



**Naval Facilities Engineering Systems Command Pacific
JBPHH HI**

Final

Bench-Scale JP-5 Evaporation Study Report

Red Hill Bulk Fuel Storage Facility

JOINT BASE PEARL HARBOR-HICKAM OAHU HI

July 2024



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ACRONYMS AND ABBREVIATIONS

ASTM	ASTM International
BTEX	benzene, toluene, ethylbenzene, and xylenes
g/hr	gram per hour
JP-5	Jet Propellant 5
NAPL	nonaqueous-phase liquid
SVE	soil vapor extraction
SVOC	semivolatile organic compound
VOC	volatile organic compound

1. Introduction

1.1 OBJECTIVES

Soil vapor extraction (SVE) pilot testing, with a potential expansion to air sparge pilot testing, will be conducted at the Red Hill Bulk Fuel Storage Facility. These pilot studies will assess the effectiveness and implementability in addressing Jet Propellant 5 (JP-5) that was released to the environment during a facility incident in November 2021.

JP-5 is a kerosene-like petroleum mixture composed of hundreds of compounds, including alkanes (paraffins), isoalkanes (isoparaffins), aromatics, cycloalkanes (naphthenes), and potentially small amounts of olefins, depending on the refining process. The exact composition of chemicals in given JP-5 fuel depends on the crude oil source(s) and on the refinery processes used for production. Irrespective of this, kerosenes/jet fuels consist predominantly of hydrocarbons with carbon numbers predominantly in the range of C₉–C₁₆, with small amounts of C₅–C₈ aliphatics and aromatics such as benzene, toluene, ethylbenzene, and xylenes (BTEX). Additional detail on the composition of jet fuels is provided in Appendix B.7 of the *Conceptual Site Model, Investigation and Remediation of Releases and Groundwater Protection and Evaluation, Red Hill Bulk Fuel Storage Facility, Joint Base Pearl Harbor-Hickam, O'ahu, Hawai'i; June 30, 2019, Revision 01* (DON 2019). It is expected that evaporation would preferentially remove more volatile compounds from the JP-5, such as lower molecular weight aliphatics and BTEX. This expected behavior is a primary remedial mechanism for air sparging and SVE to decrease the volatility of JP-5. Furthermore, it is expected that evaporation would increase the viscosity and density of the nonaqueous-phase liquid (NAPL), which would decrease NAPL mobility.

The objectives of the JP-5 evaporation study are to validate that the volatile nature of JP-5 will result in a significant decrease in NAPL mass if exposed to a continuous stream of air, and to assess the JP-5 composition change resulting from the induced volatilization. The results of this study are relevant to understanding the maximum potential effectiveness of both air sparging and SVE for addressing JP-5 in the subsurface. Although the in situ feasibility of air sparging and SVE depends on vadose zone and hydrogeologic characteristics and the distribution of the sparged and vented air in relation to the subsurface NAPL phase, this bench-scale test provides information on laboratory-controlled (“ideal”) conditions in which soil or groundwater do not inhibit the passage of air.

1.2 METHODOLOGY

Three gallons of JP-5 fuel sourced from the Red Hill supply were provided by the Naval Supply Systems Command Fleet Logistics Center on November 28, 2022, to use for the bench-evaporation study. The JP-5 is assumed to represent the NAPL composition at the time of the JP-5 release. Weathered NAPL present in the subsurface was not considered for testing because the volume of in situ NAPL that could be collected from the site was too small to support the bench testing. To date, less than 0.5 gallons of NAPL have been recovered from boreholes and temporary wells at the site, and in most cases, only a sheen (less than 0.01-foot thick) of NAPL is measured in a subset of locations. The tests were conducted by bubbling a continuous stream of compressed air (i.e., sparging) into the NAPL that was sourced from the Red Hill supply to accelerate the evaporation process.

The tests were conducted in two phases:

1. A pretest to understand the expected total evaporation and change in evaporation rate over time, which was used to inform the phase two composition sampling program.
2. An evaporation study using triplicate bottles investigating the chemical and physical NAPL characteristics and gas phase evolution of organic compounds collected at predetermined time periods.

The tests were set up in 1.0-liter glass media bottles under a safety fume hood or in proximity of a fume extractor to prevent laboratory worker exposure to volatile organic compounds (VOCs). In-house compressed air was connected to a pressure regulator and a manifold equipped with digital gas flow meters with controllers (Aalborg), as shown in Photo 1, to set flowrates in each bottle. The mass flow controllers were calibrated using a Bios DryCal Defender 520. Viton tubing was used in contact with the JP-5 as it is a material chemically compatible with the fuel. For each test bottle, a brass muffler, also compatible with JP-5, was attached at the end of the Viton tube placed inside the NAPL phase to avoid changes in height and to allow a consistent dispersion of air and bubble size.



Photo 1: Sample Experiment Setup

1.2.1 Pretest

Prior to the evaporation study, an initial screening test was conducted on a sample of JP-5 to record mass loss over time under sparging conditions. The intent of the pre-test was to understand the expected total evaporation and change in mass over time. The results of the pretest were used to inform the composition sampling program during the evaporation study. Air was sparged between 1 and 3 liters per minute into a single bottle containing 390 grams of NAPL during the pretest. Two different micro-bubble air diffusers were tested to determine the impact of bubble size on JP-5 mass loss rates. The temperature of the NAPL sample was measured and recorded as 19.4 degrees Celsius prior to initiation of testing. The pretest was continued for approximately 89 days (2,138 hours), until the final mass of the JP-5 in the bottle was reduced to approximately 34 grams. Results from the pretest are presented in Section 3.1.

1.2.2 Evaporation Study

The evaporation study used triplicate bottles, each containing approximately 500 grams of NAPL. The temperature of the NAPL sample was measured at 19.4 degrees Celsius and recorded prior to initiation of testing. The air flow rate for the composition lab tests was 3.0 liters per minute using a coarse (> 0.5 micron) air diffuser. All bottles were monitored for mass reduction of NAPL, which was determined gravimetrically using precision laboratory scales. Weight reduction of the NAPL was documented at least every 15 minutes for the first hour of testing, every 30 minutes during the next 3 hours, and twice per day thereafter. Testing continued for 52 days until approximately 60 percent of the initial mass was evaporated to ensure sufficient volume remained for collecting samples of the residual NAPL for laboratory analysis of composition and physical properties.

The change in NAPL composition over time was determined by collecting samples from the stock JP-5 and from the experimental bottles after sparging was concluded. Multiple gas samples were collected to show the composition change in the sparged air as a function of the mass loss. Gas samples were collected at the start and end of the test from the sparge air stream after the air had passed through the NAPL to quantify the start and end conditions. Additional gas samples were collected after approximately 10, 20, 50, and 80 percent of the planned mass loss was observed. The sampling program was biased towards the early part of the test to assess preferential removal of highly volatile compounds. The air samples were collected using a summa canister. The analyses and methods are presented in Section 2.

