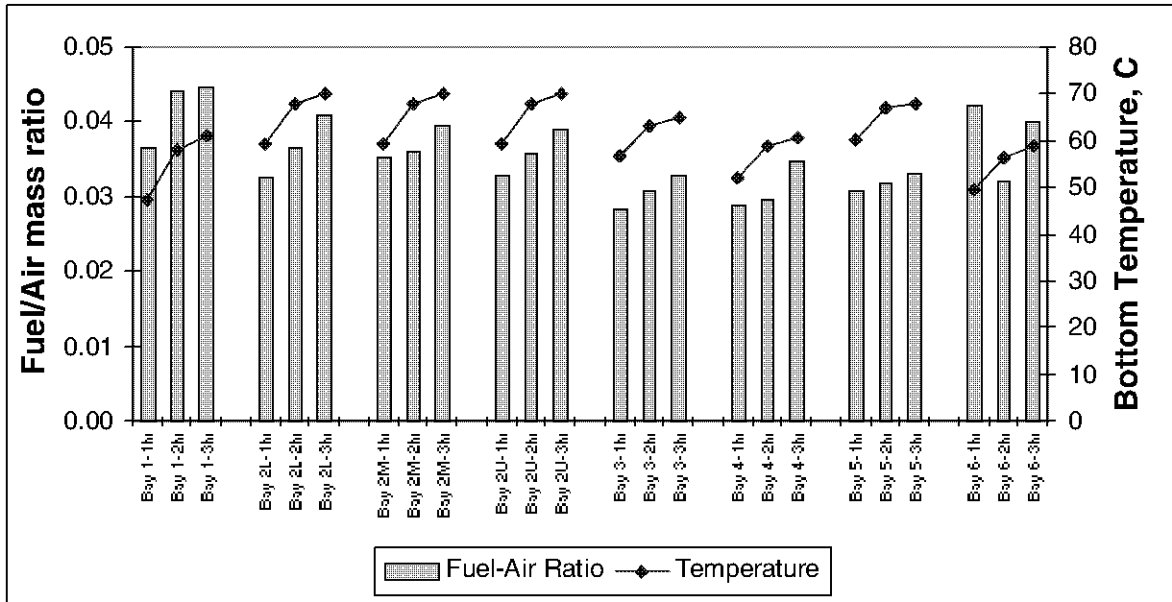


3.6 Summary of Test 1 Time Sequence

Samples were taken at one, two and three hours into Test 1. At each point the fuel vapor concentration (or fuel-to-air mass ratio) was determined and this is presented, along with bottom temperature, in Figure 3-3. In this figure, both the temperature and the fuel/air mass ratio generally increase with time over the three-hour duration of this test. The exception is bay 6 where the fuel-to-air mass ratio does not appear to follow the temperature trend. Bay 6 is the rear-most bay on the starboard side and is somewhat unique in that there are no major ECS components directly under this bay. In addition, bay 1 and bay 6 are directly connected through the vent stringer, thus there may have been some local circulation bringing extra fuel components into this bay from elsewhere in the tank.

The liquid fuel location was determined by Boeing after the tests to be pooled near spanwise beam 2, near bays 1 and 2. Considering the relative non-uniformity of the fuel distribution, the differences among the bays is relatively small. For Test 1, hour 1, the fuel/air ratio ranged from 0.028 to 0.037 (excluding bay 6) with a standard deviation of approximately 10%. The second and third hours had slightly higher standard deviations. Bay 1 had the highest concentration, with the exception of the first hour where bay 6 was highest. It appears that within each bay there is a reasonable correlation with increasing temperature and increasing fuel-to-air ratio, however, there is less of a correlation between fuel-to-air ratios and temperatures between bays.

