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HYDROCARBON FUEL SPILL DISPERSION ON WATER

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The kinetics of jet fuel (JP-4) dispersion on water is investigated in laboratory wind tunnels. Evaporation and dissolution rates of various hydrocarbons are determined under varying parameters including air and water temperature, windspeed, humidity, water composition, fuel composition, and fuel layer depth. Adequate correlations can be made for the kinetics of evaporation of JP-4. While dissolution rates of aromatic components of JP-4 into water could be measured, correlations of the results are difficult because of the complex nature of hydrodynamic effects.				
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PREFACE

This work was part of an effort to study the dispersion of a hydrocarbon fuel spill on water. The work was conducted by Battelle Columbus Division, 505 King Avenue, Columbus OH 43201, under Task Order Contract F08635-85-C-0122, Subtask 1.02 for the Engineering and Services Laboratory of the Air Force Engineering and Services Center.

This work was conducted from September 1986 through September 1987. The HQ AFESC/RDVC project officer was Mr Michael V. Henley.

This final report covers the study of dispersion in a laboratory-scale fuel spill on water.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION	1
	A. OBJECTIVE	1
	B. BACKGROUND	1
	C. SCOPE	4
II	APPROACH	5
	A. GENERAL	5
	B. MICROBALANCE SYSTEM	5
	C. BENCH-SCALE WIND TUNNEL	7
	D. INTERMEDIATE-SCALE WIND TUNNEL	7
	E. ANALYTICAL METHODS	10
	F. MATERIALS	13
	G. QA/QC	13
III	JP-4 EVAPORATION	15
	A. MICROBALANCE EXPERIMENTS	15
	B. WINDSPEED EFFECTS	18
	1. Pure Compound Evaporation	18
	2. JP-4 Evaporation	21
	C. EFFECTS OF OTHER VARIABLES ON EVAPORATION	24
	1. Temperature	24
	2. Relative Humidity	27
	3. Fuel Composition	27
	4. Fuel Layer Thickness	27
IV	JP-4 DISSOLUTION	29
	A. JP-4 DISSOLUTION IN DISTILLED WATER	32
	1. Low Velocity Data	32
	2. High Velocity Data	40
	B. DISSOLUTION IN SEA WATER	43
	C. INTERMEDIATE-SCALE DISSOLUTION EXPERIMENTS	46
	1. Mechanical Mixing	46
	D. FUEL DEPTH EFFECTS	51
	E. SPREADING RATES	51
V	CONCLUSIONS AND RECOMMENDATIONS	59

TABLE OF CONTENTS (Concluded)

Section	Title	Page
	REFERENCES	61
APPENDIX		
A	GLOSSARY OF SYMBOLS AND SUMMARY OF PHYSICOCHEMICAL PROPERTIES OF MAJOR JP-4 COMPONENTS	63
B	MICROBALANCE EXPERIMENTS	67
C	JP-4 VELOCITY EFFECT EXPERIMENTS IN BENCH-SCALE WIND TUNNEL	77
D	TEMPERATURE AND HUMIDITY EFFECT EXPERIMENTS IN BENCH-SCALE WIND TUNNEL	81
E	INTERMEDIATE-SCALE EVAPORATION RATE EXPERIMENTS	87

LIST OF FIGURES

Figure	Title	Page
1	Simplified Representation of Evaporation from a Fuel Layer	2
2	Schematic Drawing of Microbalance System	6
3	Bench-Scale Wind Tunnel	8
4	Intermediate-Scale Wind Tunnel	9
5	Multipurpose Inlet System	11
6	Preliminary Sherwood Correlation of Windspeed Effect on Evaporation of Pure Compounds	20
7	Scattergram of Initial JP-4 Evaporation Rate Data	22
8	Effect of Windspeed on Average Sherwood Numbers for all Runs	25
9	Dissolution of Benzene at High and Low Windspeeds	30
10	Recirculation in Water Container	31
11	Distribution of Benzene in Water	33
12	Evaporation Rates of Aromatic Hydrocarbons from JP-4 at 1.7 mi/hr	34
13	Benzene Dissolution from JP-4	35
14	Toluene Dissolution from JP-4	36
15	Ethylbenzene Dissolution from JP-4	37
16	Meta- and Para-Xylene Dissolution from JP-4	38
17	Ortho-Xylene Dissolution from JP-4	39
18	Evaporation Rates at 14.4 mi/hr.....	41
19	Dissolution of Aromatics at 14.4 mi/hr.....	42
20	Dissolution of JP-4 in Sea Water at Low Windspeed ($V = 1.3$ mi/hr).....	44
21	Dissolution of JP-4 in Sea Water at High Windspeed (14.9 mi/hr).....	45
22	Spreading Rate of JP-4 on Water	58

LIST OF TABLES

Table	Title	Page
1	SOLUBILITY OF HYDROCARBONS IN WATER	12
2	DIFFUSION COEFFICIENTS FOR JP-4 COMPONENTS	16
3	JP-4 INITIAL EVAPORATION RATES	17
4	EFFECT OF AIR VELOCITY ON EVAPORATION OF o-XYLENE, TOLUENE, AND OCTANE	19
5	SUMMARY OF JP-4 DATA AT DIFFERENT SPEEDS	21
6	SUMMARY OF EVAPORATION RATE CORRELATION FOR ALKANE COMPONENTS OF JP-4	24
7	APPROACH TO EQUILIBRIUM SOLUBILITY	40
8	APPROACH TO EQUILIBRIUM SOLUBILITY	43
9	DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM	47
10	DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM	48
11	DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM	49
12	DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM	52
13	DISSOLUTION OF JP-4 FROM THICK LAYER	54
14	DISSOLUTION OF JP-4 FROM THICK LAYER	56
15	DISSOLUTION OF JP-4 FROM THICK LAYER	57
A-1	SUMMARY OF PHYSICOCHEMICAL PROPERTIES	66
B-1	JP-4 EVAPORATION - BALANCE RESULTS	69
B-2	JP-4 EVAPORATION - BALANCE RESULTS	70
B-3	JP-4 EVAPORATION - BALANCE RESULTS	71
B-4	JP-4 EVAPORATION - BALANCE RESULTS	72
B-5	JP-4 EVAPORATION - BALANCE RESULTS	73
B-6	JP-4 EVAPORATION - BALANCE RESULTS	74
B-7	JP-4 EVAPORATION - BALANCE RESULTS	75
C-1	EFFECT OF AIR VELOCITY ON JP-4 EVAPORATION	79
D-1	JP-4 EVAPORATION AT ELEVATED TEMPERATURES	83
D-2	JP-4 EVAPORATION AT REDUCED TEMPERATURES	84
D-3	EFFECT OF HUMIDITY ON JP-4 EVAPORATION	85
E-1	EVAPORATION RATES IN INTERMEDIATE-SCALE SYSTEM	89
E-2	EVAPORATION RATES IN INTERMEDIATE-SCALE SYSTEM	90
E-3	EVAPORATION RATES IN INTERMEDIATE-SCALE SYSTEM	91

SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this program was to determine the kinetics of jet fuel (JP-4) dispersion on water with the goal of providing the Air Force Engineering and Services Center (AFESC) with fundamental information that is relevant to the development of a computer model for generalized assessment of fuel spill problems.

B. BACKGROUND

The Environics Division (RDV) of AFESC is the focal point for environmental quality research and development within the Air Force Systems Command. The environmental impact of Air Force specific fuels and chemicals is one of the main areas of concern to RDV.

The process of dispersion of fuels that are accidentally spilled on water is physically and chemically complex, involving such elementary processes as:

1. Physical spreading of the fuel layer.
2. Evaporation and dispersion of the more volatile fuel components in the atmosphere.
3. Partitioning of the fuel components between the fuel and water phases.
4. Mixing and transport of dissolved fuel components away from the fuel water interface.
5. Chemical, physical and biological interactions within each phase.

The complexity of the problem is further compounded because both the equilibrium states in each phase and the dynamics of approach to equilibrium are influenced by temperature, turbulence (air and water), and composition (fuel and water).

The elementary problem of interphase (either fuel/gas or fuel/water) transport can be considered in terms of diffusion across an interfacial boundary layer as represented in Figure 1. The flux, J (mass/unit time-unit area) for evaporation of each component of the fuel can be expressed in terms of Fick's first law, viz.

$$J = D(dC/dz) \quad (1)$$

where D is the diffusion coefficient. Assuming ideal solution behavior for the fuel phase and pseudo-steady-state diffusion across the boundary, the flux for each component becomes

$$J = DCoX/dz \quad (2)$$

where Co is the equilibrium vapor pressure of the pure component, and X is the mole fraction of that component in the fuel phase. The boundary layer thickness, dz , is a function of the wind speed.

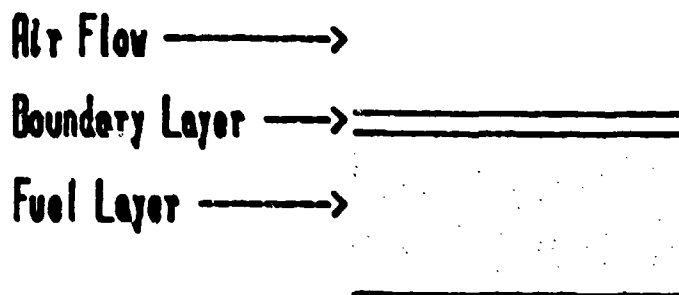


Figure 1. Simplified Representation of Evaporation from a Fuel Layer.

The correlation of evaporation rate with wind speed has been considered previously both from theoretical and experimental approaches. The most general statement of the solution is given by the Reynolds analogy (Reference 1, p. 269)

$$Sh = 0.5c_f f(Re) f(Sc) \quad (3)$$

where Sh is the Sherwood number, c_f is the coefficient of friction, Re is the Reynolds number, and Sc is the Schmidt number. (Note that Sh and Sc are respectively analogous to the Nusselt number (Nu) and the Prandtl number (Pr) which relate to heat transfer. Definition of these dimensionless groups and other parameters denoted symbolically in this report are given in the glossary contained in Appendix A.) The coefficient of skin friction for a flat plate geometry in turbulent flow is inversely proportional to the 1/5th power of the Reynolds number (Reference 1, p. 599), and $f(Sc) = Sc^{1/3}$ (Reference 1, p. 272). Therefore, we expect the correlation of evaporation rate with windspeed to have the form

$$Sh = aRe^{0.8}Sc^{1/3} \quad (4)$$

Experimentally, Gilliland and Sherwood (Reference 2) found Sh proportional to $Re^{0.83}$, and MacKay (Reference 3) found Sh proportional to $Re^{0.78}$.

A similar treatment can be applied to the process of dissolution at the fuel/water interface, but some important differences between the dissolution and evaporation processes need to be considered. The solubilities of fuel components in water are limited, and Equation (2) must be modified to include the Henry's law coefficients for each component. Because of the difference in density between the air and water phases, the diffusivities in water are approximately 1,000 times smaller than those in air. Eddy diffusion is likely to be more important than molecular diffusion in transporting fuel components away from the fuel/water interface. The scale and intensity of eddy diffusion are affected in two ways by airflow over the fuel surface. First, drag between the air and liquid layers induces flow of the liquid both at the surface and below the surface. Second, airflow enhances the endothermic process of evaporation, causing cooling and, consequently, density gradients near the fuel/water interface. Drag coefficients for airflow over a flat surface are of the order of 0.001 to 0.01, and the kinematic viscosity of water is approximately 17 times that of air. Consequently, airflow induced mixing rates are relatively low in the water phase, but are still significant when compared to molecular diffusivity. In large open bodies of water, other factors such as stream flow and thermal convection may also be expected to contribute to mixing of the water phase. Finally, evaporation of the fuel layer leads to a

situation where the activity of a given fuel component can be greater at the water side of the boundary than in the fuel layer. At this point, that component can diffuse back across the boundary layer into the fuel layer.

The simple treatment discussed above does not consider possible mass transfer resistances within the fuel layer itself, and, therefore, is strictly applicable only to "thin" fuel layers. However, because JP-4 has a low viscosity, a low surface tension, and a density less than that of water, it is expected to spread rapidly on water. A discussion of parameters that affect spreading rates of fuels is given by Fannelop and Waldman (Reference 4). For those cases where a fuel spill might be artificially confined however, a thick-layer solution analogous to that given by Coutant et al (Reference 5) is more appropriate.

C. SCOPE

A computer-based search of literature relevant to the problem of spills of jet fuel on water was conducted and information was compiled to serve as a base for this program. The results of that portion of the program have been reported separately, and served as the basis for a paper published in the open literature (Reference 6). Laboratory experiments were conducted using both small, 2.75-inch ID, and intermediate scale, 36-inch ID wind tunnels to investigate the effects of windspeed, temperature, relative humidity, fuel composition, and fuel layer depth on evaporation and dissolution rates of JP-4 components.

SECTION II

APPROACH

A. GENERAL

The approach taken in this program can be divided into a series of subtasks:

1. Literature Search. Available literature was assembled and reviewed for information relevant to the hydrocarbon spill dispersion problem. Results of this literature review were reported separately, and served as a basis for development of the detailed plan of experiments conducted in subsequent tasks.
2. Laboratory-Scale Experiments. A series of experiments was conducted to evaluate the effects of critical parameters such as air, windspeed, temperature, humidity, water composition, fuel composition, and fuel layer depth on the rates of evaporation and dissolution of JP-4 components. Initially, the evaporation potentials, DCo, were determined using a modification of the classical method of Stefan (Reference 7). Experiments were then conducted using a bench-scale wind tunnel that is described below.
3. Intermediate-Scale Experiments. The question of scaleup of the result of the bench-scale experiments was explored by performing a similar, but limited, series of experiments using an intermediate-scale system. This intermediate-scale system was approximately 12 times the size of the bench-scale system.

B. MICROBALANCE SYSTEM

Initial laboratory experiments were conducted using a Cahn Model 1000 microbalance to obtain direct mass loss data for the evaporation of both JP-4 and pure hydrocarbons, including pentane, hexane, heptane, octane, nonane, dodecane, benzene, toluene, ethylbenzene, and xylene. This system, shown schematically in Figure 2, was coupled to a Varian gas chromatograph (GC) through a heated gas sampling line. This arrangement enabled simultaneous measurements of mass loss rates and appearance rates in the vapor phase, and

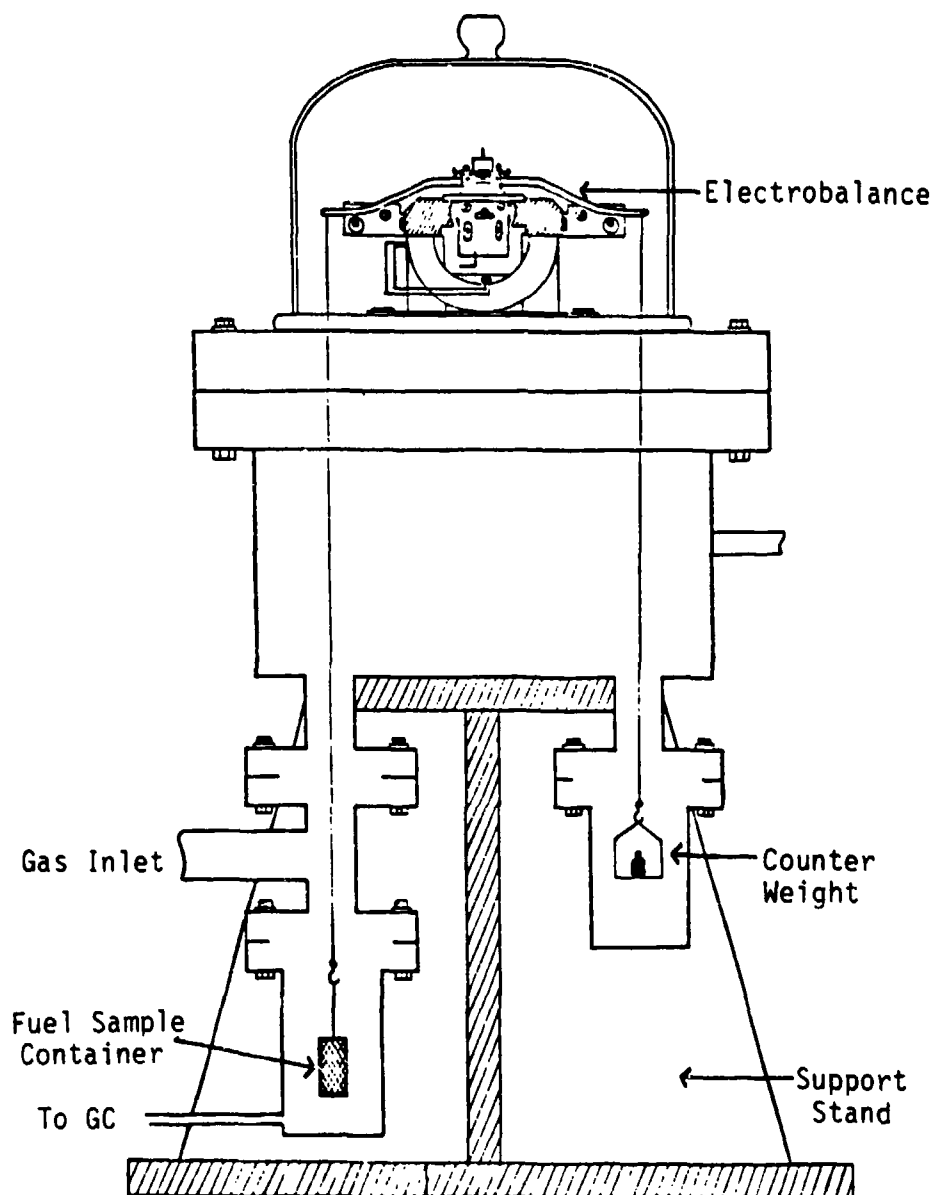


Figure 2. Schematic Drawing of Microbalance System.

provided a basis for calibration of the GC. These initial experiments were used to:

1. Validate the sampling method.
2. Evaluate the use of ideal solution theory for JP-4 evaporation.

3. Develop a self-consistent set of diffusion coefficients and vapor pressures for use in analyzing the results of experiments conducted with JP-4.

C. BENCH-SCALE WIND TUNNEL

The majority of the experiments for this program were conducted using the bench-scale wind tunnel shown in Figure 3. Construction and operational characteristics of this wind tunnel have been described previously (Reference 8). For the current work, the floor of the central working section of the tunnel was modified to include a container for water and JP-4. This container was fitted with sampling ports so that samples of the fuel and water phases could be taken periodically. Windspeeds of up to approximately 25 mi/hr and Reynold's numbers of up to approximately 50,000 can be obtained with this system. The inlet section of the tunnel is equipped with heating tapes and insulation for experiments at elevated temperatures. Experiments at subambient temperatures were conducted using outdoor air during the winter months. During operation, the liquid level of the pool was adjusted to be level with the floor of the tunnel to avoid local turbulence from edge effects.

D. INTERMEDIATE-SCALE WIND TUNNEL

An intermediate-scale wind tunnel system was constructed to enable evaluation of scale effects on the evaporation and dissolution rates. This system (Figure 4) consisted of a 3-foot-square wind tunnel driven by a fan having a free-air rating of 8500 cfm. The working section of the tunnel was located approximately 20 feet from the inlet and included a 3 by 3 by 2-foot pool for containment of the water and JP-4. A 10-foot long exit section fitted with mixing baffles served to mix the exhaust vapors. The sampling port for the vapors was located near the outer end of the exit section and consisted of a three-point sampling head to ensure a well-mixed sample.

The pool was equipped with a series of ports at 2-inch intervals for sampling of the water and fuel phases. Hypodermic syringe tubing inserted through these ports to the center of the pool provided a series of fixed

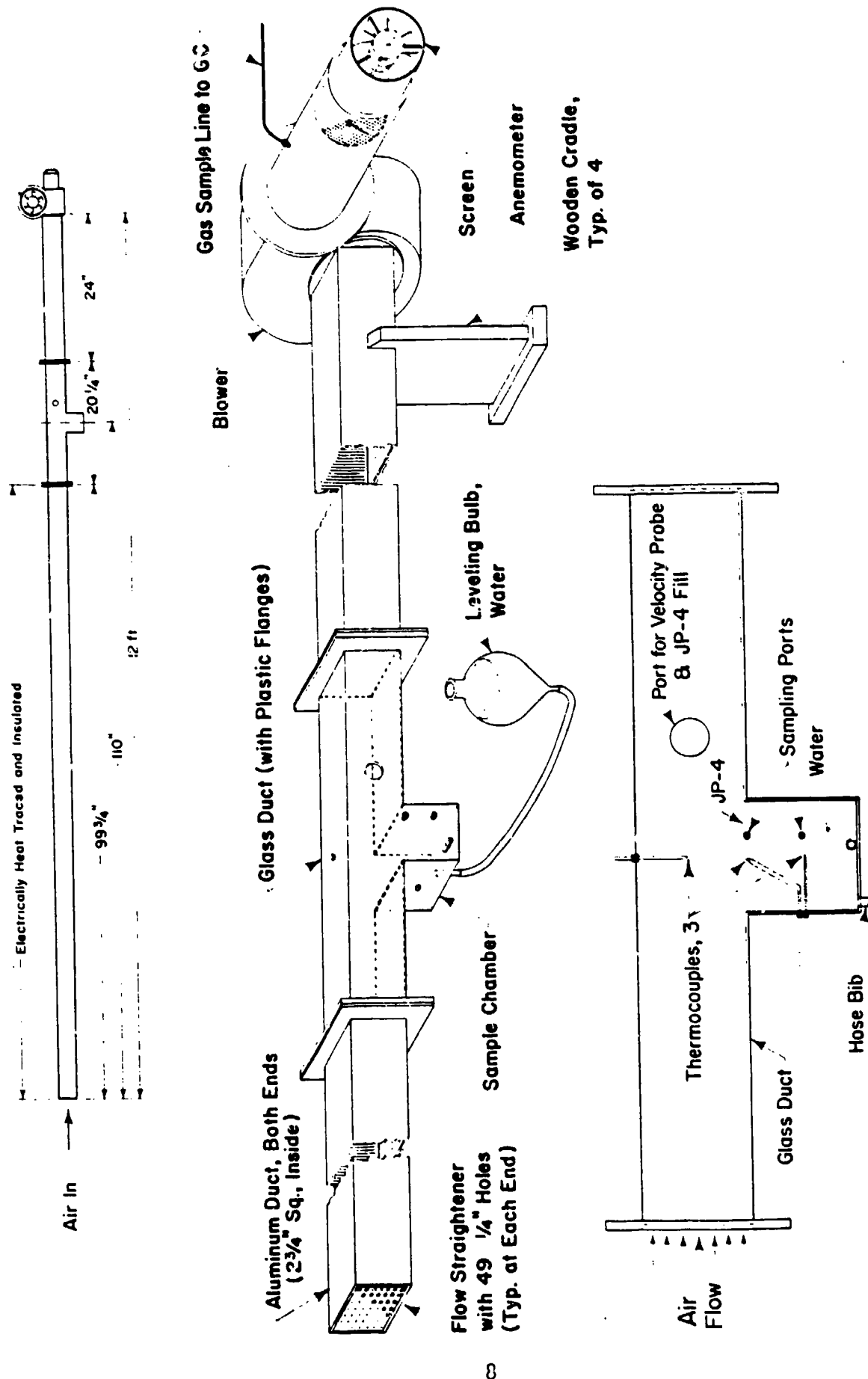


Figure 3. Bench-Scale Wind Tunnel.

