2

AFWAL-TR-87-2060
Volume II

DEVELOPMENT AND EVALUATION OF AN AIRPLANE FUEL TANK ULLAGE COMPOSITION MODEL

Volume II - Experimental Determination of Airplane Fuel Tank Ullage Compositions

A. J. Roth
BOEING MILITARY AIRPLANE COMPANY
P. O. Box 3707
Seattle, Washington 98124-2207

October 1987

FINAL REPORT for Period November 1985 through December 1986

Approved for public release; distribution is unlimited.

AERO PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE. OH 45433-6563

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

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

This technical report has been reviewed and is approved for publication.

Robert G. Clodfelter
ROBERT G. CLODFELTER
Project Engineer

FOR THE COMMANDER

Robert D. Sherrill
ROBERT D. SHERRILL, Chief
Fuels and Lubrication Division
Aero Propulsion Laboratory

"If your address has changed, if you wish to be removed from our mailing list or if the addressee is no longer employed by your organization, please notify AFWAL/POSF, WPAFB, OH 45433-6563 to help us maintain a current mailing list."

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): D180-30344-2

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFWAL-TR-87-2060, Vol. II

6a. NAME OF PERFORMING ORGANIZATION: Boeing Military Airplane Co.

6b. OFFICE SYMBOL *(If applicable)*:

7a. NAME OF MONITORING ORGANIZATION: Air Force Wright Aeronautical Labs
Aero Propulsion Laboratory (AFWAL/POSF)

6c. ADDRESS *(City, State and ZIP Code)*:
P.O. Box 3707, M/S 33-14
Seattle, WA 98124-2207

7b. ADDRESS *(City, State and ZIP Code)*:
Wright-Patterson AFB, OH 45433-6563

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL *(If applicable)*:

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-84-C-2431

8c. ADDRESS *(City, State and ZIP Code)*:

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62203F	3048	07	94

11. TITLE *(Include Security Classification)*: See reverse page

12. PERSONAL AUTHOR(S): A. J. Roth

13a. TYPE OF REPORT: FINAL

13b. TIME COVERED: FROM Nov 85 TO Dec 86

14. DATE OF REPORT *(Yr., Mo., Day)*: OCTOBER 1987

15. PAGE COUNT: 116

16. SUPPLEMENTARY NOTATION: AFWAL-TR-87-2060, Vol. I contains software documentation. AFWAL-TR-87-2060, Vol II contains distribution list letter and Statement of Terms and Conditions Release for software packages.

17. COSATI CODES

FIELD	GROUP	SUB. GR.
01	03	
21	02, 04	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: fuel tank, nitrogen-enriched air, stratification, ullage, oxygen evolution, mission simulation, inerting, diffusion

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The development and evaluation of a computer model designed to predict the composition of airplane fuel tank ullage spaces is documented in two volumes.

Volume I - Airplane Fuel Tank Ullage Computer Model

A detailed mathematical description of the model as it relates to the physical processes governing the ullage of an airplane fuel tank is included, along with user instructions and examples. Extensive comparisons of computer model predictions to experimental data are included. The model is interactive and can be used on a variety of computers including personal computers.

Volume II - Experimental Determination of Airplane Fuel Tank Ullage Compostions

Experimental work conducted using a fuel tank simulator to investigate the composition

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: Robert G. Clodfelter

22b. TELEPHONE NUMBER *(Include Area Code)*: (513) 255-4208

22c. OFFICE SYMBOL: AFWAL/POSF

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

19.
ABSTRACT (continued)

of airplane fuel tank ullage spaces is described. The investigations include ullage mixing by diffusion and convection, oxygen evolution during simulated climbs and refueling and complete mission simulations. (Keywords) →

11. TITLE

Development and Evaluation of an Airplane Fuel Tank Ullage Composition Model
Volume II - Experimental Determination of Airplane Fuel Tank Ullage Compositions

SUMMARY

An experimental investigation was performed to aid in the development and validation of a computer based mathematical model, ULLAGE, capable of predicting the composition of the vapor/air space (ullage) above the fuel in an airplane fuel tank. The experimental program, referred to as the Ullage Model Verification tests or UMV tests, was divided into separate parts, with individual objectives designed to investigate the different processes that affect ullage composition. This report, Volume II, contains a detailed description of the UMV tests and their results.

The first objective of the UMV tests, understanding environmental effects on ullage stratification, was achieved through careful single variable testing. Experimental hydrocarbon concentration profiles were compared with a Fick's diffusion law computer model to determine the dominant mixing mechanism (diffusion, natural convection or forced convection) present in the ullage at the various test conditions. Identification of which wall temperature relationships led to diffusion mixing and which led to bulk natural convection mixing was accomplished. The tests also revealed that a vent gas inlet stream promoted ullage stratification and that ullage gas mixing due to sloshing is dependent on the slosh frequency in the tank.

The second objective of the UMV tests was to understand the role of dissolved oxygen in the fuel on ullage flammability.

Reproducible and controlled mission simulations were made using the ModComp computer to control the Simulated Aircraft Fuel Tank Environment (SAFTE) facility at Wright-Patterson Air Force Base. Data logged by the ModComp, including independent variables such as altitude pressure and fuel temperature and dependent variables such as oxygen and hydrocarbon concentrations, allowed complete checkout of the ullage computer model. Validation of the computer model under simulated flight conditions achieved the third objective of the test program. Comparisons between model predictions and test data are included in Volume I of this report.

PREFACE

This is a final report of work conducted under F33615-84-C-2431 and submitted by the Boeing Military Airplane Company, Seattle, Washington for the period November 1985 through December 1986. Program sponsorship and guidance were provided by the Fire Protection Branch of the Aero Propulsion Laboratory (AFWAL/POSF), Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Project 3048, Task 07, and Work Unit 94. Robert G. Clodfelter was the project engineer. The Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) also provided funds to support this effort.

The work partially satisfies the requirements of Task II of the contract, SAFTE (Simulated Aircraft Fuel Tank Environment) Test Requirements, that requires utilization of the SAFTE system to assess the hazards associated with aircraft fuel tanks and evaluate protection measures. Other reports submitted to date under Task II include:

Document Number	Title
ITR#1	Fluorocarbon Solubility in JP-4 Test Results (December 1984)
ITR#2	C-17 O_2 Evolution Test Data Report (June 1985)
ITR#3	Analysis of SAFTE Slosh Requirements for Electrostatic Hazards Testing with Foam (January 1986)
D180-30344-1	Development and Evaluation of an Airplane Fuel Tank Ullage Composition Model, Volume I - Airplane Fuel Tank Ullage Computer Model (April 1987-draft)

Results of the ullage flammability studies were divided into two volumes. The ullage flammability computer model (Volume I) was developed to reflect the conditions within an airplane fuel tank. Its long-term application is the assessment of the vulnerability of aircraft fuel systems to fire and explosion. Volume II of this document describes testing performed in the SAFTE system to obtain data used to validate the computer model.

Boeing wishes to acknowledge with appreciation the contributions of the technical personnel of SelectTech Services, Inc., in particular, A. J. Roth, who performed and documented the computer model validation testing. Key Boeing contributors were; D. W. Seibold, computer model development, and C. L. Anderson, technical guidance during research.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (concluded)

APPENDICES

LIST OF FIGURES

LIST OF FIGURES (concluded)

LIST OF TABLES

1.0 INTRODUCTION

Fires and explosions in fuel tanks have led to destruction or severe damage to a large number of aircraft. One effective means of preventing fires and explosions is to inert the fuel tanks by restricting the oxygen concentration in the fuel tank vapor space (ullage) to 9% or less. Controlling the ullage gas concentration to safe levels is complicated by the fact that oxygen dissolved in the fuel tends to be evolved during flight and repressurization gases are required to compensate for fuel usage and descent repressurization. An additional complication is the manner in which the gases are distributed in the ullage. Thus, even though the average oxygen concentration is less than 9% on a mass weighted average basis, pockets of gas may exist in the tank where the oxygen concentration is much greater than 9%, producing a potentially hazardous situation. The purpose of this study was to experimentally obtain ullage gas concentration data to gain more insight into ullage gas distribution phenomena and validate a computer code for predicting ullage gas concentration profiles.

Ullage gas concentration data were obtained using the Simulated Aircraft Fuel Tank Environment (SAFTE) facility at Wright-Patterson Air Force Base. Since a primary purpose of the tests was to verify the ullage gas computer model, the tests will be referred to as the Ullage Model Verification (UMV) tests.

The UMV tests were grouped into three major categories: Environmental Effects Tests, Dissolved Oxygen Management Tests and Mission Simulations.

1.1 Background

The SAFTE facility has been used for a number of test programs that studied simple fuel tank processes as well as more sophisticated mission simulations Fuel scrubbing and oxygen evolution during KC-135 mission simulations have been investigated (Ref. 1) and oxygen evolution tests from fuel to the ullage during simulated C-17 flight conditions were also completed (Ref. 2). However, a systematic study to develop a computer model to predict ullage gas concentrations using data from the SAFTE facility for code validation was not made.

An ullage gas computer model (TANK/DIFFUSE) was developed by Falcon Research (Ref. 3). However, attempts to apply the model to predicting important ullage gas characteristics were unsuccessful. Therefore, the existing Boeing scrub and oxygen evolution model was chosen to be modified and validated in lieu of TANK/DIFFUSE. An iterative approach between the mathematical model and experiment was used to develop the final version of the model which was named ULLAGE.

1.2 General Objectives

The first objective of these tests was to understand the effects of fuel tank environment (pressure, temperature, slosh/vibration) on ullage flammability. The majority of experiments were designed to allow only one variable, eliminating confounding multi-variable effects and enabling comparison between experimental data and model predictions of physical processes in the ullage. The effect of wall and fuel temperature on ullage stratification, the effect of a vent gas stream on ullage stratification and the effect of fuel tank slosh on ullage stratification were studied individually in UMV Tests 1, 2 and 3 (Environmental Effects Tests).

The second objective was to understand the effect of dissolved oxygen on ullage O_2 concentrations. Dissolved Oxygen Management Tests were performed to study the effect of climbing (UMV Test 4) and refueling with air saturated fuel (UMV Test 5) on oxygen concentration in the ullage. Scrub tests were also performed to study the effect a nitrogen enriched air (NEA) fuel scrub has on ullage oxygen concentrations.

After utilizing the new understanding of the phenomena occurring in the fuel tank to refine a multi-variable ullage computer model, the third objective was to perform multi-variable mission simulations (UMV Test 6) to check out the refined ullage computer model under fully simulated flight conditions.

1.3 Approach

During these experiments, particular attention was paid to oxygen (O_2) and hydrocarbon (HC) concentrations in the ullage. In the correct proportions, an oxygen and hydrocarbon mixture can be combustible. It is important to determine how $\%O_2$ and %HC in the ullage are affected by airplane fuel tank conditions such as temperature (both skin and bulk fuel) and pressure. There are many factors that affect ullage composition but it is important to eliminate possible confounding effects by isolating and studying one variable at a time. For this reason, the first five UMV tests were conducted with a single variable. The final test consisted of mission simulations that combined all variables studied in the previous tests into a realistic mission profile that tested all facets of the computer ullage model.

UMV Tests 1 through 5 centered on certain processes that were not previously well understood. These are mixing/stratification/diffusion and dissolved oxygen evolution. Five separate sets of UMV tests were performed to deal with these two areas. They are as follows:

UMV Test 1 - Free Convection and Diffusion Driven Mixing
UMV Test 2 - Forced Convection Mixing
UMV Test 3 - Slosh Induced Mixing
UMV Test 4 - Dissolved Oxygen Evolution
UMV Test 5 - Ullage Behavior During Refueling

The sixth ullage model verification test consisted of multi-variable mission simulations. This test varied pressure, temperature, fuel burn rates and fuel type to simulate fighter cold, standard and hot day missions and transport missions. The experimental data obtained from UMV Test 6 was used to test the refined ullage computer model. UMV Test 6 was designated:

UMV Test 6 - Mission Simulations

Also included in this report are a series of tests entitled C-17 Oxygen Evolution Tests that were performed in support of the C-17 System Program Office in 1985 (Ref. 2). These tests are presented in Section 5.2 and provide extensive data for computer model comparisons.

A series of scrub tests are described in Section 5.1 along with a derivation of a successful differential equation model of an isobaric, isothermal scrub process. The scrub tests are included as an extension to the information presented in Ref. 1.

2.0 DETAILED OBJECTIVES

Due to the complexity of the ullage model development effort and the subsequent verification test program, the objectives of each test series are described here so that the relationships between tests may be better understood.

2.1 Environmental Effects Tests

UMV Test 1 - Free Convection and Diffusion Driven Mixing

Under certain wall temperature conditions (such as hot top wall) it was postulated that no natural (free) convection currents exist and that ullage mixing is diffusion dominated. Diffusion is a relatively slow process and a stratified ullage would persist. However, under other wall temperature conditions (such as cold top wall) free convection currents can be created and the ullage is mixed much faster by these convection currents than by diffusion alone. The objective of UMV Test 1 was to understand how wall temperature conditions affect the mixing process.

UMV Test 2 - Forced Convection

UMV Test 1 (Free Convection) studied ullage mixing in a sealed tank. UMV Test 2 investigated the effect an inlet vent gas stream (make-up gas due to fuel withdrawal at constant pressure) has on the homogeneity of the ullage. In contrast to UMV Test 1 where the initial hydrocarbon concentration in the ullage was much less than the equilibrium value, a well stirred ullage and equilibrium hydrocarbon concentrations were initial conditions in UMV Test 2. It was theorized that an inlet gas stream from a vent line may drive the mixing process and dominate diffusion or natural convection mixing. For example, a low vent flow rate of warm gas, vented in horizontally, may stratify the ullage. On the other hand, a high inlet gas flow rate of cold vent line gas may cause the ullage to be turbulent and remain well mixed.

Important combinations of inlet gas flow rate, initial ullage size, gas stream temperature (cold, ambient, hot), top wall temperature (cold, ambient, hot) and gas stream orientation (vertical, horizontal) were studied. Since many combinations of these variables were tested, a clear nomenclature system is imperative. Each test is specified by a four letter code.

Test nomenclature example:

```
VACH
||||----gas stream orientation (H-horizontal, V-vertical)
|||-----top wall temp.(A-ambient,C-cold(25°F<amb),H-hot(25°F>amb))
||------gas stream temp.(A-ambient,C-cold(25°F<amb),H-hot(25°F>amb)
|-------test type(V - 54% fuel @ 5 gpm withdrawal, F - 54% fuel @
                  50 gpm withdrawal, S - 90% fuel @ 5 gpm withdrawal)
```

The combination VHHH (5 gpm inlet gas flow rate, hot gas stream, hot top wall and horizontal vent) was expected to be more likely to stratify and the combination FCCV (50 gpm inlet gas flow rate, cold gas stream, cold top wall and vertical vent) was expected to remain well mixed. Other less extreme combinations were examined to determine the dividing line between stratified and well mixed forced convection. It was the objective of UMV Test 2 to simulate a vent line inlet gas stream flowing into a well mixed ullage and observe ullage behavior during and after forced convection.

UMV Test 3 - Slosh Mixing

During flight the fuel in airplane tanks is not necessarily quiescent; the fuel may vibrate or slosh depending on the airplane's mission. The slosh aspect of physical motion was studied in UMV Test 3. It was thought that a violent slosh could splash fuel into the ullage, rapidly mixing a stratified ullage. A less violent slosh could have little or no effect upon ullage stratification. The mechanical slosh drive on the SAFTE was used to simulate two degrees of slosh severity while the effect on ullage mixing was observed.

2.2 Dissolved Oxygen Management Tests

Scrub Test

The second major area of investigation in this test program was oxygen management. The quantity of dissolved oxygen in the fuel under equilibrium conditions may be evaluated using the Ostwald coefficient, a dimensionless ratio relating the volume of dissolved gas per unit volume of fuel. Nitrogen is also soluble in jet fuel but its solubility is about half that of oxygen. Thus, the ratio of dissolved oxygen to nitrogen in air saturated fuel is roughly one to two whereas in air the ratio is approximately one to four.

Since oxygen dissolved in the fuel may evolve into the ullage during a mission, it is necessary to consider the oxygen content of the fuel and its potential to evolve into the ullage. An important beginning to quantifying fuel oxygen content is to understand the process of scrubbing the fuel.

Scrubbing the fuel involves injecting a gas with low oxygen concentration into the fuel through a nozzle with many small holes. The resulting small bubbles mix with the fuel and cause dissolved oxygen to evolve as long as the partial pressure of oxygen in the scrub gases is less than that of the dissolved oxygen in the fuel.

The ullage gas computer model was based on a constant pressure, constant temperature model to describe ullage oxygen concentrations as a function of time during scrub. This model was developed to include any fuel tank system whose ullage and fuel volume, scrub flow rate and scrub gas %O_2, hydrocarbon vapor pressure, Ostwald coefficient and scrub efficiency were known. The model was tested by running three scrub tests with two different jet fuels at two different bulk fuel temperatures. Excellent agreement between predicted and measured values was obtained.

C-17 Oxygen Evolution Tests

Oxygen evolution tests were performed for simulated C-17 flight environments in support of the C-17 System Program Office and in cooperation with the McDonnell-Douglas Company. The objective of this test program was to measure the tank ullage oxygen concentration during simulated C-17 climbs to 41,000 feet altitude for various fuel/ullage conditions and to determine methods of maintaining near equilibrium conditions between fuel and ullage. Data from these tests were primarily used to verify the validity of the C-17 inerting system design and have been reported separately (see Ref. 2). However, this data is included in this report since it has significant value for ullage model comparisons.

During the C-17 tests, the effects of several variables on oxygen evolution were investigated. These variables included:

- Fuel Volume
- Fuel Temperature
- Initial Ullage Oxygen Concentration

- Fuel Circulation Rates
- Fuel Vapor Pressure
- Vibration Levels

UMV Test 4 - Dissolved Oxygen Evolution

Considerable work has been done previously to investigate oxygen evolution during climb (Ref. 1, 2 and Section 5.2). The intent of UMV Test 4 was to investigate concerns and questions regarding the sudden evolution of dissolved gases at altitude under particular conditions not previously investigated. These conditions primarily relate to OBIGGS applications where the maintenance of ullage oxygen concentrations below 9% is critical.

Oxygen equilibrium exists between fuel and ullage in a fuel tank when the partial pressure of oxygen in the ullage equals partial pressure of oxygen in the fuel. During a climb with air saturated fuel (saturated at one atmosphere), the partial pressure of oxygen in the ullage decreases (due to total pressure decrease) and a non-equilibrium condition is established in which the partial pressure of oxygen in the fuel is greater than that in the ullage. This difference tends to cause dissolved oxygen to evolve from the fuel until the fuel and ullage oxygen partial pressures are equal. As a result of this oxygen evolution, even a previously inert ullage may become able to support combustion.

It is important to quantify oxygen evolution from the fuel during climb. The objective of this test was to determine oxygen concentrations in the ullage during climb. Different inerting schemes using NEA_5 (typical OBIGGS product gas) for fuel scrubbing and ullage washing were tested, along with conditions designed to favor sudden oxygen evolution from the fuel.

UMV Test 5 - Oxygen Evolution During Refuel

Full time inerting requires maintaining safe ullage oxygen concentrations during refueling operations. If an airplane lands with a nitrogen-rich ullage (~5% oxygen) and is refueled with air saturated fuel, the partial pressure of oxygen in the fuel will be significantly higher than the partial pressure of oxygen in the ullage. This means that oxygen will evolve from the air saturated fuel into the ullage, raising the ullage oxygen concentration. The objective of this test was to simulate the refuel situation of oxygen-rich fuel in contact with a nitrogen-rich ullage and measure ullage oxygen concentration versus time. It was also possible to derive a differential equation to describe the ullage oxygen concentration as a function of time during and after refuel.

2.3 Mission Simulations

UMV Test 6 - Mission Simulations

After studying the individual effects of simulated climb, descent, fuel withdrawal, vibration, slosh and scrub on the ullage, simulated airplane missions were investigated using the SAFTE facility. Observing the effects of the flight variables individually (UMV Tests 1-5) allowed this step which combined flight variables into a realistic mission profile and "flew" the fully-instrumented tank on an airplane mission. It was necessary to use the single variable approach in the beginning because of the potentially confounding effect of a multi-variable mission. The objective of UMV Test 6 was to perform several different mission simulations which would be used for a final comparison to the ullage model. These missions were designed to exercise the ullage model over a wide range of mission conditions.

3.0 DESCRIPTION OF TEST FACILITY

As mentioned above, the test facility used for UMV testing was the SAFTE facility which is located in Bldg 71-B, I-Bay at Wright-Patterson AFB. A full description of the SAFTE can be found in the SAFTE Operating Manual (Ref. 5). A simplified schematic of the SAFTE test tank and associated subsystems includes the subsystems used to control pressure, temperature, fuel level and slosh/vibration in the SAFTE test tank (Figure 1). Also pictured is the Ullage Instrumentation System (UIS), which measures ullage gas composition at selected points in the ullage. Not included in the figure is the ModComp data acquisition and control computer which logs data and sends setpoint commands to subsystem controllers which in turn control wall temperatures, altitude pressure and other system variables.

3.1 Test Tank

The test tank (Figure 2) used for these tests is essentially a simple rectangular box with a total fuel capacity of 581 gallons. The tank structure is composed of an inner heat transfer panel and an outer heavy steel structural shell with thermal insulation between the two walls (Figure 3). The inner heat transfer panels were used to control the temperature of the tank walls during the tests.

3.2 Simulated Altitude Pressure Control System

The Simulated Altitude Pressure Control System (Figure 1) actually controls the pressure in a 30 gallon reservoir to simulate ambient pressure at any altitude. The system is composed of a water sealed vacuum pump, an instrument air source, a closed loop controller, and a feedback pressure transducer (P-ALT). The controller opens one of two throttle valves to the vacuum or air source in order to decrease or increase the altitude pressure. The controller receives a set-point command from the computer data acquisition and control system according to the altitude pressure schedule stored in memory.

A climb valve/demand regulator apparatus is in place between the 30 gallon altitude tank and the test tank which can simulate any airplane fuel system vent/pressurization scheme. The climb valve is a relief valve which vents ullage gas from the test tank to the altitude tank when test tank pressure