Post-treatment samples were collected from the remaining NAPL for analysis of saturated hydrocarbons, VOCs, and semivolatile organic compounds (SVOCs) to determine the change in NAPL composition and the extent of VOCs and SVOCs removal. In addition to chemical analyses, the density and viscosity of the NAPL were measured before and after evaporation to evaluate changes in NAPL physical properties. The analytical methods used for this test are presented in Section 2.

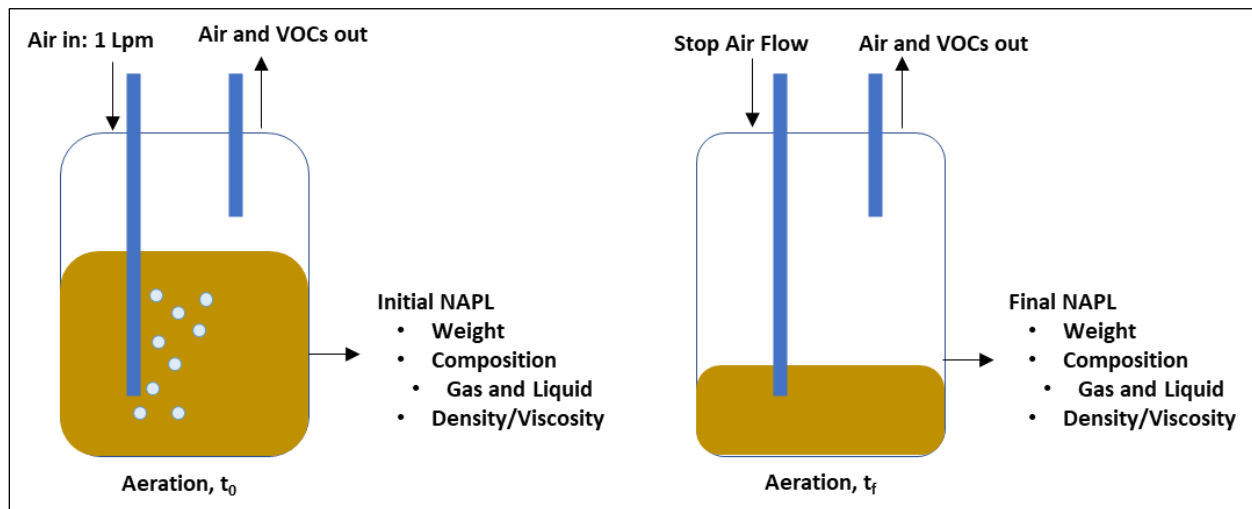


Figure 1: Conceptual Bench Test Configuration

2. Analytical Methods

The analytical program required the services of multiple laboratories. The AECOM Technical Services, Inc. treatability laboratory located in Austin, Texas, followed standard methods for the in-house weight measurements.

A summary of the parameters and matrix that were analyzed is presented in Table 1.

Table 1: Parameters Summary

Parameter	Matrix	Analytical Method	Frequency	Number of Test Samples	Number of Control Samples	Total Samples
Simulated Distillation PIANO	NAPL	ASTM D2887 ASTM D6623	Start and End	3	N/A	6
VOCs and SVOCs	Gas	TO-3, TO-15, and TO-17	Start, 10%, 20%, 50%, 80%, and End	3	1	24
NAPL Density	NAPL	ASTM D4052	Start and End	3	N/A	6
NAPL Viscosity	NAPL	ASTM D7042	Start and End	3	N/A	6

% percent
 ASTM ASTM International
 PIANO paraffins, isoparaffins, aromatics, naphthenes, and olefins
 N/A not applicable

3. Data Analysis and Reporting

3.1 PRETEST RESULTS

An initial screening phase was conducted using a single air sparging test on JP-5 to determine collection times for the TO-3, TO-15, and TO-17 samples during the evaporation testing phase. The test was conducted by varying air flowrates and bubble size to determine the optimal configuration for evaporation of the JP-5. The mass loss was monitored over time until approximately 90 percent of the initial mass was evaporated. The findings are discussed in the following paragraphs.

Air sparging of the JP-5 was conducted for 2,138 hours during the pretest. The total JP-5 mass loss was 358.6 grams with a starting mass of 393.0 grams and a final mass of 34.4 grams. Appendix A tabulates the mass loss over the initial screening test.

During the testing, several air flowrates and air diffusers were tested to determine the optimal condition for the compositional air sparging experiments. The air flowrates tested were 1.0, 2.0, and 3.0 liters per minute and the air diffusers tested had bubble sizes > 0.5 micron (coarse) and < 0.5 micron (fine). Table 2 summarizes the conditions, hours tested, mass loss, and average rate change for each condition. After evaluating three different test conditions (three air injection flow rates evaluated for both the fine and coarse diffusers), a decision was made to complete the rest of the test at an air injection flow rate of 3 liters per minute using the coarse diffuser, as this condition yielded the greatest rate of evaporation (i.e., the slope of the mass versus time trend). Figure 2 shows the graphical trend for the remaining mass of JP-5 in the test bottle for different test configurations.

Table 2: Overall Condition Change Impacts on JP-5 Mass Loss

Air Flowrate (lpm)	Bubbler Type	Length of Exposure (hr)	Total Mass Loss (g)	Average Rate Change (g/hr)
1	Coarse	140	45.6	0.26
2	Coarse	80	24.0	0.33
3	Coarse	204	69.8	0.35
1	Fine	122	10.6	0.09
2	Fine	69	11.3	0.18
3	Fine	100	24.1	0.24
3	Coarse	1,423	173.2	0.11