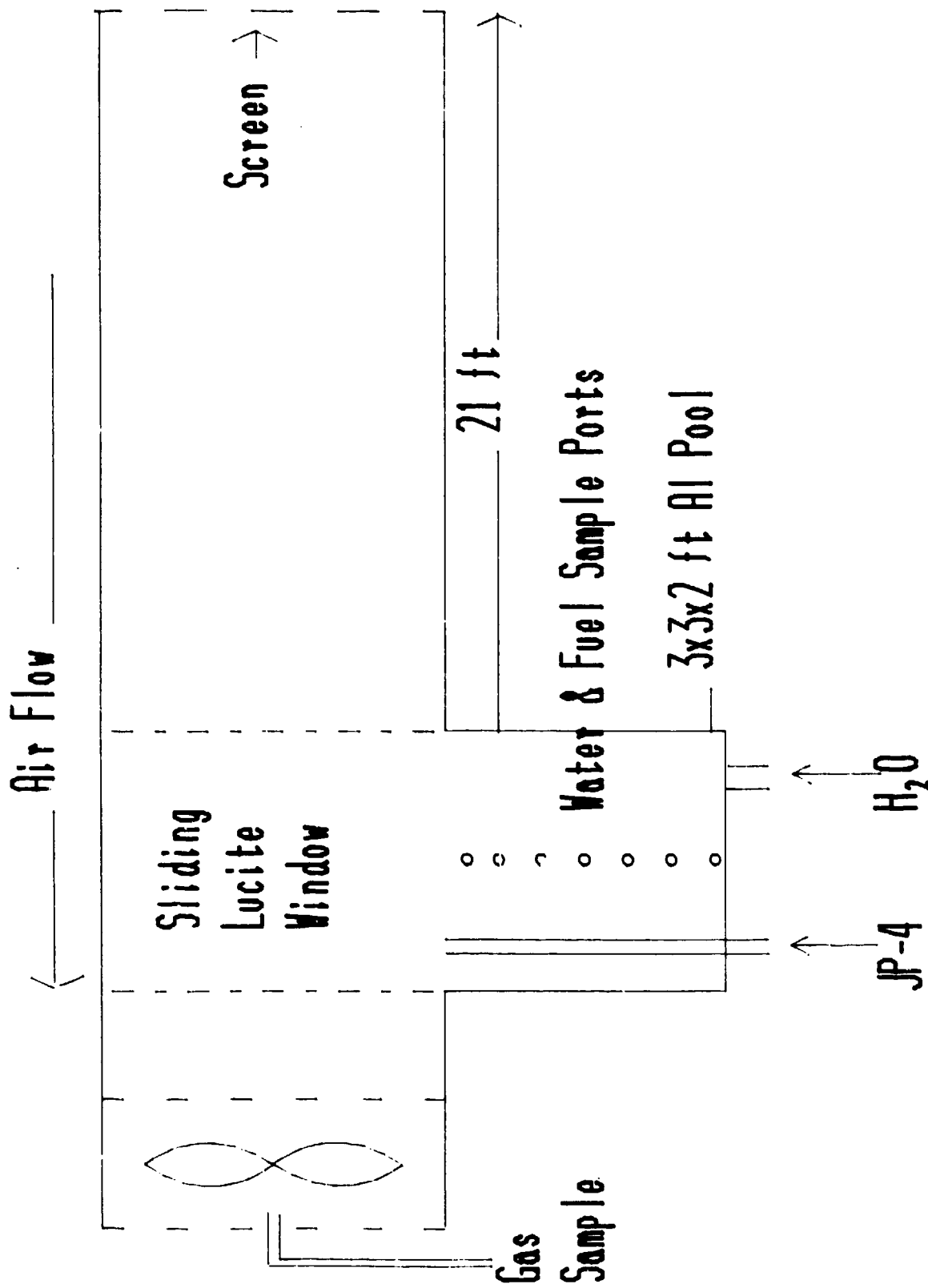


Figure 4. Intermediate-Scale Wind Tunnel.

sampling points in the system. In use, end caps were removed from the sampling tubes, and the equivalent of two to three tubing volumes of liquid was allowed to flush through the tubes. Close fitting 5-inch sections of 1/8-inch aluminum tubing were then placed over the ends of syringe tubes to capture the liquid samples. The sample tubes were tightly capped before analysis.

In experiments where mechanical mixing of the pool was employed, the mixer was mounted horizontally through the middle water sampling port. A simple paddle-wheel impeller was used in these experiments.

E. ANALYTICAL METHODS

All fuel, gas, and aqueous phase samples were analyzed, using a Varian Model 3700 GC equipped with a Hewlett-Packard Model 3388 integrator, a 50 meter fused-silica capillary column, a flame-ionization detector, and a multipurpose inlet interface. The multipurpose inlet interface is shown schematically in Figure 5. This system consists of a cryogenic trap, a Nafion dryer, a heated injector, two gas inlets, a fixed-volume sample pump, and two multiport switching valves. Samples of JP-4 vapor were obtained by flushing the trap (operated at room temperature) and injecting the known volume (1.01 cc-atm) of the trap. Fuel samples, typically 1 to 5 μ L, were first injected into evacuated and heated 1.7 L aluminum cylinders. The total pressure in the cylinder was then raised to approximately 15 psia, and a vapor aliquot was sampled and analyzed as with the JP-4 vapor samples. Aqueous samples were vaporized in the heated injection port, after which they passed through the Nafion dryer. The hydrocarbon components of the aqueous samples were then collected on the cryogenic trap ($T = -180^{\circ}\text{C}$). This procedure allowed direct injection of water samples as large as 50 μ L, and multiple injections could be used for sample concentration where needed.

Inasmuch as the water analysis procedure outlined above is not a standard procedure, a series of measurements of the solubilities of representative hydrocarbons was performed to validate this procedure. Samples of water and various pure hydrocarbons were sealed in vials having septum caps, and were allowed to equilibrate for several days with occasional gentle agitation. Samples of the water phase were withdrawn through the septum caps and were

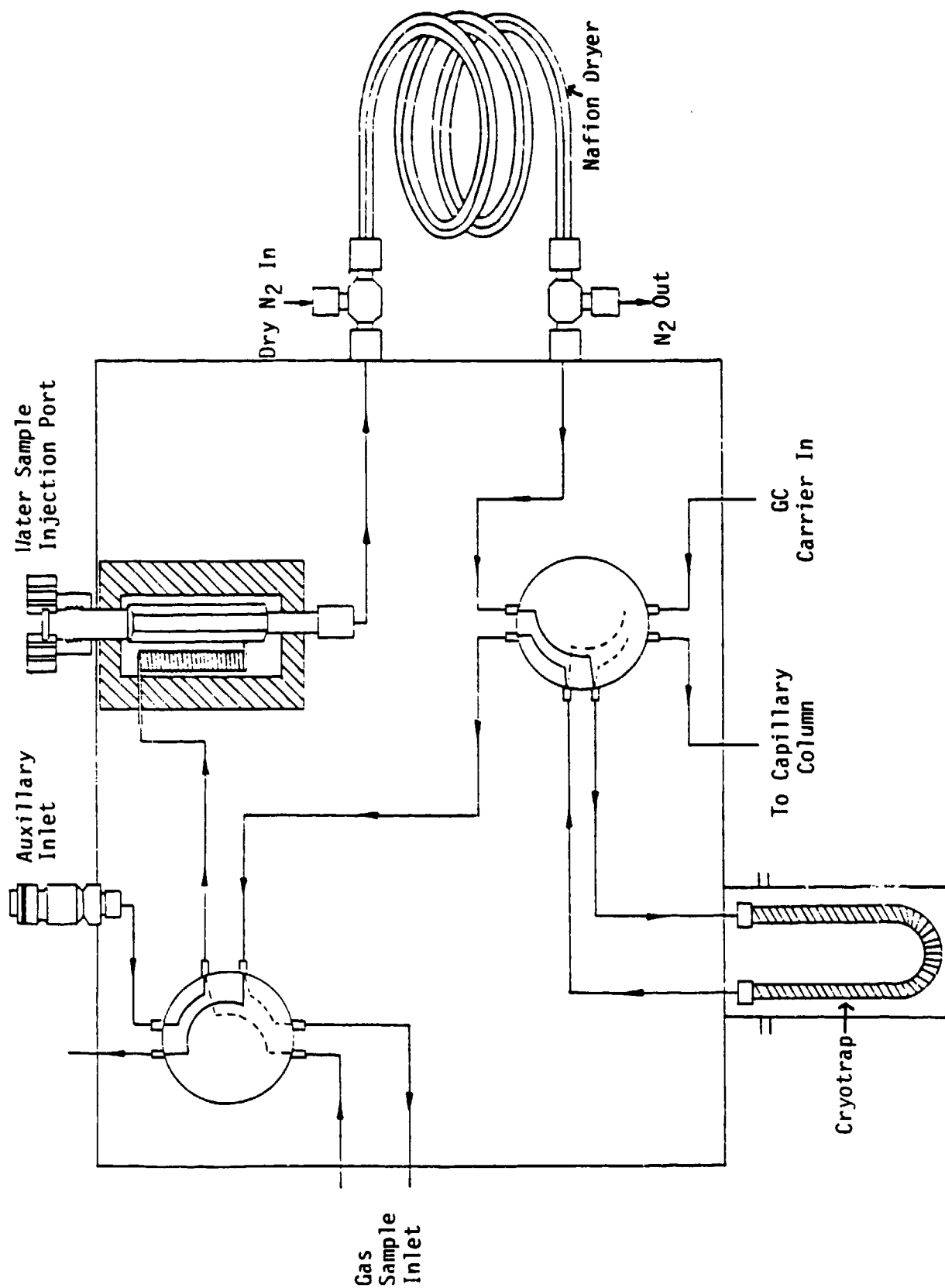


Figure 5. Multipurpose Inlet System.

analyzed, with results shown in Table 1. The probable error associated with the literature values cited in Table 1 is unknown, but, based on previous experience (Reference 9), is likely to be about 3 to 5 percent. The solubilities determined by the current method are, therefore, in excellent agreement with the literature values.

TABLE 1. SOLUBILITY OF HYDROCARBONS IN WATER

Hydrocarbon	Water Solubility, mg/L	
	Literature Value	Measured Value ^a
o-Xylene	168	176 +/- 8
Ethylbenzene	130	172 +/- 6
Toluene	558	538 +/- 15
Benzene	1780	1650 +/- 20
n-Hexane	10	14 +/- 1
n-Octane	0.66	1.25 +/- 0.03
n-Heptane	2.9	2.9 +/- 1.9 ^b

^aMean and standard deviation.

^bInterfering contaminant in water.

Samples were routinely monitored for 29 major components of JP-4. Identification of components was based on column retention times. Integrator outputs included the mass of each component detected, weight fraction in the sample for each component, mole fraction in the sample, and evaporation rates (where applicable). Inasmuch as JP-4 consists of many minor components as well as those being monitored directly, a procedure was developed to enable estimation of the masses and mole fractions of the unidentified components in order to account for the total sample. Because the molecular weights of identified components were linearly correlated with their retention times, it was assumed that the molecular weights of unidentified components were similarly correlated. It was also assumed that the unidentified components were all saturated hydrocarbons and that their FID response factors (weight basis) were

the same as those determined for the identified saturated hydrocarbons. This procedure permitted estimation of total JP-4 evaporation rates, as well as rates for the individual components. On the average, the identified components comprised approximately 68 weight percent of the JP-4 fuel samples and 82 weight percent of the gas phase samples.

F. MATERIALS

A supply of JP-4 was obtained from Rickenbacker Air Force Base. This material was broken down into 1-gallon lots that were stored in sealed cans under refrigeration. Samples for use in the laboratory were transferred to smaller containers on an "as-needed basis," and excess quantities of the fuel in the smaller containers were discarded after each experiment.

G. QA/QC

All integrator outputs were compared with their corresponding chromatograms for accuracy in peak selection. Obvious machine errors were corrected by manual recalculation of sample amounts, mole fractions, etc. Questionable appearing data were retained when no error could clearly be identified. All chromatograms are on file at Battelle. Secondary processing of data was conducted using spreadsheet files stored on floppy disks.

SECTION III

JP-4 EVAPORATION

A listing of physicochemical properties used in analyzing the data is given in Appendix A. Detailed tabulations of the results for each category of experiment are given in Appendixes B through D. The discussion below focuses on summary and correlation of the results.

A. MICROBALANCE EXPERIMENTS

In the microbalance experiments, the fuel samples were contained in a cylindrical holder having an open end area of 0.17 cm^2 . The distance from the open end of the cylinder to the surface of the fuel varied but was of the order of a few centimeters. Under these conditions, the appropriate form of Equation (2) is

$$J = DXCo/L \quad (5)$$

where L is the distance from the surface of the fuel to the open end of the tube. While reliable values of Co , the vapor pressure, are generally available for the hydrocarbons, only limited data are available for the diffusion coefficients. The approach we took, therefore, was to estimate the diffusion coefficients using the method of Fuller, Schettler, and Giddings, FSG (Reference 10) to provide a self-consistent set of data. Table 2 shows a summary of the estimated diffusion coefficients along with literature values for selected hydrocarbons where such is available. Note that values of D from the literature show considerable scatter. The FSG values are based on correlation of many of these same data plus data on other organic species in an attempt to gain smooth representation of the data. FSG diffusion coefficients are expected to be in error by no more than 5 to 10 percent. Vapor pressure data also may be in error by 5 to 10 percent, so that the expected range of error for evaporation rates estimated using Equation (5) is 10 to 20 percent.

TABLE 2. DIFFUSION COEFFICIENTS FOR JP-4 COMPONENTS

Hydrocarbon	Calculated by FSG	Measured Values from References				
		11	12	13	14	15
Iso-butane	0.0971		0.0905			
n-Butane	0.0971		0.096			
Iso-pentane	0.086					
n-Pentane	0.086	0.0842				
2-Methylpentane	0.0779					
3-Methylpentane	0.0779					
n-Hexane	0.0779	0.0732		0.0801		
Methylcyclopentane	0.0789			0.0804		
Benzene	0.0962	0.0932			0.0948	
Cyclohexane	0.0853			0.0804		
2-Methylhexane	0.0717					
3-Methylhexane	0.0717					
1,2-Dimethylpentane	0.0725					0.0723
n-Heptane	0.0717					0.0719
Methylcyclohexane	0.0725					
Toluene	0.086	0.0849				
2-Methylheptane	0.0667					
3-Methylheptane	0.0667					
n-Octane	0.0667	0.0616				0.0705
Ethylbenzene	0.0739	0.0755				
m-Xylene	0.0739	0.0688				
p-Xylene	0.0739	0.067				
o-Xylene	0.0739	0.0727				
n-Nonane	0.0627					
n-Decane	0.0593					0.0595
n-Undecane	0.0564					
n-Dodecane	0.0538					
n-Tridecane	0.0516					
n-Tetradecane	0.0496					

A simple finite-difference method was used to estimate the evaporation rates of the JP-4 components as a function of time to provide a comparison with the experimental data given in Appendix B. The approach included correction of the fuel-phase composition as the evaporation proceeded. Examination of the results showed that the calculated and measured rates were "parallel," but were slightly offset. Because of this parallel behavior, we concluded that only the initial rates need be considered in any further detail. Table 3 shows the ratios of measured to calculated rates for the microbalance experiments.

TABLE 3. JP-4 INITIAL EVAPORATION RATES
(Measured/Calculated)

Temperature, °C -	25	30	35	25	10	-20	-5		RSD ^a ,
Run No. -	1021	1022	1023	1027	11586	11686	11786	Mean	%
Hydrocarbon									
Iso-butane	0.74	0.85	0.95	0.77	0.53	0.71	0.00	0.80	10
n-Butane	0.48	0.54	0.57	0.50	0.39	0.74	0.66	0.55	11
Iso-pentane	0.50	0.55	0.57	0.53	0.40	0.76	0.70	0.60	15
n-Pentane	0.21	0.23	0.24	0.23	0.16	0.23	0.32	0.23	4.3
2-Methylpentane	0.58	0.67	0.68	0.63	0.46	0.65	0.84	0.64	6.3
3-Methylpentane	0.69	0.79	0.79	0.76	0.54	0.96	0.98	0.83	13
n-Hexane	0.69	0.81	0.81	0.78	0.55	0.97	0.97	0.84	12
Methylcyclopentane	0.68	0.78	0.78	0.76	0.52	1.01	0.90	0.82	13
Benzene	2.06	2.20	2.09	2.22	1.45	0.00	2.97	2.14	3.3
Cyclohexane	0.51	0.69	0.58	0.67	0.49	1.29	0.89	0.67	19
2-Methylhexane	0.69	0.79	0.77	0.75	0.50	0.81	0.87	0.78	7.7
3-Methylhexane	0.82	0.14	0.92	0.89	0.60	0.97	1.09	0.94	9.6
1,2-Dimethylpentane	1.09	1.00	1.20	1.20	0.78	0.24	1.54	1.12	7.1
n-Heptane	0.85	0.97	0.95	0.92	0.63	0.80	1.22	0.90	6.7
Methylcyclohexane	0.87	0.14	0.98	0.93	0.60	1.35	1.06	0.96	7.3
Toluene	1.27	1.55	1.44	1.32	0.72	0.52	1.44	1.40	7.1
2-Methylheptane	0.93	1.04	0.96	0.88	0.21	0.96	0.00	0.95	5.3
3-Methylheptane	1.13	1.28	1.19	1.08	0.78	1.00	1.17	1.14	7.9
n-Octane	1.28	1.39	1.23	1.18	0.63	0.00	0.10	1.27	6.3
								Average	9.05

^aRelative standard deviation.

Table 3 shows that the offset between measured and calculated rates is relatively constant for each compound, but differs from one compound to the next. Several components, pentane and benzene, and, possibly, toluene appear to behave differently from the rest of the components. Both of the aromatics evaporate considerably faster than would be expected, based on their vapor pressures and the overall JP-4 composition. This is possibly an activity effect, and further evidence for such an effect will be seen in the data from the wind tunnel experiments. The rates for the C4-C5 compounds are all generally lower than predicted. These are all rapidly evaporating components.

We would, therefore, expect any liquid phase-resistance effects to be greatest for these compounds. For nearly all of the higher molecular weight components, the calculated and measured rates agree within the combined uncertainties in the experimental data, the diffusivities, and the vapor pressures.

B. WINDSPEED EFFECTS

The bench-scale wind tunnel experiments were conducted primarily to examine velocity effects on evaporation rates and dissolution rates. However, these experiments also included examination of the effects of relative humidity, temperature, water composition (using sea water), and fuel composition. In examining the effects of fuel composition, no alterations were made to the initial JP-4 composition, but rather the instantaneous rates were correlated with the normal changes in fuel composition resulting from evaporation and dissolution. While selected experiments were conducted explicitly for the purpose of examining windspeed effects, additional information on this variable is present in all runs conducted in both the bench-scale and intermediate-scale systems. The approach used in determining the effect of this variable consisted of initial runs made with pure compounds to verify the general form of the correlation followed by modification and refinement of the correlation with respect to results from subsequent runs made with JP-4.

1. Pure Compound Evaporation

Windspeed effects were initially determined using xylene, toluene, and octane as reference compounds to enable a time-efficient first approximation to the form of the correlation to be used. Results of these measurements analyzed in terms of the Reynolds number, Re , the Schmidt number, Sc , and the Sherwood number, Sh , are given in Table 4.

The initial correlation derived from the data in Table 4 was

$$Sh = 0.051Re^{0.79}Sc^{1/3} \quad (6)$$

A plot of these data is shown in Figure 6.

TABLE 4. EFFECT OF AIR VELOCITY ON EVAPORATION OF o-XYLENE, TOLUENE, AND OCTANE

(Area = 48.82 cm²)

Temperature, C		Velocity		Re	Sc	Rate, mg/min	Sh ^a	Sh ^b	% Dev.
Air	Fuel	Q, cfm	fpm						
<u>o-Xylene</u>									
22	21.4	0.81	15	358	1.29	6.33	7.15	5.85	22.22
21.8	21.2	1.24	24	549	1.29	8.95	10.22	8.21	24.53
21.4	20.2	2.24	43	994	1.29	18.4	22.20	13.14	68.90
21.5	20.4	4.91	94	2,178	1.29	23.9	28.52	24.48	16.50
21.6	20.5	6.79	129	3,010	1.29	25.6	30.38	31.64	-3.98
21.8	20.8	33.25	633	14,721	1.29	113	131.90	111.40	18.40
21.9	20.5	34.4	655	15,221	1.29	99.2	117.71	114.39	2.90
22	20.4	43.37	826	19,179	1.29	132	157.50	137.41	14.62
22.4	20.2	53.2	1,013	23,470	1.29	153	184.58	161.27	14.45
<u>Toluene</u>									
22	20	2.05	39	907	1.22	38.7	10.65	12.01	-11.30
22	20	3.01	57	1,331	1.22	39.6	10.90	16.28	-33.07
22	19.9	6.79	129	3,003	1.22	62.2	17.20	31.03	-44.57
21.8	19.1	14.5	276	6,420	1.22	155	44.61	56.69	-21.32
21.9	18	33.25	633	14,713	1.22	327	99.46	109.43	-9.12
22	16.8	43.1	821	19,060	1.22	367	118.61	134.37	-11.73
<u>n-Octane</u>									
22.2	21	6.09	116	2,690	1.36	37.9	17.19	29.46	-41.63
22.2	20.4	9.3	177	4,108	1.36	62.6	29.35	41.21	-28.76
22	20.6	22.5	429	9,950	1.36	195.8	90.81	83.11	9.26
22.2	20.4	44.8	853	19,788	1.36	321.8	150.92	143.37	5.27
22.4	20	79.8	1,520	35,206	1.36	436.7	209.42	226.39	-7.50
Average--									-0.80
RMSC--									27.40
RMSd--									15.80

^aSherwood number = duct size times rate per unit area divided by vapor concentration (mg/cc) times diffusion coefficient (cm²/min).

^bRate calculated equal to $0.051Re^{0.793}Sc^{0.33}$.

^cRoot mean square deviation using all data points.

^dRoot mean square deviation omitting 1 point for xylene, two points from toluene data set, and one point for octane.

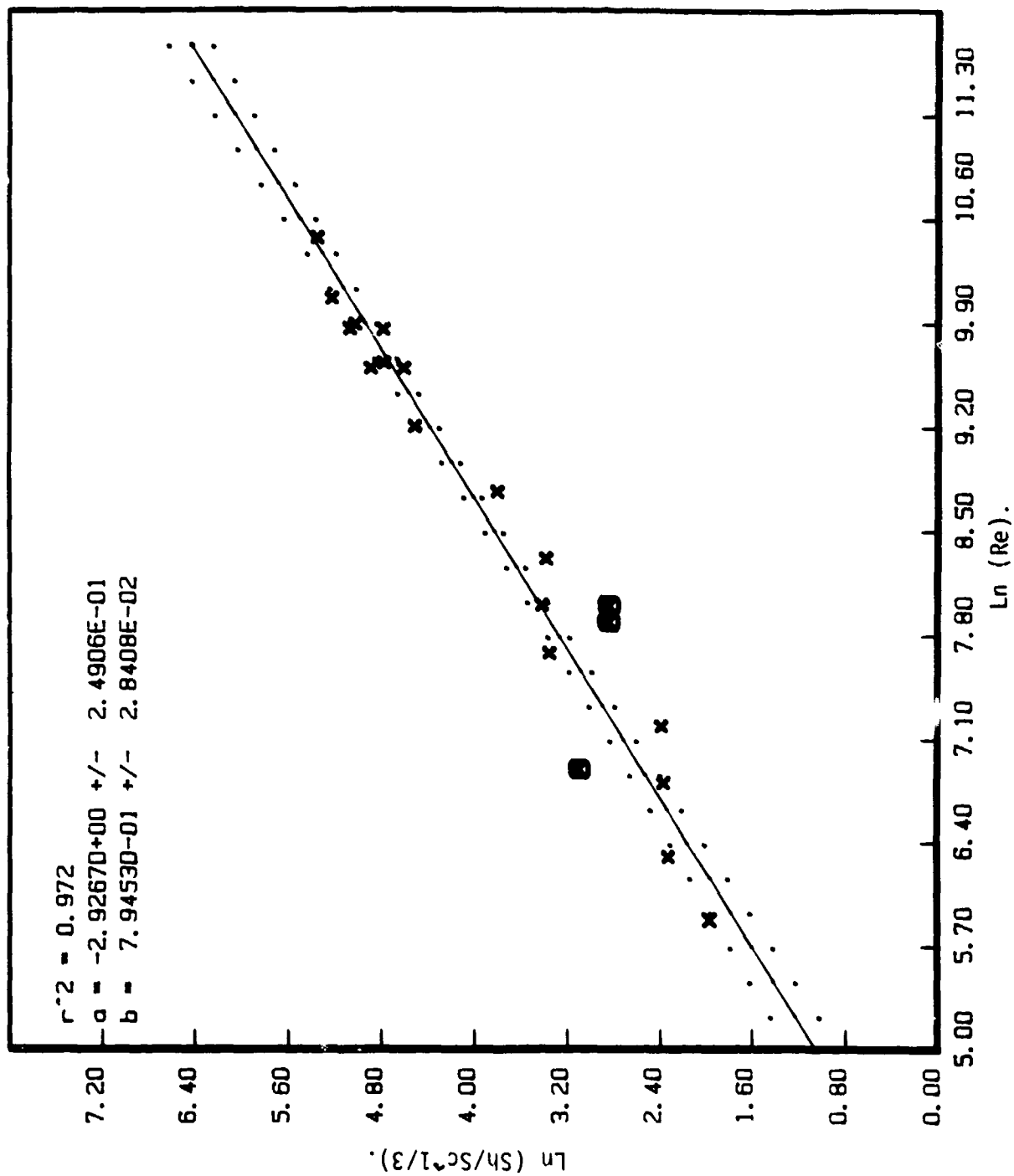


Figure 6. Preliminary Sherwood Correlation of Windspeed Effect on Evaporation of Pure Compounds.