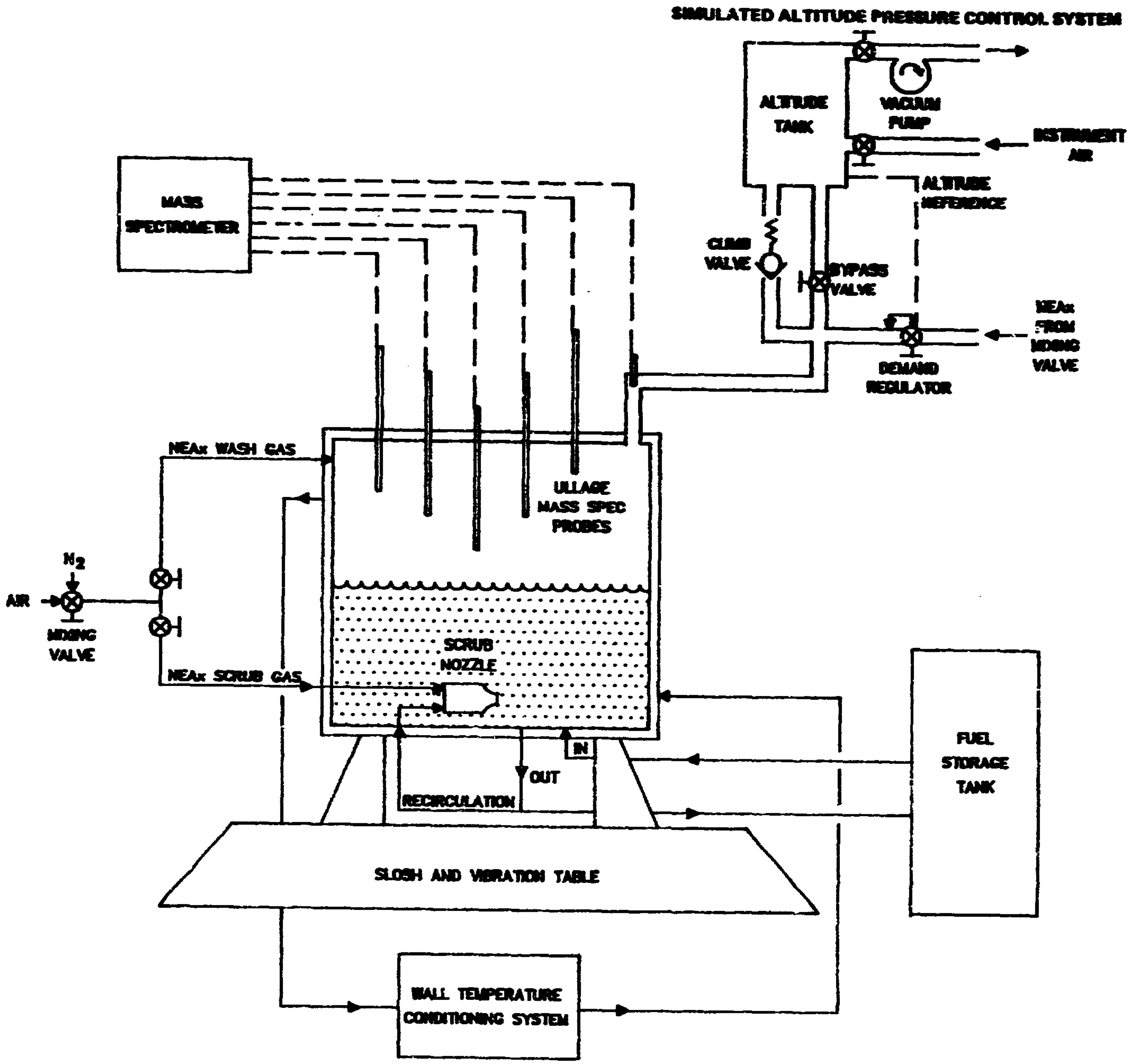
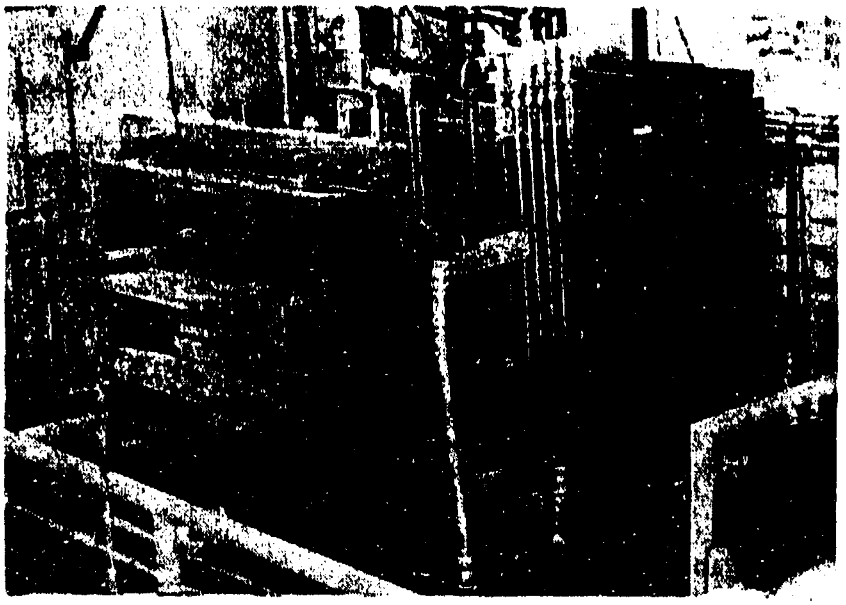
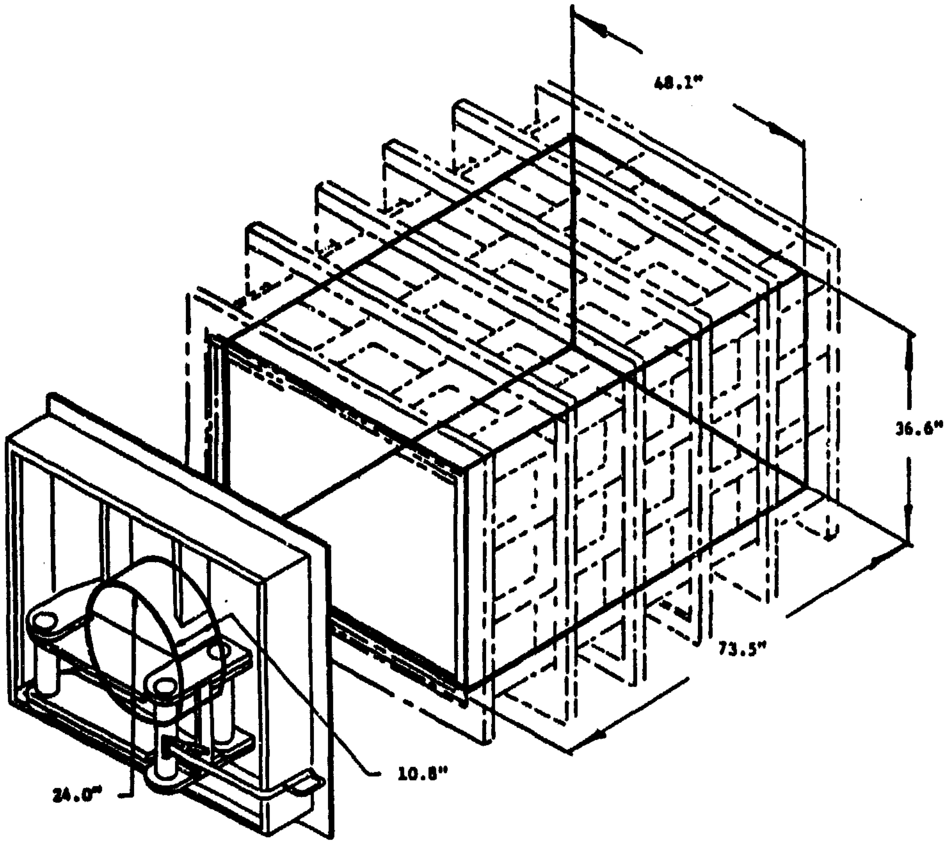


Figure 1. Simplified SAFTE Subsystems Schematic



A. Test Tank Photograph



B. Test Tank Internal Dimensions

Figure 2. Test Tank

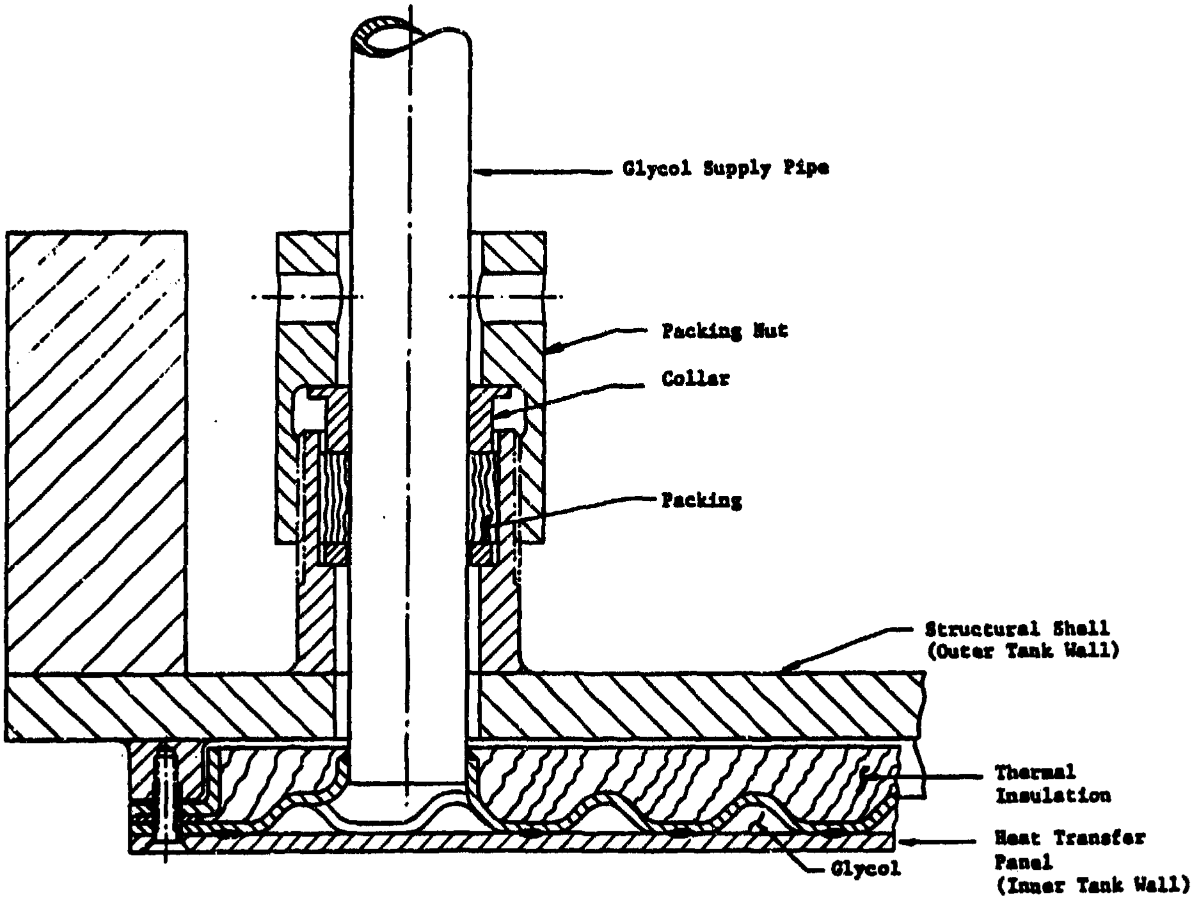


Figure 3. Tank Wall Section

exceeds altitude tank pressure by a predetermined amount. The demand regulator is a differential regulator which provides make-up gas (NEA_x) to the test tank when its pressure drops below the regulator setting.

Also, a hand valve is in place which bypasses the climb valve/demand regulator apparatus. Opening this valve sets test tank pressure equal to altitude tank pressure and effectively simulates a vented fuel system.

3.3 Wall Temperature Conditioning System

Five test tank walls are contacted by a heat transfer working fluid. These walls are: bottom, top and three out of four side walls. A manway located in one end of the test tank precludes having any selected heat transfer capability in that wall, although it is insulated. The working fluid is ethylene glycol contained in two independent loops (A and B) which in turn contact hot and cold primary brine loops, depending on the desired test tank wall temperatures. The glycol loops each consist of a temperature controller, a circulating pump and a manual valve board to determine which loop contacts which wall.

Also included in the top wall glycol circuit is an ullage vent line heat exchanger which conditions ullage vent gas to top wall temperature. In many airplanes the wing tank vent lines consist of channels built into the wing skins. This means that the make-up gas temperature will be top skin temperature. The system (Figure 4) automatically conditions inlet gas temperature to that of the top wall since they share a common glycol circuit. The system is designed so that glycol can flow to the top wall or ullage inlet heat exchanger or both. This allows temperature conditioning of top wall or ullage inlet gas or both (although at the same temperature). If the ullage inlet heat exchanger is not used, make-up gas will enter the tank at room temperature.

3.4 Scrub/Wash Subsystem

Also pictured in Figure 1 is the fuel scrub/ullage wash apparatus. Air and bottled N_2 are mixed in a three way controlled valve to produce about 0.23 pounds per minute of NEAx, where x is any oxygen concentration from $x=0$ (pure N_2) to $x=20.9$ (pure air). Valves downstream from the mixing valve permit

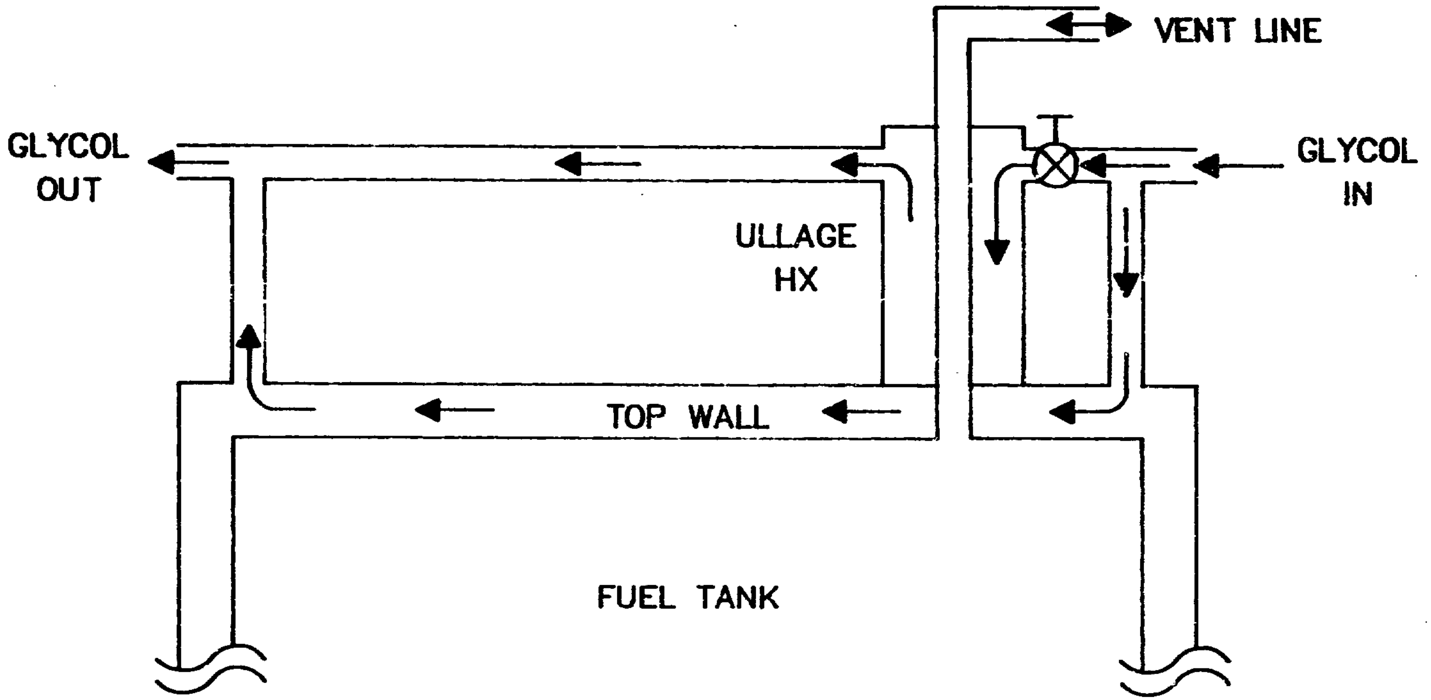


Figure 4. Top Wall/Ullage Inlet Heat Exchanger

a choice of either ullage wash (gas stream into fuel tank ullage) or fuel scrub (gas stream into scrub nozzle).

In order to condition the fuel with the proper amount of dissolved gases prior to the start of each test, a controlled concentration of NEAx was bubbled through the fuel. A C-5A scrub nozzle was used for this purpose due to its efficiency at mixing gases and liquids. The scrub nozzle mixes a gas and liquid stream by producing a high velocity jet of fuel with very small entrained gas bubbles. Gas dissolves into the fuel or evolves from the fuel, depending on the partial pressure of each gas constituent present in the scrub gas stream or dissolved in the fuel.

3.5 Fuel Storage Tank

Fuel for testing is stored in a 750 gallon storage tank where it can be thermally conditioned to the desired initial temperature before being pumped into the test tank. This is accomplished via a temperature controller and a conditioning loop which contacts the same hot and cold primary brine loops as the wall temperature conditioning system.

The fuel is pumped into the tank via a centrifugal pump and throttle valve and is metered with a turbine flow meter which measures flow rate and total gallons. A flow rate of 100 GPM into the tank is possible. The fuel also passes through a 10 micron filter as it enters the test tank.

Fuel is removed from the test tank via a similar pump, throttle valve and flow meter. The outlet pump is also used to provide the fuel re-circulation flow which can be mixed with scrub gas in the scrub nozzle to scrub the fuel. Fuel level in the tank is calculated by the ModComp computer based on the difference between inlet and outlet totalizers.

3.6 Slosh and Vibration Table

The vibration table transmits vibration in the vertical axis to the test tank which is firmly fastened to the mounting surface of the vibration platform. The entire vibration platform can be rocked back and forth up to $\pm 15^{\circ}$, with or without vibration, causing fuel inside the test tank to slosh.

When vibration was used during a test, levels were maintained up to 10 mils at 50 Hz (1.35 g's). For UMV Test 3 (Slosh Mixing), two levels of slosh were used: 9 cpm, which produced a mild rotation of the tank around the fuel and a natural frequency slosh (40 cpm), which caused a very violent fuel motion.

3.7 Ullage Instrumentation System

The ullage gas in the fuel tank simulator was analyzed continuously during UMV testing via the use of a mass spectrometer. The entire system is termed the Ullage Instrumentation System (UIS) (Figure 5). Ullage gas is continuously transported from the test tank to the mass spectrometer. There are six separate samples (UIS probes 1, 2, 3, 4, 5 and 6) that are obtained in parallel. Any one of the six ullage gas sample streams can be analyzed in quick succession by the mass spectrometer via a selector valve. A calibration gas can also be selected for mass spectrometer set-up. The mass spectrometer provides data on the concentrations of nitrogen, oxygen, argon and hydrocarbons directly in percent by volume. Appendix A contains a detailed description of the mass spectrometer and its theory of operation.

It should be noted that the concentrations provided by the mass spectrometer are independent of the ullage pressure in the test tank. This is because the sample gas pressure at the actual entrance to the mass spectrometer is controlled at a constant temperature and pressure.

The vertical position of the ullage sample probes is controlled by the ModComp control and data acquisition computer. Two modes of probe positioning were available from the ModComp and were selected by the test engineer. The first mode controls the probe distance down from the tank top wall while the second mode controls the probe distance above the fuel surface. Note that probes 1-5 were mounted on hydraulic probe positioners and probe #6 was located in the vent line and was not moveable.

The ullage gas sample must travel approximately 60 feet as it is transported to the mass spectrometer, causing a delay of roughly 30 seconds. The mass spectrometer is therefore actually providing composition data on gas that was in the tank 30 seconds earlier. This 30 second delay was not corrected for in any data plots contained in this report. However, the delay is not believed to be significant for these tests because of the relatively slowly changing concentrations.

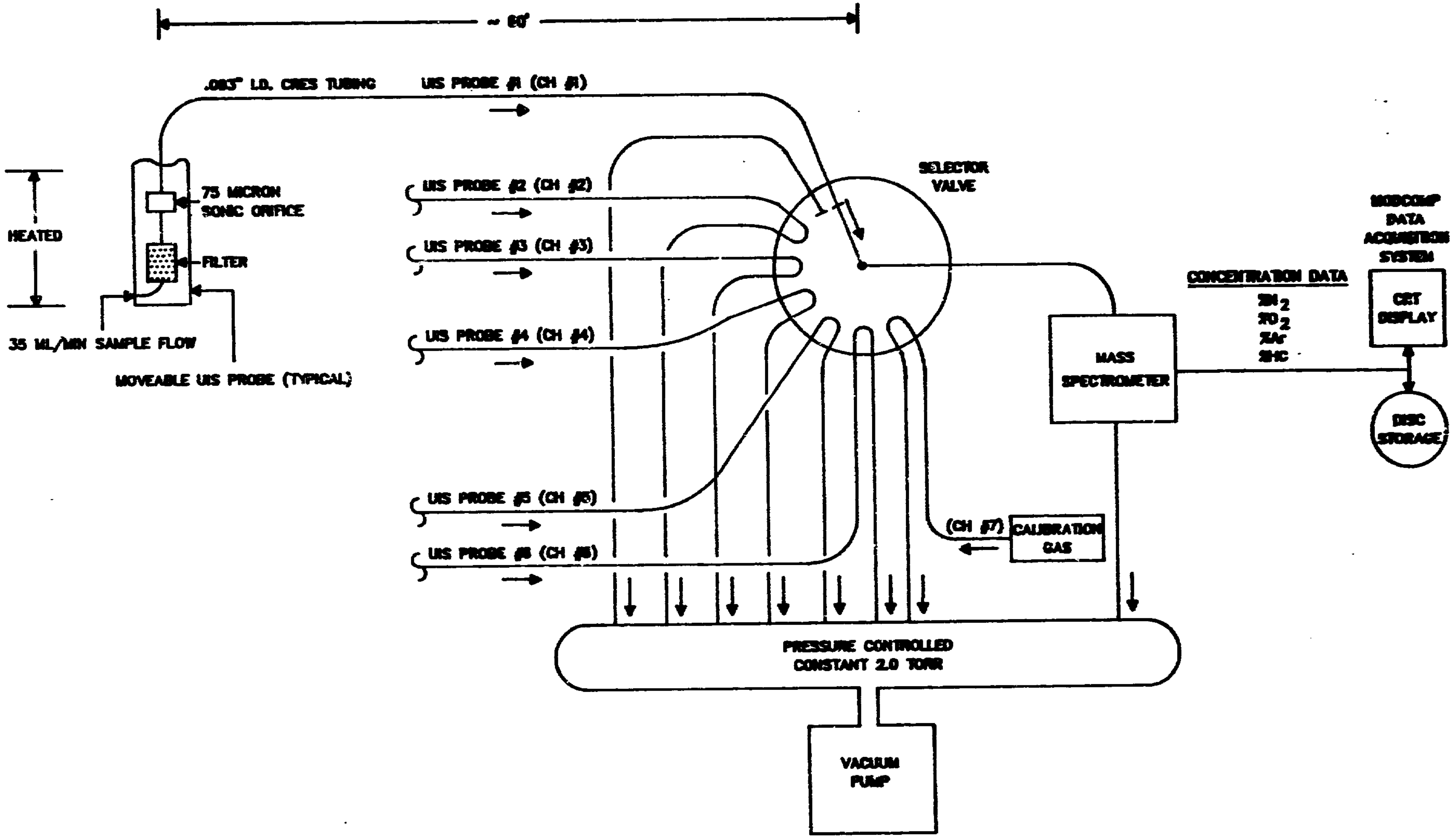


Figure 5. Ullage Instrumentation System Schematic

The accuracies of the individual constituent concentrations are inter-dependent due to automatic normalization of concentrations performed by the mass spectrometer. For example:

$$\text{Normalized } \%O_2 = \frac{\%O_2}{\%N_2 + \%O_2 + \%Ar + \%HC}$$

All five constituents are automatically normalized in this fashion so that the sum of all constituents is always equal to 100%.

The estimated accuracies achieved by the mass spectrometer for oxygen and hydrocarbons are as follows:

Constituent	Accuracy (Worst Case)
%HC	± 5% of Reading
$\%O_2$	± 3.5% of Reading

3.8 ModComp Control and Data Acquisition Computer

With the exception of slosh and vibration amplitude and frequency, all test data were obtained with a ModComp data acquisition system. The ModComp computer logged a wide array of variables obtained from the SAFTE instrumentation system. Ullage Instrumentation System (UIS) data such as $\%O_2$ and %HC were also logged by the ModComp, making it possible to have a complete picture of ullage composition and conditions. A list of data channels associated with the testing is given in Table 1. All data channels were recorded at preprogrammed intervals (disk log rate) during each test. The computer acquired data was displayed in real time on two CRT screens for monitoring by the test director. The real time information on the CRT screens could be used to check on any aspect of facility performance at any time. Printouts could be obtained for selected data points or for an entire UMV test. Data was first recorded temporarily on hard disk and later transferred to magnetic tape for permanent storage. The majority of the data from the UMV tests was analyzed after first being plotted on a flatbed plotter. Also, a routine was written that enabled data transfers from ModComp disk to IBM PC diskette for further analysis using Lotus 1-2-3 software.

Table 1. Variable List Logged by ModComp

Symbol	Description	Approximate Range
	Temperatures	
TW1DPM	Top Wall Temperature	-50 to 300°F
TW2DPM	Side Wall Temperature	-50 to 300°F
TW3DPM	Side Wall Temperature	-50 to 300°F
TW5DPM	Side Wall Temperature	-50 to 300°F
TW6DPM	Bottom Wall Temperature	-50 to 300°F
TULAGE	Single Point Ullage Temperature	-50 to 300°F
T-BULK	Average Bulk Fuel Temperature	-50 to 300°F
T-SURF	Fuel Surface Temperature	-50 to 300°F
TVENT1	Ullage Inlet Gas Temperature	-50 to 300°F
TFSTOR	Fuel Storage Tank Temperature	-50 to 300°F
	Pressures	
P-ALT	Simulated Altitude Pressure (Abs.)	0-25 psia
PSURGE	Simulated Fuel Tank Gauge Pressure	± 10 psig
	Flows	
GPM-IN	Fuel Inlet Flowrate	0-250 gpm
GPMOUT	Fuel Outlet Flowrate	0-60 gpm
GAL-IN	Total Fuel Gallons Pumped In	0-9999 gal.
GALOUT	Total Fuel Gallons Pumped Out	0-9999 gal.
WDM1	Make-up Gas Flowrate	0-1 lbs/min
WSCR	Scrub/Wash Gas Flowrate	0-1 lbs/min
	Gas Analysis	
OXPROD	$\%O_2$ by volume in Mixing Valve Product	0-100%
$\%{-}{-}{-}O_2$	$\%O_2$ by volume in ullage	0-100%
%---N2	%N2 by volume in ullage	0-100%
%---AR	%Ar by volume in ullage	0-100%
%---HC	%hydrocarbon by volume in ullage	0-100%
%--LEL	% of Lower Explosive Limit	0-100%
N-SCAN	Ullage Sample Probe Number (1-6)	N/A
MM--Px	Ullage probe distance from top wall of tank in mm (x= 1 to 5)	0-1000 mm
	Miscellaneous	
MMULAG	Ullage Size in millimeters	0-1000 mm
M-TIME	Mission Time in minutes	-4 to 9999 min

In addition to its data logging capability the ModComp was used to send setpoint commands to subsystem controllers. A computer data file called the Test Direction File (TDF) was created for each test and entered into the ModComp. The ModComp read subsystem variables from the TDF and then supplied them as setpoints to the controllers to control altitude pressure, wall temperature, fuel withdrawal rate and probe positions. The Test Direction File variable list is given in Table 2. In this way a complex multi-variable mission could be entered on a Test Direction File and the SAFTE test tank could be "flown" through a desired mission.

3.9 Test Facility Performance

Facility performance was especially critical during Mission Simulations (UMV Test 6), where the test tank was "flown" through a variety of airplane missions. Tank skin temperatures, altitude and fuel flow rates in the SAFTE were controlled by a ModComp II computer which was fed desired mission conditions via a Test Direction File. Comparison of set points with actual skin temperatures, altitudes and fuel burn rates logged by the ModComp was routinely compared to input setpoints to the SAFTE system for each mission to assure accurate simulation (Figure 6). Satisfactory agreement between actual tank conditions and input mission profiles indicates that the test tank actually "flew" the desired airplane mission.