g gram
 g/hr gram per hour
 hr hour
 lpm liter per minute

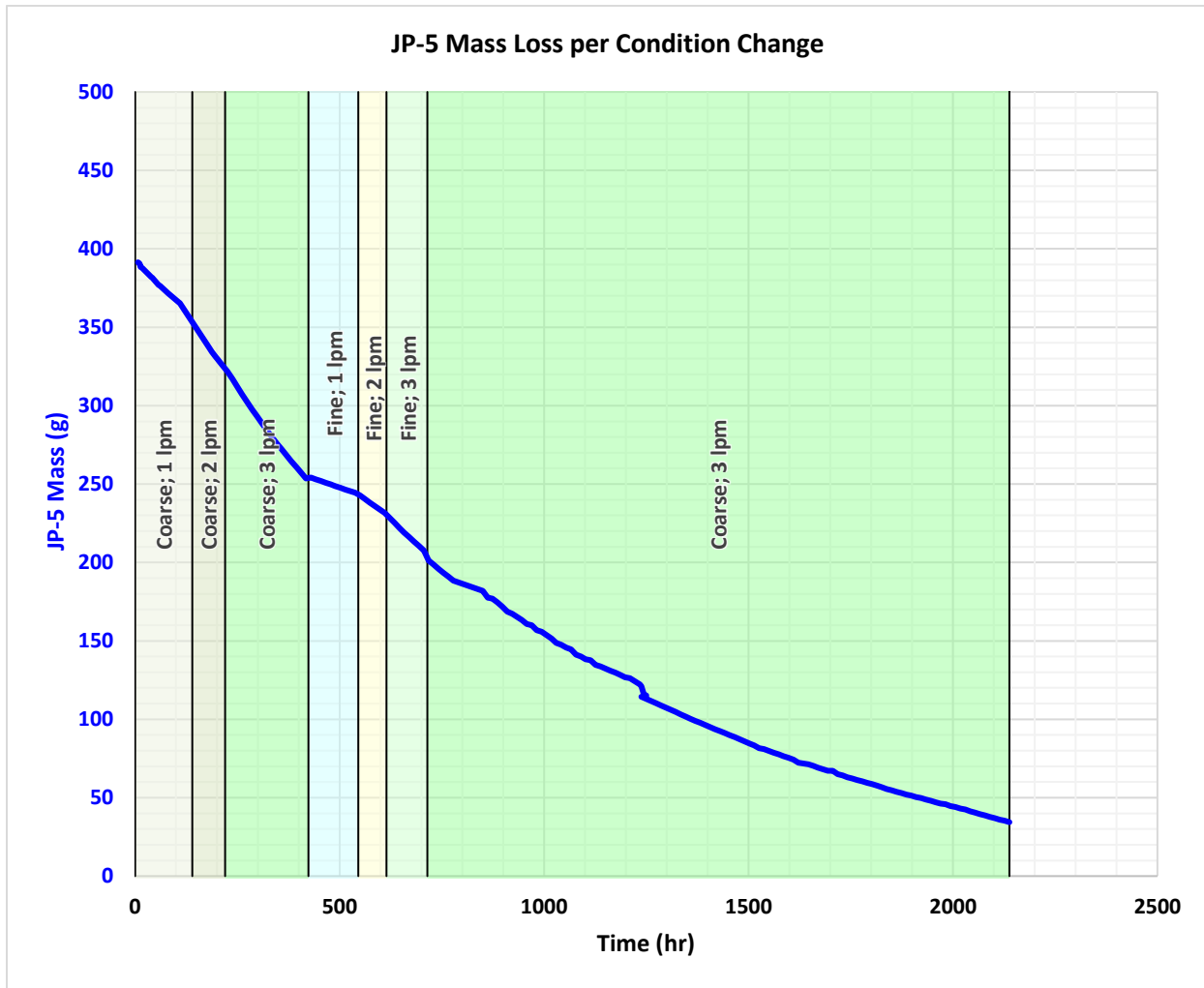


Figure 2: JP-5 Mass Loss as a Function of Condition Change during Initial Screening Test

The results in Table 2 and on Figure 2 show a large difference in the rate of mass removal based on the bubble size, where the larger bubbles (> 0.5 micron) had a larger impact on mass loss compared to the smaller bubbles (< 0.5 micron). Furthermore, the increase in air flowrate from 1.0 to 2.0 to 3.0 liters per minute impacted the rate of mass loss in the fine bubbler more than the coarse bubbler with a definitive difference in the average rate change going from 0.09, 0.18, to 0.24 grams per hour (g/hr) for the fine bubbles compared to 0.26, 0.33, and 0.35 g/hr for the coarse bubbles. Part of the drastic rate change observed between the coarse and fine bubbler could be partially attributed to the preferential evaporation of more volatile compounds earlier in the pretest; however, the dramatic decrease in slope from the 3.0-liter-per-minute, coarse-bubbler condition (0.35 g/hr) to the 1.0-liter-per-minute, fine-bubbler condition (0.09 g/hr) demonstrated that air injection flow rate and diffuser were the dominant variables controlling evaporation rate.

3.2 EVAPORATION

3.2.1 Evaporation Study Results

Based on the pretest results, the evaporation study testing was conducted using the coarse (> 0.5 micron) air diffuser with an air flow rate of 3.0 liters per minute. The evaporation study included the preparation of three 1-liter test bottles, each containing approximately 500 grams of JP-5 to initiate the testing. The mass loss versus time results for the triplicate tests are nearly identical, demonstrating repeatability, as shown on Figure 3.

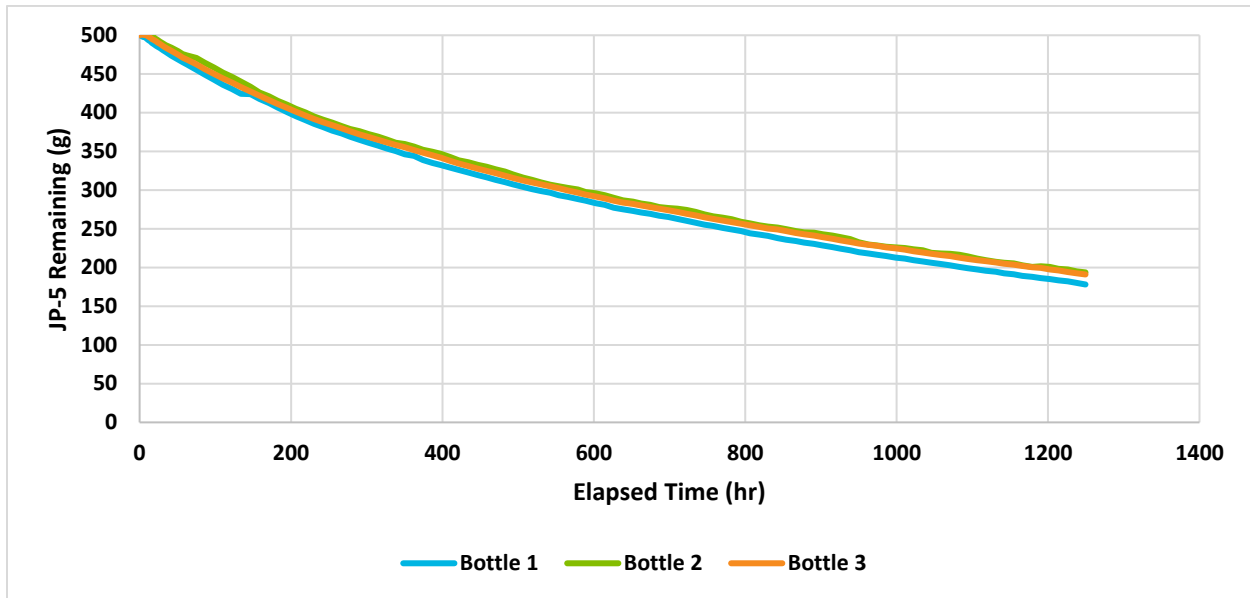


Figure 3: JP-5 Mass Loss versus Time for Triplicate Bottles During Evaporation Study

3.2.2 Bulk NAPL Evaporation

Figure 4 shows a chart of the average progression of JP-5 mass removal in grams and estimated JP-5 mass removal rates in g/hr as a function of time since sparging began. Mass removal rates were approximated from mass and time measurements using central difference approximations (Fausett 1999).