2. JP-4 Evaporation

Results for four runs made with JP-4 (on water) are summarized in Table 5. For these runs, the JP-4 was allowed to evaporate for various time periods before the evaporation rates, R , were determined. Therefore, not all of the normal components were detected. Calculated rates, R_{cal} , were based on the Sherwood correlation given above and liquid phase (JP-4) compositions measured simultaneously with the rate determinations. The calculated rates for the alkanes are consistently high at the different velocities, but the correlations predict the evaporation rates of the aromatics with reasonable accuracy. A similar observation was made above with respect to the microbalance experiments. This is more clearly shown in Figure 7, where we have plotted a

TABLE 5. SUMMARY OF JP-4 DATA AT DIFFERENT SPEEDS

Component	Measured Rate/Calculated Rate at Velocity (mi/hr)				
	1.06	5.06	10.78	19.00	Mean
Iso-butane					
n-Butane	0.23				(0.23)
Iso-pentane					
n-Pentane					
2-Methylpentane	0.35				(0.35)
3-Methylpentane	0.38				(0.38)
n-Hexane	0.39	0.60	0.59		0.53
Methylcyclopentane	0.36	0.43	0.47		0.42
Cyclohexane	0.36	0.47	0.48	0.44	0.44
2-Methylhexane	0.43	0.56	0.59	0.52	0.52
3-Methylhexane	0.42	0.55	0.58	0.52	0.52
1,2-Dimethylpentane	0.55	0.66	0.76	0.66	0.66
n-Heptane	0.44	0.61	0.61	0.53	0.55
Methylcyclohexane	0.42	0.55	0.59	0.53	0.52
Toluene	0.96	1.09	1.20	0.76	1.00
2-Methylheptane	0.49	0.63	0.63	0.58	0.58
3-Methylheptane	0.53	0.67	0.71	0.61	0.63
n-Octane	0.56	0.70	0.75	0.64	0.66
Ethylbenzene	0.00	0.82			0.41
m&p-Xylene	1.01	1.17	1.30	0.67	1.04
o-Xylene	0.49	1.30	1.16		0.98
n-Nonane	0.61	0.80	0.81		0.74
Average	0.47	0.73	0.75	0.59	0.63

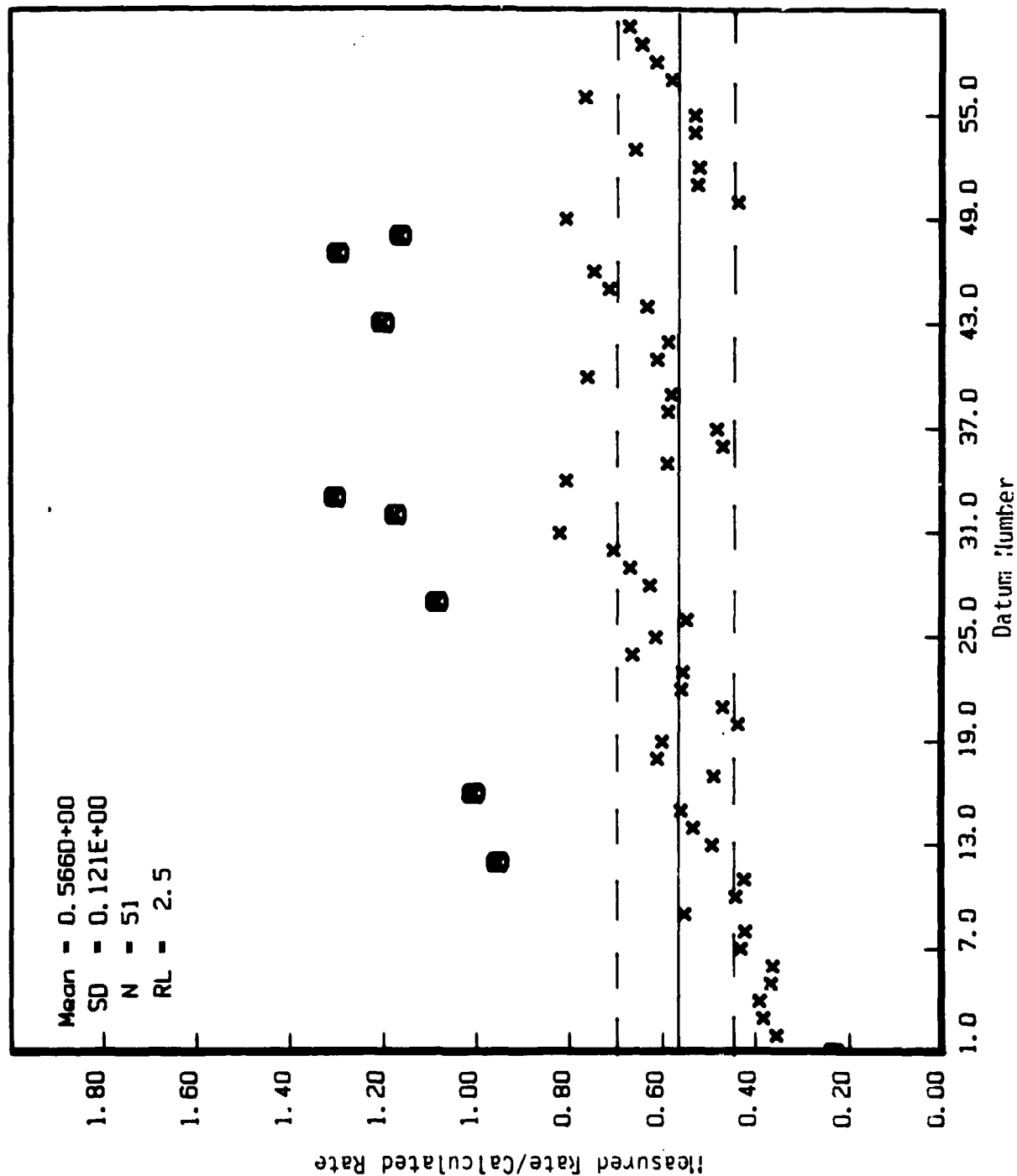


Figure 7. Scattergram of Initial JP-4 Evaporation Rate Data.

scattergram of the rate ratios. In this figure, all of the high rejected points (those circled) are data for the aromatics. The average ratio for the remaining data is 0.56 ± 0.12 . This implies a different evaporation mechanism for the alkanes than that for the aromatics, and suggests that the Sherwood correlation for the alkanes should be

$$Sh = 0.028Re^{0.79}Sc^{1/3} \quad (7)$$

The reason for this discrepancy between the correlation determined for the pure liquids and that determined for the alkanes in JP-4 is probably related to the entropy of the alkanes at the fuel surface. Ideal solution theory, which is being used to estimate the vapor pressures of the JP-4 components as a function of fuel composition, assumes that species are both present and available at the surface in proportion to their liquid mole fractions. This may be appropriate for the aromatics because of their relatively compact structure. On the other hand, the straight chain hydrocarbons may be subject to orientation effects where some of the molecules may be partly "submerged" and would, therefore, not be equally available for evaporation.

Evaporation data for subsequent runs in both the bench-scale wind tunnel and the intermediate-scale system were analyzed using Equation (6) for the aromatics and Equation (7) for the alkanes. The experimental Sherwood number for each compound was normalized by dividing by the cube root of the Schmidt number for that compound. The resulting values were averaged and outliers were rejected. (For example, observations of tetradecane, tridecane, and some of the other relatively involatile JP-4 components in the vapor phase were rejected.) Finally a comparison of the resulting averages was made with the values predicted based on Equations (6) and (7). The results for the alkanes are summarized in Table 6, and results for both the alkanes and aromatics are shown graphically in Figure 8. Because of the fewer data points for the aromatics, scatter in those data appears more pronounced, but correlations for both groups of compounds are good to at least 20 percent on the average. Considering the complexity of the system and the number of variables involved, (for example, the individual vapor pressures and diffusivities) this degree of agreement seems rather good.

TABLE 6. SUMMARY OF EVAPORATION RATE CORRELATION FOR ALKANE COMPONENTS OF JP-4

Experiment Series	Re	Sh/Sc ^{1/3}		SDev	RSD	Exp/Cal
		Cal	Exp			
Low temp	35,300	113	128	15	13	1.13
Low temp	57,229	166	181	12	7	1.09
Low temp	13,685	53	51	11	21	0.96
Low temp	7,594	33	18	4	12	0.54
Ambient temp	2,172	12	9.5	1.4	11	0.77
Ambient temp	10,760	44	44.4	6	14	1.01
Ambient temp	20,027	72	75.4	11	15	1.04
Ambient temp	35,259	113	111	11	10	0.98
Humid air	17,809	66	90	19	29	1.37
Humid air	10,115	42	74	13	31	1.76
High temp	5,747	27	28.8	7	26	1.07
High temp	10,717	44	75	10	23	1.71
High temp	19,657	71	114	6	8	1.60
Int. Scale	90,145	238	283	45	19	1.19
Int. Scale	105,230	269	195	59	22	0.72
Int. Scale	105,170	269	299	93	35	1.11
				Average	18	1.13

C. EFFECTS OF OTHER VARIABLES ON EVAPORATION

Detailed data relevant to the effects of temperature, relative humidity, and fuel composition on evaporation rates for JP-4 are given in Appendices C and D. Inasmuch as the summary given in Table 6 includes the data from those runs, the discussion below addresses only briefly the impact of each of these variables on the Sherwood correlation.

1. Temperature

The Sherwood correlation includes explicitly several variables that contribute to the effect of temperature on evaporation rate. The most significant of these is probably the vapor pressures of the individual JP-4 components. A variety of equations have been developed for expressing the dependence of vapor pressure on temperature, including the Clausius-Clapeyron

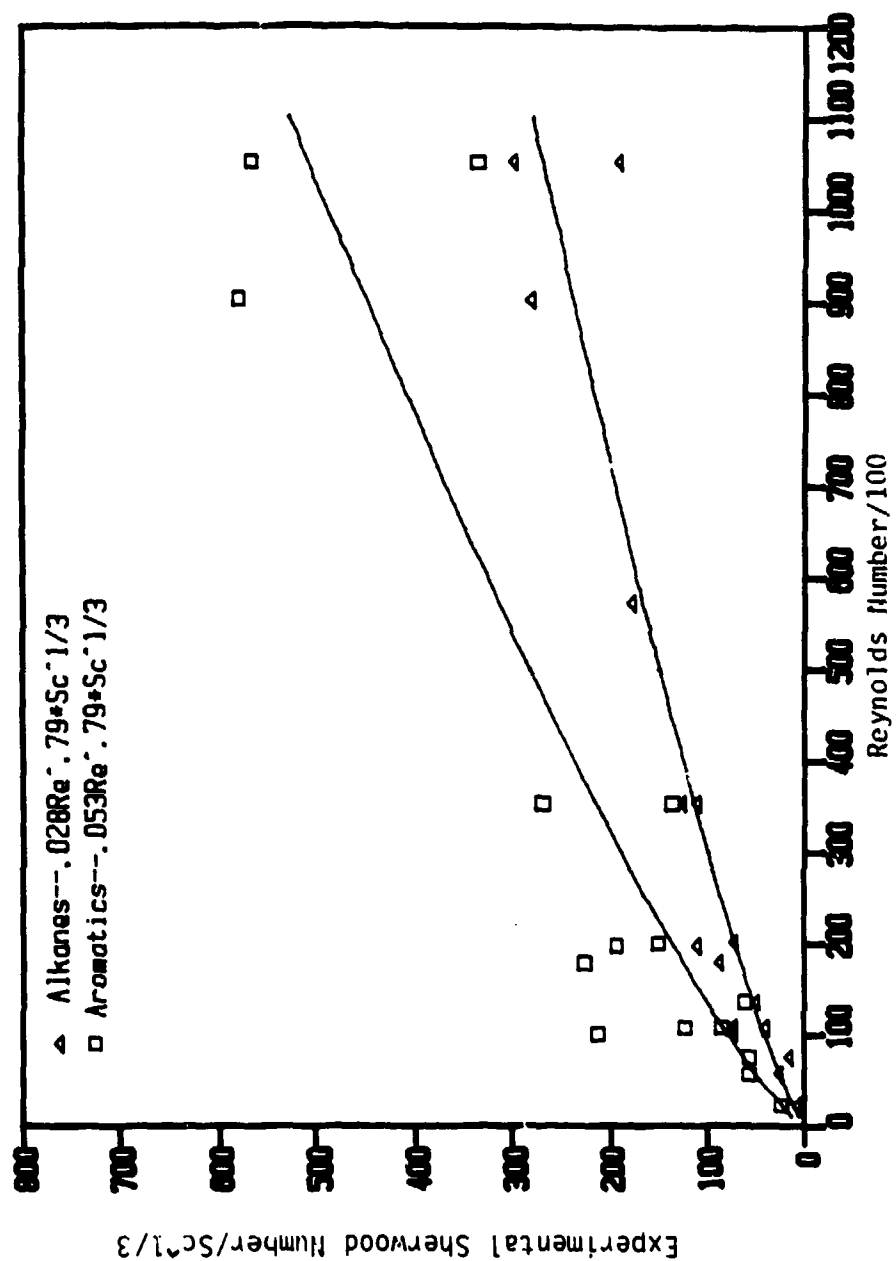


Figure 8. Effect of Windspeed on Average Sherwood Numbers for all Runs.

equation, the Antoine equation and various polynomials based on detailed thermodynamics or statistical thermodynamics. Generally, the more elaborate equations are required for accurate description of the temperature dependence of vapor pressures of hydrocarbons over wide temperature ranges. However, the simple Clausius-Clapeyron equation is adequate over the relatively narrow range of temperatures relevant to the hydrocarbon spill problem. This equation can be expressed as

$$\ln P = A - B/T \quad (8)$$

The vapor concentration required for Equation (2) is therefore given by

$$C_o = (M/RT)e^{(A-B/T)} \quad (9)$$

where M is the molecular weight and R is the gas constant. In applying this simple equation, care should be taken to determine the appropriate values of A and B over the ambient temperature range.

Diffusion coefficients for dilute gaseous species in air at normal ambient pressures are generally given by an equation of the form (Reference 16)

$$D = aT^{1.75} \quad (10)$$

The Reynolds number contains two parameters that are temperature-dependent: gas density and viscosity. The density is inversely proportional to temperature, and viscosity is proportional to $T^{0.75}$ (Reference 16) so that the overall temperature-dependence of Re is given by

$$Re = bT^{-1.75} \quad (11)$$

The Schmidt number contains three temperature-dependent parameters: density, viscosity, and the diffusion coefficient. However, consideration of the dependencies of each of these variables cited above leads to the conclusion that the Schmidt number is independent of temperature.

In analyzing the data obtained from the current experiments, the temperature dependencies of each of the variables cited above were considered. The data shown in Table 6 reflect no consistent additional temperature effects.

2. Relative Humidity

Most of the experiments were conducted at normal ambient relative humidity, 40 to 50 percent. The two runs conducted at high humidities, 68 and 93 percent, appear to reflect slightly higher evaporation rates than those calculated from the Sherwood correlation. This observation however is inconsistent with the expected effect of humidity on the variables in the correlation. The main variable affected by the high humidity is the gas density. Water vapor has a smaller molecular weight than air, so that the effective density of the air is lowered slightly by increased humidity. The diffusion coefficient of a hydrocarbon in air is expected to be increased slightly by increased humidity. Neither effect is expected to be significant within the range of variables that we employed, and they should to some extent cancel each other. A reconsideration of the physics of the evaporation process suggests no other possible humidity effect, and it is concluded that the slightly higher evaporation rates obtained at high humidities represent experimental error.

3. Fuel Composition

The correlation explicitly includes the effect of fuel composition through the assumption of ideal solution theory and the use of the fuel component mole fraction to correct the equilibrium vapor concentration of each component.

4. Fuel Layer Thickness

The effect of fuel layer thickness was studied, primarily with respect to dissolution, and was, therefore, not included in the summary given above. However, some evaporation rate data were also taken in those experiments. Most of the bench-scale wind tunnel experiments were conducted using

initial fuel layers that were 0.25-inch thick. Intermediate-scale experiments used fuel layers approximately 0.17-inch thick. For three thick-layer runs where evaporation rate data were available, the average ratio of experimental to calculated rates is 1.24, a value consistent with the data in Table 6. In one experiment where the fuel depth was increased to 2 inches, the composition at the top of the fuel layer was compared to that at the bottom after a 60-minute evaporation period. Concentration differences are in the range of 8-15 percent, indicating that turbulence induced in the fuel layer by the airflow was sufficient to provide good mixing, and that liquid-phase resistance was not a significant factor.

SECTION IV

JP-4 DISSOLUTION

The planned approach for measurement of dissolution rates of JP-4 components involved measurement of aqueous concentrations as a function of time and depth followed by integration of the depth profiles to obtain the total amount dissolved per unit time. Initial experiments were conducted using benzene as a model compound. The remaining experiments were conducted using JP-4. The initial experiments with benzene were conducted as indicated above, but several observations suggested faults in the procedure:

1. At either very high windspeeds or essentially zero windspeed, concentrations of benzene followed a smooth decline from the fuel/water interface to the bottom of the container (see Figure 9).
2. At intermediate windspeeds, concentrations were frequently higher at the 0.5- to 1-inch level than those at the 0.25-inch level. Furthermore, concentrations at the 0.5- to 1-inch level were nonreproducible, being dependent on the precise lateral and horizontal positioning of the sampling syringe.
3. Experiments conducted using a water soluble dye in the fuel layer showed surface movement of the fuel as indicated in Figure 10a; and "peeling off" of the interfacial layer accompanied by recirculation as represented in Figure 10b. This recirculation occurred primarily at depths of about 1 inch at intermediate windspeeds.

These observations confirm the notion that the scale of eddy transport of fuel components away from the fuel/water interface is much more important than molecular diffusion. They also emphasize the futility of attempting to derive the kinetics of dissolution from a limited number of measurements in a system where the scale of the instabilities is much greater than the sampling volume. Because of these facts, analysis of further experiments was confined to specification of the local concentrations, and estimation of the maximum effect of mixing on dissolution.

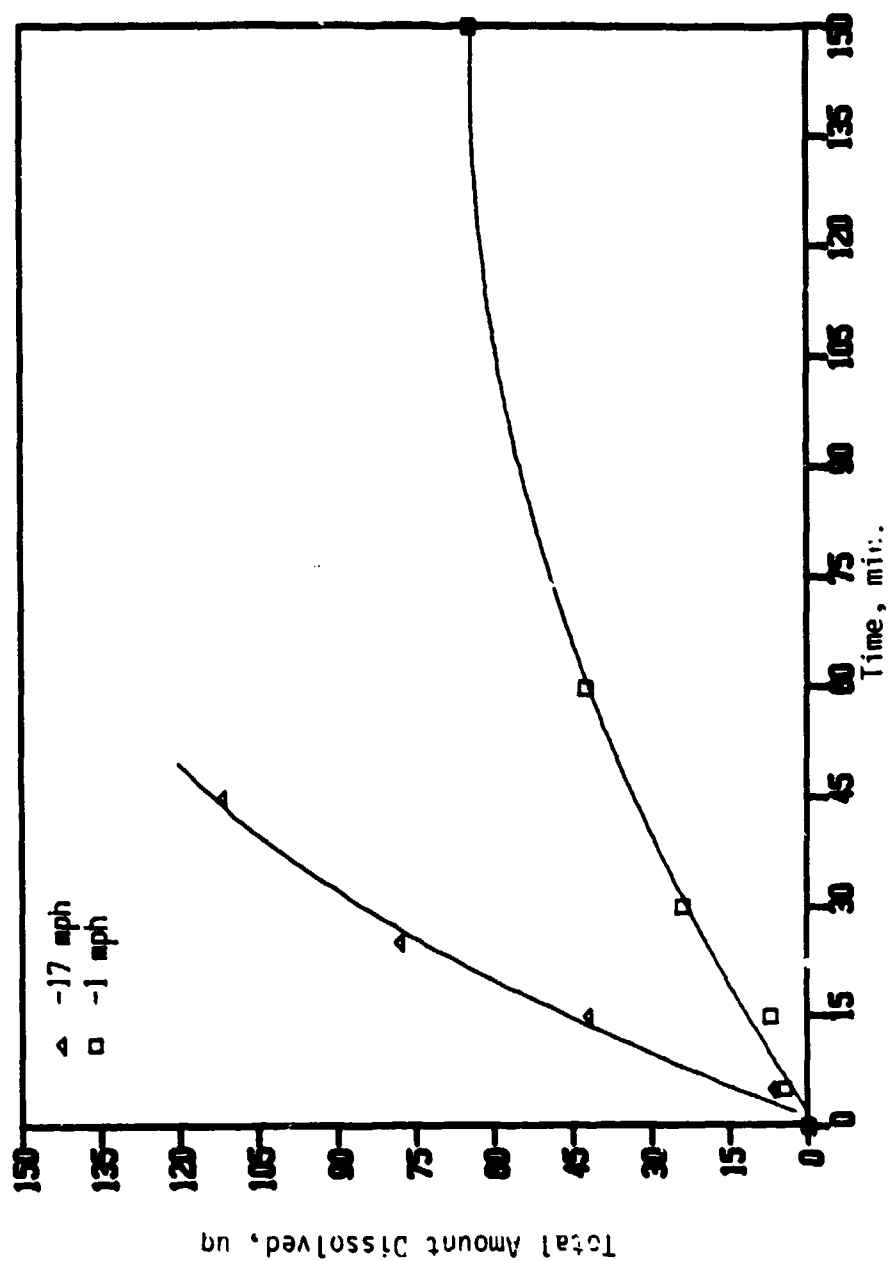


Figure 9. Dissolution of Benzene at High and Low Windspeeds.

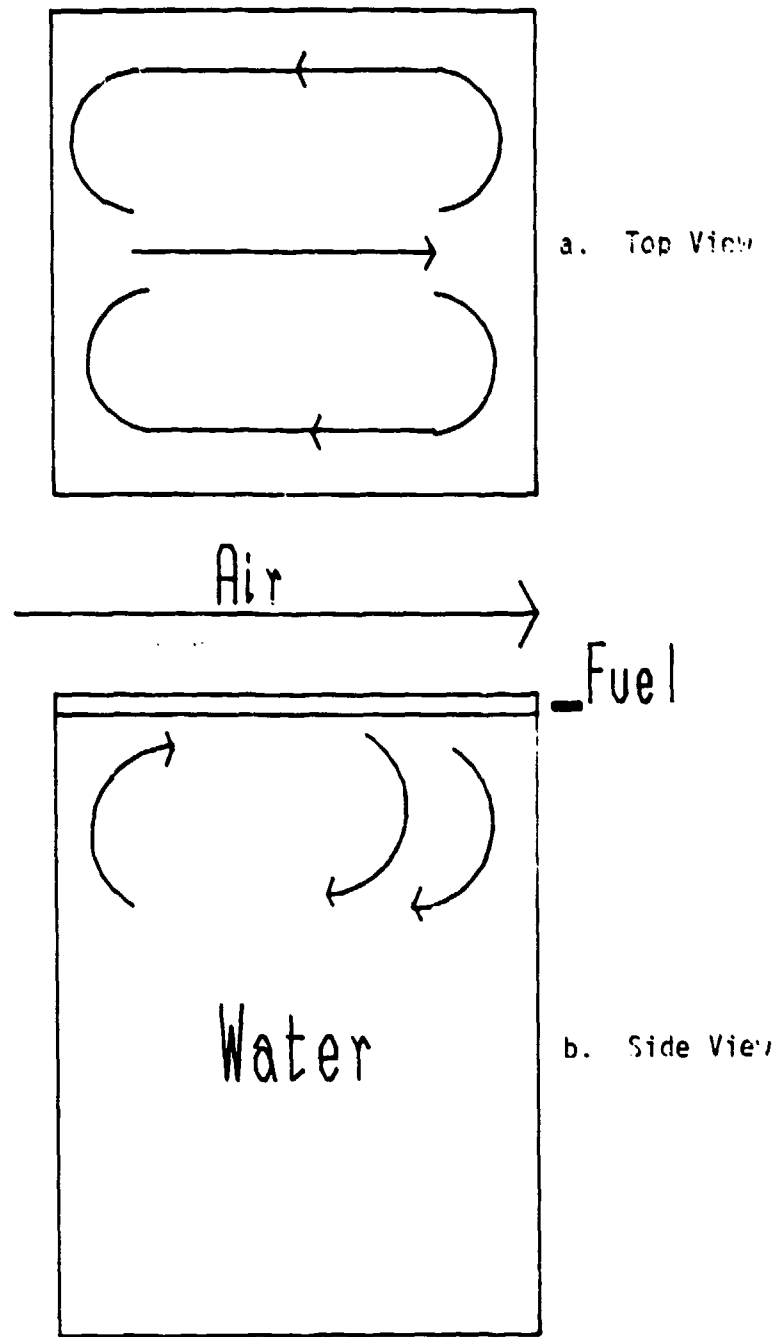


Figure 10. Recirculation in Water Container.

A. JP-4 DISSOLUTION IN DISTILLED WATER

Dissolution runs were made at two air velocities, 1.7 and 14.4 mi/hr in the bench-scale systems. In both experiments, the only hydrocarbons detected in the aqueous phase were the aromatic hydrocarbons benzene, toluene, ethylbenzene, m&p-xylene, and o-xylene.