TABLE 2. Test Direction File Variable List

DESCRIPTION		VARIABLE NAME
1.	Phase end time (minutes)	-
2.	Disk log interval of general data (sec)	-
3.	Altitude tank pressure (psia)	P-ALTSP
4.	Fuel tank wall T, two loops (^{o}F)	TLPASP,TLPBSP
5.	Fuel out flowrate (gal/min)	GPMSP
6.	Total fuel out (gal)	TOT-SP
7.	UIS probe positioning mode	-
8.	Disk log interval of UIS data (sec)	-
9.	Probe positions (mm)	MM--P1
		MM--P2
		MM--P3
		MM--P4
		MM--P5

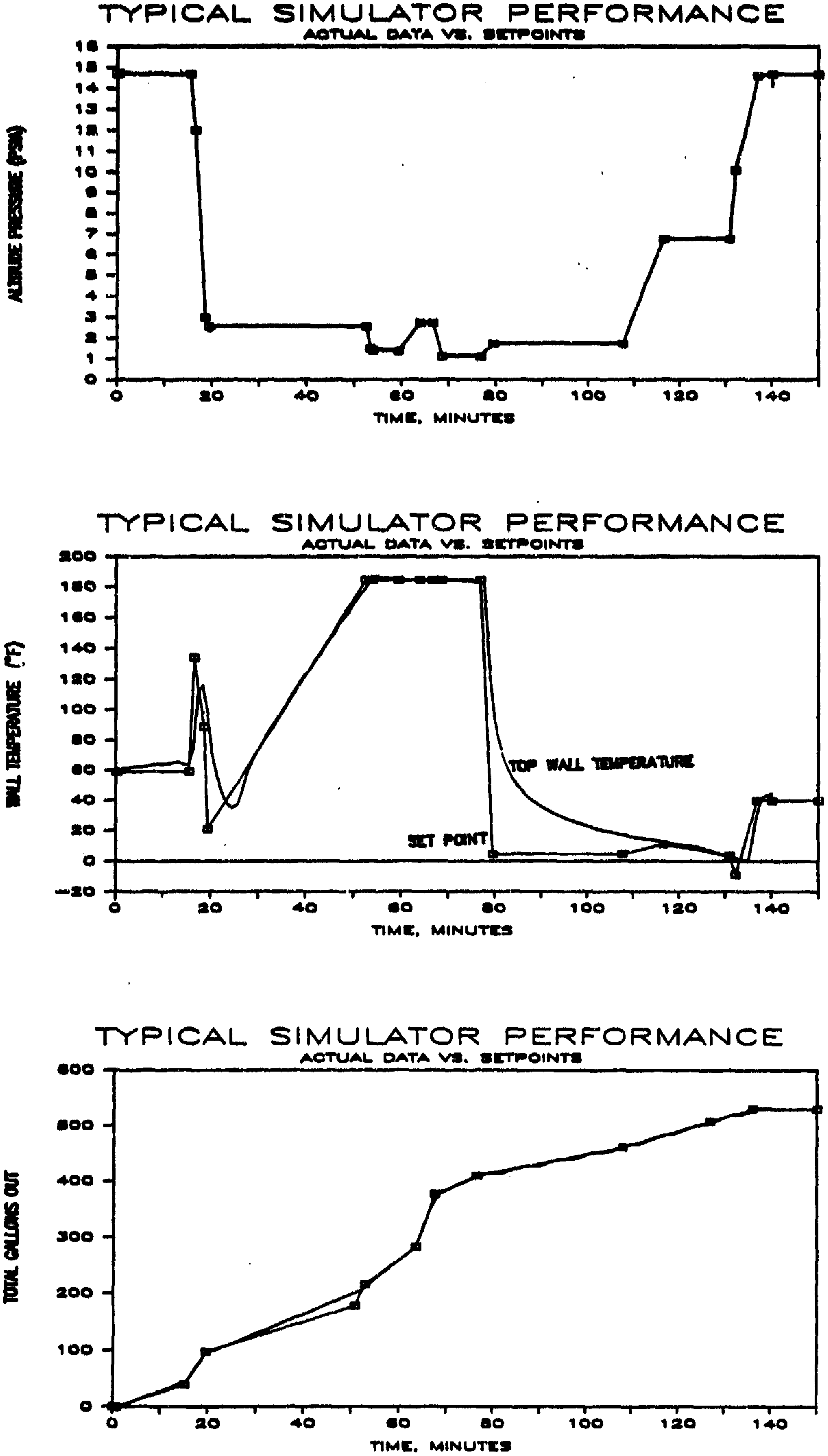


Figure 6. SAFTE Performance

4.0 ENVIRONMENTAL EFFECTS TESTS

4.1 Free Convection and Diffusion Driven Mixing (UMV Test 1)

4.1.1 Test Procedure

The following initial conditions were first established:

- Empty SAFTE tank, no baffles
- Relatively low fuel vapor concentration (weathered tank)
- Tank vented to ambient pressure (nominally 14.4 psia)
- No slosh or vibration
- Probes positioned at 50, 100, 200, 400 and 800 mm above the anticipated fuel surface
- Tank walls at temperatures specified in Test Matrix (Table 3)

Once the desired initial conditions were established, the test procedure was:

- Introduce small quantity (60 gal) of JP-4 into the test tank
- Seal tank to prevent vent flow
- Measure ullage gas composition (%HC) vs. ullage height as a function of time

4.1.2 Results

The following tests produced a stratified ullage with diffusion dominated mixing:

Test A - Isothermal
Test B - Hot top wall
Test C - Cold fuel
Test F - Hot top, cold bottom, hot probes
Test G - Hot top, cold bottom, cool probes

The following tests produced a well mixed ullage due to natural convection mixing:

Test D - Hot top wall, cold side walls
Test E - Cold top wall

Table 3. Wall Temperature Test Matrix - UMV Test 1

TEST	FUEL	TOP	BOTTOM	SIDES	COMMENTS
A	amb	amb	amb	amb	isothermal
B	amb	25^{o}>amb	amb	amb	hot top wall
C	25^{o}<amb	amb	25^{o}<amb	amb	cold fuel
D	amb	25^{o}>amb	amb	25^{o}<amb	hot top, cold sides
E	amb	25^{o}<amb	amb	amb	cold top wall
F	amb	25^{o}>amb	25^{o}<amb	amb	hot probes
G	amb	25^{o}>amb	25^{o}<amb	amb	cool probes

Note: All temperatures are in ^{o}F.

Tests A, B and C had either no thermal gradient or the reverse of the thermal gradient that was necessary to create natural convection currents (Figure 7, Tests A, B and C). Natural convection occurs when a higher surface is colder than a lower surface: warm gas rises from the lower surface due to decreased density, is cooled at the higher surface and with increased density sinks to the lower surface again (Figure 7, Tests D and E). These natural convection currents were sufficient to produce a well mixed ullage in Tests D and E. Due to the hot top wall in Test D, natural convection cells were only able to form on the side walls. This is evident in the slower mixing of the ullage in Test D. A temperature difference of only 25°F was sufficient to set up natural convection currents in the ullage which completely masked the much slower diffusion mixing.

The different nature of the convection cells in Tests D and E is reflected in plots of normalized percent hydrocarbon vs. distance above fuel surface (Figure 8). Some early stratification is evident in Test D although both Tests D and E were well mixed at t>90 minutes. Test E ullage mixed faster than Test D ullage because of Test D's less efficacious convection cells which were inhibited by the hot top wall.

It is not immediately obvious from the plots of normalized %HC vs. distance above fuel surface that a thin boundary layer of ullage existed at a very small distance above the fuel surface. Within the boundary layer, %HC was assumed to be %HC at equilibrium, which accounts for a normalized hydrocarbon concentration of 1 plotted on Figure 8 at 0 mm above fuel surface for all tests. Due to probe positioner constraints, the ullage could be sampled no closer than 50 mm above the fuel surface. In reality, the ullage in Test E was well mixed down to the boundary layer, which was very thin. This can be seen by the absence of a concentration gradient between 50 mm and 800 mm above fuel surface, indicating a well mixed bulk ullage. While natural convection currents mix the bulk ullage, diffusion is the only mass transfer process for hydrocarbon in the boundary layer at the fuel surface. Diffusion is a slow process and it controlled the rate of change of percent hydrocarbon in the ullage for both diffusion dominated mixing cases and, due to the boundary layer, natural convection mixing cases. In the case of Tests D and E, where natural convection dominated diffusion in the bulk ullage, the presence of the boundary layer didn't allow hydrocarbon equilibrium throughout the tank (normalized %HC = 1) until t≈150 minutes.

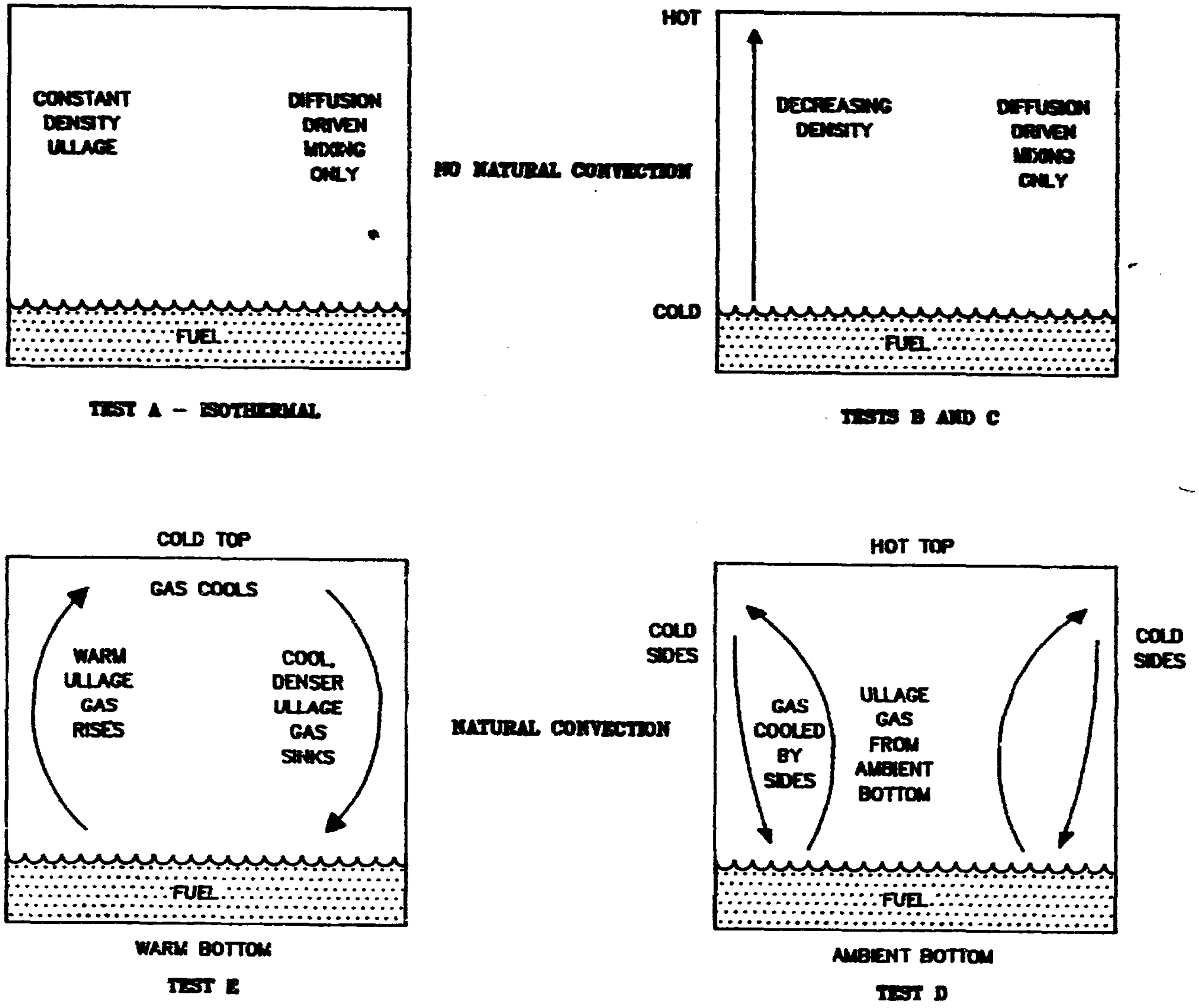


Figure 7. Natural Convection and Diffusion Mixing Diagrams

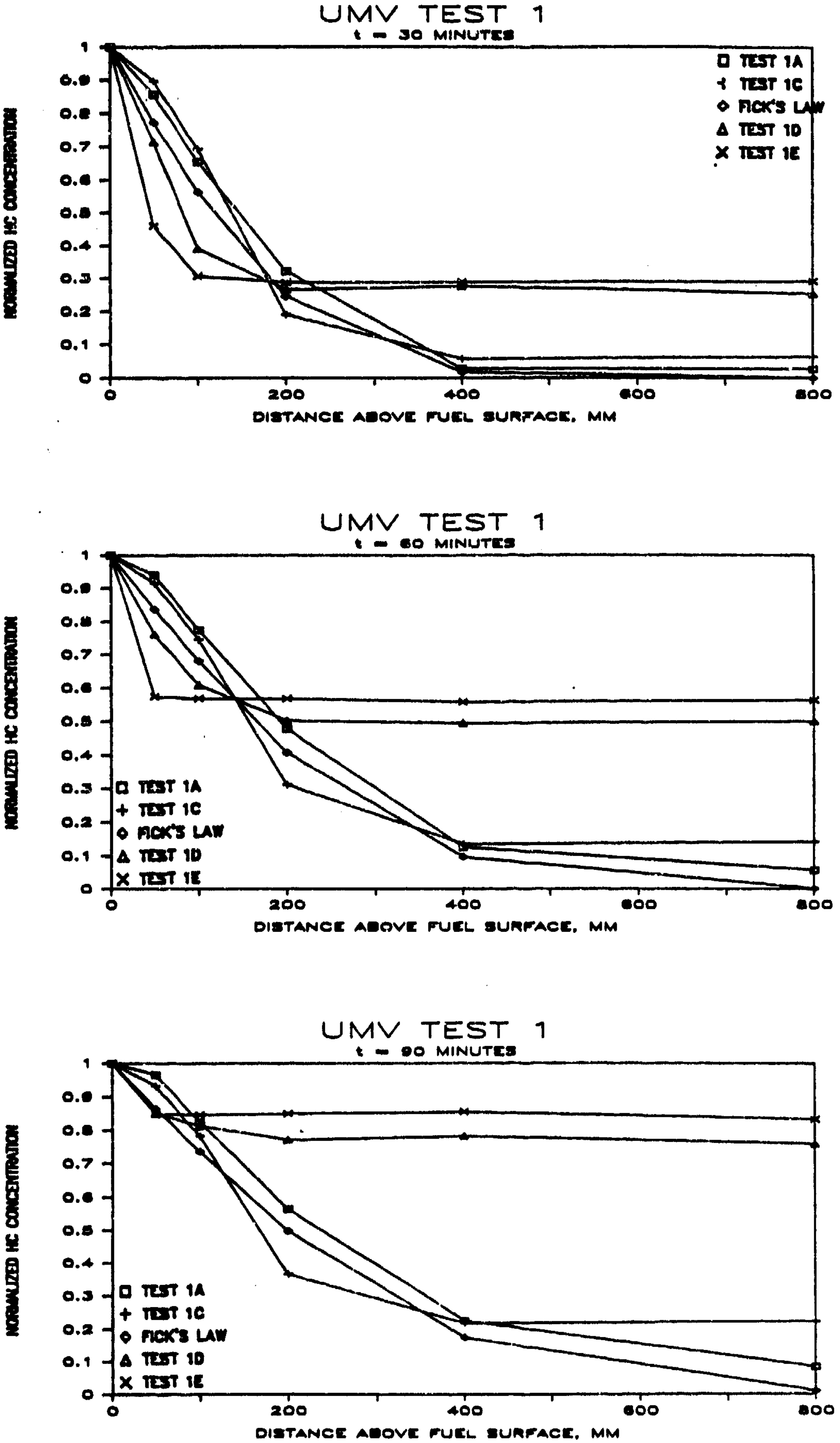
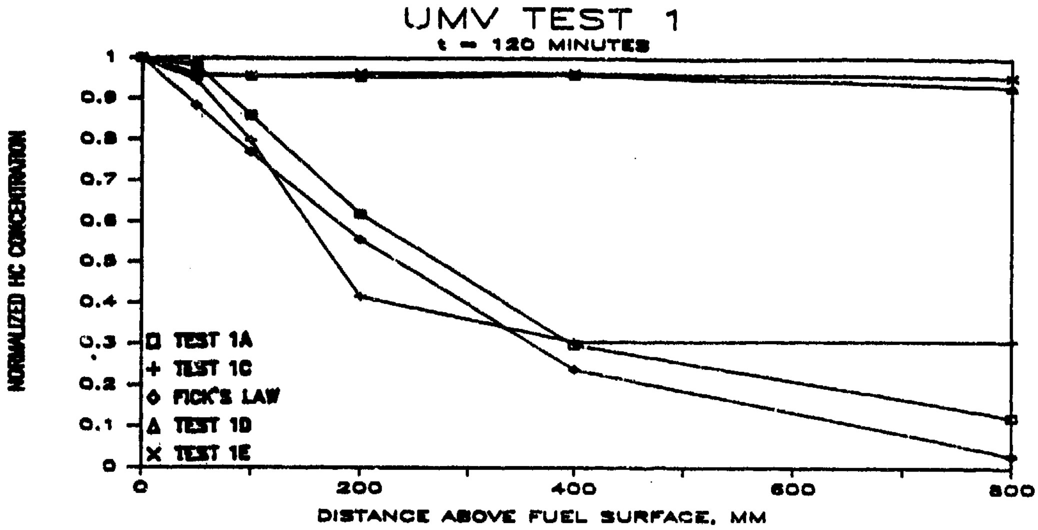
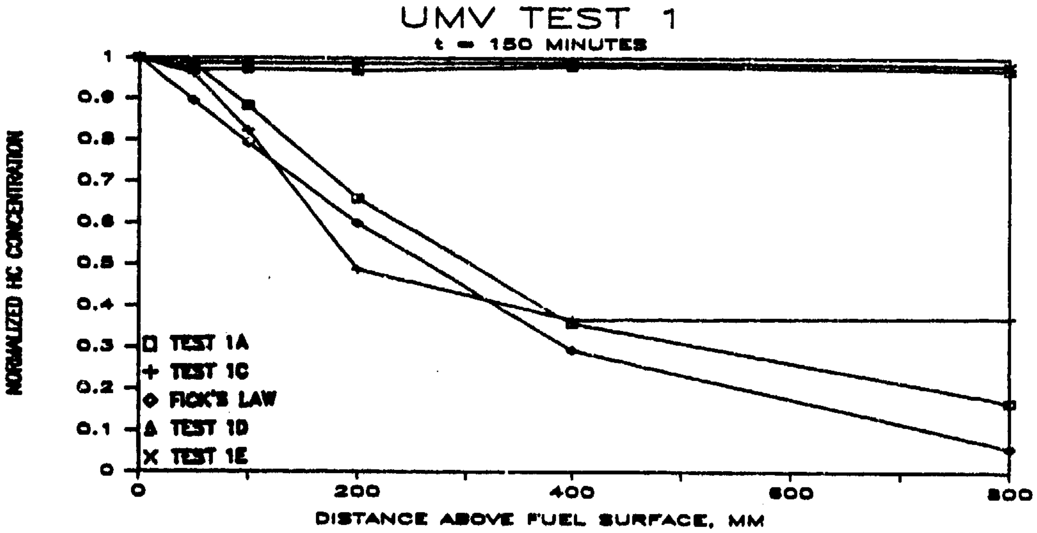


Figure 8. Free Convection and Diffusion Driven Mixing Normalized Hydrocarbon Concentration Profiles (1 of 2)





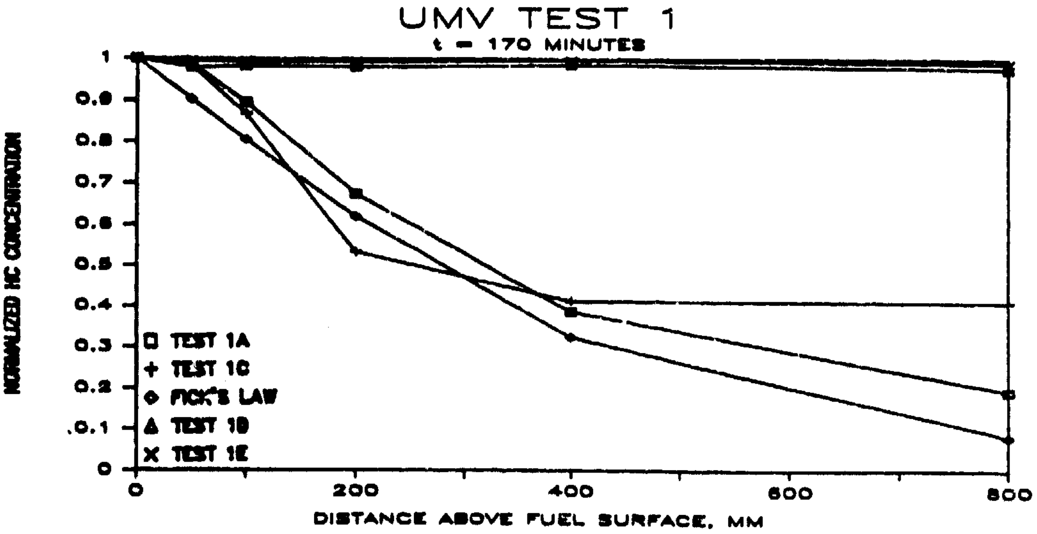


Figure 8. Free Convection and Diffusion Driven Mixing Normalized Hydrocarbon Concentration Profiles (2 of 2)

These normalized percent hydrocarbon vs. distance above fuel surface plots (Figure 8) also include Test A and Test C. Stratification is clearly evident, even to t=170 minutes, indicating a slow mixing process. To determine if this mixing was diffusion dominated, a Fick's law equation is also plotted.

Fick's 2nd law states: $\frac{dC}{dt} = \frac{Dd^2C}{dx^2}$ (Reference 6)

where

D = diffusion coefficient
C = concentration
x = distance above fuel surface
t = time

Further discussion of Fick's law and the derivation of a finite equation used in a computer model for comparison with experimental data is found in Appendix B.

The Fick's law equation assumes no ullage gas movement and that all ullage mixing is due to diffusion. This pure diffusion case is shown on the normalized hydrocarbon concentration vs. distance above fuel surface plots (Figure 8). Test A follows Fick's law closely while Test C indicates the presence of some ullage gas movement which increased the rate of ullage mixing. It is clear, however, that mixing was diffusion dominated in Tests A and C and was natural convection dominated in Tests D and E.

Figures in this report show normalized hydrocarbon concentration vs. distance above fuel surface or time. Normalizing in this case meant dividing percent hydrocarbon data by equilibrium percent hydrocarbon for each test. This eliminates the effect of bulk fuel temperature differences between tests and enables a clear look at stratification and comparison of the tests to each other and to Fick's law.

Fick's law and data from Tests A, C, D, E, F and G are also plotted on Figure 9. These are plots of normalized hydrocarbon concentration difference ("bottom" - "top") vs. time. They are intended to demonstrate that stratification persisted longer in Tests A, C, F and G (diffusion mixing) and that ullage mixing occurred relatively rapidly in Tests D and E (natural convection). These figures show how closely Fick's law was followed by diffusion tests but also show what seems to be a significant degree of top to bottom hydrocarbon stratification early in the natural convection tests.

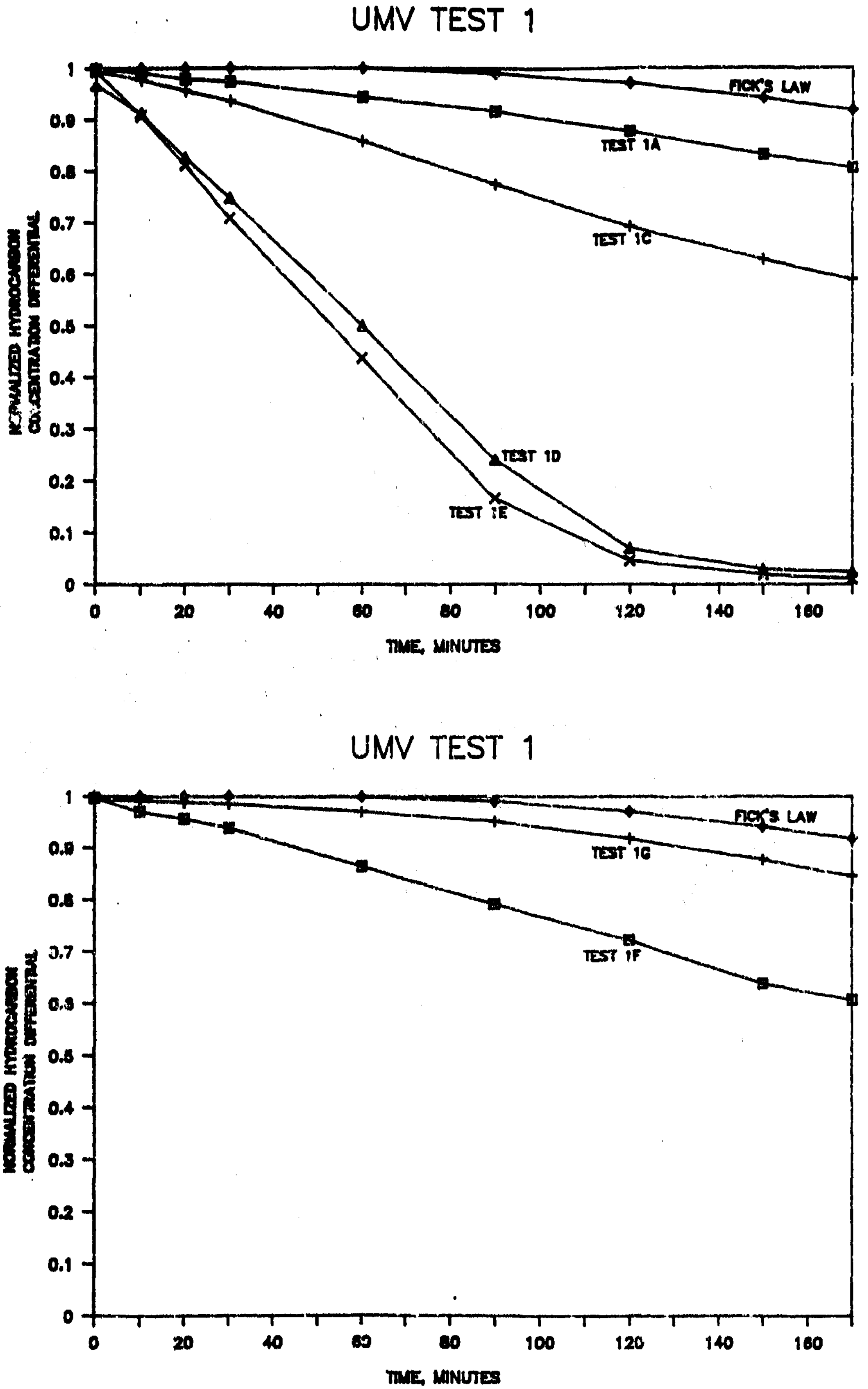


Figure 9. Free Convection and Diffusion Driven Mixing Normalized Hydrocarbon Concentration Differential

Since the probe nearest to the fuel surface was located at 50 mm above the fuel surface, a value of 1 was used for the normalized hydrocarbon concentration at the fuel surface ("bottom"). This value of 1 was arrived at when %HC was assumed to be at the equilibrium value within the boundary layer at the fuel surface. %HC at equilibrium was determined experimentally from UIS data at the end of a test while using a mixing fan in the ullage. Probe data at 800 mm was used for the "top" value. The apparent hydrocarbon stratification present in the natural convection tests resulted from the use of 1 as the theoretical normalized hydrocarbon concentration at the fuel surface. As mentioned previously, diffusion is the only mode of mass transport in the boundary layer and %HC in the bulk ullage increased at a rate that is diffusion controlled. Therefore, the significant normalized hydrocarbon concentration differential in Tests D and E just reflects the fact that the %HC in the bulk ullage was less than the %HC at equilibrium until $t > 120$ minutes. The bulk ullage in natural convection Tests D and E was well mixed and no true stratification existed in the ullage outside the boundary layer as confirmed in Figure 8.