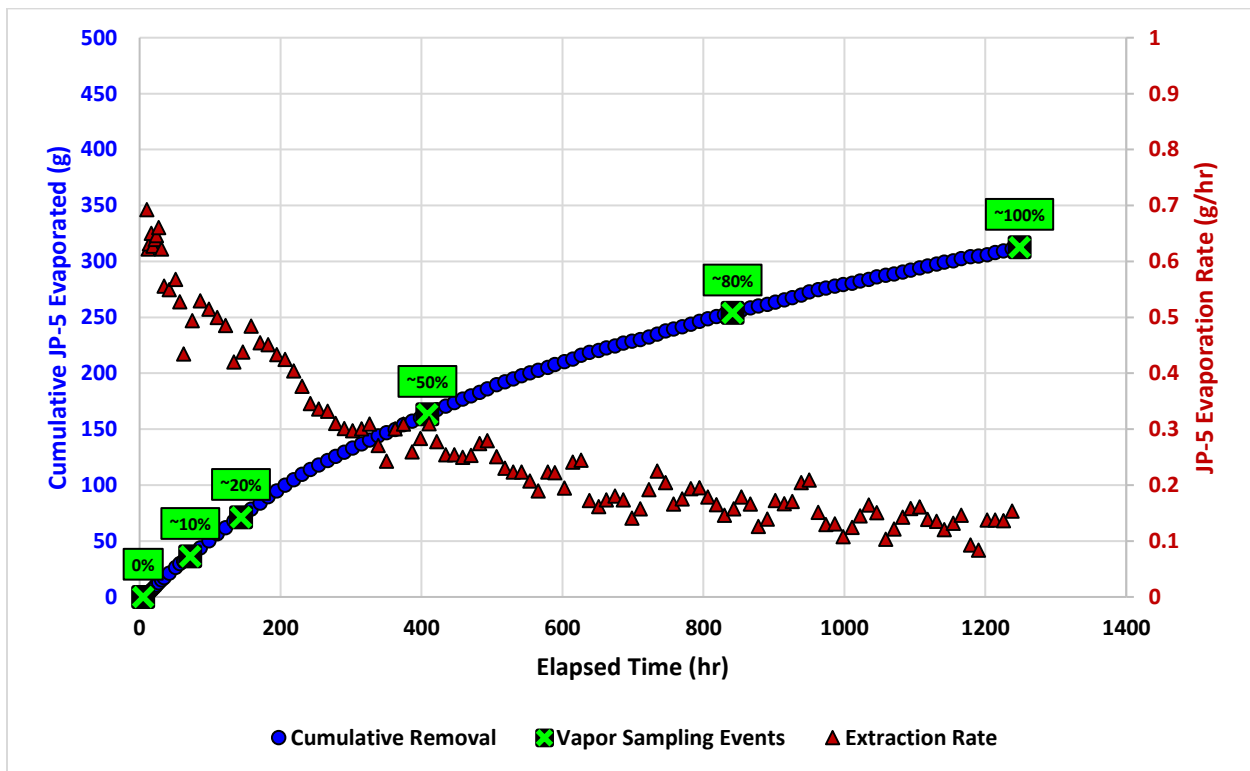


Figure 4: Mass of JP-5 Evaporated and Rate of JP-5 Evaporation during Bench-Scale Study

Note: Vapor sampling intervals based on the pretest results are shown in green.

One of the objectives of the bench-scale JP-5 evaporation study was to estimate the mass fraction of JP-5 that can be expected to evaporate at ambient temperatures. As evaporation proceeds, more volatile components in the JP-5, such as lower molecular weight compounds, are lost preferentially. Because JP-5 is a mixture of hundreds of hydrocarbon compounds, the composition of the NAPL changes as the lighter compounds are removed and the evaporation rate gradually slows down within these laboratory-controlled conditions. Evaporation rates estimated from the evaporation study are plotted as a function of mass fraction removed on Figure 5.

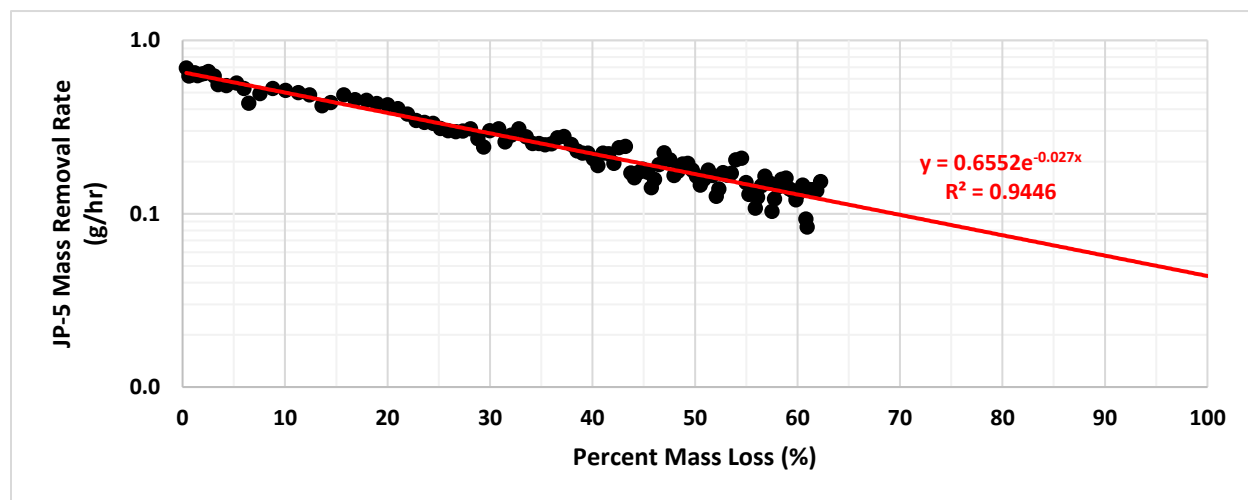


Figure 5: JP-5 Evaporation Rate versus Cumulative Fraction of NAPL Evaporated.

In accordance with studies on other fuels, the evaporation rate decreases exponentially as a function of mass loss (Fingas 1997; Okamoto et al. 2009). While the bench-scale study results indicate that a large fraction of the JP-5 will evaporate with sufficient air exchange, the test conditions are not expected to reflect the mass removal efficiency for the planned field-scale testing conditions where the feasibility of air sparging and SVE depends on the properties of subsurface materials and the distribution of air flow in relation to the distribution of NAPL.

3.3 NAPL COMPOSITION CHANGE

Samples of the NAPL were collected from each of the three tests before sparging was initiated and after sparging was concluded to evaluate changes in composition. The NAPL samples were submitted to Triton Analytics in Houston, Texas, for simulated distillation analysis by ASTM International (ASTM) D2887 and detailed hydrocarbon analysis by ASTM D6623.

The simulated distillation results provide information on the bulk composition using gas chromatography to separate NAPL constituents by boiling point. A comparison of the boiling point distributions in the six NAPL samples (three pre-sparging and three post-sparging) is presented on Figure 6. The boiling points for normal alkanes from octane (nC8) through heptadecane (nC12) are plotted as horizontal dashed lines on Figure 6. The samples collected after sparging (i.e., represented by the Final_Bottle lines) are shifted up and have a shallower slope than the initial samples on Figure 6 as they are missing lower molecular weight, more volatile components.

The measured boiling point distributions were used to estimate mass fractions by carbon number on Figure 7 based on standard boiling points of normal alkanes (ASTM D2887). Hydrocarbons with the same number of carbon atoms can have different boiling points depending on molecular structure. Because the fractions presented on Figure 7 were estimated assuming an all-aliphatic composition, the mass fractions are approximate.