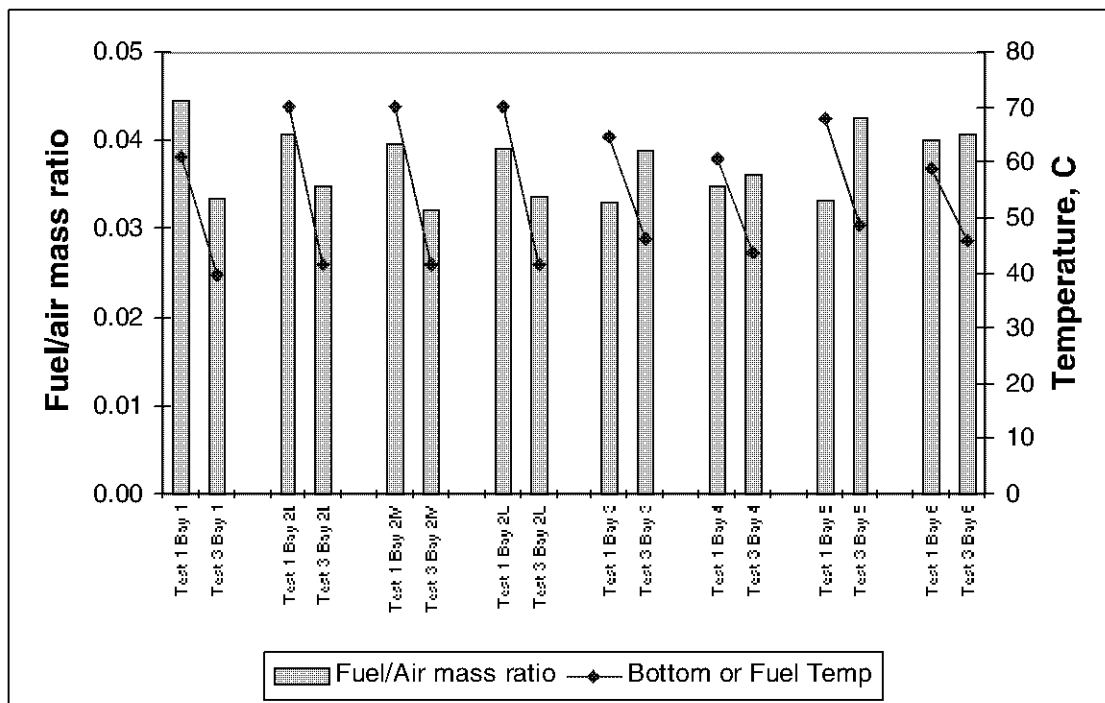
Figure 3-3. Time Series for Test 1 (50 gallons fuel) by Bay. Each Bay is Presented With the Fuel-to-Air Mass Ratio and Bottom Temperature at Each Time Interval.



3.7 Comparison of Tests 1 and 3 at Three Hours

Both Tests 1 and 3 had vapor samples taken at three hours and these two sets of data are compared in Figure 3-4 along with the bottom or fuel temperature. Test 1 used 50 gallons in the CWT, while Test 3 used 1800 gallons. Figure 3-4 shows that the additional fuel lowered the temperature that was observed at each sample point; however, it did not reduce the fuel-to-air ratio in all cases. Bays 1 and 2 had lower fuel-to-air ratios with the additional fuel, but bays 3, 4, 5 and 6 all showed higher or similar fuel-to-air ratios with the greater amount of fuel. If we take 0.030 as the lower flammability level, then all bays in all tests would be considered flammable at three hours in both tests. While the lower temperature should have lowered the fuel-to-air mass ratio, this may have been partially offset by the increased fuel mass loading in the tank.

Figure 3-4. Comparison of Three-Hour Samples for Test 1 (50 gallons fuel) and Test 3 (1800 gallons) by Bay. Each bay is Presented with the Fuel-to-Air Mass Ratio and Bottom or Fuel Temperature.



3.8 Comparison with Temperature and Vapor Pressure Data

To compare the results of this field sampling with previous laboratory work on the vapor pressure of Jet-A fuel, we needed to convert the present data to partial pressures, expressed in millibars (mbar). The data are presented on Table 3-4 and in Figure 3-5. Table 3-4 shows the fuel partial pressure and the bottom or fuel temperature measured for each sample. Figure 3-5 shows the fuel partial pressure vs. temperature for both the field samples and the laboratory vapor pressure data measured by James Woodrow at the University of Nevada, Reno. The laboratory vapor pressure data are for a sample from Test 1 and was determined by headspace gas chromatography (Woodrow and Seiber, 1997). The fuel sample from Test 3 was sufficiently similar that the difference would not be visible on this plot. The data are presented with each sample