1. Low Velocity Data

Figure 11 illustrates the behavior observed with the concentration versus depth data at two different times. At 15 minutes, the benzene concentrations show a smoothly decreasing gradient from the surface (0 depth) to the bottom of the water. However, at 60 minutes, the water is relatively depleted in benzene near the surface, reflecting loss of benzene. Most of the benzene evaporates from the JP-4 layer within the first 30 to 40 minutes (Figure 12), so that this turnaround of the gradient in the water phase is to be expected. Similar behavior is observed for the other aromatics as well, but their evaporation rates generally follow more slowly declining curves so that their concentrations in the water continue to rise for longer periods of time.

Figures 13 to 17 show both the aqueous-phase and fuel-phase concentrations of each of the aromatics for the low-velocity experiment. The fuel concentrations of benzene and toluene tend to decline relatively early in the experiment, but the fuel concentrations of the heavier aromatics actually rise. This is caused by the loss of the lighter hydrocarbons from the fuel layer. Consequently, the driving force for dissolution of the heavier aromatics also increases. Thus, we see very little of the heavy aromatics early in the experiment, but their presence in the water-phase increases later. Table 7 summarizes the relative degree of equilibration of each of the aromatics at each time period for which data were obtained. The observed aqueous concentrations represent no more than 10-15 percent equilibration.

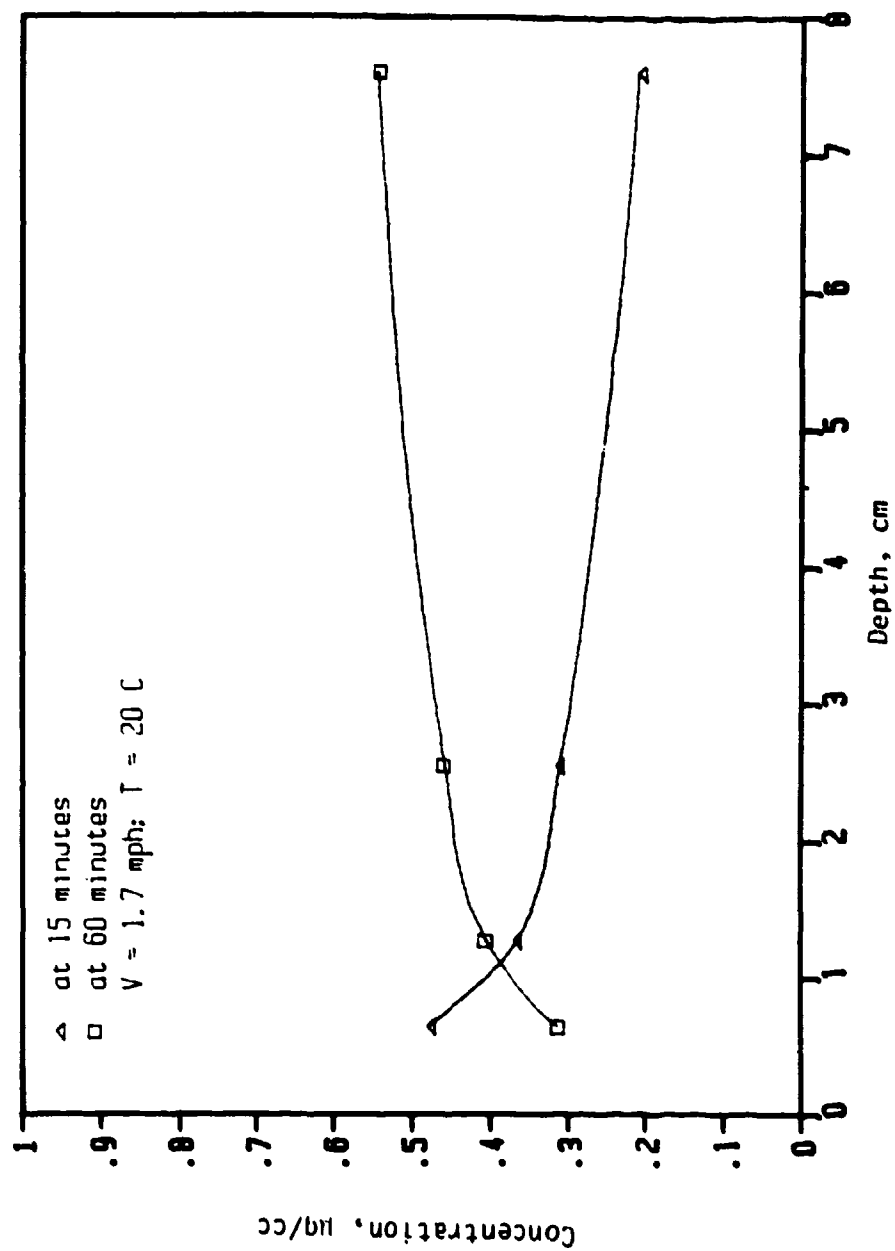


Figure 11. Distribution of Benzene in Water.

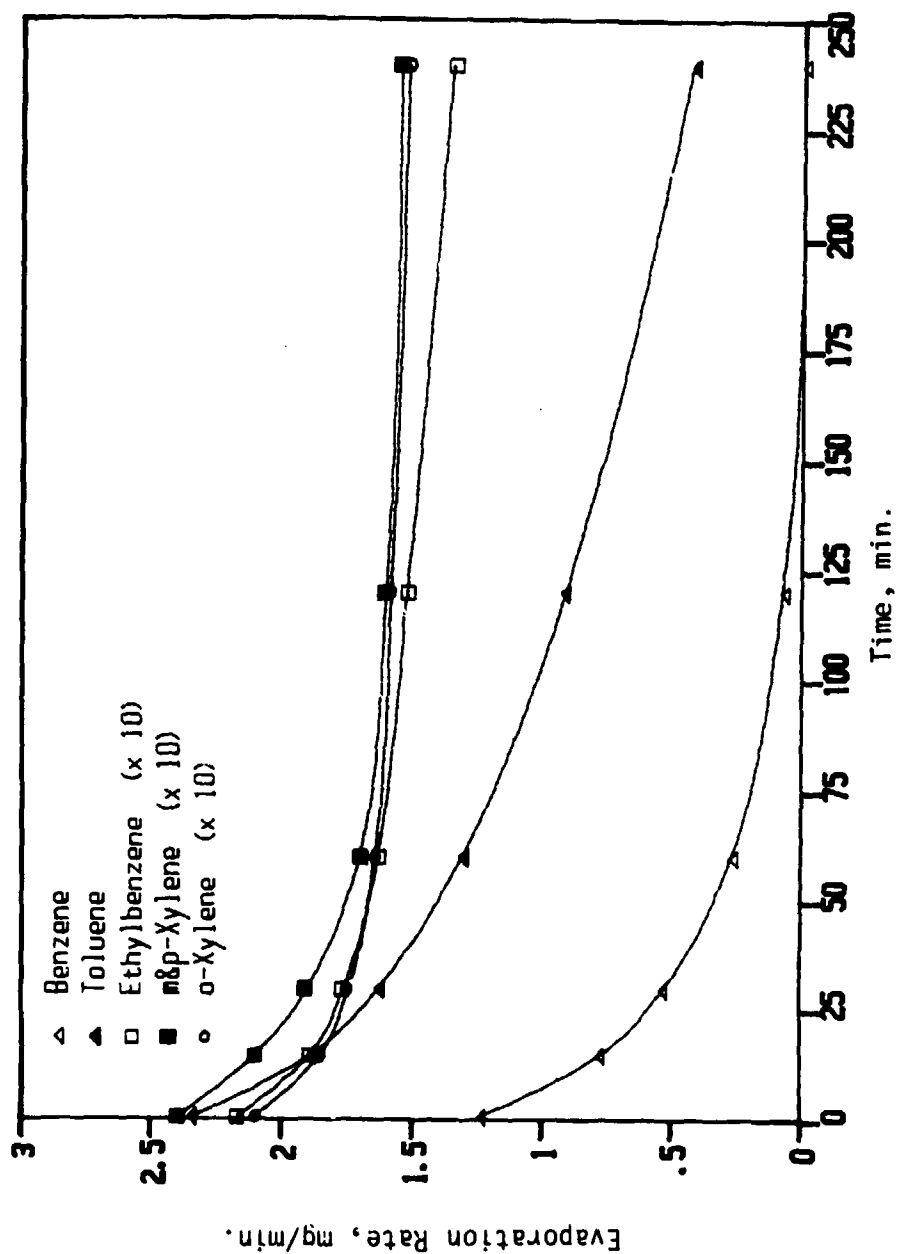


Figure 12. Evaporation Rates of Aromatic Hydrocarbons from JP-4 at 1.7 mi/hr.

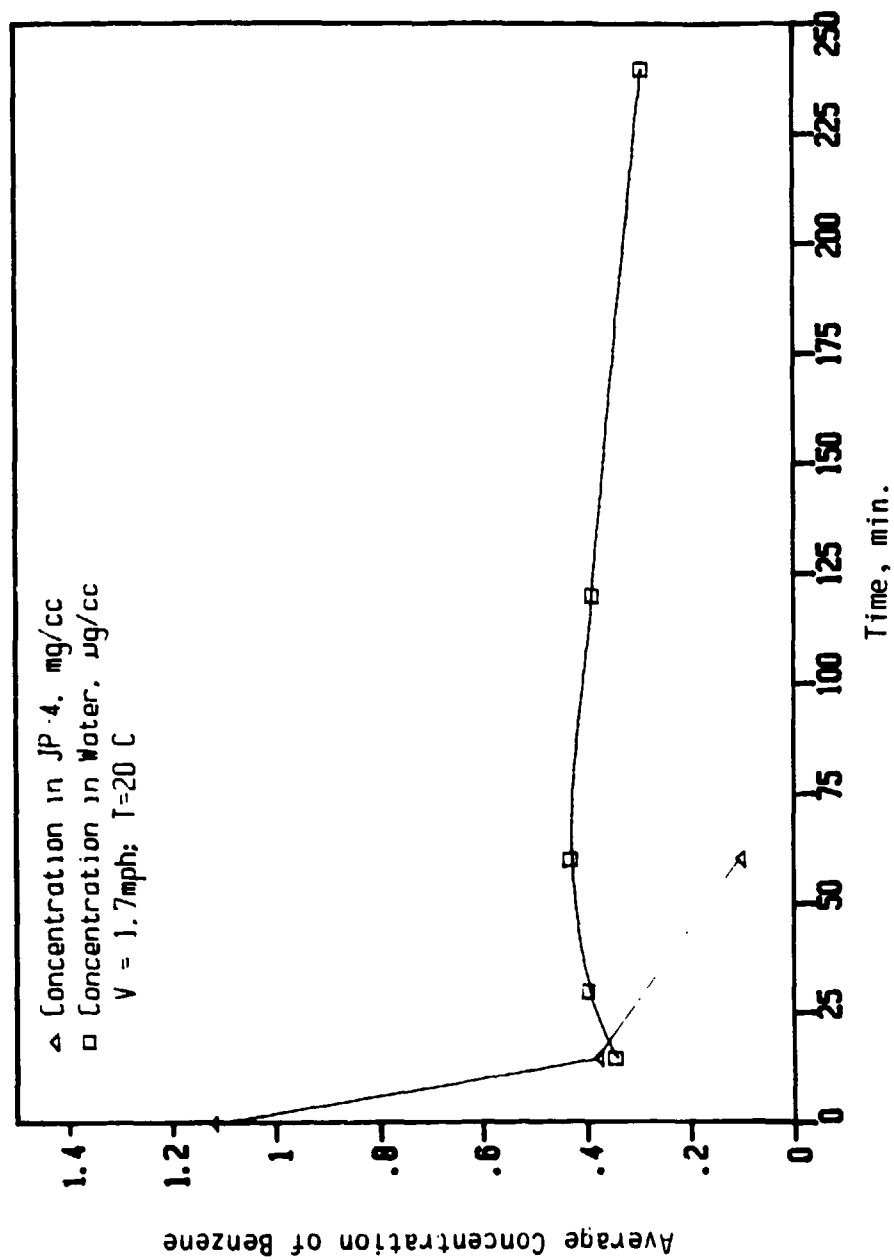


Figure 13. Benzene Dissolution from JP-4.

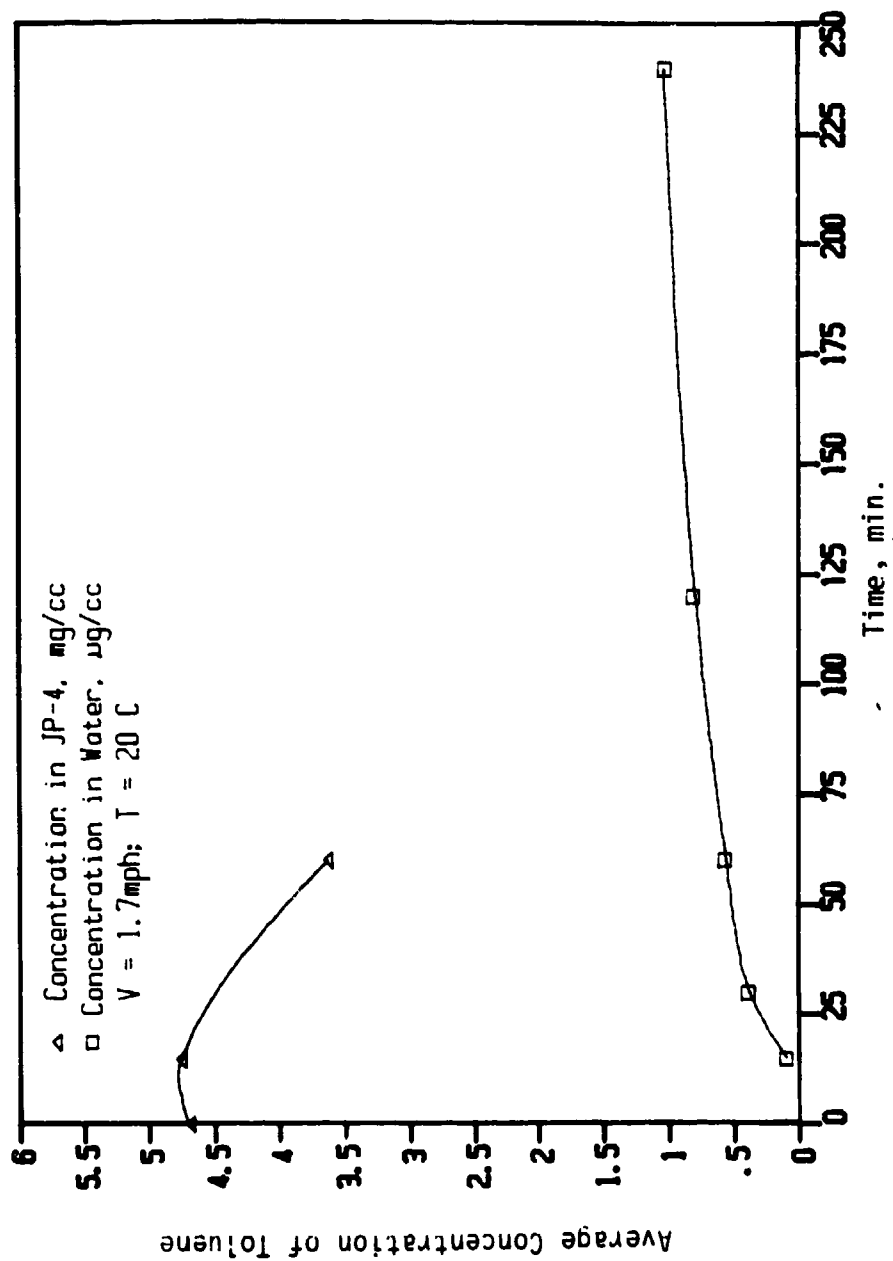


Figure 14. Toluene Dissolution from JP-4.

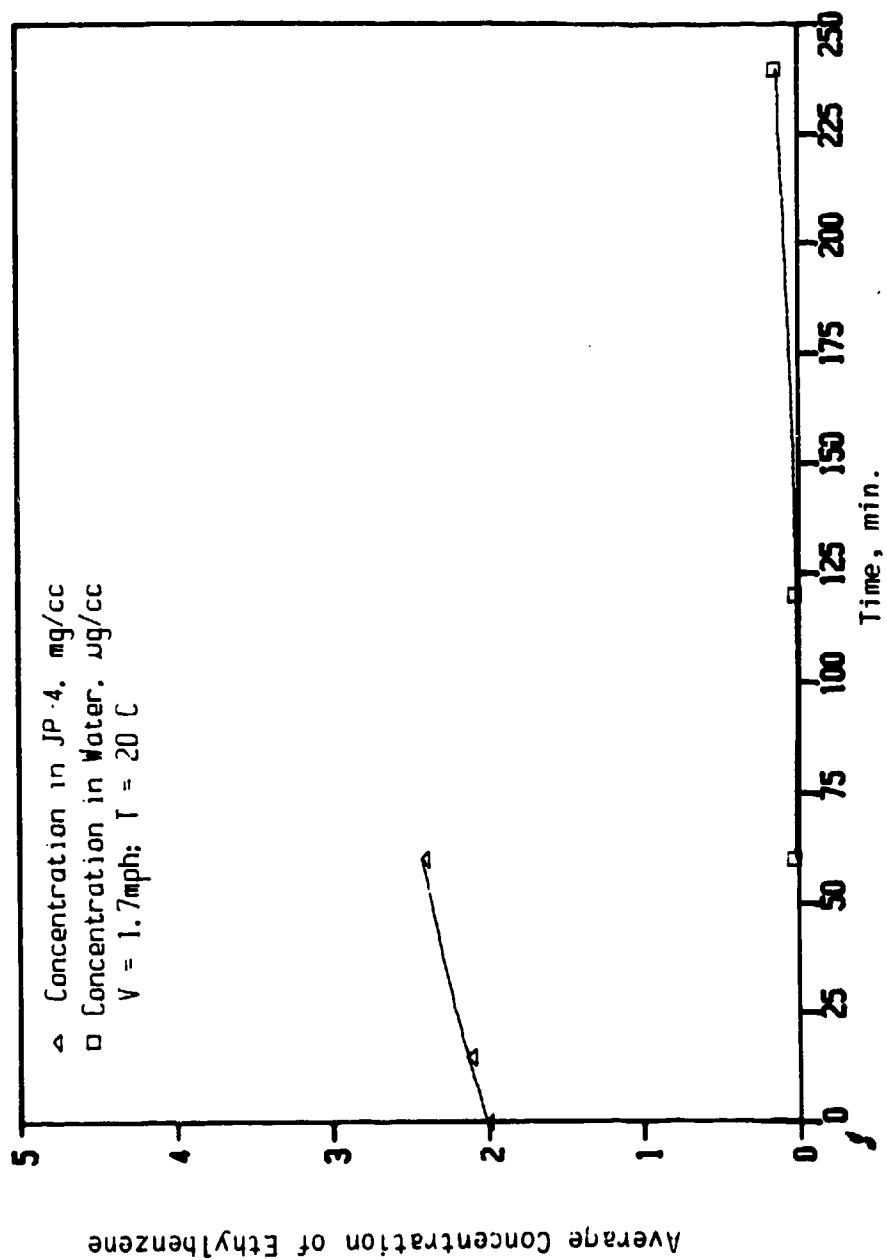


Figure 15. Ethylbenzene Dissolution from JP-4.

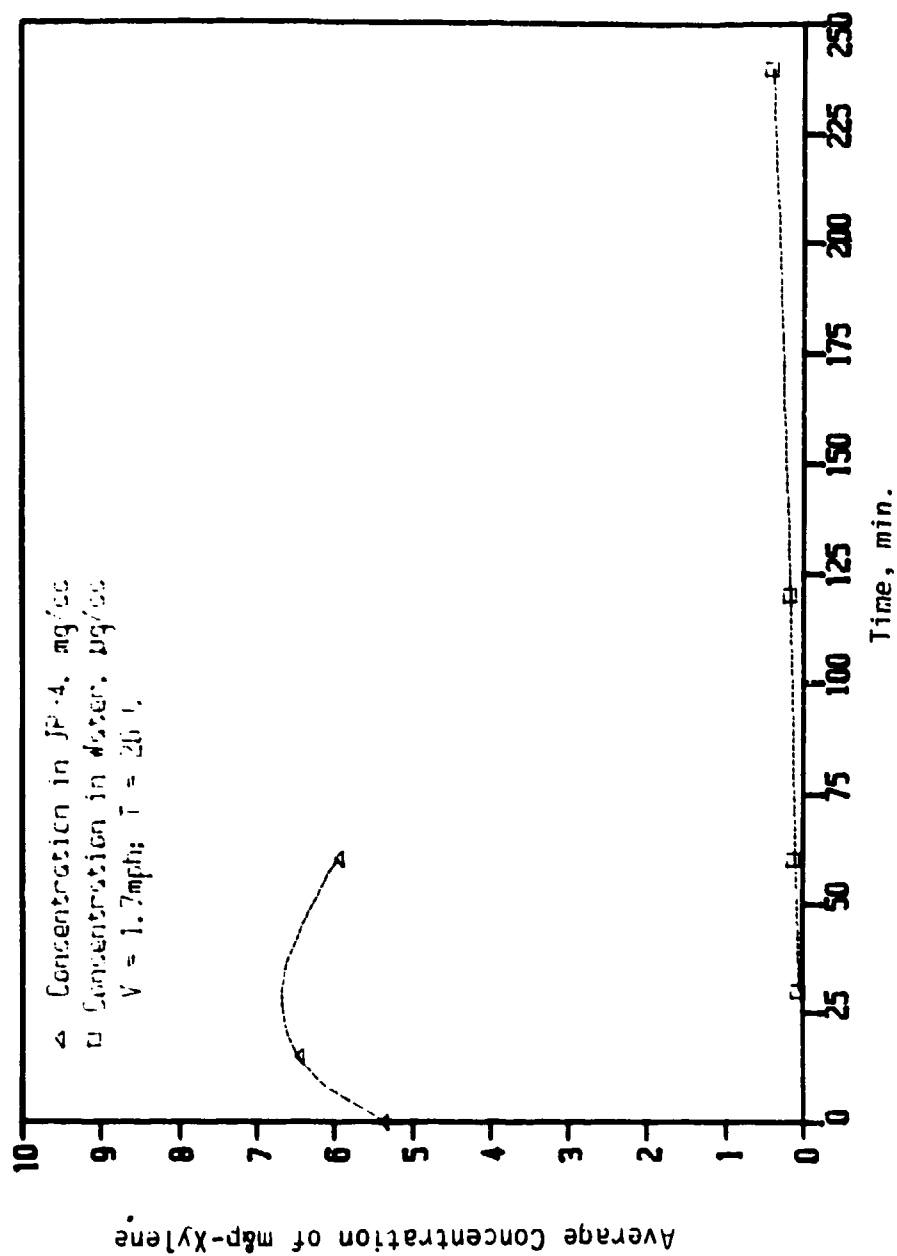


Figure 16. Meta- and Para-Xylene Dissolution from JP-4.

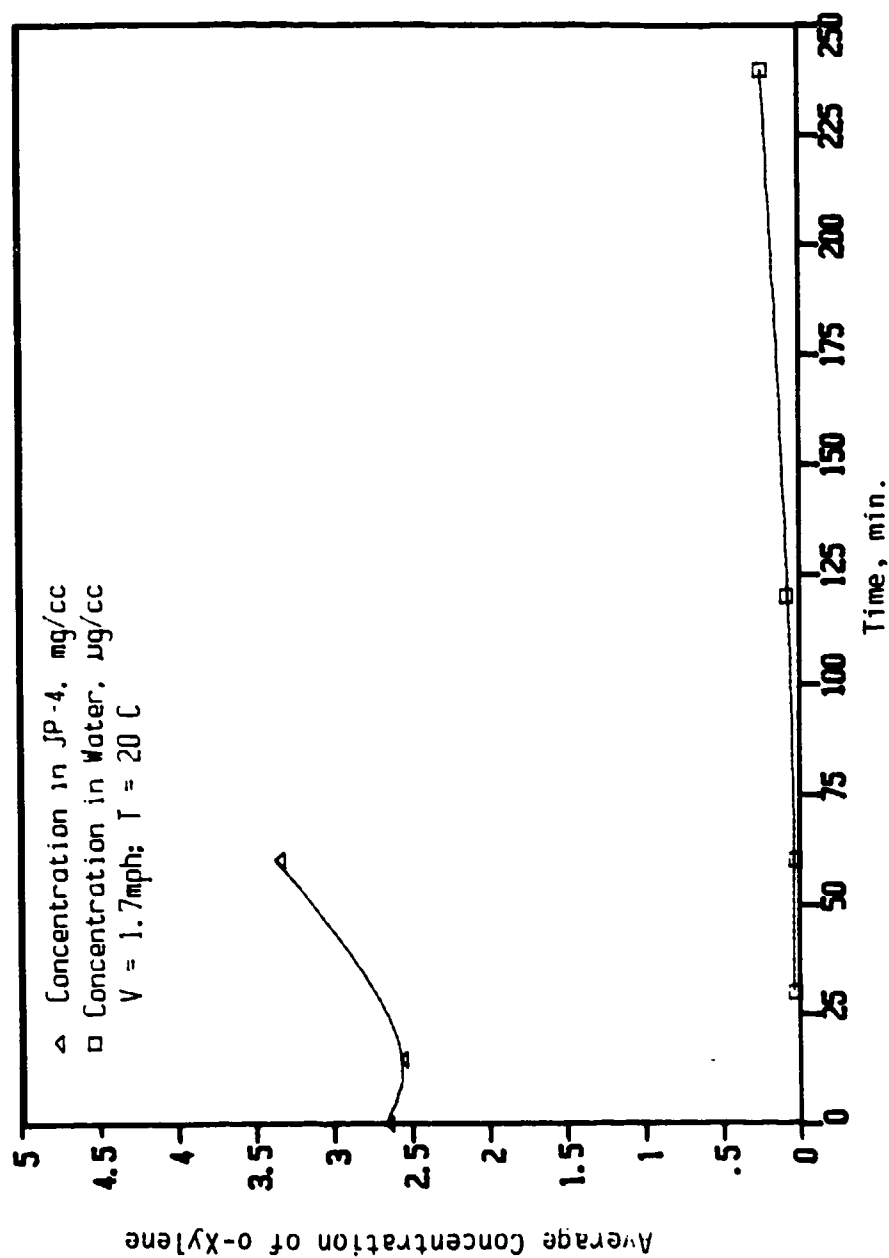


Figure 17. Ortho-Xylene Dissolution from JP-4.