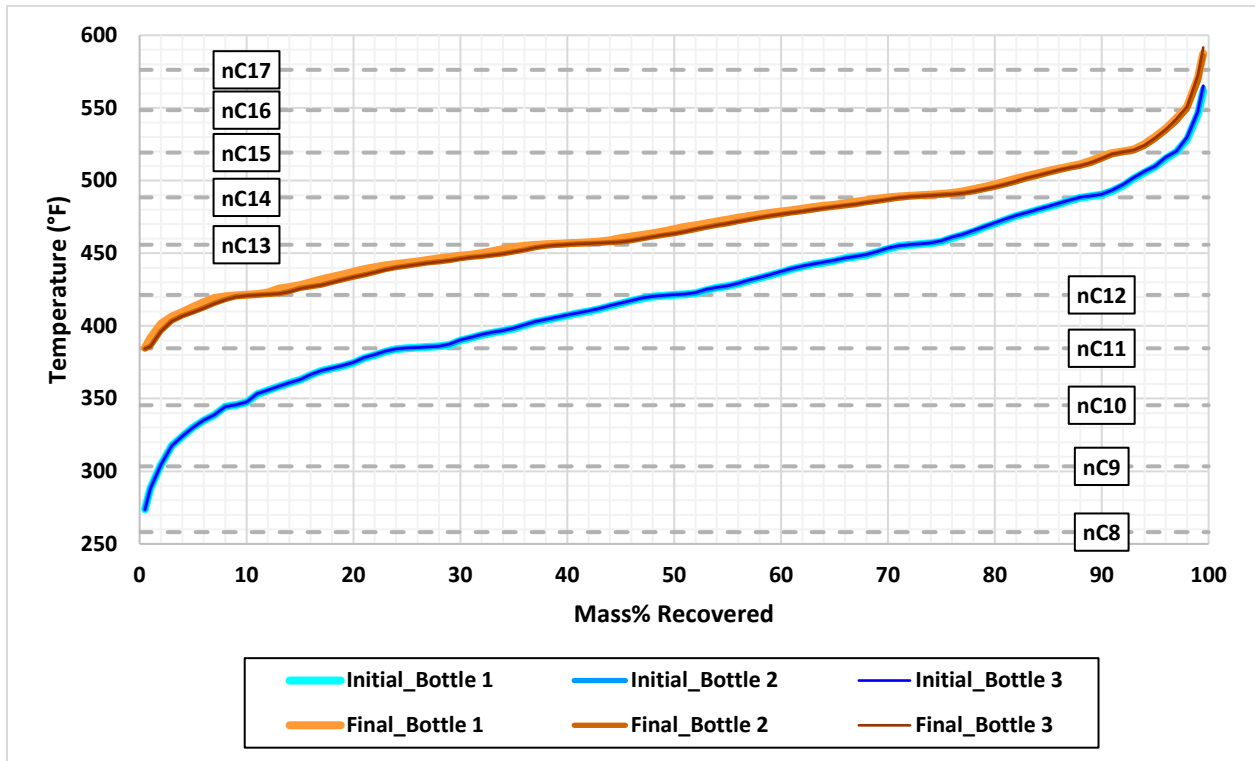


Figure 6: Simulated Distillation Curves for Fresh and 62% Evaporated JP-5 Samples

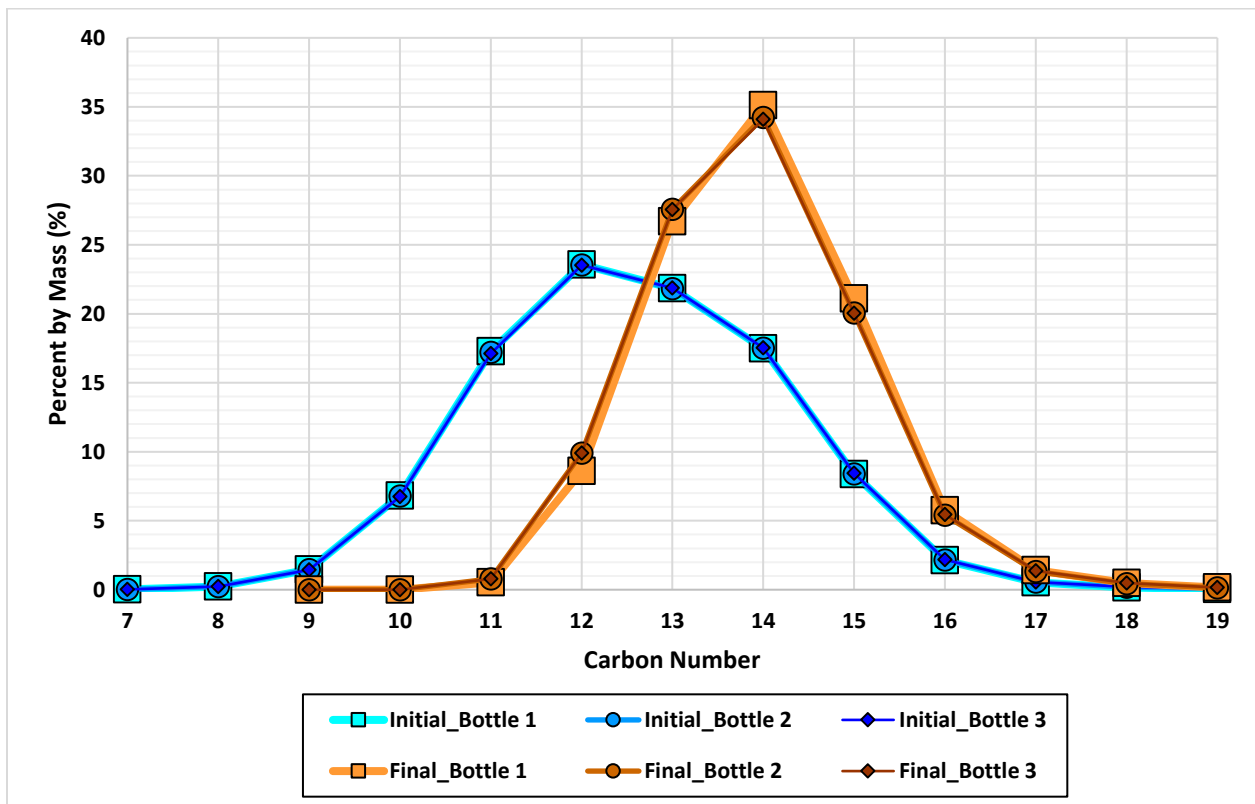


Figure 7: Distribution of Hydrocarbons in Pre- and Post-Sparging NAPL Samples by Carbon Number

The shift in bulk composition after evaporation of 60 percent of the initial mass of NAPL is exhibited on Figure 7. Components with less than 11 carbon atoms comprise approximately 26 percent of the initial samples but are completely removed from the final samples. Likewise, compounds with 13 or more carbon atoms are enriched in the final samples.