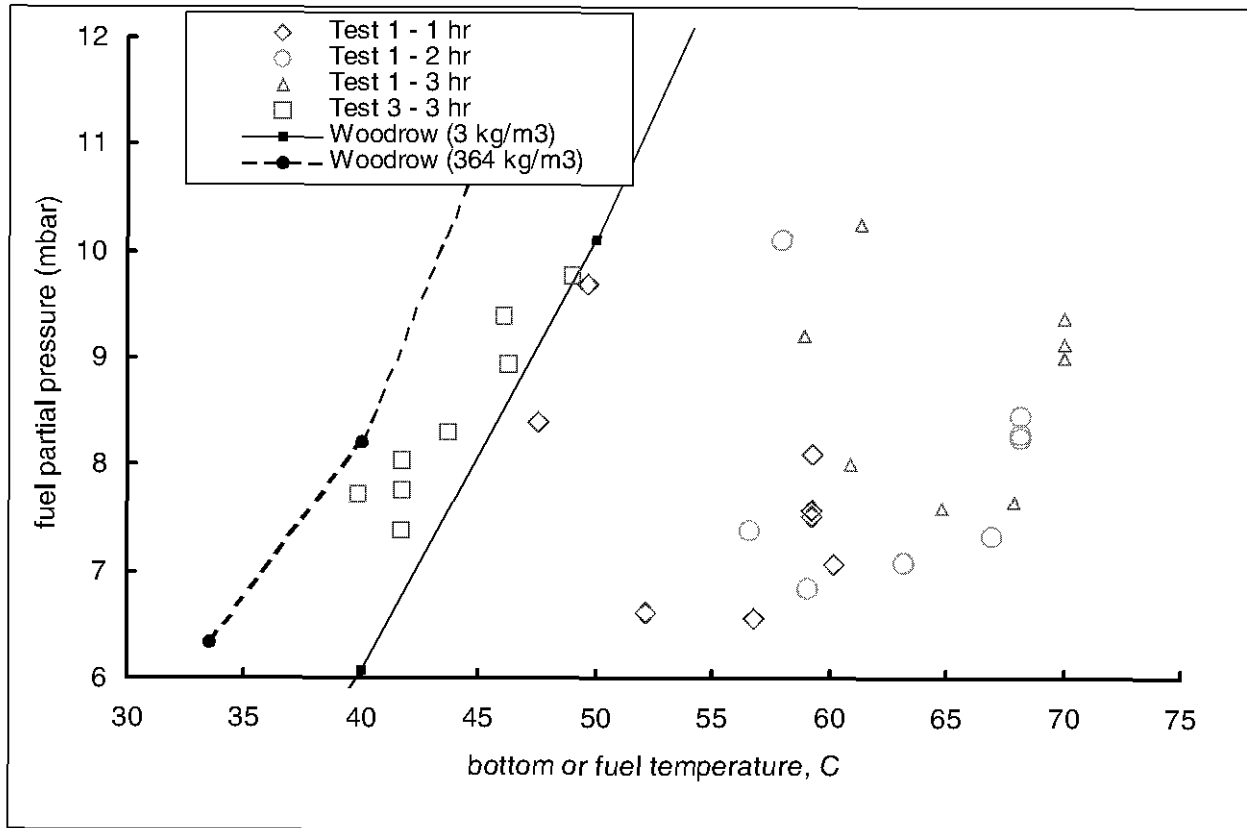
group as a different symbol and the laboratory vapor pressure data show the conditions of 3 kg/m^3 , which is roughly equivalent to 50 gallons in the CWT, and 364 kg/m^3 , which represents a half-full tank.

Table 3-4. Fuel Partial Pressures in millibars (mbar) for Each Sample.

Bay	Test	Press. (mbar)	Bottom or Fuel¹ Temp, °C
1	1 - 1hour	8.41	47.5
2 - Lower	1 - 1hour	7.51	59.3
2 - Middle	1 - 1hour	8.10	59.3
2 - Upper	1 - 1hour	7.58	59.3
3	1 - 1hour	6.56	56.8
4	1 - 1hour	6.63	52.1
5	1 - 1hour	7.06	60.2
6	1 - 1hour	9.69	49.7
1	1 - 2 hours	10.11	58.0
2 - Lower	1 - 2 hours	8.46	68.1
2 - Middle	1 - 2 hours	8.28	68.1
2 - Upper	1 - 2 hours	8.24	68.1
3	1 - 2 hours	7.10	63.2
4	1 - 2 hours	6.84	59.1
5	1 - 2 hours	7.33	67.0
6	1 - 2 hours	7.38	56.6
1	1 - 3 hours	10.25	61.3
2 - Lower	1 - 3 hours	9.38	70.1
2 - Middle	1 - 3 hours	9.12	70.1
2 - Upper	1 - 3 hours	9.00	70.1
3	1 - 3 hours	7.59	64.8
4	1 - 3 hours	8.00	60.9
5	1 - 3 hours	7.65	67.9
6	1 - 3 hours	9.20	58.9
1	3 - 3 hours	7.73	39.9
2 - Lower	3 - 3 hours	8.04	41.7
2 - Middle	3 - 3 hours	7.38	41.7
2 - Upper	3 - 3 hours	7.76	41.7
3	3 - 3 hours	8.94	46.2
4	3 - 3 hours	8.31	43.7
5	3 - 3 hours	9.78	49.0
6	3 - 3 hours	9.39	46.1

¹ Bottom or fuel temperature is inner surface temperature for Test 1 and fuel temperature for Test 3.