TABLE 7. APPROACH TO EQUILIBRIUM SOLUBILITY

(V = 1.7 mi/hr; T = 20°C)

Component	Fraction of Equilibrium Solubility ^a at			
	t = 15 min	60 min	120 min	240 min
Benzene	0.13	0.09		
Toluene	0.04	0.08	(.13) ^b	(.22) ^b
Ethylbenzene		0.01	0.01	0.11
o-Xylene		0.02	0.04	(.12) ^b

^aEquilibrium solubility = solubility of pure liquid times mole fraction in fuel phase.

^bMole fraction in fuel phase estimated from data trend.

2. High Velocity Data

At an air velocity of 14.4 mi/hr, the evaporation rates are greatly enhanced (Figure 18). In this experiment the apparent peak benzene concentration was observed for the 30-minute series of samples. However, the scatter in the data at this velocity caused considerable difficulty in attempts to interpret the data. For this reason, Figure 19 summarizes those data sets appearing to be comprised of consistent data, while Table 8 summarizes the apparent degrees of equilibration for these data. In this case, the degrees of equilibration appear to be somewhat larger than for the low velocity experiment, presumably because of the increasing mixing induced by the higher air velocity.

In both of these experiments, the evaporation rates are of the order of mg/min, whereas the dissolution rates are of the order of $\mu\text{g/min}$. That is, the evaporation process is roughly three orders of magnitude faster than the dissolution process, as might be anticipated from the relative magnitudes of the air and water diffusion coefficients. Both of these processes are accelerated by high air velocities, but because of the relative magnitudes of the viscosities of the two fluids (air and water) it is to be expected that an

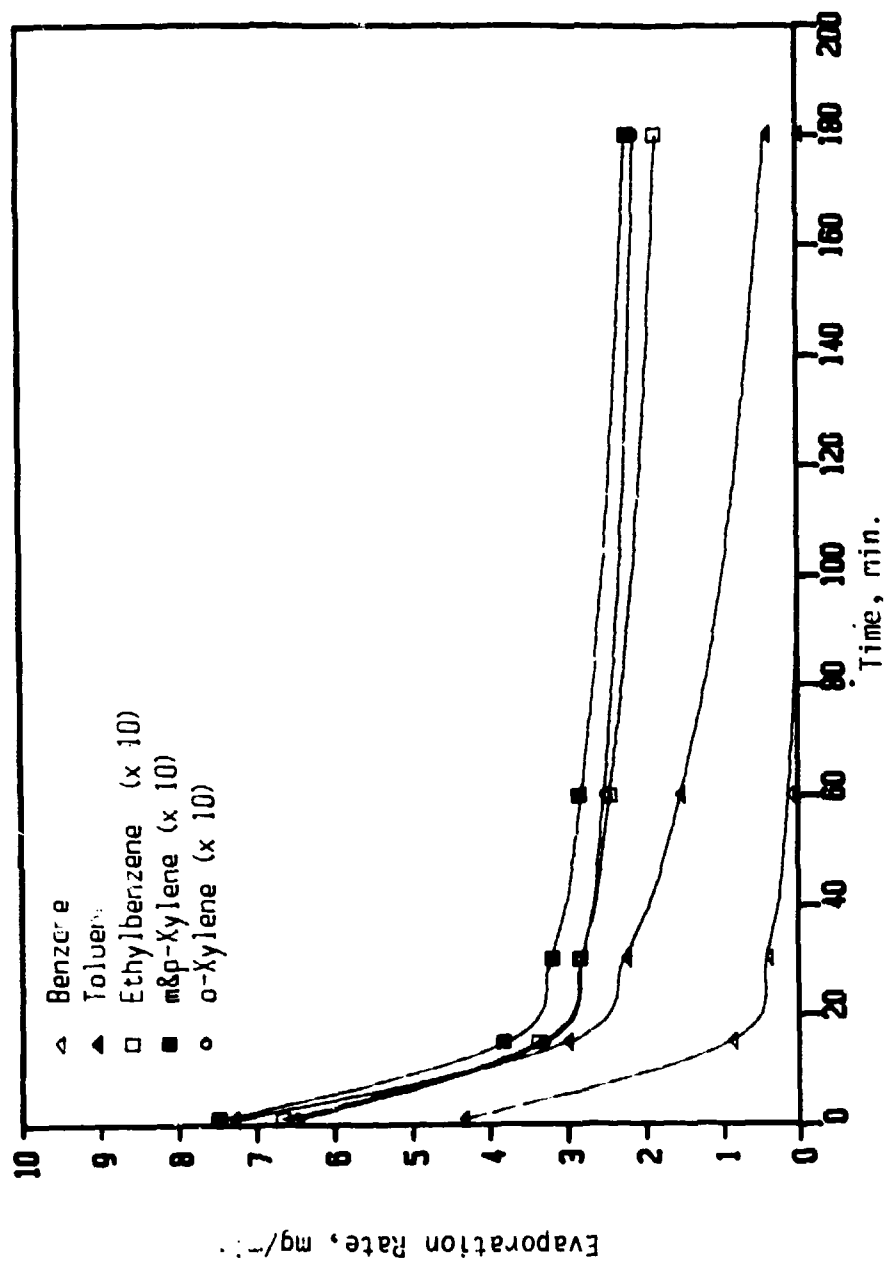


Figure 13. Evaporation Rates at 14.4 mi/hr.

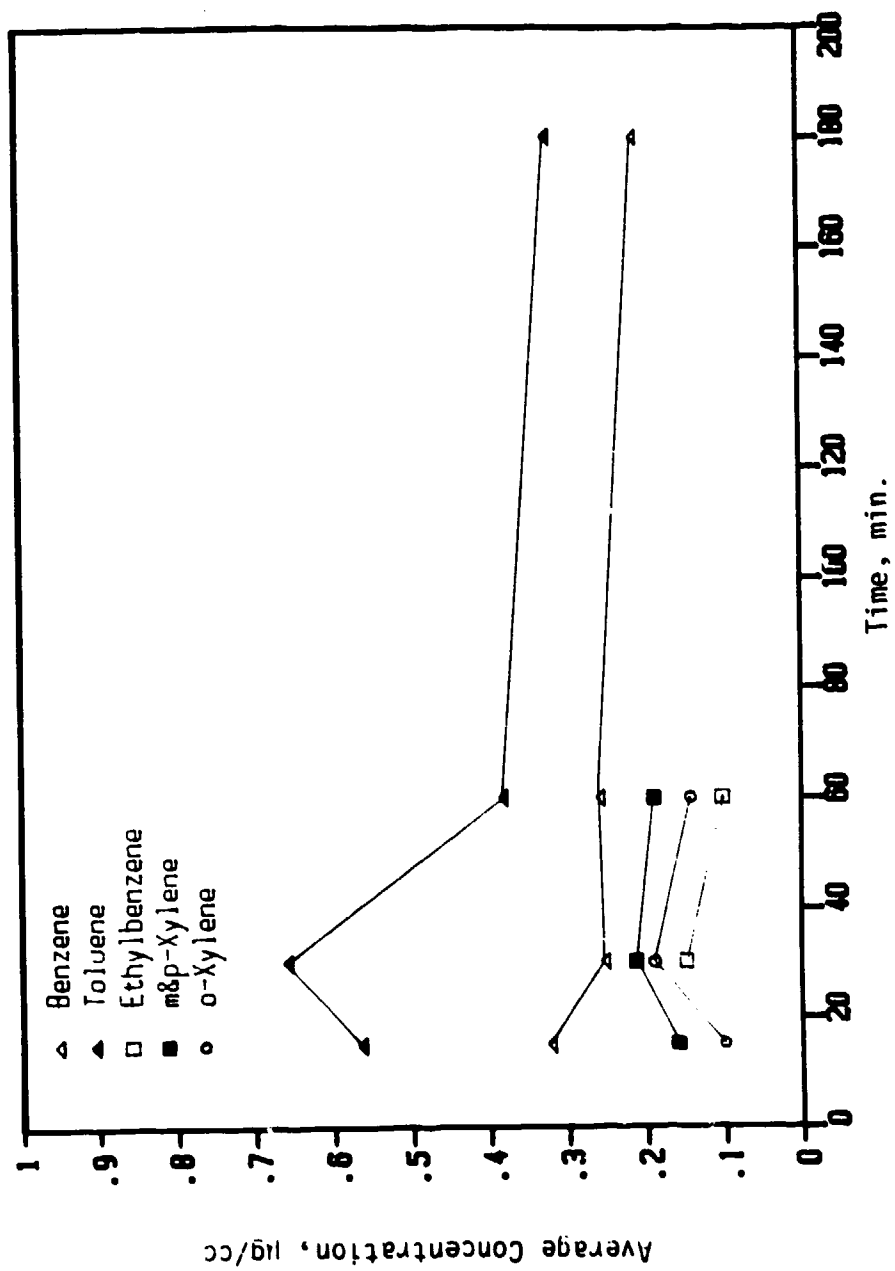


Figure 19. Dissolution of Aromatics at 14.4 mi/hr.

TABLE 8. APPROACH TO EQUILIBRIUM SOLUBILITY

(V = 14.4 mi/hr; T = 20°C)

Component	Fraction of Equilibrium Solubility ^a at		
	t = 15 min	30 min	60 min
Benzene	0.13		
Toluene	0.12	0.30	
Ethylbenzene		0.15	0.09
o-Xylene	0.05	0.13	

^aEquilibrium solubility = solubility of pure liquid times mole fraction in fuel phase.

increase in air velocity would increase mixing (turbulence) more readily in the air phase than in the water phase. Thus, we would expect increased air velocity to increase the ratio of the evaporation rate to the dissolution rate. This is the case -- the evaporation rates are increased by a factor of approximately five while the dissolution rates are enhanced by two to three, at most.

B. DISSOLUTION IN SEA WATER

Experiments to determine the rates of dissolution of JP-4 components in sea water were similar to those above conducted using distilled water. Water for these experiments was obtained from the Gulf of Mexico.

Results for experiments at high (15 mi/hr) and low (1.3 mi/hr) air velocities are shown in Figures 20 and 21, respectively. These curves are quite similar in shape to those reported for JP-4 dissolution in distilled water, but the absolute amounts of each of the aromatics dissolved at any given time are considerably lower in the sea water experiments. With benzene, for example, the peak concentration found at low velocities is only slightly greater than one-half that found with distilled water. Presumably, this is due to the effect of the high ionic strength of the sea water (ca. 0.725)

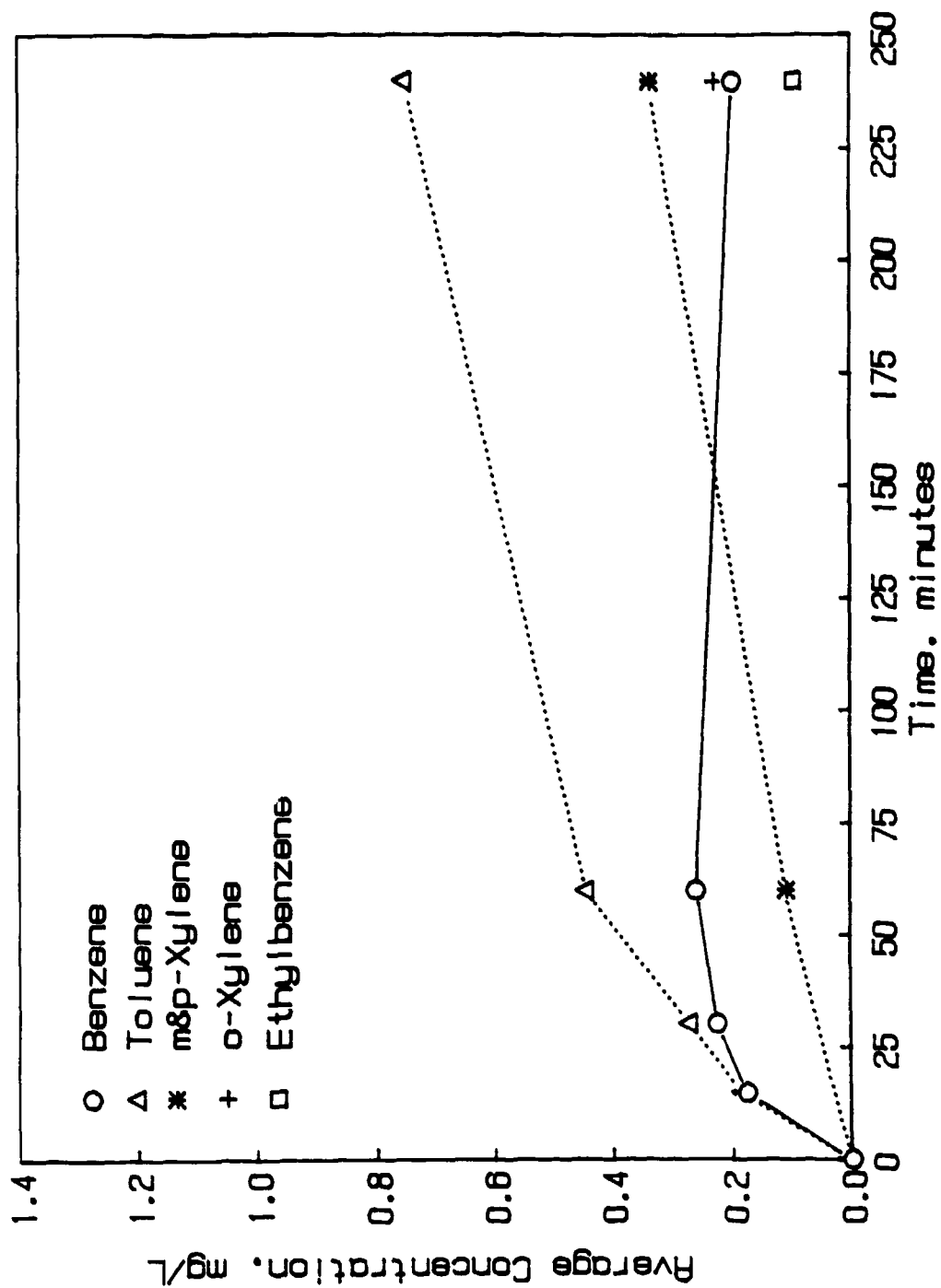


Figure 20. Dissolution of JP-4 in Sea Water at Low Windspeed ($V = 1.3$ mi/hr)

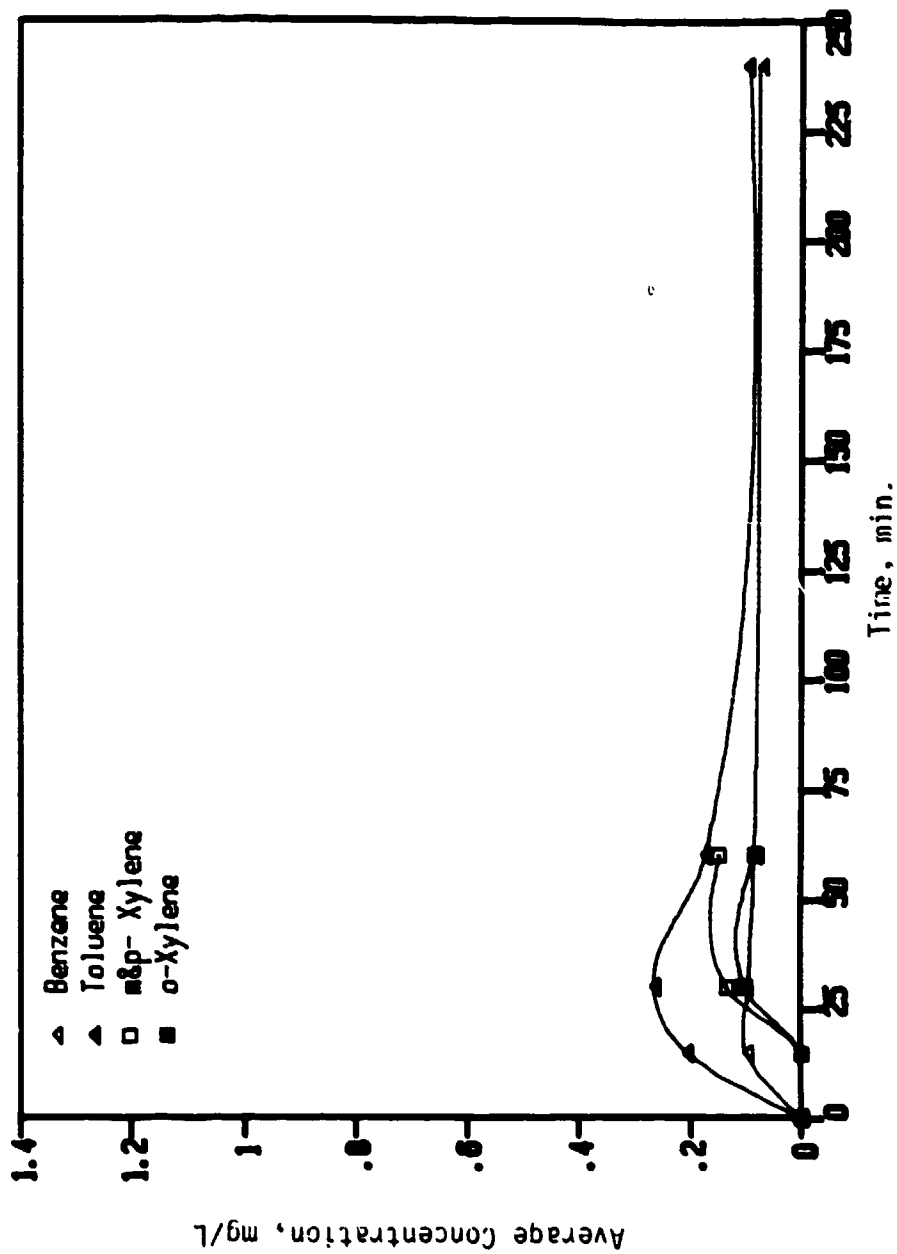


Figure 21. Dissolution of JP-4 in Sea Water at High Windspeed (14.9 mi/hr)

(Reference 17) on the solubility of the organics. As in the previous experiments, evaporation dominates the overall dispersion even more at the high velocity than at the low velocity.

C. INTERMEDIATE-SCALE DISSOLUTION EXPERIMENTS

Dissolution experiments using the intermediate-scale wind tunnel were similar to those with the bench-scale system, but the increased depth (2 feet) of the water pool permitted the taking of more water samples. Tables 9 and 10 show the results of measurements made at high and low windspeeds in the intermediate-scale system. Again, only the aromatics were found in detectable quantities in these experiments. The data show that mixing was effected even to near the bottom of the pool in these experiments, and that, partly as a consequence of this mixing, the concentrations are somewhat lower than those observed in the bench-scale system. However, the effect of eddy flow on nonuniformities in the concentrations also is evident. As with the bench-scale system, concentrations at some points are higher than at other depths closer to the fuel layer.

1. Mechanical Mixing

Mechanical mixing of the water pool was used to investigate the extreme condition of a well-mixed system. This was achieved by inserting a horizontal paddle-wheel mixer at the center of the pool. The water movement induced by this mixer was in the same direction as that created by airflow through the wind tunnel, but was significantly more effective in turning over the pool than the highest wind velocity available in the tunnel. Measurements of the water velocity at the top of the pool indicated that the mixer yielded surface mixing rates approximately 10 times those that could be achieved with an airflow rate of 1400 cfm. Because of the fact that the mixer was located at the center of the pool, mixing within the pool is expected to have been even more effective than a factor of ten.

Results of the experiment with mechanical mixing are given in Table 11. These results should be compared with those given in Table 9 where the air velocity was comparable, but no mixing was used. The concentrations

TABLE 9. DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM

(Q = 1440 cfm; T = 23.5°C)

		Concentrations (mg/L) at Various Times (min) and Depths (in.)				
	Time---->	5	15	50	100	240
Sampling Depth						
<u>Benzene</u>						
0.5		BS ^b	0.061	0.045	0.03	
1.5		0.05	0.032	NS ^c	NS	
3.5		0.048	0.057	NS	NS	
5.5		0.054	NS	NS	0.042	
9.5		NS	NS	0.044	NS	
13.5		NS	0.066	0.038	0.036	
17.5		0.025	0.058	NS	NS	
21.5		NS	NS	NS	0.046	
Mole Frac in JP-4	3.23e-3	1.11e-3	0.00	0.00	0.00	
Eq. Solubility ^d	5.75	1.98				
<u>Toluene</u>						
0.5		BS	0.135	0.088	0.065	
1.5		0.072	0.07	NS	NS	
3.5		0.053	0.09	NS	NS	
5.5		0.063	NS	NS	0.094	
9.5		NS	NS	0.046	NS	
13.5		NS	0.08	0.041	0.073	
17.5		0.061	0.072	NS	NS	
21.5		NS	NS	NS	0.136	
Mole Frac in JP-4	1.28e-2	1.22e-2	1.04e-2	6.82e-3	0.00	
Eq. Solubility	7.14	6.81	5.80	3.81	0.00	

^aEthylbenzene and xylenes found in only trace amounts at longer time periods. Detection limit = 0.02 mg/L.

^bBS = bad sample.

^cNS = no sample.

^dAssuming activity in fuel phase equals mole fraction.

TABLE 10. DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM

(Q = 1350 cfm; T = 23.6°C)

		Concentrations (mg/L) at Various Times (min) and Depths (in.) ^a			
Sampling Depth	Time---->	5	30	60	260
<u>Benzene</u>					
0.5		0.0402	0.0393	0.0083	0.0322
1.5		0.0231	0.0176	NS ^b	NS
3.5		0.0205	0.0237	NS	NS
5.5		0.0262	NS	0.0147	0.0208
9.5		NS	0.0235	0.0143	NS
13.5		NS	0.0257	0.0201	0.0206
17.5		0.027	0.00	NS	NS ^b
21.5		NS	NS	0.0188	BS ^b
Mole Frac in JP-4		2.24e-3	0.00	0.00	0.00
Eq. Solubility ^c		3.99	0.00		
<u>Toluene</u>					
0.5		0.0368	0.0372	0.0375	0.0708
1.5		0.0126	0.0177	NS	NS
3.5		0.0114	0.0231	NS	NS
5.5		0.0171	NS	0.0229	0.0322
9.5		NS	0.0212	0.0247	NS
13.5		NS	0.0253	0.0315	0.0441
17.5		0.0151	0.00	NS	NS
21.5		NS	NS	0.0249	BS
Mole Frac in JP-4		1.21e-2	1.38e-2	1.06e-2	0.00
Eq. Solubility		6.75	7.70	5.91	0.00

^aEthylbenzene and xylenes found in only trace amounts at longer time periods. Detection limit = 0.002 mg/L.

^bNS = no sample.

^cAssuming activity in fuel phase equals mole fraction.