Tests F and G were performed to study the effect of probe temperature on diffusion-type mixing. Ullage mass spectrometer probes are mounted on 2" diameter hydraulic cylinders which can move up and down, positioning probes where desired. Since these cylinders protrude into the tank and were heated (~200°F) to avoid ullage gas condensation in the sample lines, it was thought that the high temperature of the hydraulic cylinders induced some natural convection currents, mixing an ullage faster than a pure diffusion driven mixing case.

Both Tests F and G were run with identical "diffusion conditions" wall temperatures: hot top wall and cold bottom wall. Test F used hot probes set at their normal operating temperature, 200°F. Test G used cool probes at about 90°F.

Early in the test, both F and G concentration gradients adhered closely to Fick's law. As t increased, however, Test F (hot probes) deviated more from Fick's law, indicating the presence of some ullage gas movement. This led to the conclusion that probe temperature does indeed have an effect on mixing when diffusion is the otherwise dominant mixing mechanism (Figure 9).

Diffusion dominated mixing conditions were difficult to establish and maintain on the SAFTE tank, especially with large ullage volume. Even relatively small surfaces (such as the ullage mass spectrometer probes), under the proper temperature conditions, caused natural convection to occur and mask diffusion mixing. Still, diffusion can be selected as the dominant mixing mechanism if certain wall temperature conditions are satisfied:

- hot top wall
- cold bottom wall/cold fuel
- isothermal

If a cold top wall or hot bottom wall/hot fuel is present, natural convection currents will be created and the ullage will be well mixed. All of the surfaces exposed to the ullage gas must be considered when attempting to determine the dominant mixing mechanism in the ullage. Top skin, fuel surface, side walls, rib & spar-webs, plumbing etc. may all play a role in causing significant natural convection. As shown in the difference between Tests F and G, where only probe temperature was varied, even relatively small surfaces can cause natural convection to occur.

4.2 Forced Convection (UMV Test 2)

4.2.1 Test Procedure

The following initial conditions were first established:

- SAFTE Tank JP-4 level <u>Test V and F</u> <u>Test S</u>
  54% 90%
- Well mixed ullage
- %HC = equilibrium %HC throughout tank
- Temperatures set according to test matrix (Table 4)
- Gas stream orientation set according to test matrix
- No slosh or vibration
- Test tank vented to altitude tank (nominally 14.7 psia)

After establishing initial conditions:

- Take data to confirm well mixed ullage
- Begin fuel withdrawal
- Measure ullage gas composition vs. time
- Maintain constant ullage pressure during fuel withdrawal
- End fuel withdrawal at time specified in Test Matrix
- Seal tank to prevent vent flow
- Continue taking data until t = 170 minutes

The test nomenclature code is repeated here for reference:

Test nomenclature example:

```
WACH
||||----gas stream orientation (H-horizontal, V-vertical)
|||-----top wall temp.(A-ambient,C-cold(25°F<amb),H-hot(25°F>amb))
||------gas stream temp.(A-ambient,C-cold(25°F<amb),H-hot(25°F>amb)
|-------test type(V - 54% fuel @ 5 gpm withdrawal, F - 54% fuel @
                    50 gpm withdrawal, S - 90% fuel @ 5 gpm withdrawal)
```

Table 4. UMV Test 2 Test Matrices

Test Matrix - 5 GPM withdrawal from t=0 to t=50 min., (Test V)

	Gas Stream T	Top Wall T	Gas Stream Orientation
VAAH	Amb	Amb	Horizontal
VCAH	Cold	Amb	Horizontal
VACH	Amb	Cold	Horizontal
VAHH	Amb	Hot	Horizontal
VAAV	Amb	Amb	Vertical

Test Matrix - 50 GPM withdrawal from t=0 to t=5 min., (Test F)

	Gas Stream T	Top Wall T	Gas Stream Orientation
FAAH	Amb	Amb	Horizontal
FACH	Amb	Cold	Horizontal

Test Matrix - 5 GPM withdrawal from t=0 to t=5 min.,
small ullage, (Test S)

	Gas Stream T	Top Wall T	Gas Stream Orientation
SAAV	Amb	Amb	Vertical
SACV	Amb	Cold	Vertical

4.2.2 Results

All W tests (5 gpm withdrawal for 50 minutes) except WACH showed stratification increasing during fuel withdrawal until there was a large normalized hydrocarbon differential at t = 50 minutes (Figure 10). Isotime plots of normalized HC concentration or $\%O_2$ vs. distance above fuel (Figure 11) also demonstrate the stratification present in Tests WAHH, WAAV, WCAH, WAAH at any time and show the well mixed nature of the bulk ullage in Test WACH (cold top wall).

From the isotime plots for WACH (Figure 11) it can be understood that the small top to bottom concentration differential at t = 50 minutes for WACH (Figure 10) was due to the presence of a boundary layer probably no more than a few millimeters thick and that at t = 50, $\%HC_{\text{bulk ullage}} < \%HC_{\text{equilibrium}}$. The bulk ullage was well mixed.

After t = 50 (inlet gas shutoff, fuel withdrawal shutoff), the ambient or hot top wall tests mixed following Fick's law fairly closely (see WAAH, WAAV, WCAH, WAAH on Figure 10). This indicates diffusion dominated mixing which was expected from the results of UMV Test 1. Since diffusion mixing was dominant in Tests WAHH, WAAV, WCAH and WAAH, the inlet gas stream stratified ullage persisted and was mixed very slowly. Fick's law is plotted on Figure 10 only for t >50 because forced convection due to fuel withdrawal (0<t<50) completely dominated diffusion mixing (a slow process) and stratified the ullage. The Fick's law program from UMV Test 1 was modified to accommodate non-zero initial conditions and was used to generate the Fick's law line. The Fick's law initial hydrocarbon concentration profile in the tank was obtained from WAAH test data at t = 50 minutes.

In the WACH case, natural convection currents were present due to the cold top wall. Natural convection mixing, which masked diffusion driven mixing in UMV Test 1, also dominated the stratifying effect of the gas inlet and a well mixed bulk ullage was maintained during and after forced convection in the WACH test.

The ambient or hot top wall tests, where no natural convection was present, showed that an inlet gas stream (at this flow rate and ullage size) is a stratifying force. The WACH test showed that a cold top wall and the resulting natural convection is a powerful enough mixing force to overcome the stratifying

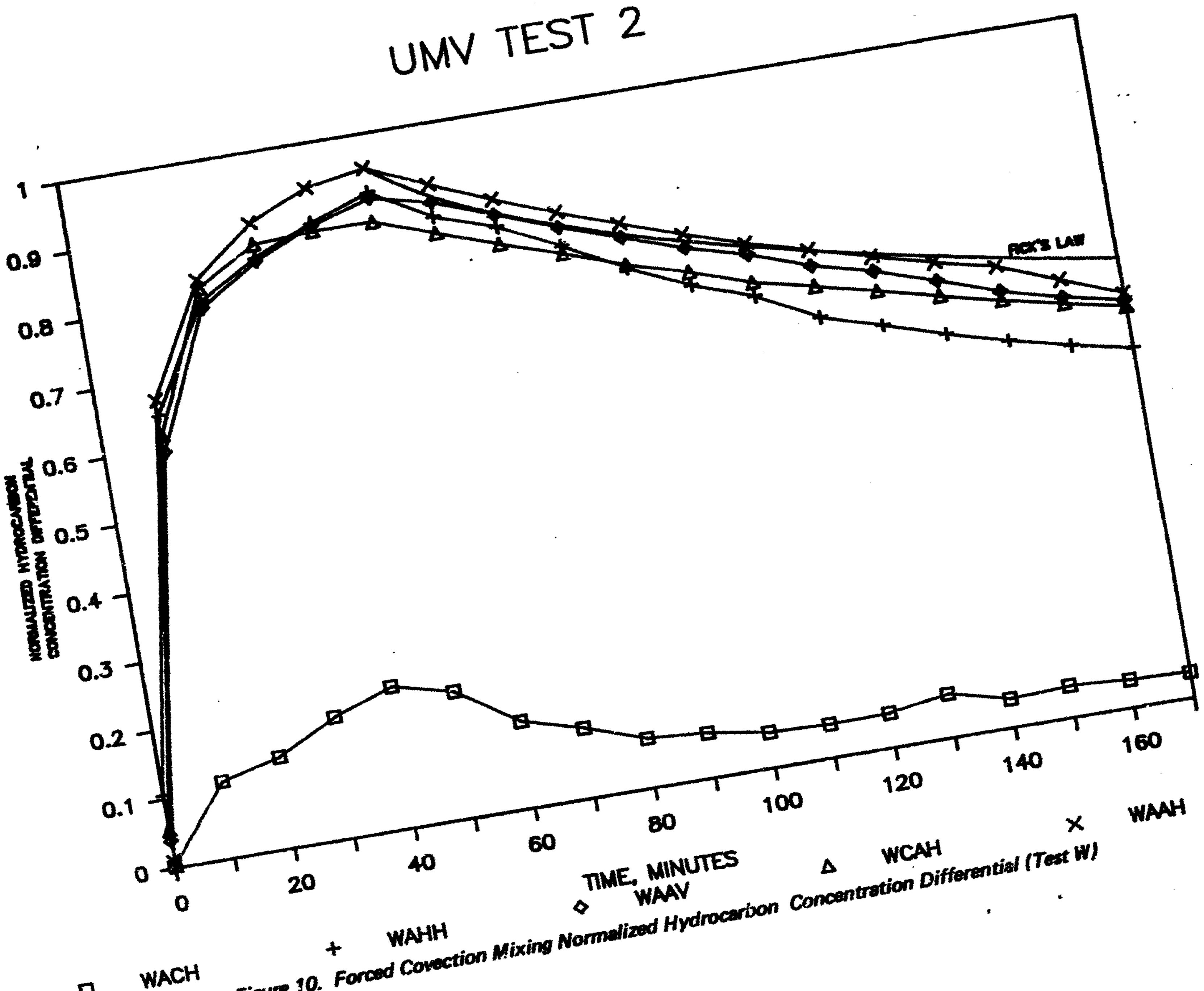


Figure 10. Forced Covection Mixing Normalized Hydrocarbon Concentration Differential (Test W)

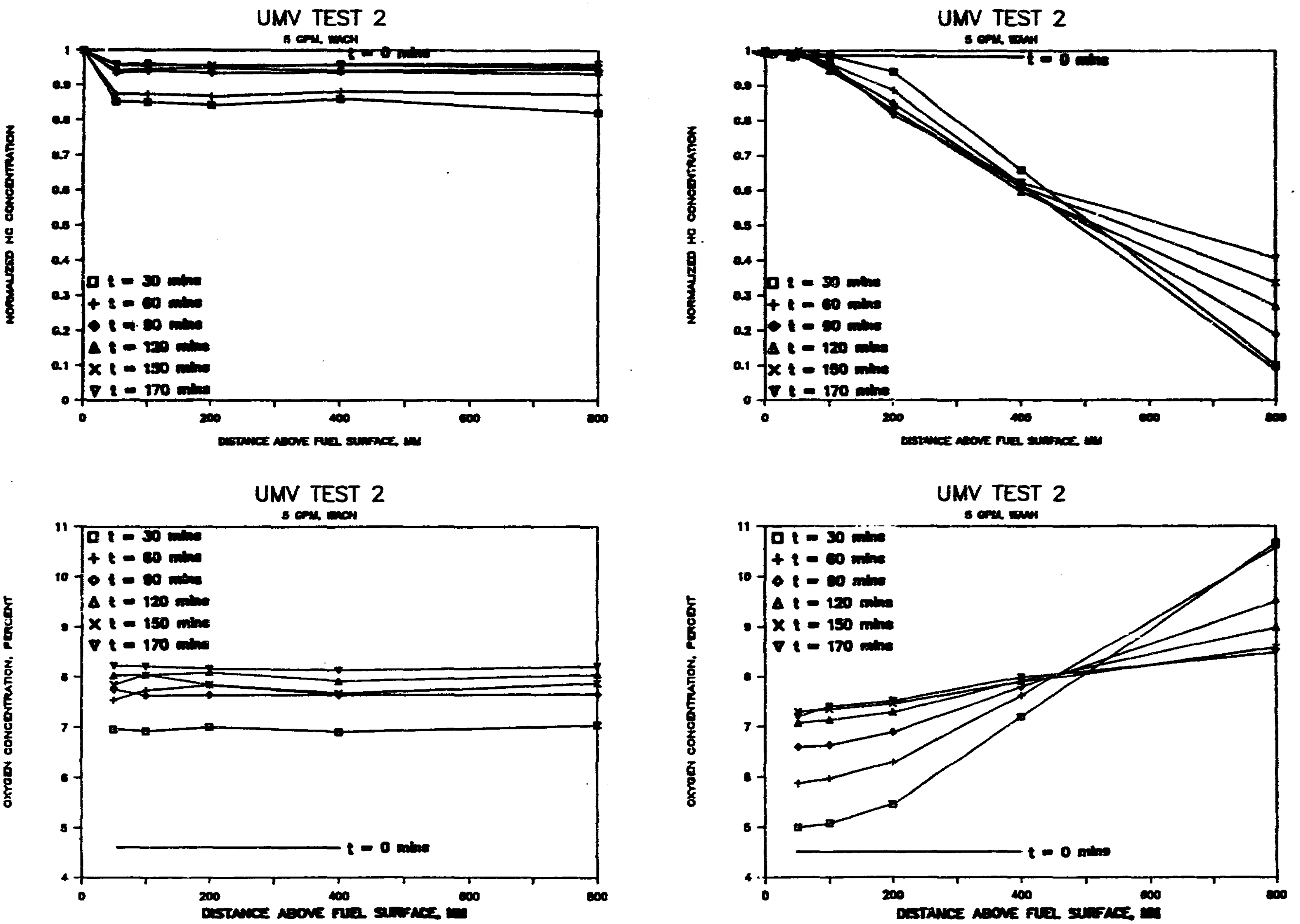


Figure 11. Forced Convection Mixing Ullage Oxygen and Hydrocarbon Concentration Profiles (Test W) (1 of 3)

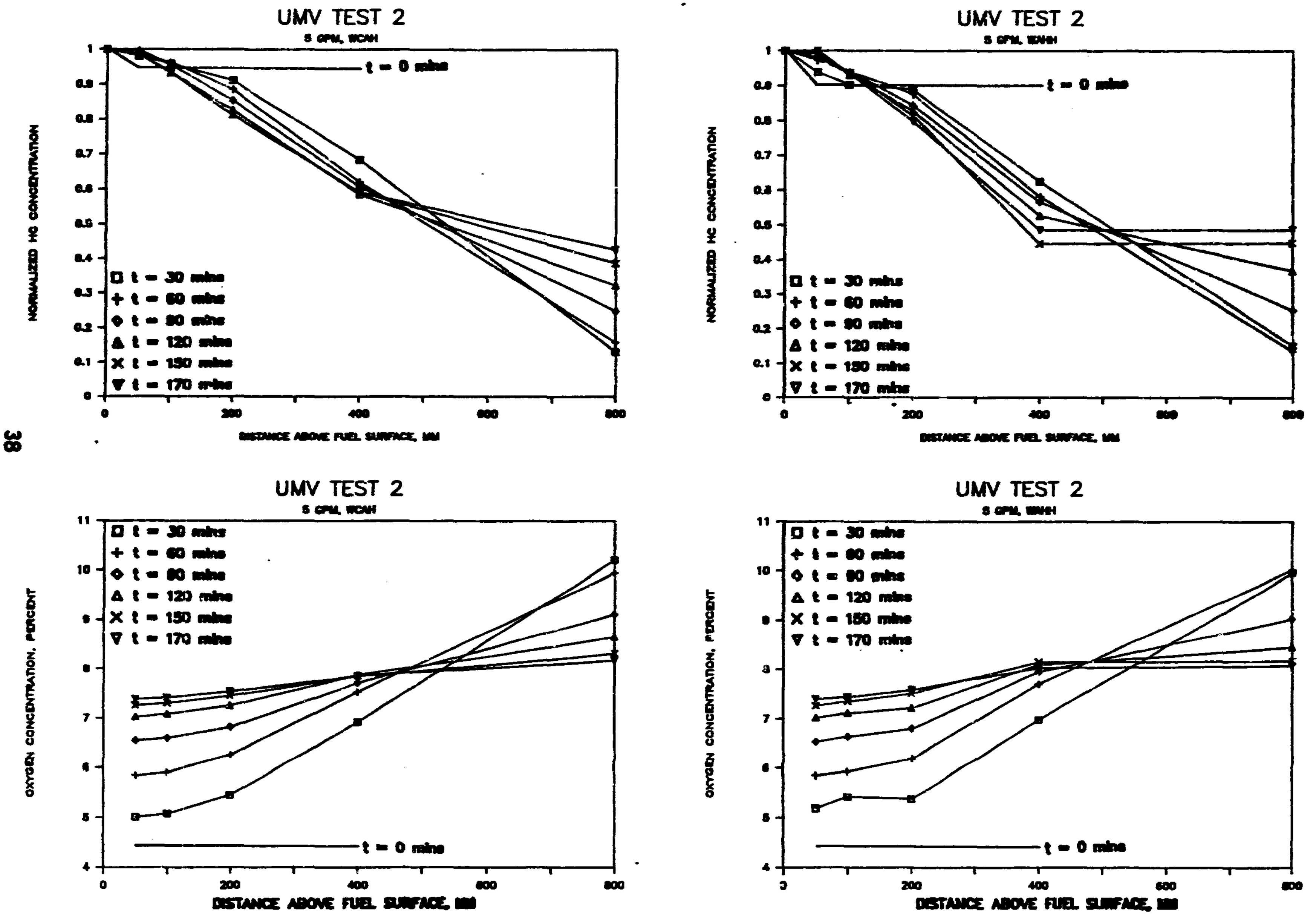


Figure 11. Forced Convection Mixing Ullage Oxygen and Hydrocarbon Concentration Profiles (Test W) (2 of 3)

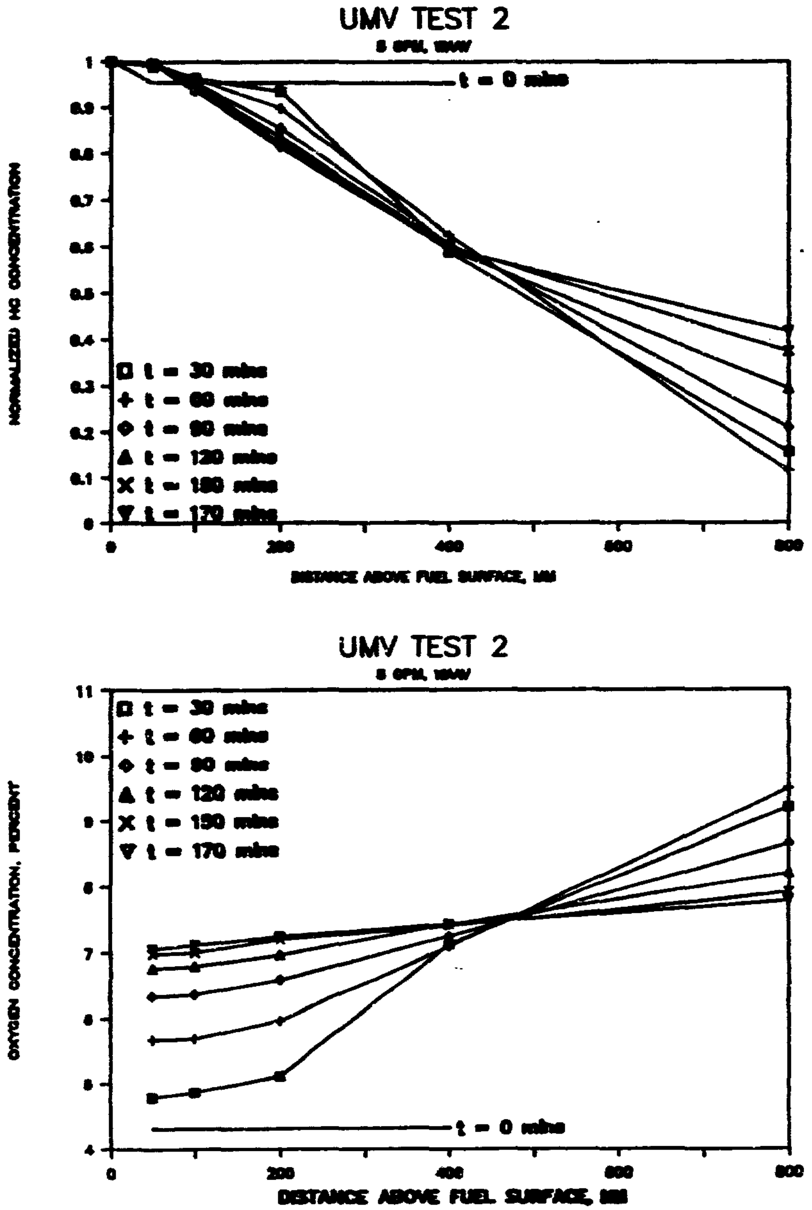


Figure 11. Forced Convection Mixing Ullage Oxygen and Hydrocarbon Concentration Profiles (Test W) (3 of 3)

effect of the inlet gas stream. Since diffusion mixing only was present in Tests VAHH, VAAV, VCAH and VAAH, the inlet gas stream stratified ullage persisted and was mixed very slowly.

In the F tests (50 gpm fuel withdrawal for 5 minutes), the gas inlet stream was a more dominant stratifying force during the 5 minutes of fuel withdrawal. At t = 5 minutes (end of fuel withdrawal), stratification was almost as pronounced in the FACH case (cold top wall) as in the FAAH case (ambient top wall) (Figure 13). The top to bottom normalized HC concentration differential was not due just to the boundary layer because a concentration gradient in the bulk ullage existed for both FAAH and FACH (Figure 12). Natural convection in the FACH case soon mixed the ullage after the inlet vent gas stream was shut off. However, the 50 gpm inlet gas stream stratifying force was powerful enough to mask natural convection as well as diffusion in contrast to the 5 gpm (W) tests, where natural convection mixing present in the cold top wall (WACH) test dominated gas inlet stratification and the bulk ullage remained well-mixed.

It is evident that fast gas inlet stratification almost completely masks natural convection mixing (due to cold top wall) as well as diffusion mixing. At t > 5 minutes (after fuel withdrawal was complete) Fick's law is plotted and natural convection mixing is evident in FACH while mixing in the FAAH case was diffusion dominated (Figure 13). Fick's law initial hydrocarbon concentrations were obtained from FAAH data at t=5 minutes.

Two tests using a 5 gpm inlet gas flow rate with a small ullage space were performed (S tests) because it was thought that a slow (5 gpm) vertical gas inlet into a small ullage space might cause less stratification due to the inlet vent gas. Turbulence in the ullage, due to the vertical gas stream, would cause forced convection mixing in the ullage and the bulk ullage would remain well mixed.