The paraffins, isoparaffins, aromatics, naphthenes, and olefins were quantified for the mass fraction of individual compounds in the NAPL samples by detailed hydrocarbon analysis, and for vapor samples by United States Environmental Protection Agency Methods TO-15 and TO-17. The average from each of the three tests for concentrations of select indicator compounds (BTEX, naphthalene, 1-methylnaphthalene, and 2-methylnaphthalene) are presented in Table 3 to evaluate changes in VOCs and SVOCs in the NAPL and sparged air over the course of the study.

The tendency of a specific compound to partition from the NAPL phase into the vapor phase is controlled by its vapor pressure and the relative abundance of the compound in the NAPL mixture. Specifically, the partial vapor pressure of a given compound in a gas phase that is in equilibrium with a NAPL mixture can be estimated using Raoult's law (USACE 2002).

Equation 1

$$P_{vi} = X_i \times P^{\circ}_i$$

Where:

P_{vi}	=	The partial vapor pressure of constituent "i" in the gas phase (atm)
X_i	=	The mole fraction of constituent "i" in the NAPL mixture (mol/mol)
P°_i	=	The vapor pressure of constituent "i" in its pure, condensed phase (atm)

The pure phase vapor pressures (P°_i) for each of the indicator compounds at a reference temperature of 25 degrees Celsius are included in Table 3 (Yaws 2015). While the concentration of benzene in the initial NAPL samples was below detection limits, benzene was detected in the vapor samples prior to initiating sparging. The initial concentration of benzene in the NAPL mixture can be estimated using Equation 1, yielding an estimated initial benzene concentration of approximately 0.0002 percent by mass.

In general, Table 3 shows that compounds with higher vapor pressures were more depleted by evaporation, as expected. Compounds with lower vapor pressures showed increasing concentrations in the early stages of the study. For example, the average concentration of naphthalene in vapor samples gradually increased from 2,000 to 6,300 micrograms per cubic meter while 14 percent of the overall NAPL mass was evaporated. This trend is not surprising considering that the initial NAPL composition included a larger fraction of lighter compounds with higher vapor pressure than naphthalene. For example, Figure 6 and Figure 7 indicate that approximately 10 percent of the initial NAPL consists of compounds with boiling points less than decane. Decane has a pure phase vapor pressure of approximately 1.4 millimeters of mercury, nearly 20 times greater than that of naphthalene (Yaws 2015). The more volatile compounds and compounds present at greater concentrations were preferentially lost early in the evaporation study in accordance with Raoult's law (Equation 1), and heavier, less volatile components like naphthalene were initially enriched in the NAPL mixture. Later in the study, after concentrations of more volatile compounds had been depleted from the NAPL, concentrations of heavier compounds like naphthalene began to decrease.

The NAPL and vapor composition data will be used to assess the degree of JP-5 volatilization that has occurred under natural conditions, and during the planned SVE testing to be completed at the Red Hill Bulk Fuel Storage Facility. For example, soil gas data collected during the SVE pilot study can be compared to the bench-scale test results to infer changes in NAPL mass within the subsurface.

Table 3: Concentrations of Indicator Compounds in NAPL and Sparge Air during the Evaporation Study

Sample Media		NAPL		Vapor					
Sample Date		10/31/23	12/22/23	10/31/23	11/3/23	11/6/23	11/17/23	12/5/23	12/22/23
Percent NAPL Evaporated		0% (initial)	62% (final)	0% (initial)	6%	14%	32%	51%	62% (final)
Analyte	P _v (mm Hg)	Percent by Mass (%)		Micrograms per Cubic Meter (µg/m ³)					
Benzene	95	<0.005	<0.005	983	<590	<400	<198	<132	<55.6
Toluene	28	0.015	<0.005	26,300	187	<470	<234	<156	<65.6
Ethylbenzene	9.6	0.028	<0.005	19,300	3,270	317	<270	<180	<75.6
m&p-Xylenes	8.7	0.131	<0.010	79,000	19,000	2,530	<270	49.4	<75.6
o-Xylene	6.6	0.083	<0.005	36,300	11,700	2,230	<270	<180	<75.6
Naphthalene	0.085	0.829	0.477	2,000	3,300	6,300	3,270	1,750	1,270
1-Methylnaphthalene	0.074	0.515	0.965	8,200	2,100	5,400	2,830	3,800	3,000
2-Methylnaphthalene	0.055	1.083	0.744	13,900	3,500	8,900	4,600	6,000	4,430

Note: *Italicized* values indicate those below laboratory detection limits.

% percent
µg/m³ microgram per cubic meter
mm Hg millimeters of mercury

3.4 CHANGES TO NAPL PHYSICAL PROPERTIES

Samples of the NAPL were collected from each of the three tests before sparging was initiated and after sparging was concluded to evaluate changes in density and viscosity as a result of evaporative mass loss. The NAPL samples were submitted to Triton Analytics in Houston, Texas, for analysis of density by ASTM D4052 at a temperature of 60 degrees Fahrenheit and viscosity by ASTM D7042 at a temperature of 75 degrees Fahrenheit. Results of the analyses are presented in Table 4.

Table 4: Changes in NAPL Physical Properties During Evaporation Study

NAPL Sample	Density at 60°F (g/cc)	Viscosity at 75°F (cP)
Initial – Bottle 1	0.8168	1.5
Initial – Bottle 2	0.8169	1.5
Initial – Bottle 3	0.8169	1.5
Final – Bottle 1	0.8232	2.2
Final – Bottle 2	0.8231	2.2
Final – Bottle 3	0.823	2.1

°F degree Fahrenheit
cP centipoise
g/cc gram per cubic centimeter

Density and viscosity of the NAPL samples collected prior to sparging were similar to a previous sample of JP-5 (0.8135 grams per cubic centimeter at 60 degrees Fahrenheit and 1.234 centipoise at 76 degrees Fahrenheit, respectively) collected from the Red Hill Fuel Storage Facility and analyzed in October 2018 (DON 2019). As expected, removal of the lighter molecular weight volatile compounds increased both the density and viscosity of the NAPL. On average, the density of the NAPL increased by less than 1 percent, and the viscosity increased by approximately 44 percent. While the primary remedial mechanisms during SVE include volatilization and biodegradation, increase in density and viscosity of the NAPL will reduce its potential mobility. Increases in viscosity generally have a proportional influence on NAPL mobility because it is inversely proportional to effective NAPL conductivity (Charbeneau and Beckett 2007). While NAPL density has a proportional relationship to effective NAPL conductivity, the density also influences the distribution of NAPL and the percentage of pore space occupied by the NAPL, where higher light non-aqueous phase liquid density can lead to a reduction in mobility (Charbeneau and Beckett 2007).

3.5 UNCERTAINTY

The use of triplicate experiments for this study helped to address aspects of experimental variability. However, the findings of this bench-scale study, such as evaporation and mass reduction rates, and changes in NAPL physical properties assume laboratory-controlled conditions. The laboratory testing did not attempt to simulate many of the conditions that play an integral role in determining the feasibility of air sparging and SVE under in situ conditions, including humidity, temperature conditions, vadose zone and hydrogeologic characteristics, and the distribution of sparged and vented air in relation to the in situ NAPL phase. Additionally, the bench-scale study did not evaluate enhanced aerobic biodegradation, which is likely to play a key role in determining how the composition of NAPL changes and the overall mass removal rate under in situ conditions. These potential sources of uncertainty will be considered when comparing these bench-scale study results to the degree of JP-5 volatilization that has occurred under natural and pilot testing conditions at the Red Hill Bulk Fuel Storage Facility.