Figure 3-5. Comparison of Field Sample Partial Pressure with Temperature and with Laboratory Determined Vapor Pressures.



The observed distribution of partial pressures from the ground testing is not well correlated with temperature for the three samples from Test 1. For Test 3 there is a good correlation. The range of partial pressures seen in all tests is approximately the same, between about 6.5 and 10 mbar. The reason why Test 3 shows better correlation with temperature may be related to the fuel distribution. In Test 3, there was sufficient fuel to completely cover the bottom of the tank in all bays, resulting in a more uniform temperature and thus better correlation. In Test 1, with only a small amount of fuel, the temperature may vary more within the bays and convection can move fuel from hotter, higher concentration areas to cooler areas, thus causing a poor correlation with temperature. Test 3, with 1800 gallons is between the two fuel loadings simulated by the

headspace gas chromatography, which were the nominally empty and half-full conditions. Thus the fact that these points lie between those two lines is reasonable. For the other samples, the location of the pool of fuel was determined by Boeing to be near spanwise beam 2, between bays 1 and 2 and this uneven fuel distribution led to the lack of correlation between these test results and the laboratory tests.

3.9 Summary of Results

The analysis of the vapor samples showed approximately 59 to 92 ppthC of total fuel components. These calculate to fuel-to-air mass ratios of 0.028 to 0.045 at Marana, Arizona (1850') where these samples were taken and would be 0.045 to 0.071 at 14,000'. Speciation of the fuel vapors showed an average carbon composition of 9.03 carbons per molecule with 1.8 hydrogens per carbon, or an average composition of $C_{9.03}H_{16.25}$ for a molecular weight of 124.83 g/mol. Some differences in carbon group distribution were noted between Tests 1 and 3, with Test 3 having a slightly lighter average composition.

The tank as a whole is well mixed as evidenced by the generally similar results overall and the similar temperatures and fuel concentrations in the lower, middle, and upper samples taken in bay 2. Test 1 generally showed increases in temperature and fuel-to-air ratios over the three-hour test run. While this trend was strong within each bay, there was less correlation with temperatures between bays, which suggests that convective flow could move material from hotter, higher concentration areas to cooler lower concentration areas.

The addition of approximately 1800 gallons in Test 3 resulted in overall lower temperatures, but did not significantly lower fuel-to-air ratios. In bays 3, 4, 5 and 6 the

fuel-to-air ratio was higher with the greater amount of fuel. This may be due to the greater mass loading in Test 3.

Comparisons with laboratory-determined vapor pressure and temperature showed that the fuel partial pressure was generally correlated with temperature for Test 3, but not well correlated for Test 1, despite the partial pressures being in the same range. This may be due to the non-uniformity in the fuel distribution during Test 1.

4.0 SUMMARY AND CONCLUSIONS

The sampling and analysis program described in this report is the first attempt to quantify the amount of fuel vapor in each bay of the CWT of a 747 aircraft. Overall the results are similar to those seen in the July 1997 flight tests (Sagebiel, 1997), with fuel-to-air ratios in the range of 0.028 to 0.045.

The CWT appears to be well mixed overall, as evidenced by the three vertical samples taken in bay 2 and the comparisons between bays. The correlation of partial pressure of fuel with temperature was not very strong for Test 1 where only 50 gallons of fuel were in the CWT, but was reasonably well correlated with 1800 gallons in the tank. This may be related to the better fuel temperature uniformity with more fuel in the tank.

All bays in the tank were above the lower flammability limit of 0.03 after three hours in both tests.

5.0 REFERENCES

Sagebiel, J.C. 1997. Sampling and Analysis of Vapors from the Center Wing Tank of a Test Boeing 747-100 Aircraft. Final Report to the National Transportation Safety Board, November, 1997.

Woodrow, J.E. and J.N. Seiber. 1997. The Laboratory Characterization of Jet Fuel Vapor Under Simulated Flight Conditions. Final Report to the National Transportation Safety Board under order NTSB12-97-SP-0255, November, 1997.