Percent O_2 and normalized HC concentration vs. distance above fuel surface is plotted (Figure 14). The ambient top wall test (SAAV) stratified while the cold top wall test (SACV) remained well mixed due to natural convection. Turbulent, forced convection mixing didn't have any greater effect on the small ullage than on the larger ullage that was tested. The S and W tests vent gas flow rate (5 gpm) didn't dominate the natural convection present in the cold top wall tests (WACH, SACV). Stratification persisted in the SAAV (amb top wall) test

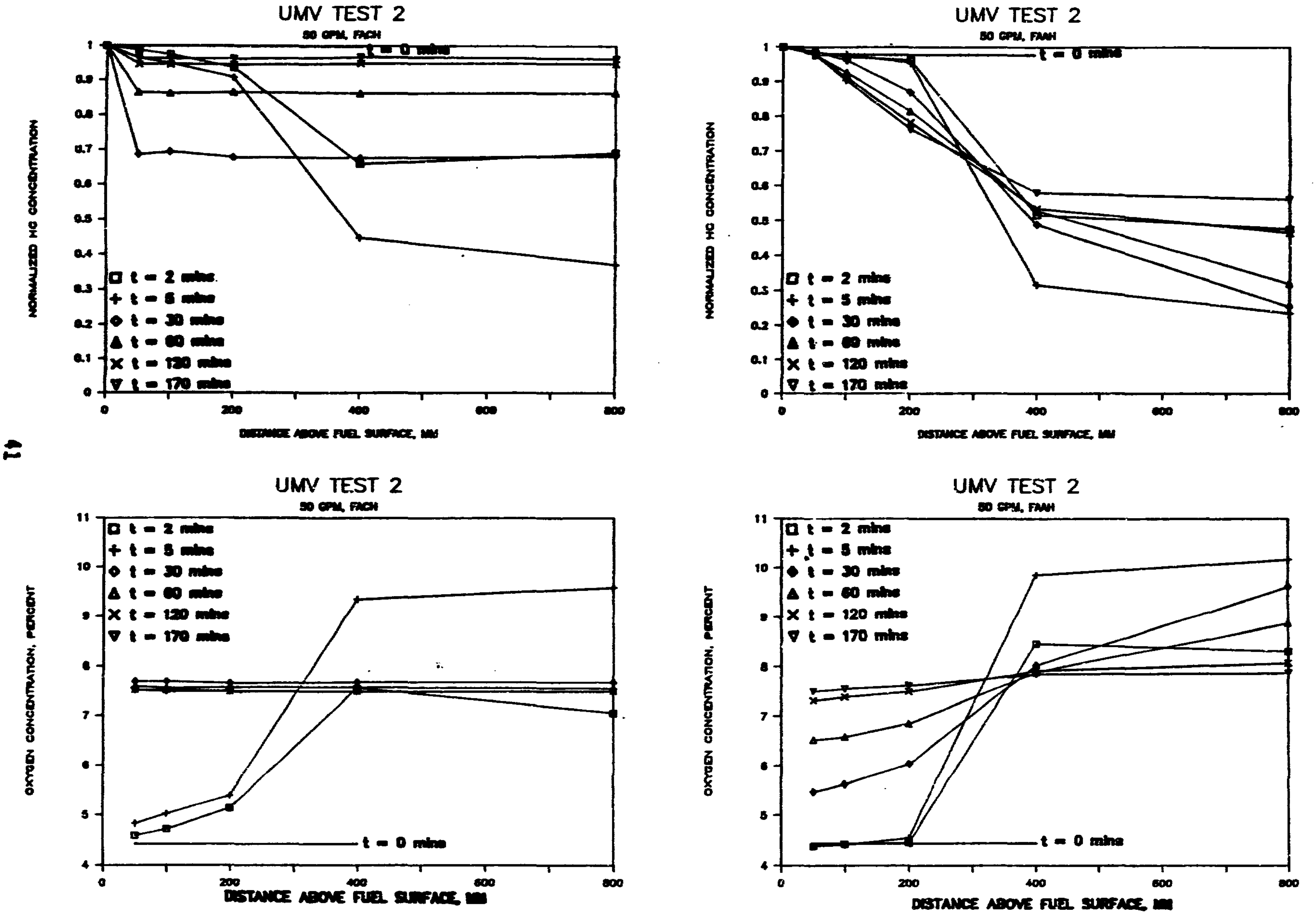


Figure 12. Forced Convection Mixing Ullage Oxygen and Hydrocarbon Concentration Profiles (Test F)

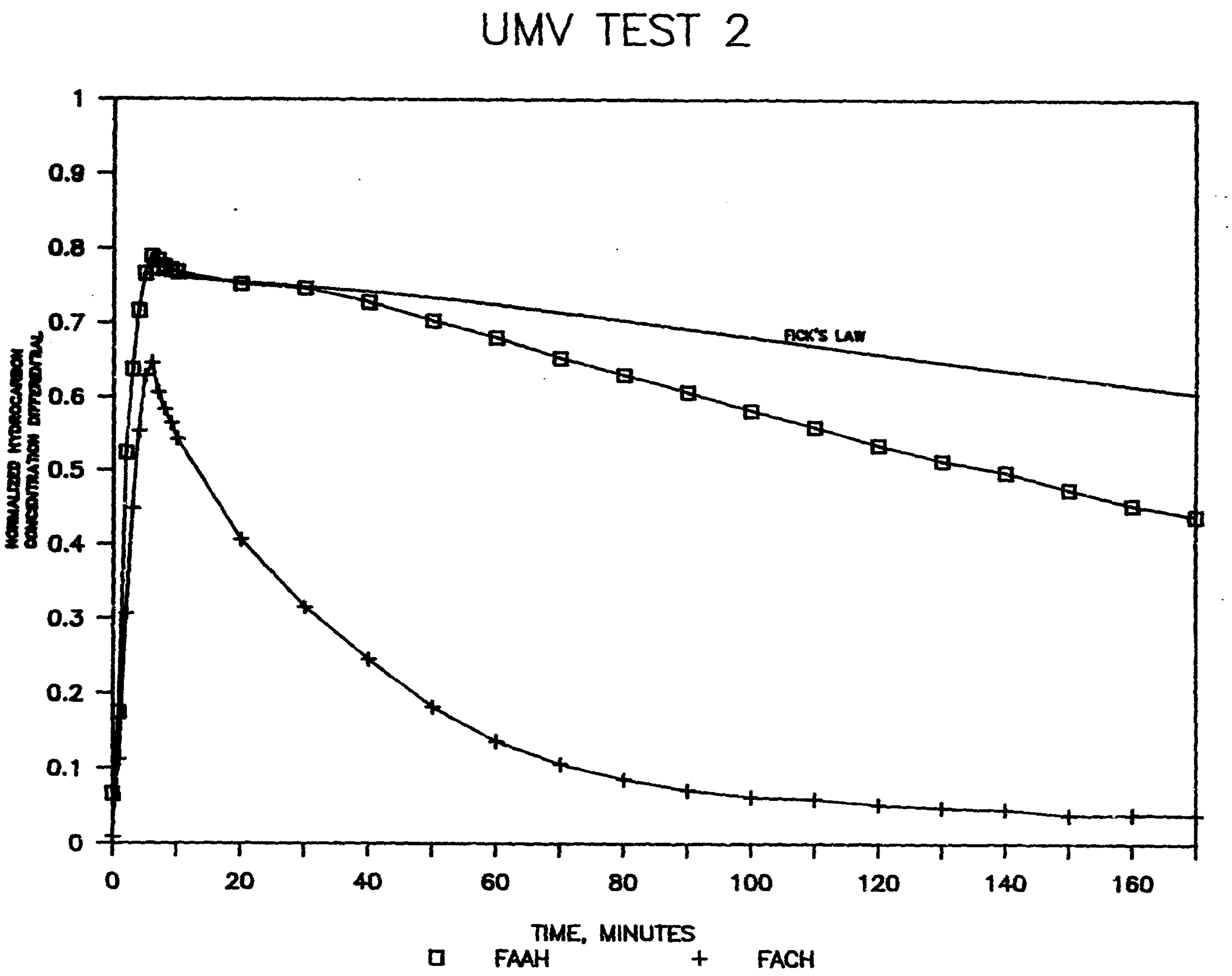


Figure 13. Forced Convection Mixing Normalized Hydrocarbon Concentration Differential (Test F)

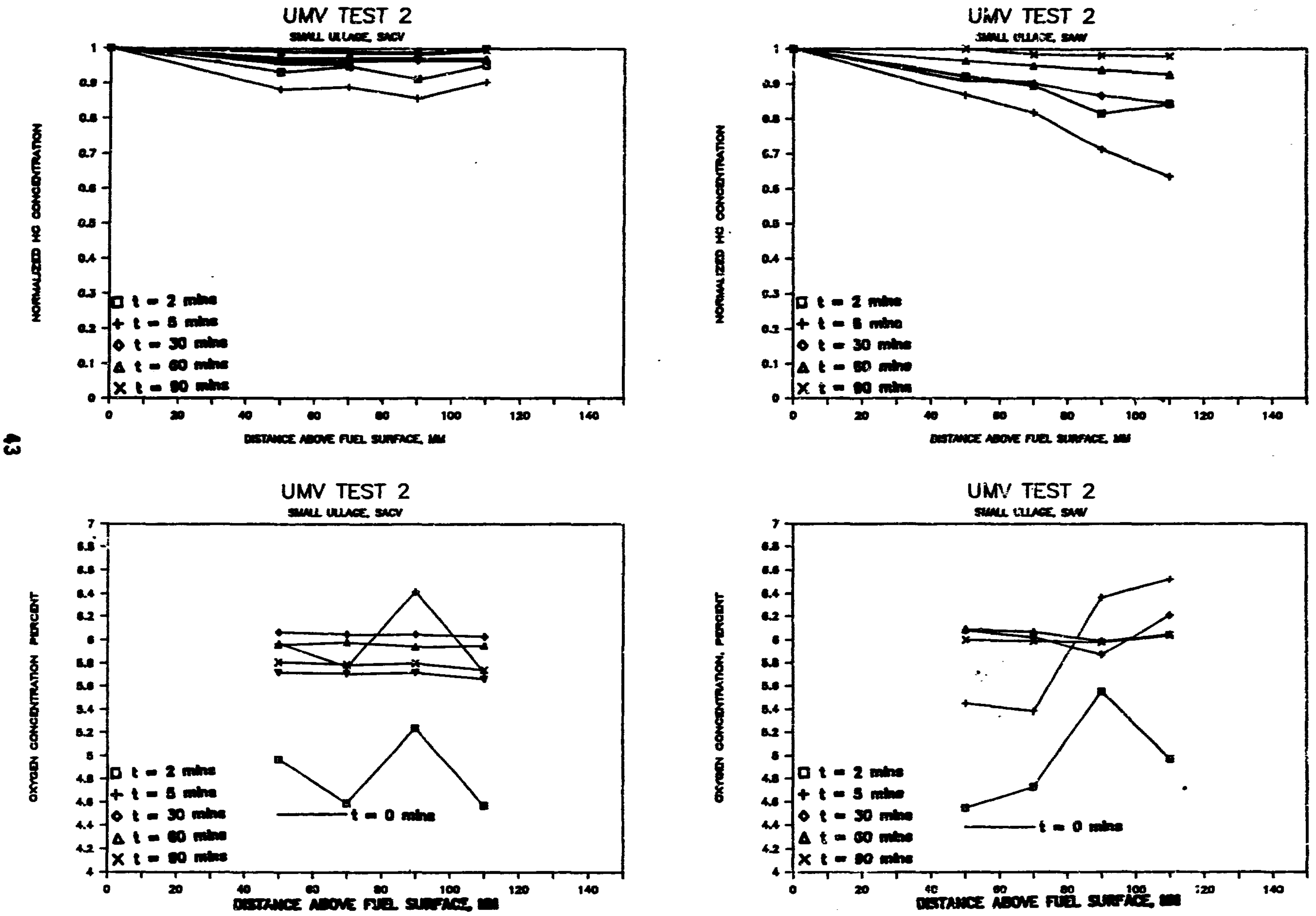


Figure 14. Forced Convection Mixing Ullage Oxygen and Hydrocarbon Concentration Profiles (Test S)

after inlet vent gas shutoff because diffusion was the dominant mixing force. The ullage in the SACV (cold top wall) test was well mixed and the presence of the small top to bottom concentration differential is due to the boundary layer effect (Figure 15). Fick's law (initial conditions - SAAV data at t=5 minutes) is plotted after t = 5 minutes and diffusion mixing only is evident in the SAAV test. It appears that SAAV mixed more slowly than diffusion would predict. This is probably due to the fact that the Fick's law program accounts for only z direction concentration gradient while it is probable that concentration gradients actually occurred in the x, y and z directions during a SAFTE simulation and this condition was exacerbated by the small ullage size.

It is apparent that a gas stream inlet during fuel withdrawal tended to stratify the ullage. The turbulence afforded by a high velocity gas inlet stream did not lead to a well mixed tank; rather high velocity was perceived to lead to more pronounced masking of natural convection and diffusion mixing. The low (5 gpm) gas flow rate tests showed that natural convection mixing masked gas inlet stratification. The 50 gpm inlet gas flow rate tests showed that gas inlet stratification masked both natural convection mixing and diffusion mixing. After the completion of the fuel withdrawal, mixing (either natural convection or diffusion) occurred as observed in UMV Test 1 according to the wall temperature conditions. That is, a cold top wall promoted natural convection where a hot or ambient top wall led to ullage mixing via diffusion.

The combinations studied in UMV Test 2 did not cover large temperature differences between inlet vent gas, ullage and top wall. It is possible that a very cold top wall will promote natural convection mixing to such an extent that no vent gas stream could mask it and stratify the ullage. Also, it is possible that a vent gas much colder than the ullage may have a forced convection mixing effect and not stratify the ullage at all. UMV Test 2 showed that an inlet vent gas stream was an ullage stratifying force at the small temperature difference conditions that are shown in the Test Matrix (Section 4.2.1).

4.3 Slosh Mixing (UMV Test 3)

4.3.1 Test Procedure

Two kinds of slosh were studied in UMV Test 3 (Table 5). Nine cycles per minute slosh at ± 10° produced a mild tank rotation around the fuel (the fuel remained

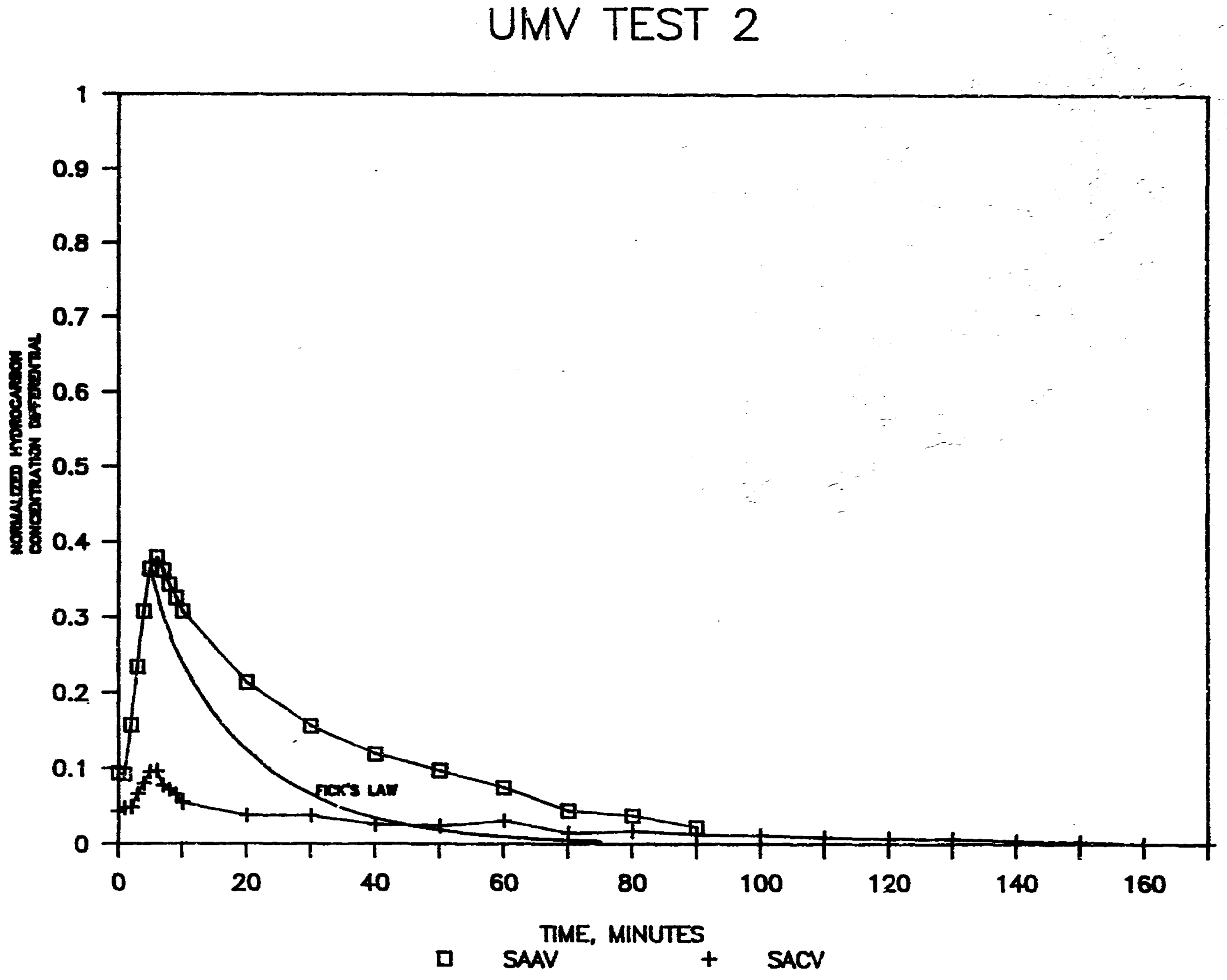


Figure 15. Forced Convection Mixing Normalized Hydrocarbon Concentration Differential (Test S)

Table 5. Slosh Mixing Test Matrix - UMV Test 3

Event Time	Event Duration	Cycles/Minute	Comments
t = 61 min	5 min 45 cycles	9 cpm	± 10° rocking motion slight fuel disturbance
t = 61 min	6 seconds 4 cycles	40 cpm	violent slosh

relatively level). Natural frequency (40 cpm) slosh caused a violent slosh effect, including fuel rollover and fuel splashing through the ullage.

Each test was performed as follows:

- A stratified ullage was set up by pumping a small amount of fuel into the tank, which had an initially low HC concentration.
- Diffusion was established (during the first 60 minutes) as the dominant mixing force by controlling top wall temperature to 25°F greater than ambient (hot top wall).
- Data was logged to confirm the existence of a stratified ullage.
- The slosh event was produced.
- Data was again logged to measure ullage stratification after the slosh event.

4.3.2 Results

The top to bottom normalized hydrocarbon concentration differential plot (Figure 16) illustrates the effect of slosh, both gentle and violent, on ullage stratification. A Fick's law prediction for diffusion mixing of the ullage is also plotted. It can be seen that both slosh cases followed Fick's law closely before the slosh events at 61 minutes. This indicates that the hot top wall established in the initial conditions caused diffusion to be the dominant mixing mechanism prior to the slosh events. The effect the sloshing had on the ullage is related to the violence of the slosh. The violent, natural frequency (40 cpm) slosh mixed the ullage completely in just 4 cycles. The mild rocking motion slosh (9 cpm) did not completely mix the ullage, even after 45 cycles (5 minutes).

Also, isotime plots of normalized hydrocarbon concentration or $\%O_2$ vs. distance above fuel surface (Figure 17) show a significant change in slope (from stratified to well mixed) between 58 and 70 minutes for the slosh at natural frequency and a less dramatic change in slope for the 9 cpm slosh. This difference is due to the fact that the 40 cpm slosh actually sprayed liquid fuel through the ullage while the 9 cpm slosh essentially only rotated the tank around the fuel. The 9 cpm slosh mixed the ullage somewhat but then returned to a diffusion controlled rate of mixing after the end of the slosh event. This can be observed by the slope of the top to bottom normalized HC concentration differential vs. time line for 9 cpm becoming equal to the slope of the Fick's law line after the slosh events (Figure 16).

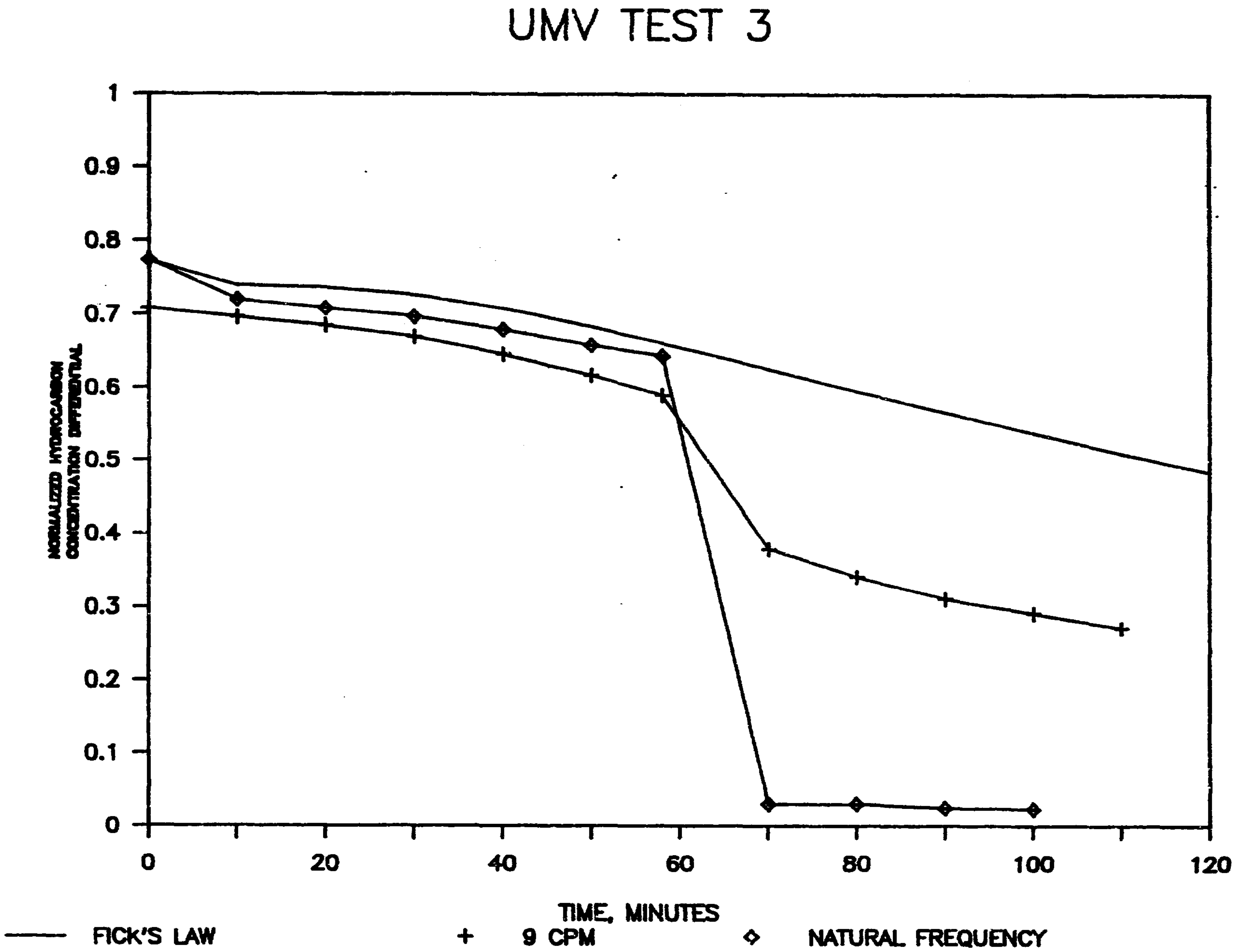
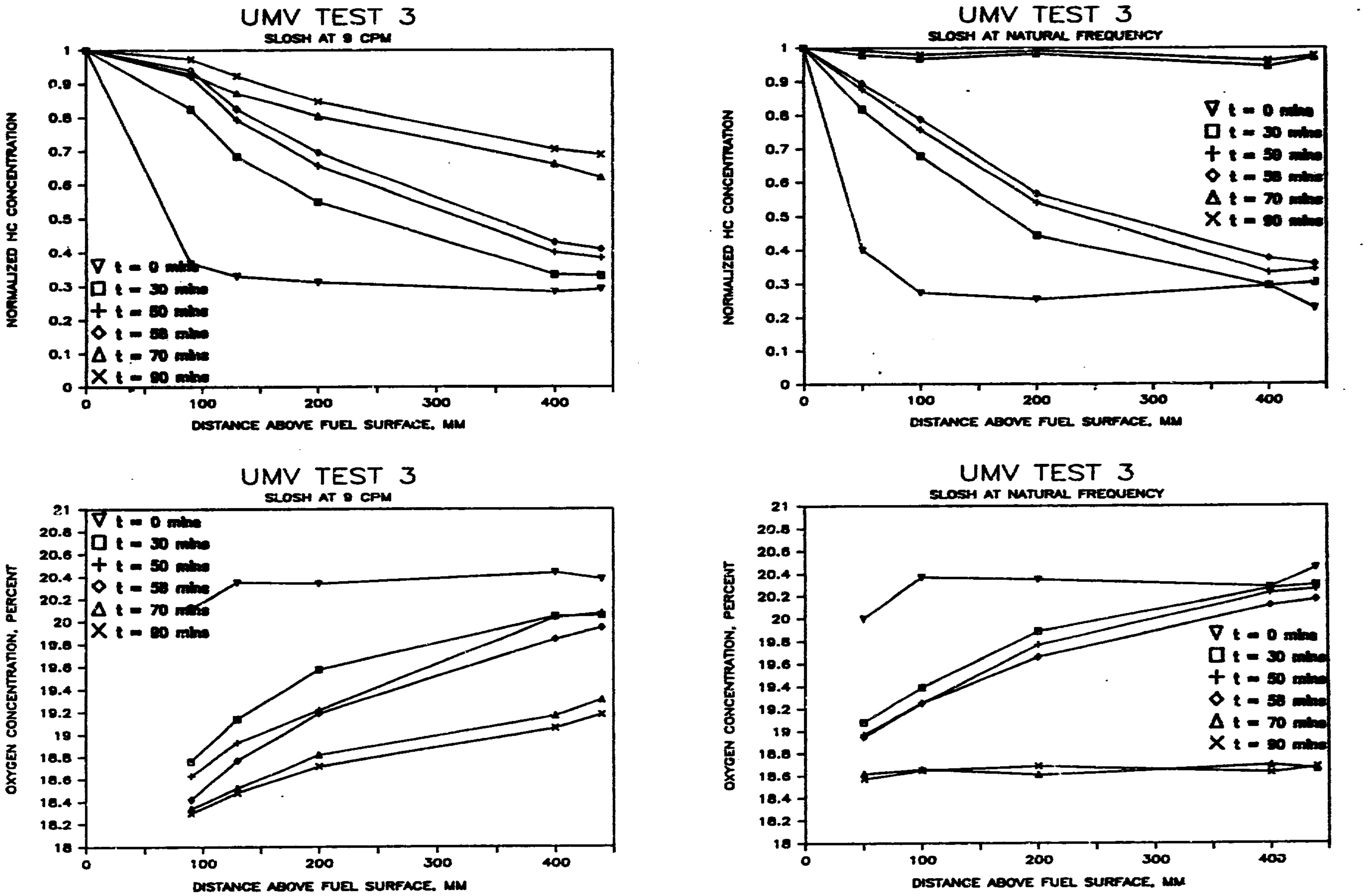


Figure 16. Slosh Mixing Normalized Hydrocarbon Concentration Differential



UMV TEST 3
SLOSH AT 9 CPM

UMV TEST 3
SLOSH AT NATURAL FREQUENCY

UMV TEST 3
SLOSH AT 9 CPM

UMV TEST 3
SLOSH AT NATURAL FREQUENCY

Figure 17. Slosh Mixing Ullage Oxygen and Hydrocarbon Concentration Profiles

5.0 DISSOLVED OXYGEN MANAGEMENT TESTS

5.1 Scrub Test

5.1.1 Model Derivation

O_2 material balance in the ullage ->

in = out + accumulate + dissolve

where in = liters of O_2 into fuel-tank system per unit time

out = liters of O_2 out of fuel-tank system per unit time

accumulate = $\frac{dN(t)}{dt}$, rate of change of liters of O_2 in ullage

dissolve = liters of O_2 dissolving into fuel per unit time

N(t) = liters of O_2 in ullage as a function of time

Material balance yields a differential equation with solution:

$$N(t) = \left(1 - \frac{\text{HC vapor P}}{760\ \text{mmHg}}\right)(\%O_{2\ \text{scrub}})(\text{ullage V})$$

$$+ XC/\left(\frac{\text{Wscrub}}{\text{ullage V}} - X*\text{EFF}^{-1}\right)\exp(-Xt/\text{EFF})$$

$$+ K*\exp(-\text{Wscrub}*t/\text{ullage V})$$

where $X = \dfrac{\text{Wscrub}}{\text{Ostwald coeff.}*\ \text{fuel V}}$

$C = (\text{Ostwald coeff.})(\text{fuel V})(\%O_{2\ \text{ullage},\ t=0} - \%O_{2\ \text{scrub}})$

EFF = scrub nozzle efficiency ($0<\text{EFF}\leq 1$)

ullage V = ullage volume, liters

Wscrub = scrub gas flow rate, liters per minute

$\%O_{2\ \text{scrub}}$ = oxygen concentration in scrub gas ($0<\%O_{2\ \text{scrub}}<1$)

HC vapor P= hydrocarbon vapor pressure in mmHg at test temp.

t = time, minutes   fuel V = fuel volume, liters

$\%O_2$ $_{ullage, t=0}$ = ullage oxygen concentration at beginning of scrub

K is an integration constant that is determined from
N(0) = liters of O_2 in ullage at t = 0

A scrub efficiency term (EFF) is included in the scrub model equation. An efficiency <1 indicates an imperfect scrub nozzle. A perfect scrub nozzle breaks the scrub gas stream into tiny entrained bubbles, each of which equilibrate completely with the fuel before breaking the fuel surface.