4. Conclusions

The bench-scale evaporation study provides a proof-of-concept test under laboratory-controlled (“ideal”) conditions that informs the feasibility of air sparging and SVE to deplete NAPL mass under site conditions. Significant findings from the evaporation study include:

- Air sparging and SVE can be used to effectively change the composition of JP-5 by removing lower molecular weight compounds, making the remaining NAPL less volatile.
- The rate of mass loss by volatilization decreases exponentially as the average molecular weight of the NAPL increases. This means the volatilization remediation mechanism for technologies like air sparging and SVE will require much longer timeframes to address the final 20 percent of the NAPL mass than the initial 20 percent.
- Removal of lower molecular weight compounds from the NAPL by volatilization will increase its density and viscosity and reduce the overall mobility of the NAPL.

The NAPL and vapor composition data acquired during the evaporation study will be used to assess the degree of JP-5 volatilization that has occurred under natural conditions, and during the planned SVE and potentially air sparging field tests to be completed at the Red Hill Bulk Fuel Storage Facility. Soil gas data collected during the SVE pilot study will be compared to the bench-scale test results as an additional line of evidence to infer changes in in situ NAPL mass within the subsurface.

5. Deviations from Plan

Deviations from the original work plan, along with the rationale, are documented here. Deviations from the plan may occur for various reasons, such as the availability of reagents/amendments, turnaround times from subcontracted laboratories, unexpected results during data collection, and changes in the original scope.

During the initial screening of JP-5, a steady flow of air, 1.0 liter per minute, was expected to be tested. However, it was quickly realized that the volatilization of the VOCs and SVOCs was slower than expected. The slower evolution of organics led to the air flowrate being varied between 1, 2, and 3 liters per minute and two different air diffusers being tested, generating different bubble sizes. Furthermore, the JP-5 volume was reduced from the prescribed 0.5 liter to 0.4 liter because the initial test took 2,138 hours.

The various conditions tested during the initial screening confirmed the following conditions for the compositional sampling tests: a flowrate of 3.0 liters per minute and using the coarse bubbler. During the initial and compositional experiments, the air sparging was allowed to proceed for the entirety of the tests.

The work plan called for stopping the flow of air at night; however, the lack of rapid mass loss conveyed the need for continuous air flow.

In addition to the design deviations, the mass loss was not recorded every hour after the initial onset of recordings. As stated previously, the mass loss was slower than expected and therefore the mass was recorded approximately every 12 hours.

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**Appendix A:
Pre-Test Mass Loss Data**

Table A-1: Mass Loss Data for Initial Screening

Condition	Time (hours)	Weight (g)	JP-5 wt (g)	JP-5 rec. (g)	Rate Change (g/hr)	Average Rate Change (g/hr)
1.0 Liter per Minute, Coarse Bubbler	0.25	965.6	393	0	0.000	0.26
	0.5	965.6	393	0	0.000	
	0.75	965.5	392.9	0.1	0.400	
	1	965.4	392.8	0.2	0.400	
	1.5	965.3	392.7	0.3	0.200	
	7	964	391.4	1.6	0.236	
	8	963.8	391.2	1.8	0.200	
	9	963.6	391	2	0.200	
	10	963.4	390.8	2.2	0.200	
	11	963	390.4	2.6	0.400	
	12	962.6	390	3	0.400	
	13	961.1	388.5	4.5	1.500	
	15	960.8	388.2	4.8	0.150	
	17.5	960.2	387.6	5.4	0.240	
	39	954.8	382.2	10.8	0.251	
	42	954.2	381.6	11.4	0.200	
	57.5	949.6	377	16	0.297	
61	948.9	376.3	16.7	0.200		
81	944.3	371.7	21.3	0.230		
105.5	938.8	366.2	26.8	0.224		
109.5	938	365.4	27.6	0.200		
2.0 Liters per Minute, Coarse Bubbler	180.5	909.7	337.1	55.9	0.399	0.33
	187.5	907	334.4	58.6	0.386	
	197.5	903.6	331	62	0.340	
	201.5	902.3	329.7	63.3	0.325	
	206.5	900.7	328.1	64.9	0.320	
	212.5	898.7	326.1	66.9	0.333	
3.0 Liters per Minute, Coarse Bubbler	225.5	894.5	321.9	71.1	0.323	0.35
	238	889.6	317	76	0.392	
	250	884.5	311.9	81.1	0.425	
	262	879.7	307.1	85.9	0.400	
	274	874.9	302.3	90.7	0.400	
	286	870.2	297.6	95.4	0.392	
	298	865.8	293.2	99.8	0.367	
	310	861.3	288.7	104.3	0.375	
	322	857	284.4	108.6	0.358	
	334	852.9	280.3	112.7	0.342	

Condition	Time (hours)	Weight (g)	JP-5 wt (g)	JP-5 rec. (g)	Rate Change (g/hr)	Average Rate Change (g/hr)
3.0 Liters per Minute, Coarse Bubbler (cont'd)	346	848.6	276	117	0.358	0.35
	358	844.9	272.3	120.7	0.308	
	370	840.9	268.3	124.7	0.333	
	382	837.1	264.5	128.5	0.317	
	394	833.4	260.8	132.2	0.308	
	406	829.7	257.1	135.9	0.308	
	418	826.2	253.6	139.4	0.292	
1.0 Liter per Minute, Fine Bubbler	430	826.8	253.2	139.8	0.033	0.09
	442	825.6	253	140	0.017	
	454	824.6	252	141	0.083	
	466	823.4	250.8	142.2	0.100	
	478	822.4	249.8	143.2	0.083	
	490	821.2	248.6	144.4	0.100	
	502	820.3	247.7	145.3	0.075	
	514	819.1	246.5	146.5	0.100	
	526	818.1	245.5	147.5	0.083	
2.0 Liters per Minute, Fine Bubbler	538	817.1	244.5	148.5	0.083	0.18
	550	815.3	242.7	150.3	0.150	
	562	813.1	240.5	152.5	0.183	
	574	810.8	238.2	154.8	0.192	
	586	808.6	236	157	0.183	
	598	806.4	233.8	159.2	0.183	
	610	804.3	231.7	161.3	0.175	
3.0 Liters per Minute, Fine Bubbler	622	801.1	228.5	164.5	0.267	0.24
	634	797.9	225.3	167.7	0.267	
	646	794.8	222.2	170.8	0.258	
	658	791.6	219	174	0.267	
	670	788.8	216.2	176.8	0.233	
	682	785.9	213.3	179.7	0.242	
	694	783.2	210.6	182.4	0.225	
3.0 Liters per Minute, Coarse Bubbler (Increment One)	706	780.2	207.6	185.4	0.250	0.20
	718	773.9	201.3	191.7	0.525	
	730	771.2	198.6	194.4	0.225	
	742	768.6	196	197	0.217	
	754	765.9	193.3	199.7	0.225	
	766	763.5	190.9	202.1	0.200	
	778	761.1	188.5	204.5	0.200	
850	754.4	181.8	211.2	0.093		