TABLE 11. DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM

(Q = 1350 cfm; T = 22.6°C; Mechanical mixing)

Sampling Depth	Time----->	Concentrations (mg/L) at Various Times (min) and Depths (in.)			
		5	30	60	240
<u>Benzene</u>					
0.5		0.103	0.216	0.172	NS ^a
1.5		0.12	0.235	0.223	NS
3.5		0.107	0.082	0.273	0.11
5.5		0.08	0.159	0.227	NS
9.5		0.089	0.281	0.243	0.224
21.5		0.066	0.23	0.277	0.181
Mole Frac in JP-4		3.27e-3	0.00	0.00	0.00
Eq. Solubility ^b		5.82	0.00		
<u>Toluene</u>					
0.5		0.062	0.251	0.231	NS
1.5		0.074	0.26	0.339	NS
3.5		0.085	0.11	0.412	0.224
5.5		0.079	0.145	0.398	NS
9.5		0.058	0.236	0.374	0.406
21.5		0.056	0.221	0.481	0.353
Mole Frac in JP-4		1.2e-2	1.26e-2	1.07e-2	1.27e-2
Eq. Solubility		6.70	7.03	5.97	7.09
<u>Ethylbenzene</u>					
0.5		ND ^c	0.018	0.016	NS
1.5		ND	0.021	0.024	NS
3.5		ND	0.013	0.026	0.014
5.5		ND	ND	0.027	NS
9.5		ND	ND	0.026	0.061
21.5		ND	ND	0.037	0.058
Mole Frac in JP-4		7.3e-3	9.03e-3	8.33e-3	1.04e-2
Eq. Solubility		0.95	1.17	1.08	1.35

TABLE 11. DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM (CONCLUDED)

(Q = 1350 cfm; T = 22.6°C; Mechanical mixing)

Sampling Depth	Time---->	Concentrations (mg/L) at Various Times (min) and Depths (in.)			
		5	30	60	240
<u>m&p-Xylene</u>					
0.5		ND	0.014	0.057	NS
1.5		ND	0.063	0.079	NS
3.5		ND	0.03	0.08	0.026
5.5		ND	ND	0.089	NS
9.5		ND	ND	0.071	0.127
21.5		ND	ND	0.117	0.218
Mole Frac in JP-4		1.69e-2	2.09e-2	2.36e-2	2.37e-2
Eq. Solubility		2.84	3.51	3.96	3.98
<u>o-Xylene</u>					
0.5		ND	0.025	0.024	NS
1.5		ND	0.015	0.043	NS
3.5		ND	0.022	0.028	0.068
5.5		ND	ND	0.037	NS
9.5		ND	ND	0.047	0.127
21.5		ND	0.013	0.057	0.118
Mole Frac in JP-4		7.1e-3	13-2	1.19e-2	1.22e-2
Eq. Solubility		1.19	1.68	2.00	2.05

^aNS = no sample.^bAssuming activity in fuel phase equals mole fraction.^cND = not detected.

of the aromatics are three to five times those observed in the unmixed experiment, and even ethylbenzene and the xylenes were observed at the longer time periods. However, the maximum concentrations observed are less than 5 percent of the estimated equilibrium concentrations, indicating that the evaporation process is dominant in dispersion of the JP-4, even with strong mixing of the water pool.

D. FUEL DEPTH EFFECTS

In many cases of JP-4 spills on water, rapid spreading of the fuel can be expected to occur and any effects due to significant fuel depths will be precluded. However, it is conceivable that spills may occur on small confined bodies of water. Several experiments were, therefore, conducted to examine possible differences in dissolution with thick fuel layers. One of these runs was conducted in the intermediate-scale system with a fuel thickness of 0.85 inch. Additional experiments were conducted in the bench-scale system with fuel layers of 0.5, 1.0, and 2.0 inches. Results from these four runs are given in Tables 12 to 15. For those runs conducted in the bench-scale system, fewer water depths than normal could be examined because of the use of the available space by the fuel layer. The results generally reflect higher concentrations of the aromatics because of the longer contact times (longer times for evaporation of the fuel layer).

E. SPREADING RATES

Several experiments were conducted to determine the approximate spreading rates of JP-4. In these experiments, small quantities (0.3-0.75 cc) of JP-4 were gently released at the center of a 36-inch pool of water, and the rate of advance of the fuel layer was timed with a stopwatch. A least-squares analysis of the data indicated that the radius of the layer was proportional to the square root of time. Figure 22 shows a plot of the layer size versus $t^{1/2}$, which is consistent with the model of Fannelop and Waldman (Reference 4). In each case, the effect of evaporation of the JP-4 was quite evident -- while the initial spreading was quite uniform to a layer thickness estimated to be

TABLE 12. DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM

(Q = 1350 cfm; T = 22.3°C)

Fuel Depth = 0.85 in.

Sampling Depth	Time---->	Concentrations (mg/L) at Various Times (min) and Depths (in.)			
		10	30	60	240
<u>Benzene</u>					
0.5		0.848	0.806	0.785	0.71
1.5		0.0868	0.134	0.194	NSa
3.5		0.088	0.144	0.145	0.181
5.5		0.0922	0.157	NS	NS
9.5		0.1021	0.159	0.173	0.213
13.5		0.113	0.0867	0.138	NS
17.5		0.101	0.084	0.138	0.182
21.5		0.131	0.122	0.197	NS
Mole Frac in JP-4		3.27e-3	0.00	0.00	0.00
Eq. Solubility ^b		5.82	0.00		
<u>Toluene</u>					
0.5		0.907	0.894	1.25	1.4
1.5		0.0536	0.0789	0.149	NS
3.5		0.0458	0.0689	0.12	0.292
5.5		0.0392	0.0983	NS	NS
9.5		0.0466	0.103	0.154	0.247
13.5		0.0404	NS	0.1	NS
17.5		0.0283	0.0182	0.973	0.248
21.5		0.0662	0.0442	0.116	NS
Mole Frac in JP-4		1.2e-2	1.26e-2	1.07e-2	1.27e-2
Eq. Solubility		6.70	7.03	5.97	7.09
<u>Ethylbenzene</u>					
0.5		0.0642	0.0575	0.0916	0.0558
1.5		ND ^c	0.0117	ND	NS
3.5		ND	0.0117	ND	ND
5.5		ND	ND	NS	NS
9.5		ND	ND	ND	ND
13.5		ND	ND	ND	NS
17.5		ND	ND	ND	0.012
21.5		ND	ND	ND	NS
Mole Frac in JP-4		7.3e-3	9.03e-3	8.33e-3	1.04e-2
Eq. Solubility		0.95	1.17	1.08	1.35

TABLE 12. DISSOLUTION OF JP-4 IN INTERMEDIATE-SCALE SYSTEM (CONCLUDED)

(Q = 1350 cfm; T = 22.3°C)

Fuel Depth 0.85 in.

Sampling Depth	Time---->	Concentrations (mg/L) at Various Times (min) and Depths (in.)			
		10	30	60	240
<u>m&p-Xylene</u>					
0.5		0.0178	0.193	0.289	0.149
1.5		ND	0.0325	0.0191	NS
3.5		ND	ND	ND	0.0116
5.5		0.0115	0.031	NS	NS
9.5		ND	0.0134	0.0348	0.0304
13.5		ND	ND	ND	NS
17.5		ND	ND	ND	0.0359
21.5		ND	ND	0.175	NS
Mole Frac in JP-4		1.69e-2	2.09e-2	2.36e-2	2.37e-2
Eq. Solubility		2.84	3.51	3.96	3.98
<u>o-Xylene</u>					
0.5		0.0595	0.0834	0.147	0.0434
1.5		ND	ND	ND	NS
3.5		ND	ND	ND	0.028
5.5		0.0102	ND	NS	NS
9.5		ND	0.0099	0.01	0.0197
13.5		ND	ND	ND	NS
17.5		ND	ND	ND	0.0168
21.5		ND	ND	ND	NS
Mole Frac in JP-4		7.1e-3	1e-2	1.19e-2	1.22e-2
Eq. Solubility		1.19	1.68	2.00	2.05

^aNS = no sample.^b = Assuming activity in fuel phase equals mole fraction.^cND = not detected. Detection limit = 0.002 mg/L.

TABLE 13. DISSOLUTION OF JP-4 FROM THICK LAYER

(Q = 7.88 cfm; T = 22.4°C)

Fuel Depth = 0.5 in.

		Concentrations (mg/L) at Various Times (min) and Depths (in.)			
Time---->		10	30	60	240
Sampling Depth					
<u>Benzene</u>					
1		0.401	0.783	0.94	0.834
2		0.269	0.833	0.505	0.775
3		0.142	0.506	0.329	0.965
Mole Frac in JP-4		3.59e-3	3.23e-3	2.32e-3	0.00
Eq. Solubility ^a		6.39	5.75	4.13	
<u>Toluene</u>					
1		0.278	0.661	1.01	1.49
2		0.245	0.757	0.449	1.52
3		0.106	0.433	0.232	1.65
Mole Frac in JP-4		1.5e-2	1.51e-2	1.59e-2	1.23e-2
Eq. Solubility		8.37	8.43	8.87	6.86
<u>Ethylbenzene</u>					
1		ND ^b	0.0236	0.0493	0.0852
2		ND	0.032	0.016	0.105
3		ND	ND	ND	0.116
Mole Frac in JP-4		8.85e-3	8.83e-3	1.19e-2	9.42e-3
Eq. Solubility		1.15	1.15	1.55	1.22
<u>m&p-Xylene</u>					
1		ND	0.088	0.165	0.273
2		ND	0.108	0.064	0.357
3		ND	0.022	0.032	0.378
Mole Frac in JP-4		1.22e-2	9.66e-3	1.77e-2	2.01e-2
Eq. Solubility		2.05	1.62	2.97	3.38

TABLE 13. DISSOLUTION OF JP-4 FROM THICK LAYER (CONCLUDED)

(Q = 7.88 cfm; T = 22.4°C)

Fuel Depth = 0.5 in.

Sampling Depth	Time---->	Concentrations (mg/L) at Various Times (min) and Depths (in.)			
		10	30	60	240
		<u>o-Xylene</u>			
1		ND	0.0477	0.0721	0.149
2		ND	0.0494	0.024	0.179
3		ND	ND	ND	0.162
Mole Frac in JP-4		5.2e-3	3.32e-3	7.41e-3	1.08e-2
Eq. Solubility		0.87	0.56	1.24	1.81

^aAssuming activity in fuel phase equals mole fraction.^bND = not detected. Detection limit = 0.002 mg/L.

TABLE 14. DISSOLUTION OF JP-4 FROM THICK LAYER

(Q = 7.88 cfm; T = 19.8°C)

Fuel Depth = 1.0 in.

		Concentrations (mg/L) at Various Times (min) and Depths (in.)			
Time---->		5	30	60	240
Sampling Depth					
<u>Benzene</u>					
1		0.2	0.583	1.28	0.662
2		0.0605	0.0767	0.094	0.444
Mole Frac in JP-4		3.59e-3	3.23e-3	2.32e-3	0.00
Eq. Solubility ^a		6.39	5.75	4.13	
<u>Toluene</u>					
1		0.243	0.567	1.17	2.31
2		0.014	0.06	0.051	0.476
Mole Frac in JP-4		1.5e-2	1.51e-2	1.59e-2	1.23e-2
Eq. Solubility		8.37	8.43	8.87	6.86
<u>Ethylbenzene</u>					
1		ND ^b	ND	ND	0.149
2		ND	ND	ND	0.018
Mole Frac in JP-4		8.85e-3	8.83e-3	1.19e-2	9.42e-3
Eq. Solubility		1.15	1.15	1.55	1.22
<u>m&p-Xylene</u>					
1		ND	0.071	0.13	0.508
2		ND	ND	ND	0.04
Mole Frac in JP-4		1.22e-2	9.66e-3	1.77e-2	2.01e-2
Eq. Solubility		2.05	1.62	2.97	3.38
<u>o-Xylene</u>					
1		0.021	0.025	0.046	0.209
2		ND	ND	ND	0.022
Mole Frac in JP-4		5.2e-3	3.32e-3	7.41e-3	1.08e-2
Eq. Solubility		0.87	0.56	1.24	1.81

^aAssuming activity in fuel phase equals mole fraction.^bND = not detected. Detection limit = 0.002 mg/L.

TABLE 15. DISSOLUTION OF JP-4 FROM THICK LAYER

(Q = 7.88 cfm; T = 21.6°C)

Fuel Depth = 2.0 in.

Compound	Concentrations (mg/L) at 60 Minutes and 1 Inch Below Fuel
Benzene	0.443
Toluene	0.472
Ethylbenzene	0.044
m&p-Xylene	0.094
o-Xylene	0.093

about 1 micron, the layer immediately, thereafter, began to recede and disintegrate into many small patches on the surface of the water.

In principle, the spreading effect will affect both the evaporation and dissolution rates in direct proportion to the area of the JP-4. However, it should be noted that spreading will decrease the time available for mixing of the JP-4 to any appreciable depth in the water. Thus, much of the dissolved fuel will be more readily available for evaporation from the water phase than is observed in the current thick layer laboratory experiments.

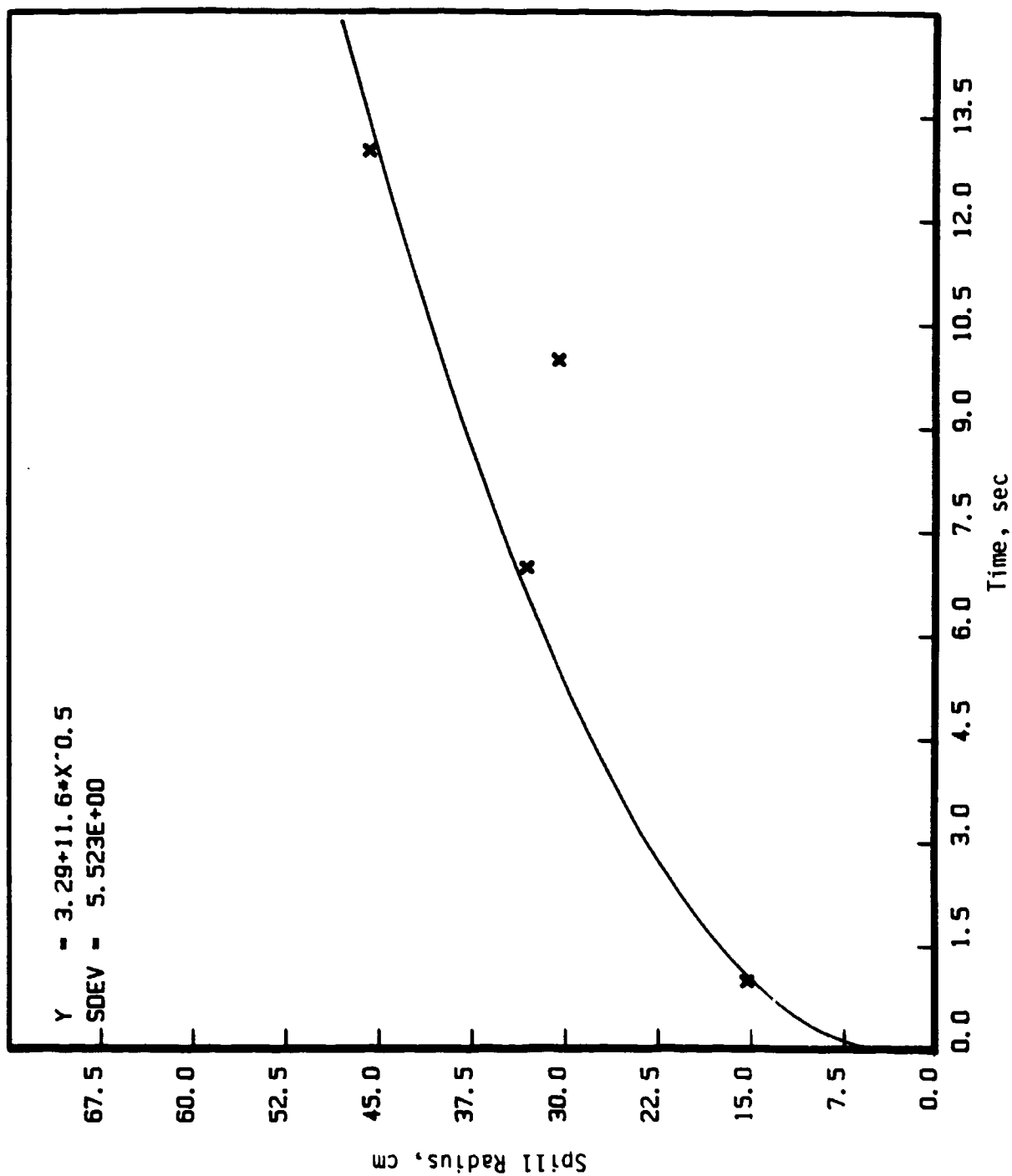


Figure 22. Spreading Rate of JP-4 on Water.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The results of this work have shown that the kinetics of evaporation of JP-4 can be adequately described using the following two correlations for the Sherwood number for each component:

For the aromatics -

$$Sh = 0.051Re^{.79}Sc^{1/3}$$

and for the alkanes -

$$Sh = 0.028Re^{.79}Sc^{1/3}$$

where Re is the Reynolds number and Sc is the Schmidt number. In applying these relationships, the vapor pressures, diffusivities, and mole fractions in the fuel phase must be known for each of the major components of JP-4. Properties of the minor constituents can be estimated from standard correlations. These correlations agree well with both theoretical and empirical correlations in the literature, with the exception that most previous work has been conducted with only pure components or simple mixtures. The dual correlations recommended here account for a previously undetected difference in evaporation rate between the aromatics and the alkanes when these are both present in a fuel mixture. The effect of temperature is included in this correlation, and no effect due to relative humidity was reliably detected. Liquid-phase resistance also was found not to be important because of the relatively good mixing induced by air movement of the fuel surface.

Limited study of the spreading rate of JP-4 on distilled water indicates that this process is very fast. Rapid spreading will enhance both evaporation and dissolution rates, but because of the more limited time available for deep mixing of the water layer, should make the evaporation process even more dominant in open systems. Because of the importance of this tentative conclusion, it is recommended that limited field experiments be conducted on different types of water bodies to determine actual spreading rates.

Only the aromatic components of JP-4 have sufficient solubility to permit detectable dissolution within the timeframe of the evaporation process. In the current work, maximum solubilities of approximately 20 percent of the equilibrium solubilities (corrected for fuel phase composition) were observed, and levels this high were seen only with poorly mixed systems. More generally, aqueous phase concentrations were of the order of a few percent of the equilibrium solubilities. The high ionic strength of sea water was found to reduce the apparent dissolution rates by about 50 percent. Correlation of the results is made difficult by the complex nature of hydrodynamic effects, e.g., eddy diffusion, which control the aqueous phase dispersion. Such effects are likely to be vastly different for different types of water bodies. Indeed, in open bodies of water, adsorption of the hydrocarbons on suspended organic particulate matter may be a more important mode of transport than pure dissolution.

SECTION VI

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APPENDIX A

GLOSSARY OF SYMBOLS AND SUMMARY OF PHYSICOCHEMICAL
PROPERTIES OF MAJOR JP-4 COMPONENTS

GLOSSARY OF TERMS AND SYMBOLS

<u>Symbols</u>	<u>Meaning</u>	<u>cgs units</u>
J	mass flow per unit area per unit time	$\text{g/cm}^2\text{-sec}$
D	diffusion coefficient	cm^2/sec
Co	equilibrium vapor concentration	g/cc
X	mole fraction in liquid phase	none
T	absolute temperature	$^{\circ}\text{K}$
ρ	gas density	g/cc
v	linear velocity	cm/sec
μ	gas viscosity	g/cm-sec
d	characteristic system dimension	cm
Q	volumetric flow rate	cc/sec

Dimensionless

Groups

Re	Reynolds number = $d\rho v/\mu$
Sc	Schmidt number = $\rho D/\mu$
Sh	Sherwood number = $Jd/DXCo$

TABLE A-1. SUMMARY OF PHYSICOCHEMICAL PROPERTIES

Hydrocarbon	Molecular Weight	Vapor Pressure ^a		Diffusion Coefficient ^b
		A	B	
Iso-butane	58.12	18.34	3001	0.0971
n-Butane	58.12	18.44	3158	0.0971
Iso-pentane	72.15	18.62	3535	0.086
n-Pentane	72.15	18.79	3685	0.086
2-Methylpentane	86.18	18.81	3985	0.0779
3-Methylpentane	86.18	18.82	4023	0.0779
n-Hexane	86.18	19.14	4188	0.0779
Methylcyclopentane	84.16	18.76	4111	0.0789
Benzene	78.12	20.12	4688	0.0962
Cyclohexane	84.16	19.52	4438	0.0853
2-Methylhexane	100.21	19.04	4424	0.0717
3-Methylhexane	100.21	19.1	4465	0.0717
1,2-Dimethylpentane	98.19	19.09	4534	0.0725
n-Heptane	100.21	19.18	4580	0.0717
Methylcyclohexane	98.19	18.65	4418	0.0725
Toluene	92.15	19.08	4696	0.086
2-Methylheptane	114.23	19.3	4858	0.0667
3-Methylheptane	114.23	19.39	4904	0.0667
n-Octane	114.23	19.64	5078	0.0667
Ethylbenzene	106.17	19.09	5022	0.0739
m&p-Xylene	106.17	19.3	5131	0.0739
o-Xylene	106.17	19.23	5171	0.0739
n-Nonane	128.26	19.22	5271	0.0627
n-Decane	142.29	19.1	5527	0.0593
n-Undecane	156.31	19.38	5924	0.0564
n-Dodecane	170.34	19.64	6298	0.0538
n-Tridecane	184.37	19.42	6455	0.0516
n-Tetradecane	198.4	20.43	7137	0.0496
Residual ^c	107	19.2	5200	0.0736

^a $\ln P(\text{torr}) = A - B/T$ (handbook values).

^b cm^2/sec at 25 C (Reference 10).

^cAverage of all unidentified volatile components.

APPENDIX B
MICROBALANCE EXPERIMENTS

TABLE B-1. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 1021)
T = 25°C Length = 2.87 cm Area = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , μg/min	Rate (μg/min) at t = min				
			0	80	190	255	340
Iso-butane	0.00036	1.50	1.11	0.39	0.00	0.00	0.00
n-Butane	0.0175	47.48	23.00	11.43	4.09	2.40	1.09
Iso-pentane	0.007	7.06	3.50	2.78	1.94	1.61	1.19
n-Pentane	0.0151	10.91	2.26	1.88	1.45	1.30	0.99
2-Methylpentane	0.021	6.12	3.55	3.31	3.05	3.05	2.83
3-Methylpentane	0.0155	4.01	2.76	2.58	2.41	2.40	2.31
n-Hexane	0.0385	7.89	5.48	5.23	5.05	5.03	4.85
Methylcyclopentane	0.025	4.49	3.06	2.95	2.89	2.83	2.78
Benzene	0.00326	0.37	0.77	0.72	0.69	0.70	0.68
Cyclohexane	0.0244	3.38	1.74	1.96	1.95	1.96	1.65
2-Methylhexane	0.0872	7.84	5.38	5.18	5.23	5.31	5.29
3-Methylhexane	0.0646	5.38	4.41	4.25	4.29	4.39	4.39
1,2-Dimethylpentane	0.0177	1.15	1.25	1.16	1.16	1.19	1.19
n-Heptane	0.0702	4.30	3.66	3.50	3.61	3.64	3.79
Methylcyclohexane	0.0398	2.45	2.13	2.06	2.08	2.18	2.15
Toluene	0.0172	0.71	0.91	0.86	0.89	0.98	0.96
2-Methylheptane	0.0522	1.50	1.40	1.35	0.95	1.45	1.34
3-Methylheptane	0.0546	1.48	1.68	1.63	1.60	1.74	1.69
n-Octane	0.0366	0.71	0.91	0.87	0.84	0.91	0.92
Ethylbenzene	0.00486	0.07	0.15	0.07	0.00	0.00	0.00
m-Xylene	0.00628	0.07	0.00	0.00	0.00	0.00	0.00
p-Xylene	0.00628	0.08	0.29	0.45	0.36	0.42	0.39
o-Xylene	0.00682	0.07	0.17	0.13	0.16	0.15	0.14
n-Nonane	0.0217	0.15	0.29	0.29	0.26	0.29	0.27
n-Decane	0.0174	0.05	0.27	0.19	0.16	0.18	0.18
n-Undecane	0.0145	0.01	0.29	0.15	0.13	0.13	0.12
n-Dodecane	0.0118	0.00	0.30	0.12	0.15	0.11	0.09
n-Tridecane	0.01	0.00	0.65	0.24	0.34	0.22	0.18
n-Tetradecane	0.00675	0.005	0.50	0.62	0.49	0.39	0.45
Residual	0.286	2.45	8.36	7.27	6.94	7.46	7.30
Total		121.69	80.22	63.57	53.15	52.41	49.18
Total by Balance			84.00	67.00	51.00	51.00	49.00