5.1.2 Test Procedure

The following initial conditions were first established:

- fuel volume = 1890 liters
- air saturated fuel
- bulk fuel T held constant according to test matrix (Table 6)
- test tank vented to altitude tank (nominally 14.7 psia)

Table 6. Scrub Test Matrix

Fuel Type	Bulk Temperature
JP-4	65°F
JP-5	65°F
JP-5	0°F

After establishing initial conditions:

- scrub fuel with NEA_5 (5% O_2)
- vent line mass spectrometer probe #6 logs $\%O_2$ in the ullage vs. time
- after approximately 1 hour, scrub with air (20.9% O_2)
- vent line MS probe #6 logs $\%O_2$ in the ullage vs. time

5.1.3 Results

Data are plotted of the model (both 100% and 50% scrub efficiency) vs. data for air and NEA_5 scrub of 65°F JP-4, 65°F JP-5 and 0°F JP-5 (Figures 18, 19 and 20). The plot of the 100% scrub efficiency model follows data for 65°F fuel quite well, indicating a near perfect scrub situation. One hundred percent scrub efficiency means that tiny bubbles of scrub gas reach equilibrium with the fuel before they break the surface. However at lower temperatures the scrub efficiency appeared to be less than 100%.

Clearly, this model did fairly well in predicting $\%O_2$ ullage during a constant pressure, constant temperature scrub. The scrub model parameters listed below can be plugged into the scrub model equation derived in Section 5.1.1 to model any constant temperature and constant pressure scrub.

SCRUB EFFICIENCY (EFF)	ULLAGE VOLUME (ullage V, l)
Wscrub (scrub gas flow rate,l/min)	FUEL VOLUME (fuel V, l)

$\%O_{2\ \mathrm{scrub}}$ (oxygen concentration in scrub gas)
OSTWALD COEFFICIENT
$\%O_{2\ \mathrm{ullage},t=0}$ (initial oxygen concentration in ullage)

FUEL VAPOR PRESSURE (mmHg)

5.2 C-17 Oxygen Evolution Tests

5.2.1 Test Hardware

The SAFTE test tank was configured differently for these C-17 tests than it was for the other UMV tests. The following description applies to the C-17 tests only. The fuel tank simulator was maintained at a constant 5° tilt for all C-17 tests to simulate the normal slope of a C-17 wing tank top skin (Figure 21); several different fuel levels were tested.

A fan was used inside the tank to provide enough convection to assure an homogeneous mixture of ullage gases. The fan itself was of a "squirrel cage" design driven by an air motor located outside the tank. The fan and motor were coupled by a special rotary feedthrough with a double rotating shaft seal.

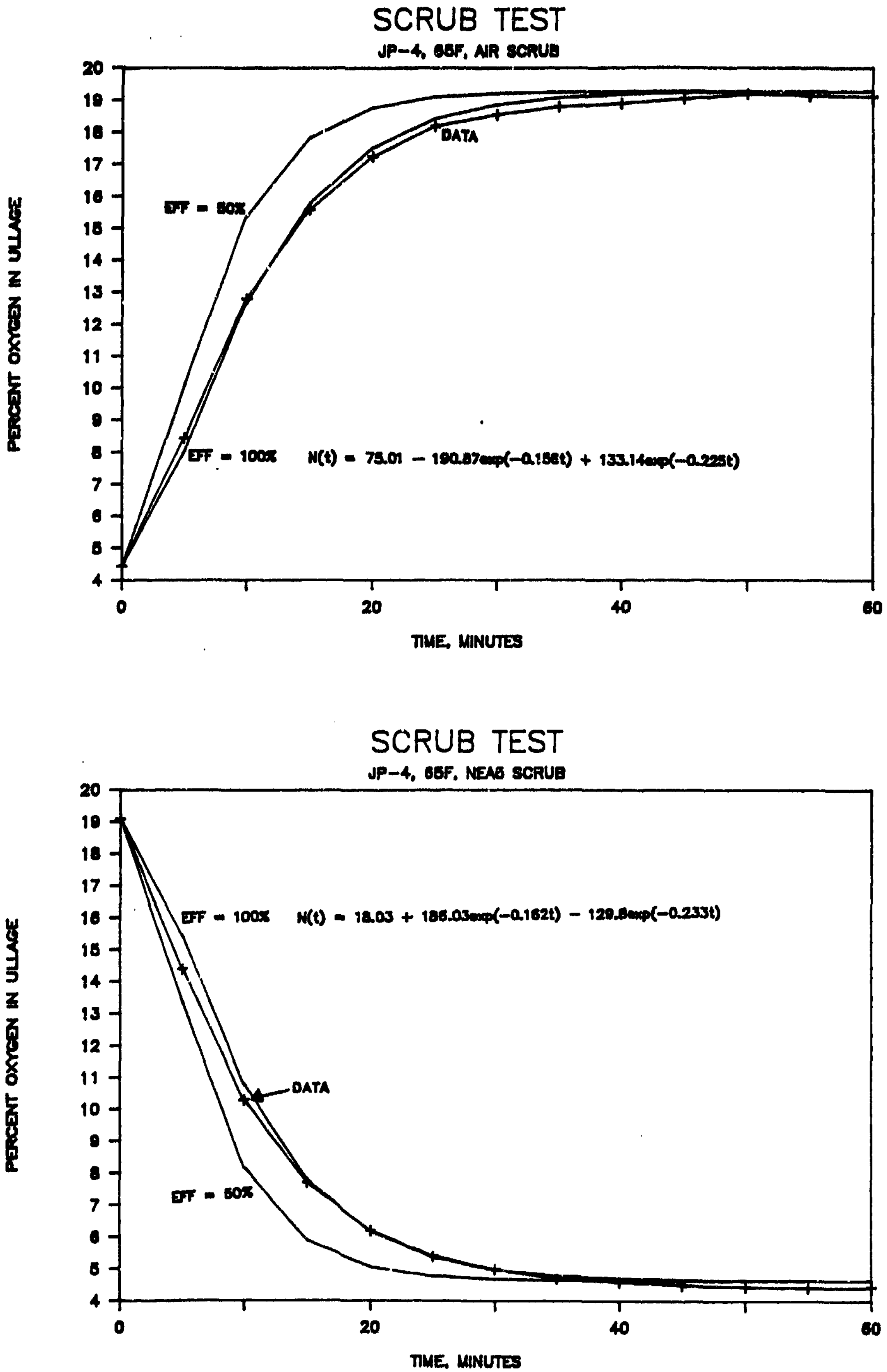
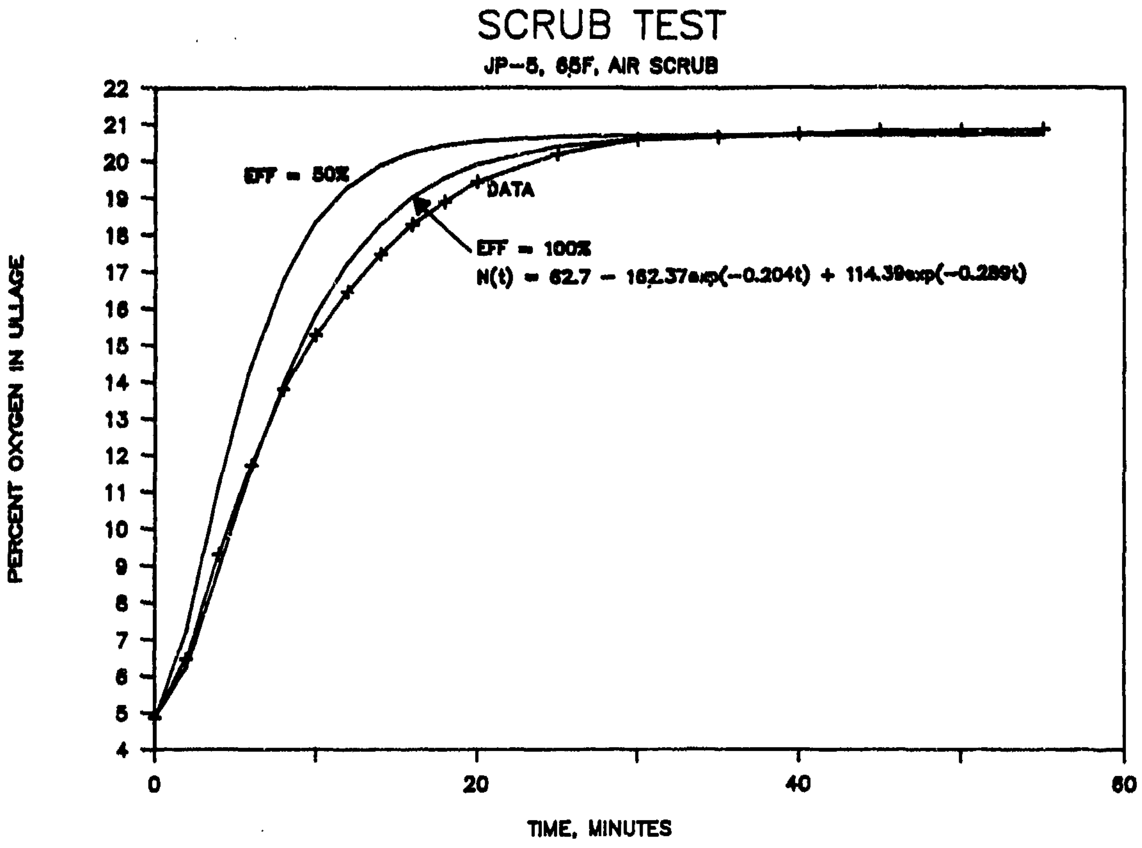


Figure 18. Oxygen Concentration in Ullage During Scrub, 65 °F JP–4



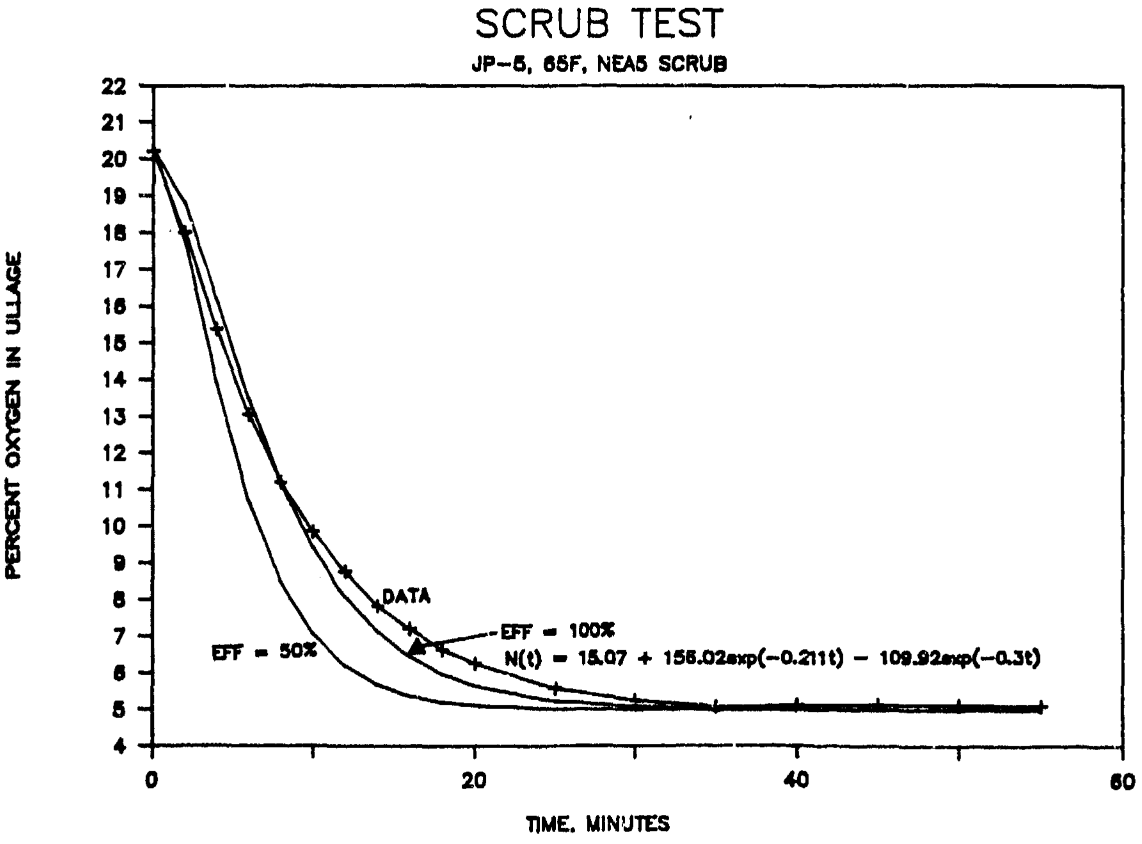


Figure 19. Oxygen Concentration in Ullage During Scrub, 65 °F JP–5

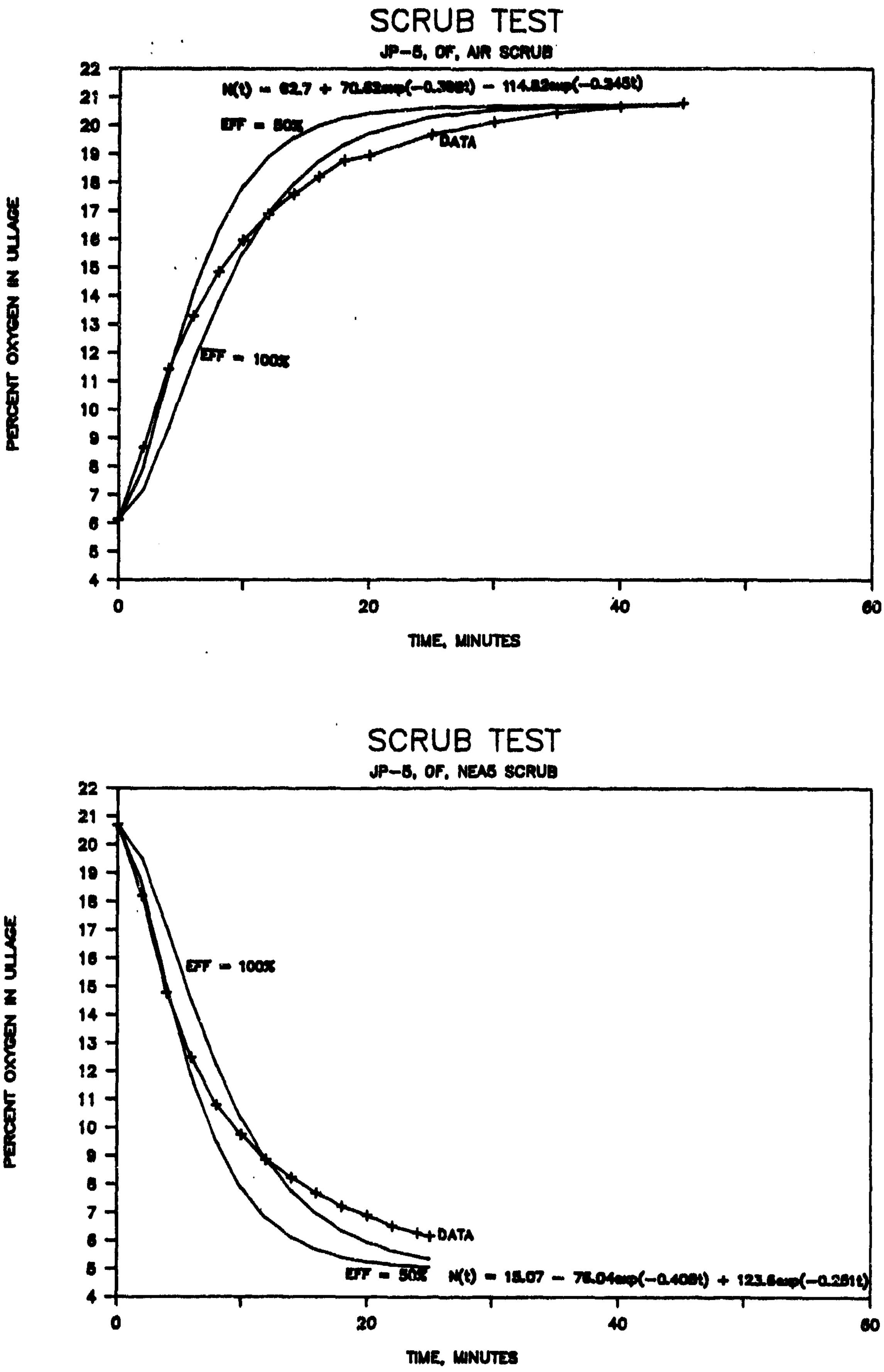


Figure 20. Oxygen Concentration in Ullage During Scrub, 0 °F JP-5

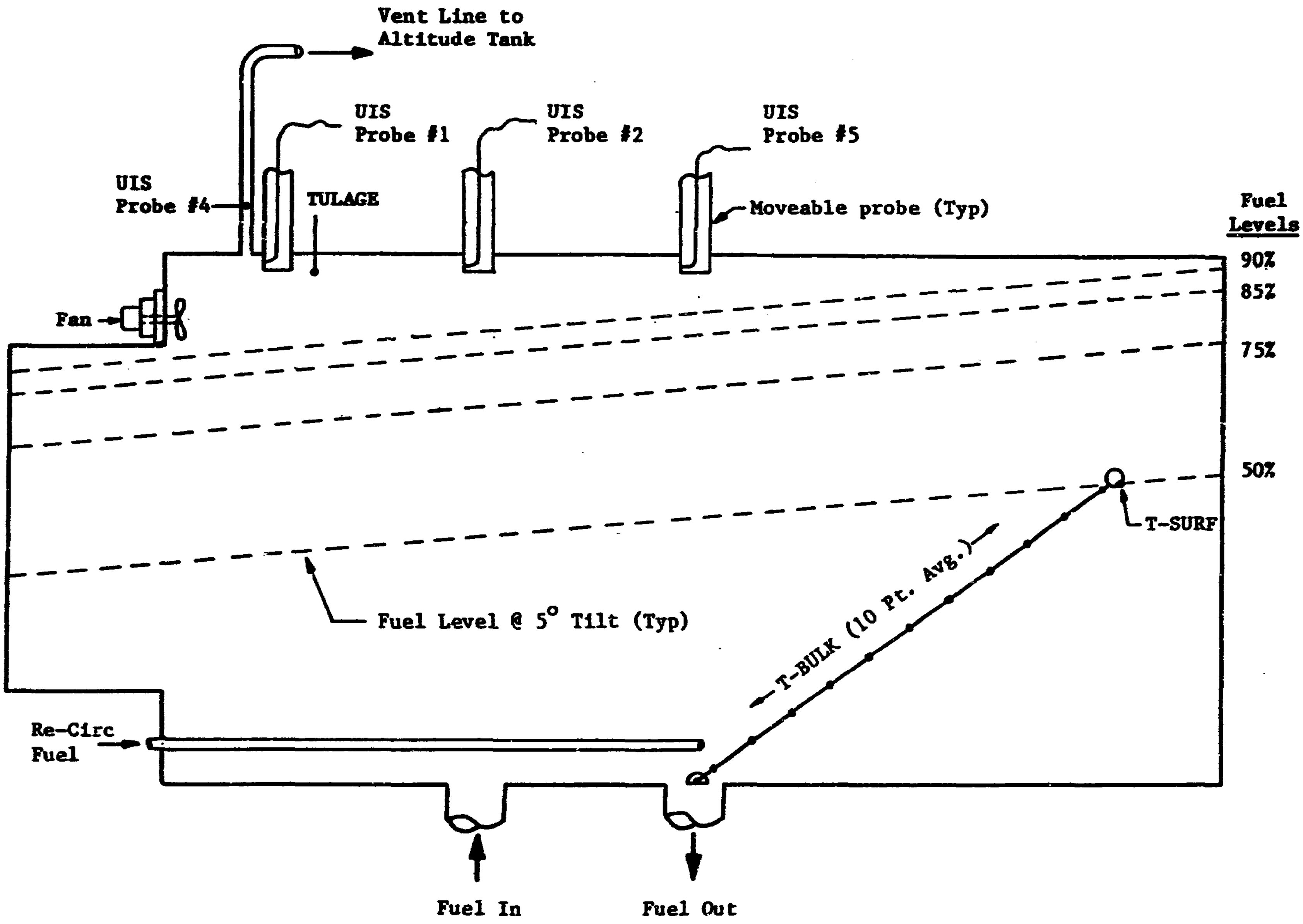


Figure 21. Test Tank Orientation Side View

In order to condition the fuel with the proper amount of dissolved gases prior to the start of each test, controlled concentrations of NEA were bubbled through the fuel. A C-5A scrub nozzle was used for this purpose due to its efficiency at mixing gases and liquids. The scrub nozzle had an exit diameter of 0.22" I.D.

Re-circulation at several different flow rates was provided by a manually operated throttle valve and a flow meter. The re-circulation flow was introduced back into the tank via either a 0.68" I.D. tube or the 0.22" I.D. scrub nozzle, the latter providing a higher velocity jet. A summary (Table 7) provides flow rates tested and their respective velocities.

5.2.1.1 Simulated Altitude Pressure Control

Even though the C-17 airplane would incorporate a pressurized fuel system with climb/dive valves, this test was performed with a vented fuel tank. The altitude pressure schedule (Table 8) was adjusted by increasing the pressure schedule by a constant 0.8 psi to compensate for the anticipated C-17 climb valve setting.

5.2.1.2 Ullage Composition Measurements

There were five sampling probes located at various positions throughout the ullage. These probes confirmed that the ullage was essentially well stirred by the fan at all times. The oxygen concentration data presented in Section 5.2.3 should be considered average values present throughout the entire ullage space.

5.2.2 Test Procedures

The general procedures which applied to all C-17 O_2 Evolution tests were as follows:

- Fill the test tank with JP-4 (RVP of approximately 2.0 to 2.2) at the desired temperature.
- Saturate the fuel with NEA of the desired oxygen concentration.
- Establish the specified fuel agitation (i.e., Vibration and Re-Circulation).
- Follow the altitude pressure climb schedule and record data until equilibrium is reached.

Table 7. Fuel Re-Circulation Flow Summary

Re-Circ Flow (gpm)	Nozzle I.D. (inches)	Average Exit Velocity (ft/sec)
10	0.68	8.8
5	0.68	4.4
2.2	0.22	18.6
1.1	0.22	9.3

Table 8. C-17 O_2 Evolution Altitude Pressure Schedule

Time (minutes)	Pressure (psia)
0.0	15.50
1.0	15.35
1.5	15.00
2.0	14.00
3.0	12.15
4.0	10.60
5.0	9.40
6.0	8.40
7.0	7.60
8.0	6.95
10.0	5.90
13.0	4.85
17.0	3.80
19.0	3.50
20.0	3.40

Notes: Pressure adjusted for 0.8 psig climb valve setting.
Control system performs linear interpolation between points in table.

Although different fuel levels and temperatures were tested, each test was conducted at constant temperature and volume.