Condition	Time (hours)	Weight (g)	JP-5 wt (g)	JP-5 rec. (g)	Rate Change (g/hr)	Average Rate Change (g/hr)
3.0 Liters per Minute, Coarse Bubbler (Increment One) (cont'd)	862	750.1	177.5	215.5	0.358	0.20
	874	749.6	177	216	0.042	
	886	747.2	174.6	218.4	0.200	
	898	744.5	171.9	221.1	0.225	
	910	741.3	168.7	224.3	0.267	
	922	739.9	167.3	225.7	0.117	
	946	736	163.4	229.6	0.162	
	958	733.4	160.8	232.2	0.217	
	970	732.5	159.9	233.1	0.075	
	982	729.4	156.8	236.2	0.258	
	994	728.5	155.9	237.1	0.075	
1,006	726.2	153.6	239.4	0.192		
3.0 Liters per Minute, Coarse Bubbler (Increment Two)	1,018	724	151.4	241.6	0.183	0.14
	1,030	721.3	148.7	244.3	0.225	
	1,042	720.1	147.5	245.5	0.100	
	1,054	718.3	145.7	247.3	0.150	
	1,066	717.2	144.6	248.4	0.092	
	1,078	713.9	141.3	251.7	0.275	
	1,090	712.7	140.1	252.9	0.100	
	1,102	710.9	138.3	254.7	0.150	
	1,114	710.3	137.7	255.3	0.050	
	1,126	707.4	134.8	258.2	0.242	
	1,138	706.3	133.7	259.3	0.092	
	1,150	705	132.4	260.6	0.108	
	1,162	703.6	131	262	0.117	
	1,174	702.4	129.8	263.2	0.100	
	1,186	701	128.4	264.6	0.117	
	1,198	699.4	126.8	266.2	0.133	
	1,210	698.8	126.2	266.8	0.050	
	1,234	694.9	122.3	270.7	0.162	
	1,238	693.6	121	272	0.325	
	1,244	688.6	116	277	0.833	
	1,250	687.7	115.1	277.9	0.150	
	1,238	686.9	114.3	278.7	-0.067	
	1,250	685.5	112.9	280.1	0.117	
	1,262	684.2	111.6	281.4	0.108	
1,274	682.9	110.3	282.7	0.108		
1,286	681.4	108.8	284.2	0.125		

Condition	Time (hours)	Weight (g)	JP-5 wt (g)	JP-5 rec. (g)	Rate Change (g/hr)	Average Rate Change (g/hr)
3.0 Liters per Minute, Coarse Bubbler (Increment Two) (cont'd)	1,298	680	107.4	285.6	0.117	0.14
	1,310	678.6	106	287	0.117	
	1,322	677.2	104.6	288.4	0.117	
	1,334	675.8	103.2	289.8	0.117	
	1,346	674.3	101.7	291.3	0.125	
	1,358	673	100.4	292.6	0.108	
	1,370	671.6	99	294	0.117	
	1,382	670.4	97.8	295.2	0.100	
	1,394	669	96.4	296.6	0.117	
	1,406	667.7	95.1	297.9	0.108	
	1,418	666.3	93.7	299.3	0.117	
	1,430	665.1	92.5	300.5	0.100	
	1,442	663.9	91.3	301.7	0.100	
	1,454	662.5	89.9	303.1	0.117	
	1,466	661.2	88.6	304.4	0.108	
	1,478	659.9	87.3	305.7	0.108	
	1,490	658.5	85.9	307.1	0.117	
1,502	657.2	84.6	308.4	0.108		
3.0 Liters per Minute, Coarse Bubbler (Increment Three)	1,514	655.9	83.3	309.7	0.108	0.08
	1,526	654.2	81.6	311.4	0.142	
	1,538	653.5	80.9	312.1	0.058	
	1,550	652.5	79.9	313.1	0.083	
	1,562	651.3	78.7	314.3	0.100	
	1,574	650.3	77.7	315.3	0.083	
	1,586	649.1	76.5	316.5	0.100	
	1,598	648.1	75.5	317.5	0.083	
	1,610	646.9	74.3	318.7	0.100	
	1,622	645	72.4	320.6	0.158	
	1,646	643.9	71.3	321.7	0.046	
	1,658	643	70.4	322.6	0.075	
	1,670	641.8	69.2	323.8	0.100	
	1,682	640.8	68.2	324.8	0.083	
	1,694	639.7	67.1	325.9	0.092	
	1,706	639.8	67.2	325.8	-0.008	
	1,718	637.6	65	328	0.183	
1,730	636.8	64.2	328.8	0.067		
1,742	635.7	63.1	329.9	0.092		
1,754	634.9	62.3	330.7	0.067		

Condition	Time (hours)	Weight (g)	JP-5 wt (g)	JP-5 rec. (g)	Rate Change (g/hr)	Average Rate Change (g/hr)
3.0 Liters per Minute, Coarse Bubbler (Increment Three) (cont'd)	1,766	633.9	61.3	331.7	0.083	0.08
	1,778	633.1	60.5	332.5	0.067	
	1,790	632	59.4	333.6	0.092	
	1,802	631.2	58.6	334.4	0.067	
	1,814	630.2	57.6	335.4	0.083	
	1,826	629.3	56.7	336.3	0.075	
	1,838	628.2	55.6	337.4	0.092	
	1,850	627.4	54.8	338.2	0.067	
	1,862	626.4	53.8	339.2	0.083	
	1,874	625.6	53	340	0.067	
	1,886	624.6	52	341	0.083	
	1,898	623.9	51.3	341.7	0.058	
	1,910	622.9	50.3	342.7	0.083	
	1,922	622.3	49.7	343.3	0.050	
	1,934	621.4	48.8	344.2	0.075	
	1,946	620.7	48.1	344.9	0.058	
	1,958	619.7	47.1	345.9	0.083	
	1,970	618.9	46.3	346.7	0.067	
	1,982	618.5	45.9	347.1	0.033	
	1,994	617.3	44.7	348.3	0.100	
2,006	616.6	44	349	0.058		
3.0 Liters per Minute, Coarse Bubbler (Increment Four)	2,018	615.7	43.1	349.9	0.075	0.07
	2,030	615	42.4	350.6	0.058	
	2,042	613.9	41.3	351.7	0.092	
	2,054	613.1	40.5	352.5	0.067	
	2,066	612.1	39.5	353.5	0.083	
	2,078	611.3	38.7	354.3	0.067	
	2,090	610.3	37.7	355.3	0.083	
	2,102	609.5	36.9	356.1	0.067	
	2,114	608.6	36	357	0.075	
	2,126	607.9	35.3	357.7	0.058	
	2,138	607	34.4	358.6	0.075	

g gram
 g/hr gram per hour
 JP-5 Jet Propellant 5