^aRo = Rate calculated at zero time

TABLE B-2. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 1022)
T = 30°C Length = 3.05 cm Area = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , μg/min	Rate (μg/min) at t = min				
			0	60	120	180	1050
Iso-butane	0.00036	1.68	1.43	0.63	0.23	0.00	0.00
n-Butane	0.0175	53.89	28.88	15.25	7.80	3.86	0.00
Iso-pentane	0.007	8.18	4.54	3.63	2.86	2.24	0.00
n-Pentane	0.0151	12.74	2.99	2.55	2.04	1.73	0.00
2-Methylpentane	0.021	7.27	4.89	4.54	4.30	3.90	1.19
3-Methylpentane	0.0155	4.78	3.78	3.58	3.41	3.14	1.05
n-Hexane	0.0385	9.48	7.68	7.28	6.96	6.55	2.68
Methylcyclopentane	0.025	5.37	4.21	4.09	3.85	3.68	1.68
Benzene	0.00326	0.46	1.01	0.99	0.93	0.89	0.33
Cyclohexane	0.0244	4.12	2.83	2.76	2.66	2.21	1.40
2-Methylhexane	0.0872	9.55	7.51	7.33	7.14	6.91	4.46
3-Methylhexane	0.0646	6.56	0.89	6.04	5.90	5.73	3.80
1,2-Dimethylpentane	0.0177	1.72	1.73	1.69	1.63	1.56	1.06
n-Heptane	0.0702	5.28	5.11	5.13	4.99	4.78	3.34
Methylcyclohexane	0.0398	2.98	0.43	2.93	2.86	2.78	1.99
Toluene	0.0172	0.88	1.36	1.34	1.26	1.29	0.85
2-Methylheptane	0.0522	1.88	1.95	1.89	1.78	1.23	1.43
3-Methylheptane	0.0546	1.85	2.36	2.29	2.19	2.15	1.70
n-Octane	0.0366	0.89	1.24	1.21	1.14	1.13	0.91
Ethylbenzene	0.00486	0.08	0.12	0.00	0.16	0.10	0.12
m-Xylene	0.00628	0.09	0.00	0.12	0.10	0.04	0.09
p-Xylene	0.00628	0.10	0.60	0.53	0.48	0.45	0.35
o-Xylene	0.00682	0.08	0.13	0.23	0.17	0.18	0.15
n-Nonane	0.0217	0.19	0.33	0.31	0.27	0.25	0.22
n-Decane	0.0174	0.06	0.17	0.15	0.12	0.12	0.10
n-Undecane	0.0145	0.02	0.12	0.11	0.00	0.07	0.08
n-Dodecane	0.0118	0.01	0.00	0.00	0.00	0.00	0.00
n-Tridecane	0.01	0.00	0.11	0.07	0.00	0.00	0.07
n-Tetradecane	0.00675	0.005	0.20	0.00	0.11	0.16	0.00
Residual	0.286	3.11	19.16	10.52	10.84	9.38	5.33
Total		143.32	105.74	87.13	76.17	66.50	34.36
Total by Balance			102.70	85.00	80.00	66.70	36.00

^aRo = Rate calculated at zero time

TABLE B-3. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 1023)
T = 35°C Length = 3.11 cm A = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , μ/g min	Rate (μg/min) at t = min						
			0	60	120	240	310	400	1390
Iso-butane	0.00036	1.96	1.86	0.67	0.23	0.00	0.00	0.00	0.00
n-Butane	0.0175	63.36	35.88	17.59	7.95	2.63	0.65	0.21	0.00
Iso-pentane	0.007	9.81	5.59	4.41	3.16	1.76	1.20	0.84	0.00
n-Pentane	0.0151	15.41	3.65	2.99	2.40	1.53	1.14	1.00	0.00
2-Methylpentane	0.021	8.93	6.04	5.64	5.15	4.35	3.93	3.58	0.69
3-Methylpentane	0.0155	5.89	4.66	4.45	4.13	3.55	3.28	2.90	0.71
n-Hexane	0.0385	11.78	9.50	9.19	8.51	7.53	7.05	6.48	2.01
Methylcyclopentane	0.025	6.65	5.18	5.08	4.73	4.34	4.08	3.78	1.35
Benzene	0.00326	0.59	1.23	1.19	1.13	1.00	0.92	0.85	0.27
Cyclohexane	0.0244	5.19	3.01	3.01	2.86	3.06	2.91	2.48	1.31
2-Methylhexane	0.0872	12.01	9.26	9.29	9.01	8.65	8.30	8.09	4.66
3-Methylhexane	0.0646	8.27	7.60	7.66	7.41	7.21	6.90	6.71	4.08
1,2-Dimethylpentane	0.0177	1.78	2.13	2.08	2.01	2.03	1.88	1.60	1.14
n-Heptane	0.0702	6.70	6.35	6.30	6.24	5.94	6.30	6.03	3.85
Methylcyclohexane	0.0398	3.75	3.66	3.69	3.59	3.50	3.41	3.39	2.24
Toluene	0.0172	1.12	1.63	1.66	1.59	1.54	1.55	1.48	1.04
2-Methylheptane	0.0522	2.42	2.33	2.34	1.63	1.58	2.29	2.23	1.81
3-Methylheptane	0.0546	2.38	2.83	2.78	2.73	2.75	2.73	2.66	2.18
n-Octane	0.0366	1.17	1.44	1.59	1.43	1.44	1.41	1.41	1.17
Ethylbenzene	0.00486	0.11	0.23	0.00	0.22	0.00	0.22	0.22	0.00
m-Xylene	0.00628	0.12	0.13	0.13	0.13	0.13	0.12	0.10	0.18
p-Xylene	0.00628	0.13	0.58	0.64	0.62	0.55	0.59	0.62	0.44
o-Xylene	0.00682	0.11	0.27	0.25	0.28	0.25	0.23	0.22	0.17
n-Nonane	0.0217	0.26	0.31	0.29	0.36	0.31	0.31	0.31	0.28
n-Decane	0.0174	0.08	0.16	0.14	0.15	0.16	0.14	0.13	0.12
n-Undecane	0.0145	0.03	0.10	0.08	0.00	0.07	0.00	0.07	0.05
n-Dodecane	0.0118	0.01	0.00	0.00	0.00	0.05	0.05	0.00	0.04
n-Tridecane	0.01	0.00	0.09	0.00	0.00	0.00	0.05	0.00	0.05
n-Tetradecane	0.00675	0.005	0.28	0.22	0.23	0.17	0.24	0.10	0.14
Residual	0.286	4.08	13.92	12.59	13.14	12.24	12.20	11.69	6.86
Total		174.11	129.87	105.92	91.00	78.29	74.05	69.36	36.84
Total by Balance			125.00	105.00	91.30	72.00	70.70	64.30	39.00

^aRo = Rate calculated at zero time

TABLE B-4. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 1027)
T = 25°C Length = 3.17 cm Area = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , ug/min	Rate (ug/min) at t = min				
			0	60	195	240	360
Iso-butane	0.00036	1.36	1.04	0.46	0.00	0.00	0.00
n-Butane	0.0175	42.99	21.50	12.15	3.69	2.71	1.35
Iso-pentane	0.007	6.39	3.40	2.73	1.64	1.49	1.02
n-Pentane	0.0151	9.87	2.31	1.88	1.22	1.15	0.87
2-Methylpentane	0.021	5.54	3.51	3.29	2.85	2.70	2.49
3-Methylpentane	0.0155	3.63	2.78	2.60	2.25	2.20	1.98
n-Hexane	0.0385	7.15	5.58	5.26	4.71	4.63	4.26
Methylcyclopentane	0.025	4.06	3.08	2.91	2.66	2.59	2.41
Benzene	0.00326	0.34	0.75	0.74	0.62	0.60	0.57
Cyclohexane	0.0244	3.06	2.04	1.69	1.54	1.56	1.73
2-Methylhexane	0.0672	7.10	5.31	5.16	4.90	4.88	4.70
3-Methylhexane	0.0646	4.87	4.35	4.21	4.04	4.01	3.89
1,2-Dimethylpentane	0.0177	1.04	1.25	1.15	1.13	1.11	1.06
n-Heptane	0.0702	3.90	3.59	3.44	3.39	3.28	3.26
Methylcyclohexane	0.0398	2.22	2.06	2.04	1.98	1.95	1.90
Toluene	0.0172	0.65	0.85	0.85	0.85	0.81	0.77
2-Methylheptane	0.0522	1.36	1.20	1.22	1.19	1.19	0.80
3-Methylheptane	0.0546	1.34	1.44	1.46	1.44	1.44	1.41
n-Octane	0.0366	0.64	0.75	0.75	0.71	0.71	0.72
Ethylbenzene	0.00486	0.06	0.00	0.00	0.00	0.00	1.10
m-Xylene	0.00628	0.07	0.02	0.07	0.10	0.06	0.07
p-Xylene	0.00628	0.07	0.27	0.31	0.33	0.24	0.25
o-Xylene	0.00682	0.06	0.09	0.12	0.09	0.09	0.10
n-Nonane	0.0217	0.14	0.14	0.13	0.13	0.14	0.16
n-Decane	0.0174	0.04	0.06	0.06	0.04	0.01	0.10
n-Undecane	0.0145	0.01	0.00	0.03	0.00	0.02	0.00
n-Dodecane	0.0118	0.00	0.00	0.03	0.00	0.00	0.00
n-Tridecane	0.01	0.00	0.24	0.19	0.04	0.07	0.01
n-Tetradecane	0.00675	0.005	0.25	0.31	0.17	0.01	0.05
Residual	0.286	2.22	7.03	6.58	6.83	6.32	4.80
Total		110.17	74.88	61.80	48.54	45.96	41.91
Total by Balance			80.00	67.00	45.00	46.00	47.00

^aRo = Rate calculated at zero time

TABLE B-5. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 11586)
T = 10°C Length = 3.05 cm Area = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , ug/min	Rate (ug/min) at t = min				
			0	60	120	240	420
Iso-butane	0.00036	0.79	0.42	0.329	0.189		
n-Butane	0.0175	24.51	9.65	8.45	6.31	3.54	1.68
Iso-pentane	0.007	3.41	1.35	1.65	1.42	1.11	0.814
n-Pentane	0.0151	5.13	0.819	0.993	0.996	0.784	0.571
2-Methylpentane	0.021	2.73	1.26	1.64	1.63	1.47	1.38
3-Methylpentane	0.0155	1.78	0.955	1.29	1.27	1.15	1.04
n-Hexane	0.0385	3.39	1.88	2.52	2.41	2.29	2.06
Methylcyclopentane	0.025	1.96	1.02	1.42	1.35	1.23	1.18
Benzene	0.00326	0.15	0.212	0.286	0.248	0.257	0.239
Cyclohexane	0.0244	1.39	0.679	0.893	0.902	0.736	0.778
2-Methylhexane	0.0872	3.23	1.63	2.25	2.19	2.12	2.04
3-Methylhexane	0.0646	2.20	1.33	1.8	1.79	1.69	1.67
1,2-Dimethylpentane	0.0177	0.46	0.362	0.171	0.483	0.456	0.445
n-Heptane	0.0702	1.72	1.08	1.34	1.37	1.27	1.32
Methylcyclohexane	0.0398	1.01	0.607	0.869	0.832	0.817	0.781
Toluene	0.0172	0.28	0.201	0.266	0.302	0.27	0.273
2-Methylheptane	0.0522	0.57	0.12	0.393	0.427	0.417	0.427
3-Methylheptane	0.0546	0.56	0.433	0.5	0.52	0.494	0.506
n-Octane	0.0366	0.26	0.164	0.243	0.207	0.243	0.223
Ethylbenzene	0.00486	0.02	0.003		0.002		
m-Xylene	0.00628	0.03	0.007		0.011	0.002	0.007
p-Xylene	0.00628	0.03	0.007		0.011	0.002	0.007
o-Xylene	0.00682	0.02	0.003	0.003	0.004	0.006	
n-Nonane	0.0217	0.05	0.018	0.002	0.009		
n-Decane	0.0174	0.02	0.006	0.004	0.011		0.014
n-Undecane	0.0145	0.00		0.004	0.005		0.007
n-Dodecane	0.0118	0.00	0.003	0.001	0.009	0.006	0.006
n-Tridecane	0.01	0.00	0.01	0.015	0.015		0.031
n-Tetradecane	0.00675	0.005	0.006	0.002	0.007	0.007	0.012
Residual	0.28589	0.88	23.465	12.866	12.57	10.533	9.289
Total		56.59	47.7	40.5	37.5	30.9	26.8
Total by Balance			41	33	33	27	27

^aRo = Rate calculated at zero time

TABLE B-6. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 11686)
T = -20°C Length = 3.17 cm Area = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , ug/min	Rate (ug/min) at t = min				
			0	60	120	240	300
Iso-butane	0.00036	0.20	0.142	0.012	0.014		
n-Butane	0.0175	5.77	4.3	3.66	3.6	2.88	2.79
Iso-pentane	0.007	0.69	0.523	0.452	0.496	0.49	0.371
n-Pentane	0.0151	0.97	0.224	0.268	0.247	0.258	0.2
2-Methylpentane	0.021	0.45	0.295	0.335	0.312	0.285	0.306
3-Methylpentane	0.0155	0.29	0.279	0.248	0.26	0.258	0.271
n-Hexane	0.0385	0.52	0.504	0.405	0.393	0.481	0.463
Methylcyclopentane	0.025	0.31	0.313	0.28	0.245	0.281	0.277
Benzene	0.00326	0.02		0.005	0.001	0.006	0
Cyclohexane	0.0244	0.19	0.247	0.009	0.147	0.141	0.113
2-Methylhexane	0.0872	0.45	0.364	0.329	0.327	0.403	0.329
3-Methylhexane	0.0646	0.30	0.292	0.27	0.253	0.284	0.275
1,2-Dimethylpentane	0.0177	0.06	0.015	0.007	0.007	0.103	0
n-Heptane	0.0702	0.22	0.179	0.165	0.158	0.001	0.185
Methylcyclohexane	0.0398	0.14	0.19	0.128	0.128	0.21	0.16
Toluene	0.0172	0.03	0.018	0.003	0.003	0.0005	0.001
2-Methylheptane	0.0522	0.07	0.064	0.006	0.003		
3-Methylheptane	0.0546	0.06	0.063		0.004	0.003	
n-Octane	0.0366	0.03			0.003		
Ethylbenzene	0.00486	0.006			0.001		
m-Xylene	0.00628	0.008					
p-Xylene	0.00628	0.008					
o-Xylene	0.00682	0.002					
n-Nonane	0.0217	0.01	0.003		0.002	0.001	0.0004
n-Decane	0.0174	0.00	0.225		0.001	0.0003	0.002
n-Undecane	0.0145	0.00	0.001		0.001	0.0009	
n-Dodecane	0.0118	0.00			0.001	0.0004	0.001
n-Tridecane	0.01	0.00	0.003		0.001		0.001
n-Tetradecane	0.00675	0.005	0.001	0.002	0.001	0.0003	0.001
Residual	0.286	0.09	1.155	1.226	1.2091	0.9126	0.4436
Total		10.88	9.4	7.81	7.81	7	6.19
Total by Balance			13	8.7	8	8.3	7.3

^aRo = Rate calculated at zero time

TABLE B-7. JP-4 EVAPORATION - BALANCE RESULTS
(Run Number 11786)

T = -5°C Length = 3.05 cm Area = 0.17 cm²

Hydrocarbon	Liquid Mole Frac	Ro ^a , ug/min	Rate (ug/min) at t = min				
			0	60	120	240	360
Iso-butane	0.00036	0.42		0.196	0.204	0.136	
n-Butane	0.0175	12.60	8.32	6.34	5.74	4.17	2.95
Iso-pentane	0.007	1.63	1.14	1.07	0.953	1.08	0.78
n-Pentane	0.0151	2.37	0.767	0.713	0.577	0.543	0.46
2-Methylpentane	0.021	1.19	0.998	0.859	0.796	0.825	0.77
3-Methylpentane	0.0155	0.77	0.757	0.649	0.682	0.643	0.606
n-Hexane	0.0385	1.42	1.38	1.13	1.24	1.21	1.17
Methylcyclopentane	0.025	0.83	0.753	0.645	0.717	0.703	0.655
Benzene	0.00326	0.06	0.165	0.121	0.143	0.116	0.01
Cyclohexane	0.0244	0.55	0.494	0.404	0.296	0.485	0.403
2-Methylhexane	0.0872	1.29	1.13	0.939	1.03	1.02	1.02
3-Methylhexane	0.0646	0.87	0.953	0.751	0.845	0.829	0.769
1,2-Dimethylpentane	0.0177	0.18	0.28	0.232	0.228	0.216	0.229
n-Heptane	0.0702	0.67	0.815	0.513	0.601	0.579	0.569
Methylcyclohexane	0.0398	0.40	0.428	0.368	0.385	0.384	0.362
Toluene	0.0172	0.11	0.153	0.003	0.004	0.0003	0.003
2-Methylheptane	0.0522	0.21	0	0.004	0.009	0.0002	0.007
3-Methylheptane	0.0546	0.20	0.237	0.244	0.152	0.146	0.25
n-Octane	0.0366	0.09	0.009	0.008	0.009	0.009	0.001
Ethylbenzene	0.00486	0.01	0.001	0.001		0.003	0.0004
m-Xylene	0.00628	0.01					
p-Xylene	0.00628	0.01					
o-Xylene	0.00682	0.01					
n-Nonane	0.0217	0.02					
n-Decane	0.0174	0.01			0.001		
n-Undecane	0.0145	0.00					
n-Dodecane	0.0118	0.00	0.001			0.001	
n-Tridecane	0.01	0.00					
n-Tetradecane	0.00675	0.005	0.001				
Residual	0.286	0.30	1.82	1.41	2.09	2.80	1.99
Total		26.24	20.6	16.6	16.7	15.9	13
Total by Balance			18.7	17.3	16.7	13.3	13.3

^aRo = Rate calculated at zero time

APPENDIX C

JP-4 VELOCITY EFFECT EXPERIMENTS
IN BENCH-SCALE WIND TUNNEL

TABLE C-1. EFFECT OF AIR VELOCITY ON JP-4 EVAPORATION^a

Hydrocarbon	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal
Iso-butane	0.00	1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Butane	2.097e-2	32.3	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iso-pentane	0.00	5.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Pentane	0.00	3.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-Methylpentane	2.485e-2	6.25	0.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-Methylpentane	2.008e-2	4.83	0.69	0.00	5.63	0.00	0.00	12.8	0.00	0.00	3.95	0.00
n-Hexane	5.087e-2	9.76	0.70	0.00	5.42	0.00	0.00	11.6	0.00	0.00	4.29	0.00
Methylcyclopentane	3.350e-2	5.29	0.66	1.467e-2	16	1.05	2.050e-2	31.4	1.02	0.00	15.2	0.00
Benzene	0.00	0.963	0.30	1.494e-2	10.3	0.76	1.850e-2	19.4	0.81	0.00	11.4	0.00
Cyclohexane	3.093e-2	3.53	0.65	0.00	1.57	0.00	0.00	2.65	0.00	0.00	0.00	0.00
2-Methylhexane	1.022e-1	9.57	0.78	1.735e-2	9.53	0.82	2.086e-2	16.7	0.83	1.103e-2	12.5	0.74
3-Methylhexane	9.210e-2	7.78	0.76	7.665e-2	34.5	0.97	8.500e-2	57.2	1.01	5.695e-2	53.3	0.89
1,2-Dimethylpentane	2.482e-2	2.12	1.00	7.203e-2	29.7	0.97	7.874e-2	46.3	1.00	5.492e-2	47.1	0.88
n-Heptane	9.425e-2	6.09	0.80	2.037e-2	7.78	1.16	2.051e-2	12.7	1.31	1.432e-2	12	1.12
Methylcyclohexane	5.742e-2	3.6	0.76	0.515e-2	28.5	1.07	8.950e-2	42.1	1.05	7.259e-2	46.2	0.90
Toluene	1.526e-2	1.35	0.95	5.151e-2	15.5	0.96	5.341e-2	24.5	1.01	4.180e-2	27	0.90
2-Methylheptane	6.293e-2	2.14	0.89	1.665e-2	6.22	1.04	1.608e-2	9.36	1.14	1.778e-2	10.3	0.72
3-Methylheptane	7.448e-2	2.56	0.96	6.924e-2	11.2	1.10	7.252e-2	16.6	1.09	6.622e-2	21.7	0.99
n-Octane	4.633e-2	1.16	1.01	8.566e-2	13.8	1.17	8.571e-2	20.7	1.23	8.297e-2	26.9	1.05
Ethylbenzene	9.643e-3	0.00	0.00	5.997e-2	7.22	1.23	5.740e-2	10.2	1.29	5.796e-2	13.9	1.10
m,p-Xylene	1.250e-2	0.339	1.00	7.785e-3	0.758	0.79	8.613e-3	0.00	0.00	9.982e-3	0.00	0.00
o-Xylene	1.284e-2	0.137	0.49	1.978e-2	2.34	1.13	1.665e-2	3.03	1.23	2.533e-2	3.73	0.63
n-Nonane	1.945e-2	0.198	1.11	6.953e-3	0.743	1.25	1.080e-2	1.43	1.10	8.963e-3	0.00	0.00
n-Decane	1.191e-2	0.20	0.00	2.965e-2	1.5	1.41	2.751e-2	1.92	1.39	3.320e-2	0.00	0.00
n-Undecane	9.272e-3	0.00	0.00	2.074e-2	0.00	0.00	1.829e-2	0.00	0.00	2.814e-2	0.00	0.00
n-Dodecane	6.730e-3	0.00	0.00	1.796e-2	0.00	0.00	1.531e-2	0.00	0.00	2.761e-2	0.00	0.00
n-Tridecane	4.615e-3	0.00	0.00	9.554e-3	0.00	0.00	1.038e-2	0.00	0.00	2.299e-2	0.00	0.00
n-Tetradecane	0.00	0.00	0.00	5.792e-3	0.00	0.00	6.443e-3	0.00	0.00	1.820e-2	0.00	0.00
Residual	1.621e-1	10.27	0.85	0.00	39.271	0.46	2.673e-1	57.32	0.53	1.082e-2	0.00	0.00
Total		121.10	0.68	2.975e-1	247.48	0.88		400.31	0.96	3.387e-1	53.719	0.75

^aSymbol Definitions -

Q = volumetric air flow rate

T_{air} = average air temperatureT_{liq} = average water temperature

N(liq) = mole function of fuel component

R = observed evaporation rate

R_{cal} = calculated evaporation rate

APPENDIX D

**TEMPERATURE AND HUMIDITY EFFECT
EXPERIMENTS IN BENCH-SCALE WIND TUNNEL**

TABLE D-1. JP-4 EVAPORATION AT ELEVATED TEMPERATURES^a

Hydrocarbon	Q, cfm N(liq)	T _{air} , C 33 R, mg/min	T _{liq} , C 25.7 R/Rcal	Q, cfm N(liq)	T _{air} , C 34.2 R, mg/min	T _{liq} , C 26.1 R/Rcal	Q, cfm N(liq)	T _{air} , C 35.4 R, mg/min	T _{liq} , C 26.6 R/Rcal
Iso-butane	0.00	1.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Butane	8.91e-3	51.2	0.29	0.00	0.00	0.00	0.00	0.00	0.00
Iso-pentane	4.84e-3	15.2	0.41	0.00	0.00	0.00	0.00	2.42	0.00
n-Pentane	3.89e-3	11.2	0.52	0.00	0.00	0.00	0.00	2.93	0.00
2-Methylpentane	1.84e-2	22.9	0.54	4.9e-4	3	1.53	4.8e-3	25.5	0.82
3-Methylpentane	1.61e-2	18.1	0.55	1.27e-3	3.66	0.81	4.71e-3	22.5	0.83
n-Hexane	4.4e-2	37.7	0.53	4.82e-3	13.1	0.96	1.44e-2	57.5	0.88
Methylcyclopentane	2.74e-2	20.7	0.53	5.72e-3	10.5	0.75	1.14e-2	35	0.77
Benzene	3.71e-3	3.81	1.21	0.00	1.04	0.00	9.84e-4	5.5	2.35
Cyclohexane	2.55e-2	14.1	0.52	8.6e-3	11.7	0.73	1.32e-2	28.7	0.73
2-Methylhexane	8.68e-2	39.5	0.62	4.37e-2	52.1	0.93	5.01e-2	97.1	0.94
3-Methylhexane	7.76e-2	32.5	0.61	4.19e-2	46.6	0.94	4.6e-2	82.1	0.93
1,2-Dimethylpentane	2.13e-2	8.59	0.76	1.15e-2	12.1	1.14	1.22e-2	21.4	1.18
n-Heptane	8.08e-2	30.5	0.75	5.97e-2	46.6	0.89	5.2e-2	75.2	1.03
Methylcyclohexane	4.82e-2	15	0.62	3.39e-2	27.4	0.92	3.11e-2	41	0.94
Toluene	1.53e-2	6.04	1.24	1.38e-2	11.9	1.54	1.17e-2	17.2	1.64
2-Methylheptane	5.45e-2	9.79	0.74	5.64e-2	25.8	1.08	4.24e-2	31.1	1.07
3-Methylheptane	6.47e-2	11.6	0.79	6.87e-2	30.6	1.12	5.01e-2	36.7	1.14
n-Octane	4.26e-2	5.76	0.83	4.98e-2	16.2	1.13	3.44e-2	19.5	1.23
Ethylbenzene	5.55e-3	0.471	0.75	8.38e-3	1.63	0.98	5.32e-3	1.99	1.18
m,p-Xylene	1.2e-2	0.096	0.08	1.95e-2	5.06	1.52	1.26e-2	0.895	0.26
o-Xylene	3.56e-3	1.05	3.74	7.19e-3	1.65	1.65	7.53e-3	1.61	0.96
n-Nonane	1.94e-2	0.373	0.32	3.03e-2	3.42	1.06	2.07e-2	4.15	1.17
n-Decane	1.15e-2	0.108	0.39	2.51e-2	1.37	1.27	2.1e-2	1.72	1.19
n-Undecane	8.11e-3	0.00	0.00	1.95e-2	0.516	1.64	2.39e-2	0.662	1.07
n-Dodecane	5.07e-3	0.00	0.00	1.25e-2	0.00	0.00	1.59e-3	0.00	0.00
n-Tridecane	2.83e-3	0.00	0.00	7.81e-3	0.00	0.00	2.26e-2	0.00	0.00
n-Tetradecane	1.37e-3	0.00	0.00	5.94e-3	0.00	0.00	6.56e-4	0.00	0.00
Residual	2.861e-1	53.252	0.38	4.635e-1	90.814	0.23	5.046e-1	138.873	0.20
Total		410.80	0.50		416.76	0.57		751.25	0.56

a Symbol Definitions -

Q = volumetric air flow rate
T_{air} = average air temperature
T_{liq} = average water temperature
N(liq) = mole fraction of fuel component
R = observed evaporation rate
Rcal = calculated evaporation rate