5.2.2.1 Initial Conditions

The fuel in the storage tank was first thermally conditioned to the desired temperature prior to filling the test tank. The test tank was then filled to either 50, 75, 85, or 90% fuel levels at the rate of 100 gpm. The test tank wall temperatures were regulated so as to control constant fuel and ullage temperatures. In order to condition the fuel with the desired amount of dissolved gases, a stream of NEA was bubbled through the fuel until equilibrium conditions were achieved. The NEA scrub flow was then terminated. The desired re-circulation flow rate and flow path along with the vibration level were then established prior to starting the climb schedule.

5.2.2.2 Climb Simulation

At the beginning of the climb simulation the computer control system held the initial conditions for four minutes, during which time the mass spectrometer was recalibrated and the initial conditions were logged by the data acquisition system. When this four minute period had transpired, the computer control system began changing the altitude pressure according to the schedule shown in Table 8.

Data was automatically recorded at preprogrammed time intervals. The tests were 60 minutes in duration except where noted otherwise. Other variations on these procedures included starting the vibration table near the end of the quiescent tests to determine if equilibrium had been reached.

5.2.2.3 Fuel Vapor Pressure Control

The initial goal for this test was to maintain the JP-4 RVP between 2.0 to 2.2 psi. However, the repeatability experienced with the RVP test apparatus was not adequate for this purpose. For all of the 70°F tests, the initial hydrocarbon concentrations (via the mass spectrometer) were used as a much more repeatable and accurate measurement of fuel vapor pressure. The initial hydrocarbon concentrations varied between 6% and 8% by volume at 15.5 psia and 70°F. As expected, the vapor pressure was noted to gradually decrease as the fuel was weathered during testing. Higher vapor pressure fuel was then periodically added to maintain vapor pressures in the range desired.

5.2.2.4 Vibration Table Operation

The vibration table was started prior to the beginning of the climb schedule. The frequency of the vibration was controlled to 50 Hz ± 1 Hz for all amplitudes except for the 1.4 mil case where 44 Hz was used to obtain the low amplitudes. The vibration was maintained at a constant frequency and amplitude throughout the entire test except where noted otherwise. Table 9 is a compilation of the different vibration levels used.

5.2.3 Results

A summary of all tests (Table 10) lists all pertinent test conditions. Only those results useable for ullage model comparisons are included in this report. More detailed information can be obtained in Reference 2. Plots of ullage oxygen concentration versus mission time show the effects of variables such as fuel level, fuel temperature and fuel type on oxygen evolution (Figures 22 through 30). These data have been corrected for leakage as discussed below.

The test tank had a finite amount of leakage to or from ambient depending on the pressure. The test results for this test are especially sensitive to leakage from ambient when the tank is at reduced pressure since this increases the measured $\%O_2$. The leakage could not be reduced below approximately 6×10^{-4} lbs/min when the tank was at 3.4 psia. While this rate was still significantly above the desired level, it was felt that useful data could still be obtained by using post test corrections to compensate for most of the leakage induced effects. Data from a baseline test with all initial dissolved oxygen removed from the tank were used as the basis of the corrections. Further information on these corrections can be obtained from Reference 2. Note that only corrected data are shown in Figures 22 through 30.

Figures 22 through 25 present the effects of varying the excitation level of the fuel using vibration and recirculation. These tests were designed to help determine if the actual C-17 fuel system design would provide enough excitation of the fuel to maintain the dissolved gases in equilibrium with the ullage

Table 9. Vibration Levels Tested

g's	mils	Hz
0.14	1.4	44
0.35	2.8	50
0.64	5	50
1.35	10	50

Table 10. C-17 O_2 Evolution Test Summary

Cond#	Initial %O_2	%Fuel	Fuel Temp (°F)	Vib Level (mils @ Hz)	Re-Circ (gpm)	Comments
2.0	6	50	70	10 @ 50	10	
3.0	6	75	70	10 @ 50	10	
4.0	6	90	70	10 @ 50	10	
4.3	6	90	85	10 @ 50	10	Hi Fuel Vapor Pressure
4.4	6	90	70	10 @ 50	10	JP-5
5.0	6	85	70	10 @ 50	10	
7.0	6	90	30	10 @ 50	10	
8.0	6	90	0	10 @ 50	10	
8.A	4	90	0	10 @ 50	10	
8.B	8	90	0	10 @ 50	10	
9.0	4	90	70	10 @ 50	10	
10.0	8	90	70	10 @ 50	10	
11.0	6	90	70	5 @ 50	0	
12.0	6	90	70	3 @ 50	0	
13.0	6	90	70	1.4 @ 44	0	
14.0	6	90	70	0	0	Quiescent, then Vib @ 42 min.
14.1	Air Sat	90	70	0	0	Quiescent, then Vib @ 42 min.
15.0	6	90	70	0	1.1 HiVel	Vibration on @ 42 minutes
16.0	6	90	70	0	5	Vibration on @ 42 minutes
17.0	6	90	70	1.4 @ 44	2.2 HiVel	
18.0	6	90	70	0	2.2 HiVel	Vibration on @ 42 minutes
19.0	6	90	70	0	10	Vibration on @ 42 minutes
20.0	6	90	70	1.4 @ 44	10	
21.0	6	90	70	2.8 @ 50	10	
22.0	6	90	70	2.8 @ 49	2.2 HiVel	
24.0	6	90	70	10 @ 50	2.2 HiVel	

Note: Data shown above are nominal values only.