TABLE D-2. JP-4 EVAPORATION AT REDUCED TEMPERATURES^a

Hydrocarbon	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/Rcal
Iso-butane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Butane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Iso-pentane	0.00	1.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Pentane	1.7e-3	2.19	0.16	0.00	0.00	0.00	0.00	0.00	0.00
2-Methylpentane	8.27e-3	14.9	0.59	0.00	0.00	0.00	0.00	0.00	0.00
3-Methylpentane	8.43e-3	13.6	0.60	0.00	0.00	0.00	0.00	0.00	0.00
n-Hexane	2.64e-2	33.1	0.61	0.00	2.08	0.00	0.00	0.00	0.00
Methylcyclopentane	2.09e-2	19.8	0.52	1.67e-3	2.14	0.43	0.00	0.00	0.00
Benzene	2.09e-3	2.12	1.09	0.00	0.00	0.00	0.00	0.00	0.00
Cyclohexane	2.26e-2	16.2	0.57	3.69e-3	4.06	0.54	1.71e-4	0.00	0.00
2-Methylhexane	8.31e-2	51.7	0.72	2.53e-2	21.4	0.60	6.74e-3	1.53	0.41
3-Methylhexane	7.55e-2	43.4	0.73	2.61e-2	20.7	0.61	7.59e-3	1.75	0.46
1,2-Dimethylpentane	2.02e-2	12.1	0.99	7.29e-3	5.42	0.75	2.16e-3	0.487	0.59
n-Heptane	8.42e-2	40.5	0.85	4.03e-2	22.2	0.59	1.58e-2	2.81	0.49
Methylcyclohexane	5.12e-2	21.9	0.72	2.48e-2	14	0.58	1e-2	1.9	0.51
Toluene	1.42e-2	7.54	1.52	1.08e-2	3.77	0.61	3.88e-3	0.315	0.36
2-Methylheptane	6.07e-2	17	1.10	5.49e-2	15.5	0.67	3.86e-2	4.09	0.64
3-Methylheptane	7.42e-2	20.4	1.17	6.57e-2	18.9	0.74	4.74e-2	5.28	0.73
n-Octane	4.9e-2	10.4	1.32	5.14e-2	9.16	0.67	4.19e-2	3.22	0.73
Ethylbenzene	9.52e-3	1.49	1.39	1e-2	0.00	0.00	8.41e-3	0.578	0.93
m,p-Xylene	1.28e-2	2.68	2.23	2.21e-2	1.69	0.49	2.2e-2	0.729	0.53
o-Xylene	5.4e-3	1.14	2.79	8.14e-3	0.00	0.00	1.01e-2	0.251	0.49
n-Nonane	2.18e-2	3.12	2.53	3.32e-2	0.00	0.00	6.26e-3	0.959	4.05
n-Decane	1.17e-2	3.32	13.34	2.53e-2	0.00	0.00	3.27e-2	0.00	0.00
n-Undecane	8.47e-3	2.78	46.18	2.24e-2	0.00	0.00	3.25e-2	0.00	0.00
n-Dodecane	5.04e-3	1.37	108.09	2.39e-4	0.00	0.00	1.93e-3	0.00	0.00
n-Tridecane	2.81e-3	0.83	245.34	1.05e-2	0.00	0.00	2.31e-2	0.00	0.00
n-Tetradecane	1.2e-3	0.00	0.00	8.03e-3	0.00	0.00	1.36e-3	0.00	0.00
Residual	3.186e-1	69	0.47	5.481e-1	25.88	0.06	6.874e-1	8.871	0.04
Total		414.01	0.69		166.90	0.25		32.77	0.13

^aSymbol Definitions -

Q = volumetric air flow rate

T_{air} = average air temperatureT_{liq} = average water temperature

N(liq) = mole function of fuel component

R = observed evaporation rate

Rcal = calculated evaporation rate

TABLE D-3. EFFECT OF HUMIDITY ON JP-4 EVAPORATION^a

Hydrocarbon	RH = 68 Percent			RH = 93 Percent		
	Q, cfm	T _{air} , C	T _{liq} , C	Q, cfm	T _{air} , C	T _{liq} , C
	43.1	33.1	26.5	25	36.8	29.8
	N(liq)	R, mg/min	R/R _{cal}	N(liq)	R, mg/min	R/R _{cal}
Iso-butane	0.00	0.00	0.00	0.00	0.00	0.00
n-Butane	0.00	0.00	0.00	0.00	13.4	0.00
Iso-pentane	0.00	1.71	0.00	0.00	12.7	0.00
n-Pentane	0.00	2.68	0.00	0.00	12.5	0.00
2-Methylpentane	7.5e-3	24.8	0.56	1.45e-2	49.7	0.79
3-Methylpentane	7.41e-3	23.2	0.60	1.3e-2	41.1	0.81
n-Hexane	2.13e-2	62.4	0.71	3.46e-2	95.8	0.89
Methylcyclopentane	1.76e-2	39.7	0.63	2.41e-2	55.1	0.85
Benzene	2e-3	8.25	1.91	2.6e-3	12.1	2.81
Cyclohexane	2e-2	35.3	0.65	2.44e-2	43	0.85
2-Methylhexane	7.56e-2	128	0.90	8.41e-2	136	1.14
3-Methylhexane	7.09e-2	110	0.89	7.46e-2	114	1.16
1,2-Dimethylpentane	1.85e-2	30	1.20	2.01e-2	31.5	1.53
n-Heptane	8.17e-2	105	1.00	9.18e-2	103	1.15
Methylcyclohexane	4.9e-2	59.7	0.95	4.95e-2	58.5	1.22
Toluene	1.71e-2	26.8	1.92	1.42e-2	25.6	2.89
2-Methylheptane	6.51e-2	55.2	1.37	6.07e-2	50.2	1.73
3-Methylheptane	7.79e-2	63.7	1.41	7.3e-2	59.5	1.82
n-Octane	5.17e-2	34.9	1.62	4.8e-2	34.6	2.22
Ethylbenzene	1.28e-2	3.9	1.05	6.03e-3	3.79	2.81
m&p-Xylene	1.61e-2	12.2	3.06	1.17e-2	13.5	5.99
o-Xylene	4.95e-3	4.16	4.16	4.07e-3	5.94	9.28
n-Nonane	2.55e-2	9.28	2.34	2.12e-2	12.4	4.82
n-Decane	1.73e-2	3.6	3.32	1.12e-2	7.1	12.83
n-Undecane	1.29e-2	1.25	4.14	6.29e-3	4.32	36.67
n-Dodecane	8.41e-3	0.484	6.26	2.31e-3	2.15	124.74
n-Tridecane	5.17e-3		0.00	1.15e-3	1.12	259.43
n-Tetradecane	2.87e-3		0.00	5.24e-4	0.899	1509.87
Residual	3.107e-1	233.786	0.60	3.063e-1	307.481	1.03

^aSymbol Definitions -

Q = volumetric air flow rate

T_{air} = average air temperatureT_{liq} = average water temperature

N(liq) = mole fraction of fuel component

R = observed evaporation rate

R_{cal} = calculated evaporation rate

APPENDIX E

INTERMEDIATE-SCALE EVAPORATION
RATE EXPERIMENTS

TABLE E-1. EVAPORATION RATES IN INTERMEDIATE-SCALE SYSTEM^a

Hydrocarbon	Time, minutes				5				15				50				100			
	Q, cfm	T _{air} , °C	T _{liq} , °C	R/R _{cal}	Q, cfm	T _{air} , °C	T _{liq} , °C	R/R _{cal}	Q, cfm	T _{air} , °C	T _{liq} , °C	R/R _{cal}	Q, cfm	T _{air} , °C	T _{liq} , °C	R/R _{cal}	Q, cfm	T _{air} , °C	T _{liq} , °C	R/R _{cal}
	2700	23.9	22		2700	24.1	22.2		2700	24	22.7		2700	23.9	23.2		2700	23.9	23.2	
	N(liq)	R, mg/min	R/R _{cal}		N(liq)	R, mg/min	R/R _{cal}		N(liq)	R, mg/min	R/R _{cal}		N(liq)	R, mg/min	R/R _{cal}		N(liq)	R, mg/min	R/R _{cal}	
Iso-butane	0.00	25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Butane	0.00	1271	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iso-pentane	0.00	824	0.00	0.00	0.00	36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-Pentane	0.00	677	0.00	0.00	0.00	68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-Methylpentane	1.61e-2	1865	0.97	0.97	5.48e-3	984	1.50	1.50	5.48e-3	984	1.50	1.50	0.00	16	0.00	0.00	0.00	0.00	0.00	0.00
3-Methylpentane	1.44e-2	1496	0.98	0.98	6.13e-3	953	1.46	1.46	6.13e-3	953	1.46	1.46	8.61e-4	42	0.44	0.44	0.00	0.00	0.00	0.00
n-Hexane	3.68e-2	3207	1.05	1.05	1.77e-2	2413	1.62	1.62	1.77e-2	2413	1.62	1.62	1.3e-3	107	0.96	0.96	0.00	0.00	0.00	0.00
Methylcyclopentane	2.51e-2	1799	0.99	0.99	1.45e-2	487	0.46	0.46	1.45e-2	487	0.46	0.46	1.6e-3	112	0.93	0.93	0.00	0.00	0.00	0.00
Benzene	3.32e-3	363	1.50	1.50	1.11e-3	254	2.93	2.93	1.11e-3	254	2.93	2.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cyclohexane	2.39e-2	1284	0.99	0.99	1.66e-2	1369	1.51	1.51	1.66e-2	1369	1.51	1.51	3.42e-3	161	0.84	0.84	0.00	0.00	0.00	0.00
2-Methylhexane	8.22e-2	3594	1.17	1.17	6.64e-2	4623	1.85	1.85	6.64e-2	4623	1.85	1.85	2.13e-2	1110	1.35	1.35	4.4e-3	405	2.34	2.34
3-Methylhexane	7.35e-2	2939	1.16	1.16	6.05e-2	3891	1.85	1.85	6.05e-2	3891	1.85	1.85	2.14e-2	1052	1.38	1.38	4.8e-3	431	2.47	2.47
1,2-Dimethylpentane	9.71e-3	384	1.49	1.49	7.79e-3	546	2.61	2.61	7.79e-3	546	2.61	2.61	2.73e-3	133	1.77	1.77	6.75e-4	57	3.00	3.00
n-Heptane	7.92e-2	2785	1.39	1.39	6.93e-2	3909	2.21	2.21	6.93e-2	3909	2.21	2.21	3.97e-2	1620	1.56	1.56	1.84e-2	773	1.57	1.57
Methylcyclohexane	4.53e-2	1406	1.22	1.22	4.06e-2	2010	1.93	1.93	4.06e-2	2010	1.93	1.93	2.1e-2	826	1.50	1.50	7.82e-3	485	2.31	2.31
Toluene	1.29e-2	498	1.34	1.34	1.22e-2	413	1.15	1.15	1.22e-2	413	1.15	1.15	1.04e-2	393	1.25	1.25	6.82e-3	209	0.99	0.99
2-Methylheptane	5.45e-2	902	1.37	1.37	5.64e-2	1530	2.23	2.23	5.64e-2	1530	2.23	2.23	4.81e-2	1086	1.81	1.81	3.21e-2	1477	3.59	3.59
3-Methylheptane	6.38e-2	1039	1.44	1.44	6.58e-2	1756	2.34	2.34	6.58e-2	1756	2.34	2.34	4.81e-2	1086	1.81	1.81	3.21e-2	1477	3.59	3.59
n-Octane	4.13e-2	500	1.51	1.51	4.43e-2	891	2.48	2.48	4.43e-2	891	2.48	2.48	4.4e-2	736	2.00	2.00	3.64e-2	1242	3.98	3.98
Ethylbenzene	1.6e-2	113	0.70	0.70	1.91e-2	190	0.97	0.97	1.91e-2	190	0.97	0.97	2.26e-2	206	0.87	0.87	1.92e-2	373	1.79	1.79
m,p-Xylene	1.7e-2	135	0.92	0.92	1.9e-2	262	1.58	1.58	1.9e-2	262	1.58	1.58	2.23e-2	325	1.62	1.62	2.5e-2	548	2.37	2.37
o-Xylene	8.1e-3	97	1.71	1.71	9.5e-3	171	2.53	2.53	9.5e-3	171	2.53	2.53	1.14e-2	192	2.30	2.30	1.1e-2	439	5.30	5.30
n-Nonane	1.98e-2	86	1.47	1.47	2.29e-2	170	2.48	2.48	2.29e-2	170	2.48	2.48	2.59e-2	188	2.36	2.36	3.44e-2	433	3.97	3.97
n-Decane	1.41e-2	48	2.92	2.92	1.75e-2	74	3.53	3.53	1.75e-2	74	3.53	3.53	2.54e-2	100	3.20	3.20	2.98e-2	162	4.31	4.31
n-Undecane	1.02e-2	0.00	0.00	0.00	1.29e-2	19	3.44	3.44	1.29e-2	19	3.44	3.44	2.36e-2	50	4.71	4.71	2.78e-2	31	2.38	2.38
n-Dodecane	1.3e-3	0.00	0.00	0.00	7.5e-3	0.00	0.00	0.00	7.5e-3	0.00	0.00	0.00	1.4e-2	38	15.64	15.64	1.38e-2	0.00	0.00	0.00
n-Tridecane	5.33e-3	0.00	0.00	0.00	3.6e-3	0.00	0.00	0.00	3.6e-3	0.00	0.00	0.00	9.87e-3	0.00	0.00	0.00	9.93e-3	0.00	0.00	0.00
n-Tetradecane	2.68e-3	0.00	0.00	0.00	1.33e-3	0.00	0.00	0.00	1.33e-3	0.00	0.00	0.00	4.18e-3	0.00	0.00	0.00	4.51e-3	0.00	0.00	0.00
Residual	3.236e-1	5041	4.56	4.56	4.019e-1	9081	6.54	6.54	4.019e-1	9081	6.54	6.54	5.682e-1	5384	2.66	2.66	6.741e-1	7072	2.87	2.87
Total		32400.00	1.44	1.44		36100.00	2.18	2.18		36100.00	2.18	2.18		15120.00	1.81	1.81		15967.00		

a) Symbol Definitions -

Q = volumetric air flow rate

T_{air} = average air temperature

T_{liq} = average water temperature

N(liq) = mole function of fuel component

R = observed evaporation rate

R_{cal} = calculated evaporation rate

TABLE E-2. EVAPORATION RATES IN INTERMEDIATE-SCALE SYSTEM

Hydrocarbon	5				30				60				260			
	Time, minutes	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}
iso-butane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-butane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
iso-pentane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-pentane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-methylpentane		1.03e-2	663	0.47	0.00	39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3-methylpentane		9.31e-3	600	0.53	0.00	41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
n-hexane		2.77e-2	1648	0.62	5.99e-3	225	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
methylcyclopentane		1.99e-2	1060	0.63	5.47e-3	120	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
benzene		2.24e-3	237	1.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cyclohexane		2.13e-2	1020	0.76	8.37e-3	348	0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2-methylhexane		7.93e-2	3650	1.06	4.23e-2	1902	1.02	1.4e-2	149	0.24	0.00	0.00	0.00	0.00	0.00	0.00
3-methylhexane		7.13e-2	3190	1.12	4.1e-2	1750	1.05	1.49e-2	152	0.25	0.00	0.00	0.00	0.00	0.00	0.00
1,2-dimethylpentane		1.9e-2	444	0.76	1.11e-2	208	0.59	4.34e-3	33	0.24	0.00	0.00	0.00	0.00	0.00	0.00
n-heptane		7.54e-2	3640	1.64	5.54e-2	2950	1.78	2.63e-2	221	0.28	0.00	0.00	0.00	0.00	11	0.00
methylcyclohexane		4.47e-2	2010	1.52	3.3e-2	1135	1.14	1.67e-2	168	0.33	0.00	0.00	0.00	0.00	1	0.00
toluene		1.21e-2	1600	3.91	1.38e-2	215	0.45	1.06e-2	55	0.15	0.00	0.00	0.00	0.00	0.00	0.00
2-methylheptane		5.73e-2	2760	3.43	6.21e-2	1340	1.50	5.29e-2	347	0.45	1.09e-2	20	0.13	1.09e-2	20	0.13
3-methylheptane		6.76e-2	3280	3.69	7.28e-2	1510	1.54	6.33e-2	458	0.54	1.46e-2	26	0.13	1.46e-2	26	0.13
n-octane		4.35e-2	2440	5.98	5.29e-2	754	1.49	5.27e-2	261	0.51	1.55e-2	45	0.30	1.55e-2	45	0.30
ethylbenzene		7.66e-3	2610	28.79	9.02e-3	102	0.94	1.07e-2	27	0.20	6.94e-3	43	0.50	6.94e-3	43	0.50
mcp-xylene		1.71e-2	1420	8.23	2.39e-2	114	0.46	2.71e-2	43	0.15	7.43e-3	62	0.80	7.43e-3	62	0.80
o-xylene		7.25e-3	1420	23.82	1.04e-2	61	0.70	1.4e-2	0.00	0.00	5.45e-3	21	0.46	5.45e-3	21	0.46
n-nonane		2.15e-2	2620	35.26	3.16e-2	47	0.42	3.96e-2	54	0.38	5.55e-2	113	0.57	5.55e-2	113	0.57
n-decane		1.42e-2	4330	221.15	2.52e-2	0.00	0.00	3.4e-2	0.00	0.00	7.98e-2	70	0.62	7.98e-2	70	0.62
n-undecane		1.15e-2	1830	314.39	1.94e-2	0.00	0.00	2.86e-2	8	0.54	6.73e-2	26	0.73	6.73e-2	26	0.73
n-dodecane		1.36e-3	104	390.82	2.63e-3	0.00	0.00	2.1e-2	32	7.52	6.85e-3	1	0.96	6.85e-3	1	0.96
n-tridecane		5.6e-3	102	187.37	6.42e-3	0.00	0.00	1.25e-2	0.00	0.00	1.89e-2	0.00	0.00	1.89e-2	0.00	0.00
n-tetradecane		2.96e-3	37	446.35	2.42e-3	0.00	0.00	4.99e-3	0.00	0.00	7.84e-3	0.00	0.00	7.84e-3	0.00	0.00
Residual		3.499e-1	49808	35.63	4.648e-1	4473	2.36	5.518e-1	594	0.26	7.030e-1	1042	0.36	7.030e-1	1042	0.36
Total			92523.00	3.99		17334.60	1.29		2591.30	0.32		1482.20	0.38			

^aSymbol Definitions -

Q = volumetric air flow rate

N(liq) = mole function of fuel component

T_{air} = average air temperature

R = observed evaporation rate

T_{liq} = average water temperature

R_{cal} = calculated evaporation rate

TABLE E-3. EVAPORATION RATES IN INTERMEDIATE-SCALE SYSTEM WITH FUEL LAYER OF 0.85 INCH

Hydrocarbon	12				30				60				240			
	Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}		Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}		Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}		Q, cfm N(liq)	T _{air} , C R, mg/min	T _{liq} , C R/R _{cal}	
Iso-butane	0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00		0.00	0.00	0.00	
n-Butane	8.25e-3	2169	0.45		4.92e-3	341	0.12		0.00	0.00	0.00		0.00	0.00	0.00	
Iso-pentane	4.36e-3	897	0.93		3.09e-3	443	0.64		0.00	0.00	0.00		0.00	0.00	0.00	
n-Pentane	3.89e-3	708	1.15		2.92e-3	397	0.85		0.00	144	0.00		0.00	0.00	0.00	
2-Methylpentane	1.75e-2	1700	1.50		1.4e-2	1412	1.54		0.00	1010	1.34		9.56e-3	0.00	0.00	
3-Methylpentane	1.5e-2	1360	1.58		1.24e-2	1207	1.68		1.05e-2	892	1.46		8.95e-3	51	0.10	
n-Hexane	3.97e-2	2850	1.59		3.37e-2	2596	1.69		2.84e-2	2070	1.60		2.73e-2	233	0.18	
Methylcyclopentane	2.6e-2	1580	1.54		2.23e-2	1450	1.63		1.97e-2	1210	1.54		2.01e-2	224	0.27	
Benzene	3.7e-3	272	1.77		3.12e-3	241	1.84		2.14e-3	196	2.18		2.19e-3	0.00	0.00	
Cyclohexane	2.25e-2	1177	1.79		2.16e-2	1032	1.62		1.91e-2	939	1.66		2.16e-2	31	0.05	
2-Methylhexane	8.21e-2	3050	1.84		7.17e-2	3080	2.11		6.8e-2	2910	2.10		8.22e-2	1560	0.91	
3-Methylhexane	7.27e-2	2483	1.83		6.39e-2	2520	2.10		6.11e-2	2410	2.10		7.49e-2	1420	0.98	
1,2-Dimethylpentane	9.23e-3	635	4.78		7.61e-3	639	5.78		7.22e-3	287	2.74		8.75e-3	167	1.28	
n-Heptane	7.6e-2	1930	1.86		7.27e-2	2520	2.52		6.69e-2	1950	2.12		9.18e-2	1750	1.35	
Methylcyclohexane	4.47e-2	119	0.19		4.06e-2	390	0.69		3.93e-2	1400	2.57		4.85e-2	903	1.31	
Toluene	1.13e-2	131	0.74		1.12e-2	148	0.63		1.12e-2	142	0.80		1.33e-2	202	0.93	
2-Methylheptane	5.3e-2	695	2.02		4.73e-2	737	2.38		2.98e-2	758	3.88		6.12e-2	963	2.34	
3-Methylheptane	6.2e-2	805	2.14		1.39e-3	46	5.41		1.74e-3	876	82.13		1.85e-3	1110	95.15	
n-Octane	4.05e-2	315	1.81		3.8e-2	393	2.38		3.93e-2	399	2.33		4.51e-2	573	2.83	
Ethylbenzene	6.42e-3	0.00	0.00		6.48e-3	0.00	0.00		6.64e-3	51	1.40		9.3e-3	79	1.49	
m,p-Xylene	1.46e-2	78	1.16		2.97e-3	0.00	0.00		1.69e-2	43	0.54		1.24e-2	118	1.97	
o-Xylene	5.69e-3	41	1.89		7.86e-3	0.00	0.00		7.12e-3	45	1.65		7.78e-3	37	1.22	
n-Nonane	1.88e-2	0.00	0.00		1.93e-2	0.00	0.00		1.97e-2	47	1.48		1.96e-2	102	3.16	
n-Decane	1.24e-2	0.00	0.00		1.55e-2	0.00	0.00		1.62e-2	0.00	0.00		1.12e-2	0.00	0.00	
n-Undecane	1.04e-2	0.00	0.00		1.56e-2	0.00	0.00		1.44e-2	0.00	0.00		9.78e-3	0.00	0.00	
n-Dodecane	6.94e-3	0.00	0.00		1.1e-2	0.00	0.00		1.16e-2	0.00	0.00		7.87e-3	0.00	0.00	
n-Tridecane	4.95e-3	0.00	0.00		8.47e-3	0.00	0.00		9.8e-3	0.00	0.00		7.32e-3	0.00	0.00	
n-Tetradecane	2.49e-3	0.00	0.00		3.69e-3	0.00	0.00		2.72e0	0.00	0.00		3.54e-3	0.00	0.00	
Residual	3.249e-1	4457	7.50		4.367e-1	5084	6.29		-2.238e0	3359	0.00		3.939e-1	3227	4.30	
Total		27452.00	1.47			24676.00	1.67			21311.00	4.41			12750.00	1.15	

a) Symbol Definitions -

Q = volumetric air flow rate

T_{air} = average air temperature

T_{liq} = average water temperature

N(liq) = mole function of fuel component

R = observed evaporation rate

R_{cal} = calculated evaporation rate