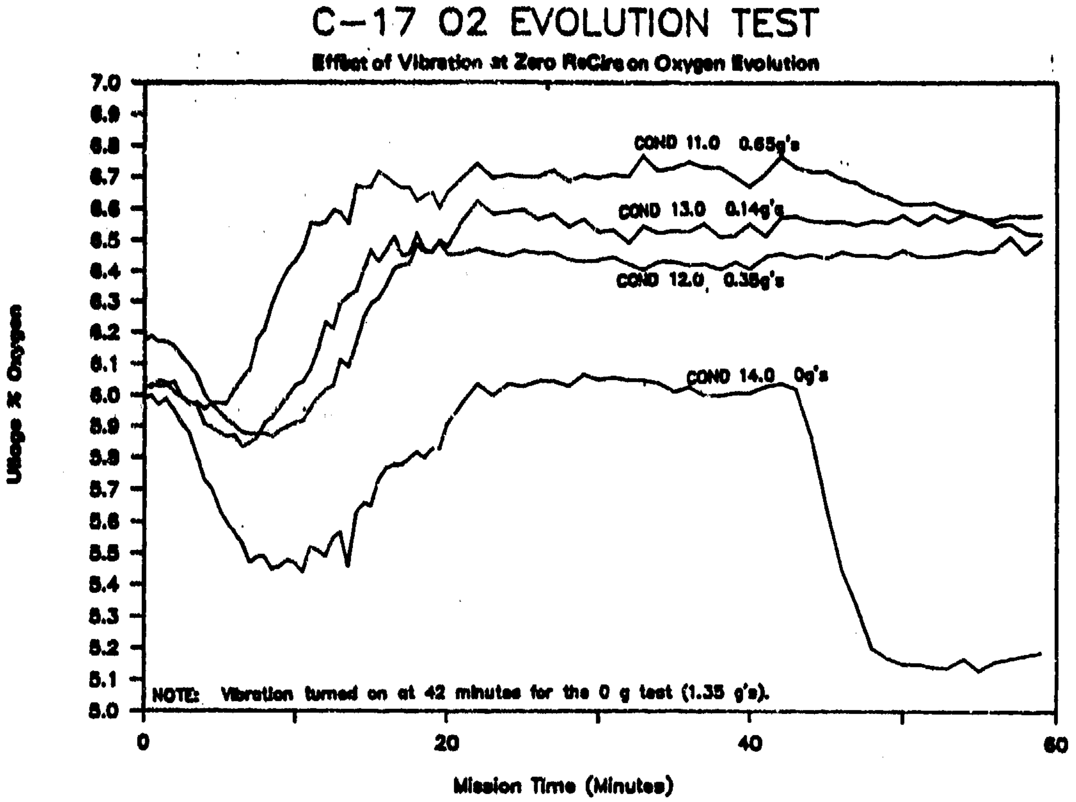


Figure 22. Effect of Vibration at Zero Recirculation on Oxygen Evolution

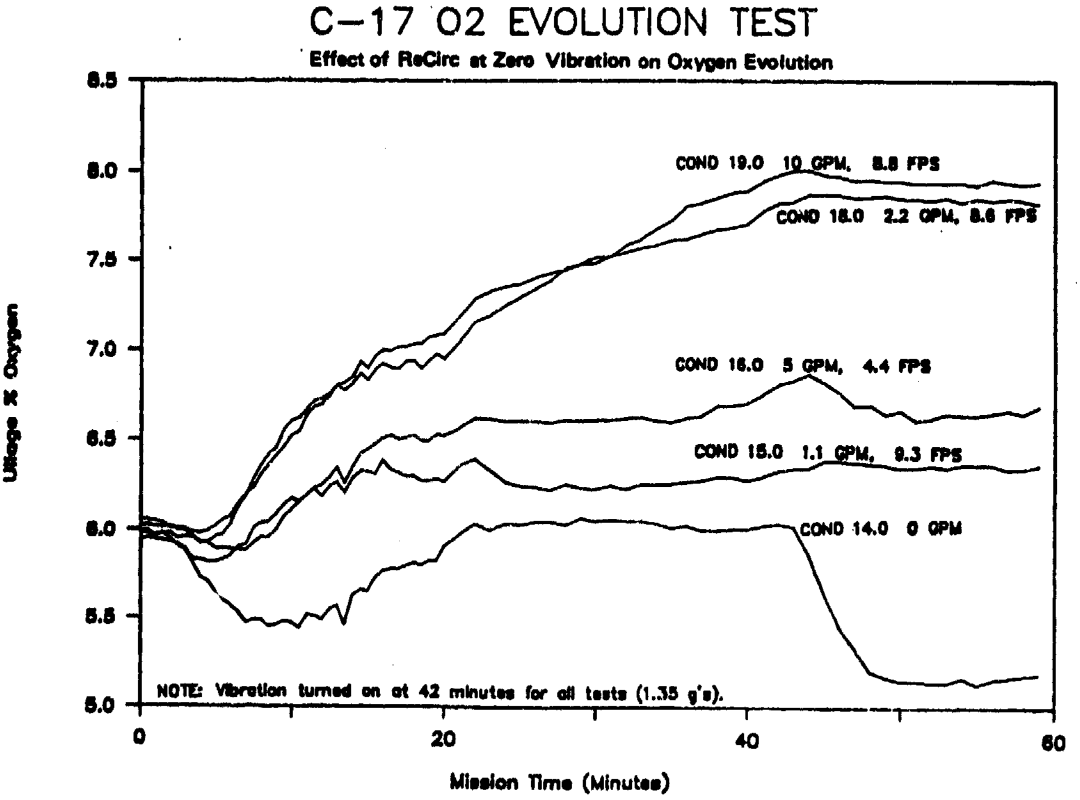


Figure 23. Effect of Recirculation at Zero Vibration on Oxygen Evolution

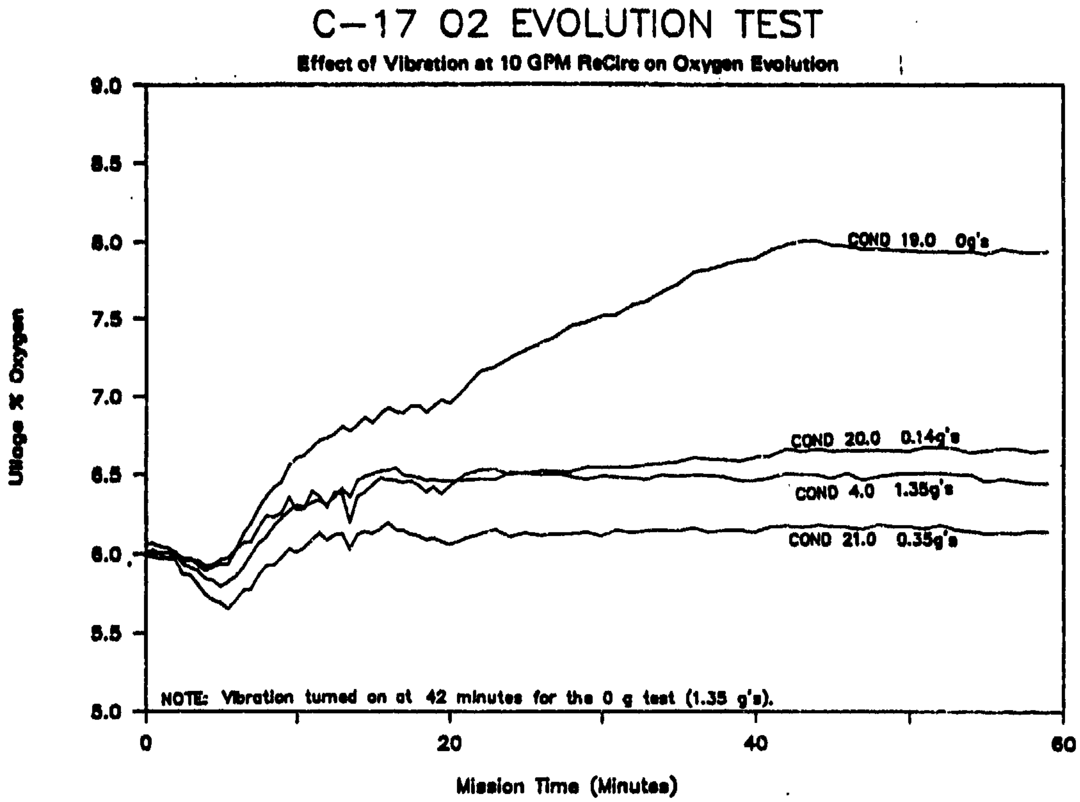


Figure 24. Effect of Vibration of 10 GPM Recirculation on Oxygen Evolution

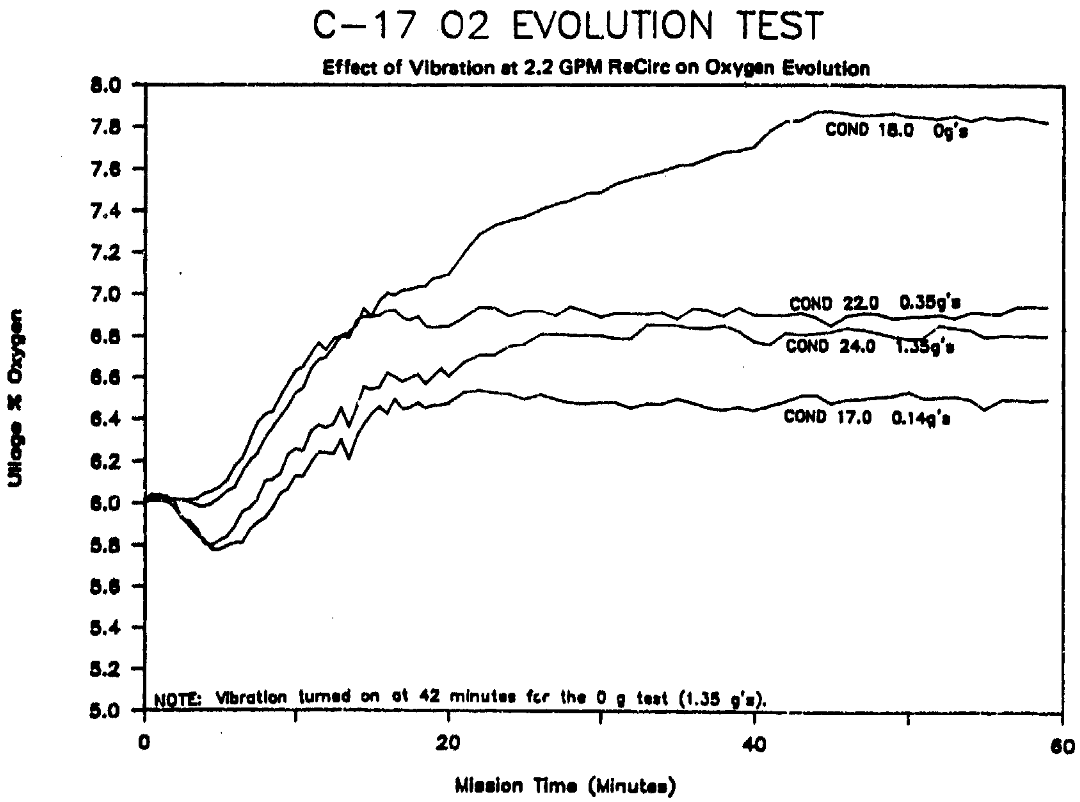


Figure 25. Effect of Vibration at 2.2 GPM Recirculation on Oxygen Evolution

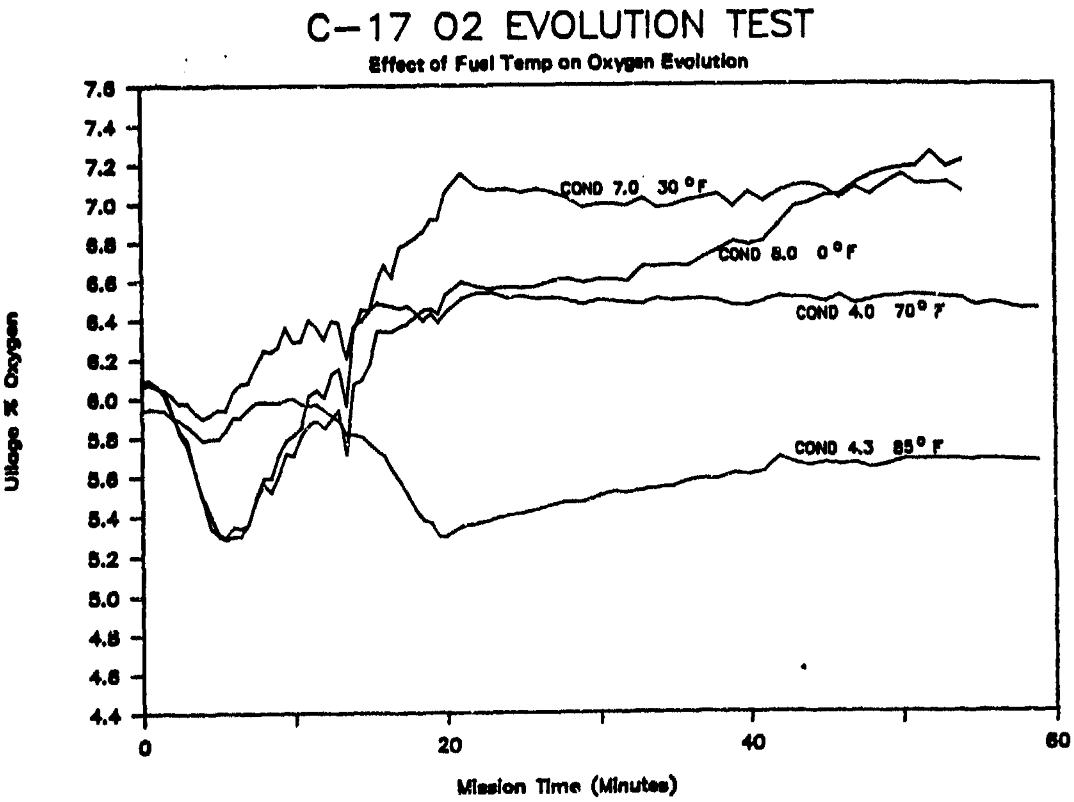


Figure 26. Effect of Fuel Temperature on Oxygen Evolution

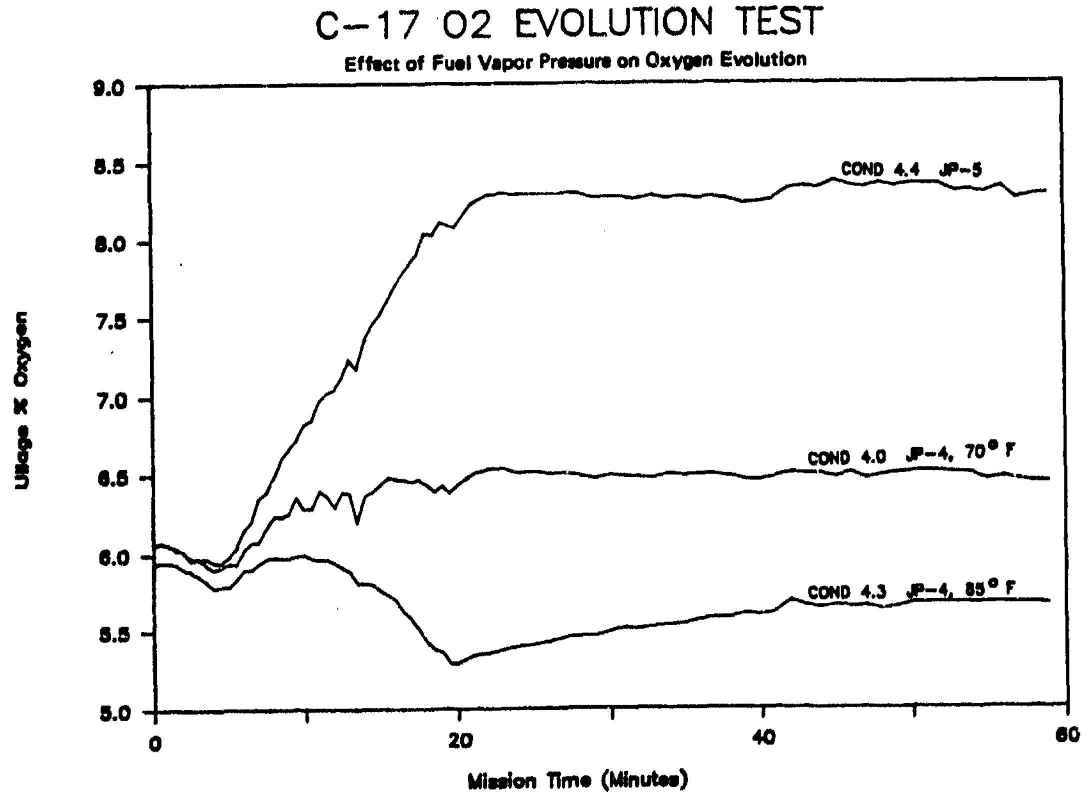


Figure 27. Effect of Fuel Vapor Pressure on Oxygen Evolution

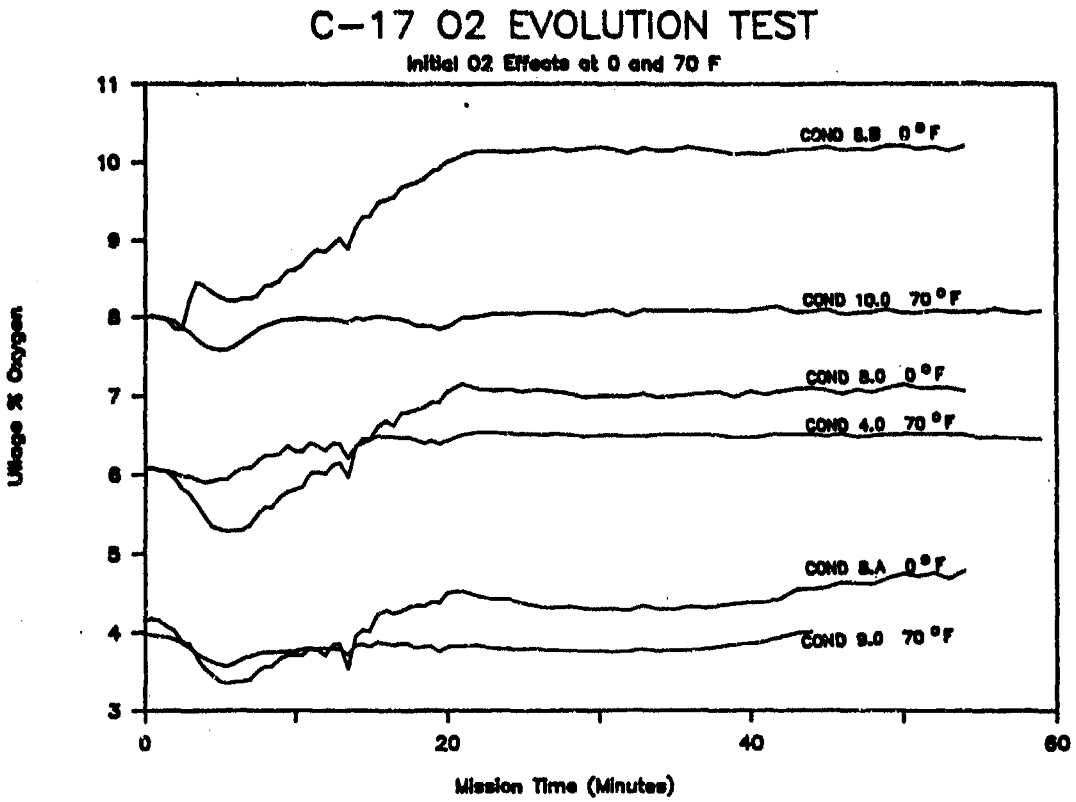


Figure 28. Initial % Oxygen Effects at 0 °F and 70 °F

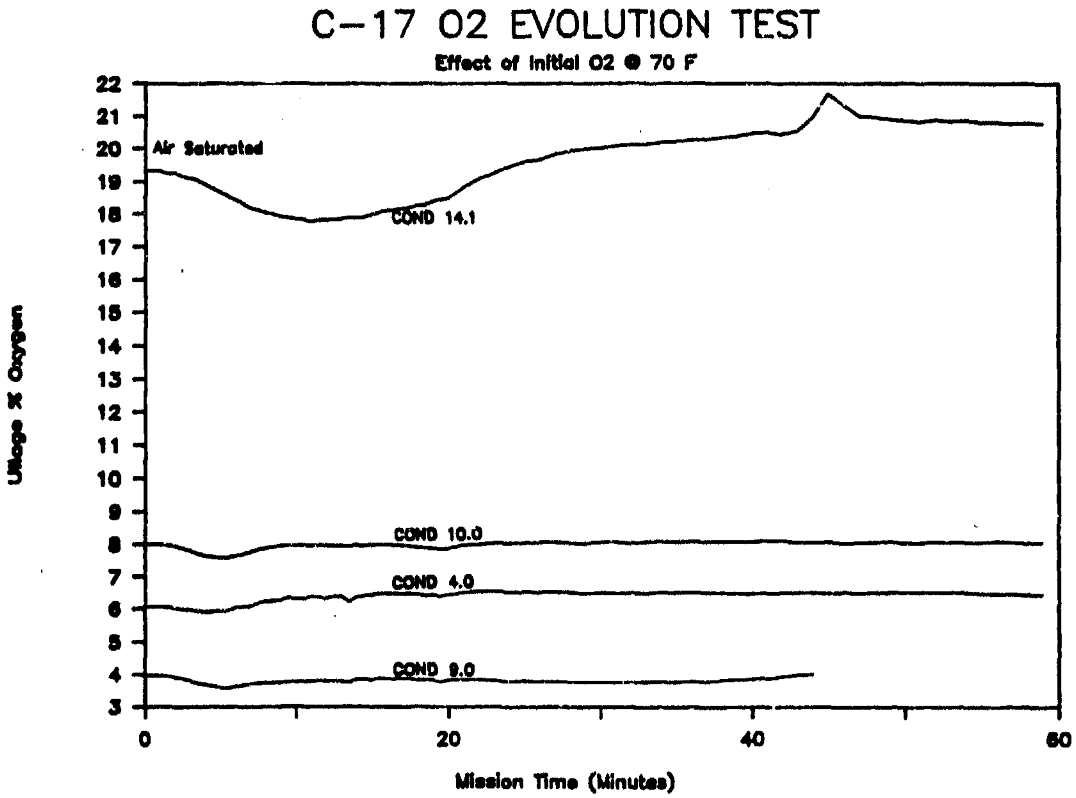


Figure 29. Effect of Initial % Oxygen at 70 °F

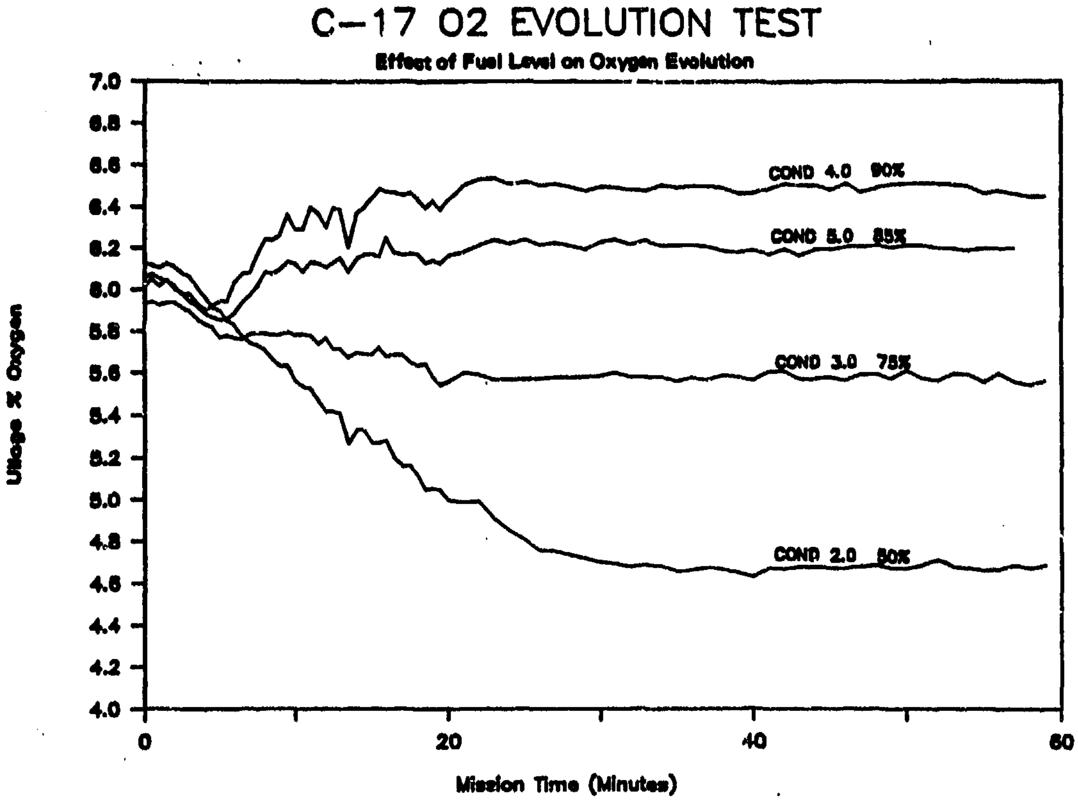


Figure 30. Effect of Fuel Level on Oxygen Evolution

throughout the simulated climb. Examining Figures 22 through 25, it can be seen that various combinations of vibration and recirculation were tested and results tend to support the following conclusions (with some minor contradictions):

- Even small amounts of vibration (as low as 0.14 g's) are adequate to maintain dissolved gas equilibrium regardless of recirculation.
- Recirculation tended to produce results closer to equilibrium as a function of exit velocity and not flow rate.

When attempting to come to a conclusion regarding the effect of delaying the evolution of dissolved gases (i.e. quiescent climb), there are several contradictions evident. Condition 14.0 (no vibration, no recirculation) yielded the lowest final oxygen concentrations of all the vibration/recirculation cases. This tends to indicate that delaying dissolved gas evolution lowers the final oxygen concentration. However, Conditions 18.0 and 19.0 (no vibration but with some recirculation) yielded the highest final oxygen concentrations.

The effects of changing fuel vapor pressure are shown in Figures 26 and 27, where tests were conducted with JP-4 at four different temperatures as well as with JP-5. The primary effect of changing fuel type or fuel temperature is to change the vapor pressure and therefore the HC concentration in the ullage. For example, the JP-4 test at 85°F yielded a HC concentration of 48% at altitude. The HC vapor displaces the oxygen and nitrogen gases and reduces their concentrations. Examining Figures 26 and 27, it can be seen that the test with JP-5 produced the highest final oxygen concentration. This can be attributed directly to the low vapor pressure of JP-5 which produced only 1% HC at altitude.

The Ostwald coefficients for both oxygen and nitrogen also vary with fuel temperature and fuel type. However, this is a second order effect compared to fuel vapor pressure.

The effect of initial oxygen concentration can be seen by examining the results presented in Figures 28 and 29. The results are also not surprising and indicate that the higher initial oxygen concentrations yield higher final values as expected. Figure 28 shows that this is also true at different temperatures.

Figure 30 depicts the effect of fuel level on final oxygen concentration and shows that the smallest initial ullage volume will produce the highest final oxygen concentration, as expected. It is interesting to note that the oxygen concentration actually decreased with ullage volumes greater than 25%.

In summary, when concerned with managing the evolution of oxygen in a fuel system during a climb, the conditions which will act to produce the greatest increase in oxygen concentrations are small initial ullage volume and low fuel vapor pressure (either from fuel type or temperature). The effect of delaying the evolution of dissolved gases cannot be determined from these tests due to the conflicting results.

5.3 Dissolved Oxygen Evolution (UMV Test 4)

5.3.1 Test Procedure

The following initial conditions were first established

- SAFTE fuel tank level constant at 86% full, JP-4
- All temperatures constant at ambient
- Fuel air saturated by scrubbing with air at 14.7 psia

After establishing the initial conditions, testing proceeded as follows:

- Begin climb simulation (Table 11)
- Initiate NEA_5 scrub or wash as required
- Test according to Matrix (Table 12)

5.3.2 Results

The six Dissolved Oxygen Evolution tests are plotted as percent oxygen vs. time (Figure 31). It is apparent from Figure 31 that the presence of vibration made no difference in ullage percent oxygen during the scrub tests. This is due to the scrub and recirculation flows agitating the fuel sufficiently to maintain oxygen equilibrium with or without vibration. The scrub tests, both continuous vibration and quiescent climb, indicated that oxygen evolution during climb was independent of ambient vibration levels as long as the fuel was agitated by a scrubbing process.

Table 11. UMV Test 4 Altitude Pressure Schedule

TIME	ALTITUDE PRESSURE
0	14.7
0.7	10.1
1.1	8.3
1.55	6.7
2.15	5.4
2.95	4.3
3.7	3.6
20.0	3.6
30.0	3.6

Table 12. Dissolved O_2 Evolution Test Matrix - UMV Test 4

Continuous Vibration 10 mils @ 50 Hz			Climb then Vibrate at t=8 min. 10 mils @ 50 Hz (Quiescent Climb)		
no scrub no wash	scrub no wash	no scrub wash	no scrub no wash	scrub no wash	no scrub wash

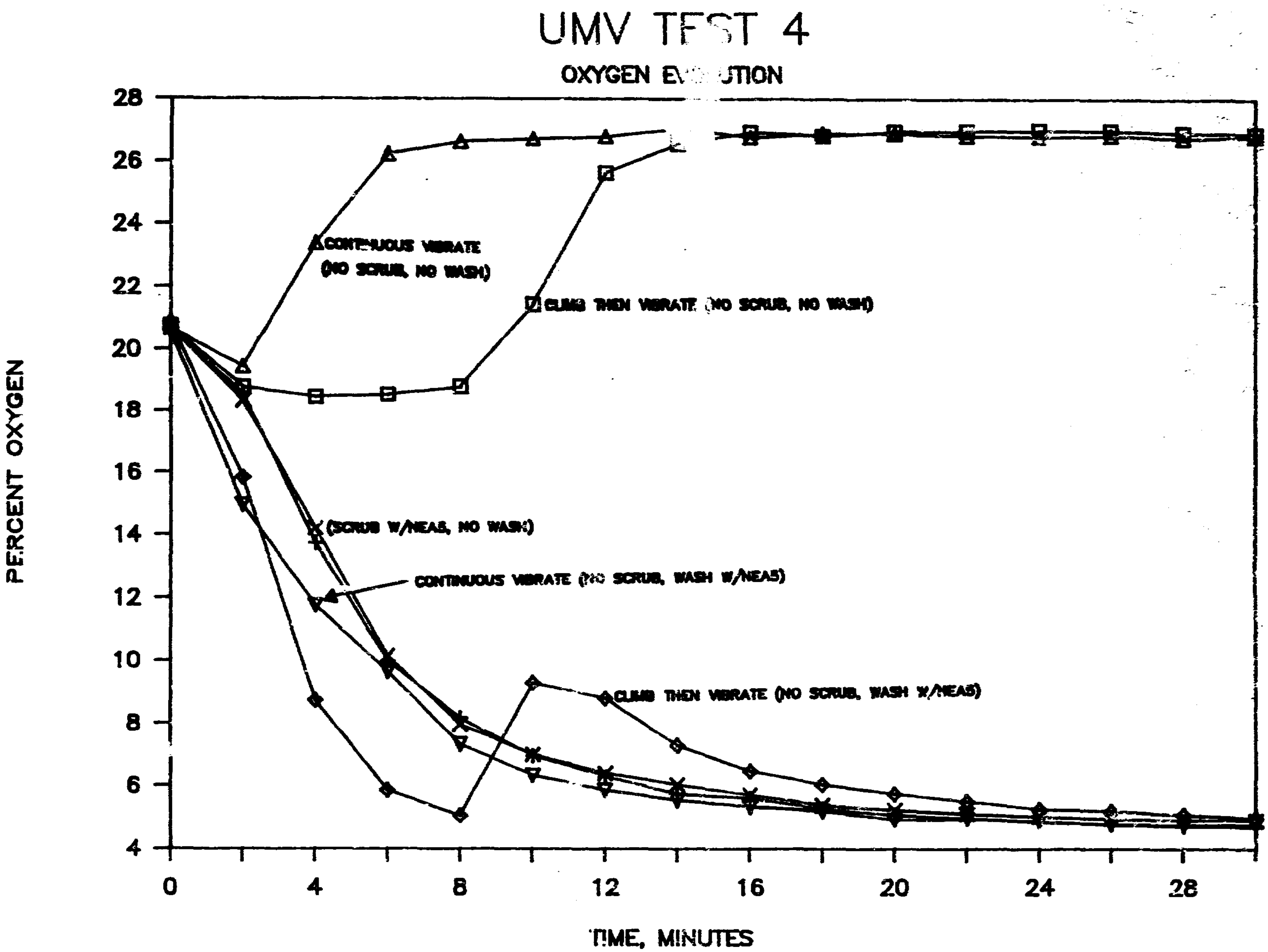


Figure 31. Oxygen Concentration in Ullage During Climb

However, there was no scrub induced agitation in the other four tests and the effect of continuous vibration vs. quiescent climb is readily apparent. The quiescent climb tests both deviated more from equilibrium during climb than the continuous vibration tests. Continuous vibration permitted faster oxygen evolution during climb by causing observed bubble formation in the fuel. In the quiescent climb tests, almost no oxygen was evolved during climb. However, at t = 8 minutes when vibration was begun after a quiescent climb, a dramatic increase in oxygen evolution was observed in the data. A foaming action was also visually observed in the tank at the same time.

Both tests with no scrub and no wash reached about 27% oxygen at equilibrium at 3.7 psi altitude pressure. Although the small ullage size (about 14%) exacerbated the rise in $\%O_2$, oxygen evolution during a climb is a significant phenomenon and should not be ignored when considering airplane fuel tank inerting schemes.

Ullage wash during quiescent climb reduced the ullage oxygen concentration relatively quickly. However, when vibration began at t = 8 minutes, the non-equilibrium condition between dissolved and ullage oxygen was revealed. In fact, O_2 was evolved from the fuel, raising $\%O_2$ in the ullage from 5% to 10% in approximately two minutes. Contrast this to the continuous vibration with wash data which smoothly approached ullage percent oxygen of 5%. Also, the continuous vibration with ullage wash had an ullage oxygen concentration always less than or equal to the scrub tests ullage oxygen concentration. The tests using scrub or wash all used NEA_5 at the same flowrate, approximately 0.23 pound per minute. If adequate vibration levels are present on the aircraft at all times during climb, ullage washing appears to be a more efficient inerting process than scrubbing.

Oxygen is evolved much more rapidly from the fuel if vibration or a recirculating agitation of the fuel is present. A quiescent climb introduces a non-equilibrium condition that is revealed by a sharp rise in ullage percent oxygen when vibration is begun. This situation is directly analogous to a glass of soda open to the atmosphere. The soda will evolve carbon dioxide at a much higher rate if agitated than if allowed to stand quietly.

5.4 Test 5 - Oxygen Evolution During Refuel (UMV Test 5)

5.4.1 Test Procedure

Two test procedures (A and B) were used in UMV Test 5.

Test A involved air saturating the fuel and washing the ullage down to 5% O_2 with the fuel in place in the test tank. This ullage washing was done quickly, so this test simulated air saturated fuel in contact with an NEA_5 ullage.

The following initial conditions were first established:

- SAFTE tank 86% full of air saturated JP-5 fuel
- Ullage in equilibrium with air saturated JP-5 fuel
- Tank at ambient temperature and pressure

After establishing initial conditions, testing was as follows:

- Wash ullage with pure nitrogen down to 5% oxygen in ullage
- Seal tank to prevent vent flow
- Run 1 - use fuel recirculation pump to agitate fuel
- Run 2 - no recirculation (quiescent fuel)
- Measure $\%O_2$ in the ullage vs. time

Test B was designed to demonstrate the effect a high refueling rate (100 gpm) of air saturated fuel had on an ullage with an initial O_2 concentration of 5%. A high rate of oxygen evolution from the fuel during the refuel was expected because of the turbulent nature of the refueling process.

The following initial conditions were first established:

- 500 gallons of air saturated JP-5 in fuel storage tank
- SAFTE tank empty, initial $\%O_2 = 5$
- SAFTE tank vented to 14.7 psia

After establishing initial conditions, testing was as follows:

- Pump air saturated JP-5 into SAFTE tank at 100 gpm up to 86% level (5 minutes).
- Measure $\%O_2$ in ullage during refuel
- No recirculation (quiescent fuel)
- Seal tank to prevent vent flow
- Continue to measure $\%O_2$ in ullage

5.4.2 Oxygen Evolution Model

Material balances for both N_2 and O_2 were written for this model because the tank was sealed and ullage pressure was non-constant. (Since Ostwald coefficient for O_2 is larger than Ostwald coefficient for N_2, more O_2 evolves than N_2 dissolves, therefore ullage pressure increased during this test).

ullage O_2 balance

in = accumulate

$$\text{accumulate} = \frac{dnO_2(t)}{dt}$$

$$\text{in} = K(PO_2\ \text{fuel} - PO_2\ \text{ullage})$$

ullage N_2 balance

in = accumulate

$$\text{accumulate} = \frac{dnN_2(t)}{dt}$$

$$\text{in} = K(PN_2\ \text{fuel} - PN_2\ \text{ullage})$$

From these material balances differential equations were written and solved:

moles of O_2 = $nO_2(t) = 1.7638 - 1.1748\exp(-0.01113t)$ in ullage

moles of N_2 = $nN_2(t) = 10.81 + 0.89\exp(-0.01144t)$ in ullage

Note - these are equations for the specific fuel tank system used in UMV Test 5; however, one can return to the material balances to derive a differential equation to describe any situation of oxygen-rich fuel in contact with nitrogen-rich ullage in a sealed tank.

5.4.3 Results

Data for two of the refuel tests versus the model are plotted (Figure 32). The model agrees best with the data obtained from Test A, run #1 with the fuel recirculation pump running. The model assumes fresh oxygen-rich fuel at the fuel-ullage interface throughout the test. The pump kept the fuel mixed and did not allow any O_2 stratification within the fuel or an oxygen depleted layer to form at the fuel-ullage interface.

Unlike UMV Test 4 where the oxygen partial pressure difference was set up by a drop in total ullage pressure, UMV Test 5 ullage pressure was always greater than or equal to 14.7 psia. Bulk oxygen transport out of the fuel into the ullage via bubbles and foaming didn't occur since total pressure of dissolved gases was never greater than total ullage pressure. Therefore all oxygen evolution occurred at the fuel-ullage interface at the molecular level.

It must be remembered that the tank walls contacting the fuel were run isothermally with the fuel, preventing the formation of any natural convection currents to mix the fuel. Without running the pump, the fuel was completely quiescent and the oxygen at the top of the fuel evolved and left an oxygen poor layer at the top of the fuel. Oxygen transports across this oxygen poor layer via diffusion and therefore the rate of oxygen evolution was very low (Figure 32, Test A, no recirculation).

As seen in UMV Test 1, diffusion is a slow process, even through gas. In all likelihood, oxygen diffuses even slower through liquid fuel than it does through fuel vapor. Slow diffusion of oxygen through fuel did not allow the fuel to equilibrate with the ullage very quickly, but if forced convection (fuel recirculation) was present, equilibrium was approached much more quickly as the model predicted. Without forced convection, the fuel formed an oxygen depleted fuel layer in contact with the ullage and evolved oxygen at a very low rate.

Test B showed a fairly high rate of O_2 evolution from the air saturated fuel into the nitrogen-rich ullage early in the test. This was due to the turbulent refueling process. Refueling lasted only 5 minutes at 100 gpm and the total amount of oxygen evolved was small and at the end of refueling, the fuel was still oxygen-rich and the ullage was nitrogen-rich. After refueling, the fuel

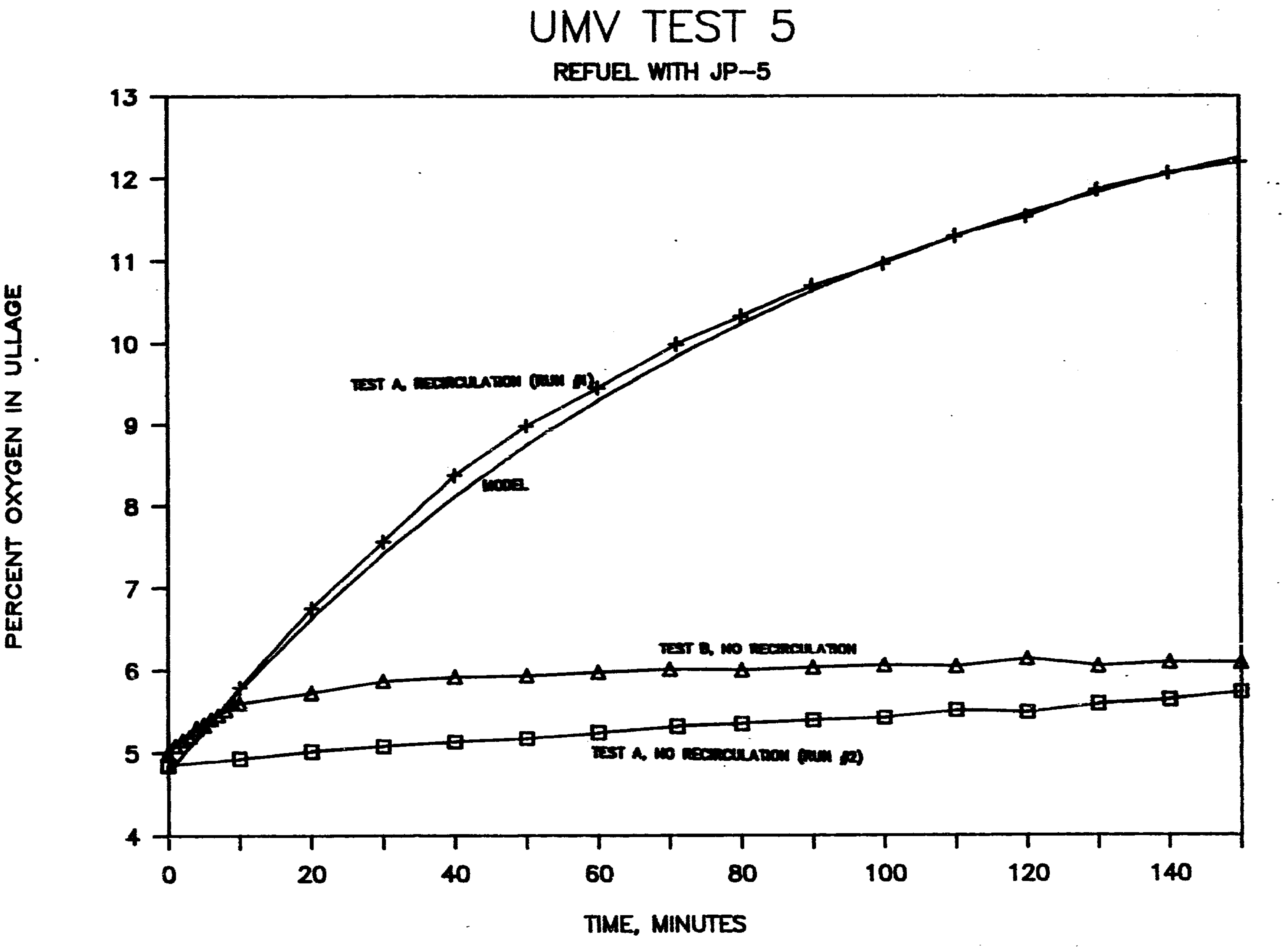


Figure 32. Oxygen Concentrations in Ullage During Refuel

was allowed to be quiescent (no recirculation) and the Test B rate of O_2 evolution was similar to the Test A run #2 rate of O_2 evolution.

Although air saturated fuel is agitated while being pumped into an airplane's fuel tank, this agitation lasts for a relatively short period of time and the partial pressure of oxygen in the fuel is still greater than the partial pressure of oxygen in the ullage after refueling an airplane fuel tank (filled with NEA_5) with air saturated fuel. This test showed that if there is not agitation of the oxygen rich fuel that is in contact with the nitrogen rich ullage, oxygen will evolve very slowly from the fuel into the ullage and a plane could sit for a long time on the runway with a oxygen non-equilibrium condition existing in the fuel tank.

6.0 MISSION SIMULATIONS (UMV Test 6)

6.1 Test Procedure

The ModComp computer was used both to supply mission variable setpoints and log data throughout the mission. Refer to Figure 6 for performance of the SAFTE vs. mission profile setpoints. Altitude, wall temperatures and fuel withdrawal in the SAFTE were held closely to the setpoints by the computer control system, indicating that the SAFTE tank ullage behaved as a flying airplane's fuel tank ullage would. The computer also logged data from the SAFTE instrumentation system, giving a complete description of ullage behavior and tank conditions during the mission.

The test procedure that follows was used for UMV Test 6 missions:

- Load setpoints into computer
- Establish initial conditions according to test matrix (Table 13)
    1. Fuel - amount, temperature, type, air saturated
    2. Wall temperatures
    3. Pressure
- Begin mission
- Computer logs data

The variety of mission simulations run on the SAFTE allowed useful comparison to the computer model for a wide range of missions.

Plots of top wall temperature and fuel surface temperature vs. time are shown for cold day, standard day, hot day and transport mission profiles (Figure 33). The variation in initial fuel temperatures for cold day (-10°F), standard day (60°F) and hot day (100°F) is evident, but the difference between top wall temperature and fuel surface temperature was virtually the same for all cold, standard and hot day missions. The transport mission plot of top wall temperature and fuel surface temperature has a much different shape, with top wall temperature less than fuel surface temperature for almost the entire 300 minute mission. This was intended to simulate a subsonic cruise at altitude.

Table 13. UMV Test 6 Mission Profile Test Matrix

Mission Type	Temp.	Run #	Fuel Type	Initial Fuel Level	Demand Gas	Scrub
Fighter	Cold	2	JP-4	82%	NEA_5	NEA_5 0-19 min
	Standard	1	JP-4	86%	NEA_5	NEA_5 0-19 min
		2	JP-4	97%	NEA_5	NEA_5 0-19 min
		3	JP-4	97%	NEA12	NEA_5 0-19 min
		4	JP-4	97%	NEA12 peak dmd	NEA_5 0-19 min
	Hot	1	JP-4	87%	NEA_5	NEA_5 0-19 min
		2	JP-5	87%	NEA_5	NEA_5 0-19 min
Transport	Standard	1	JP-4	97%	air	none
		2	JP-5	97%	air	none

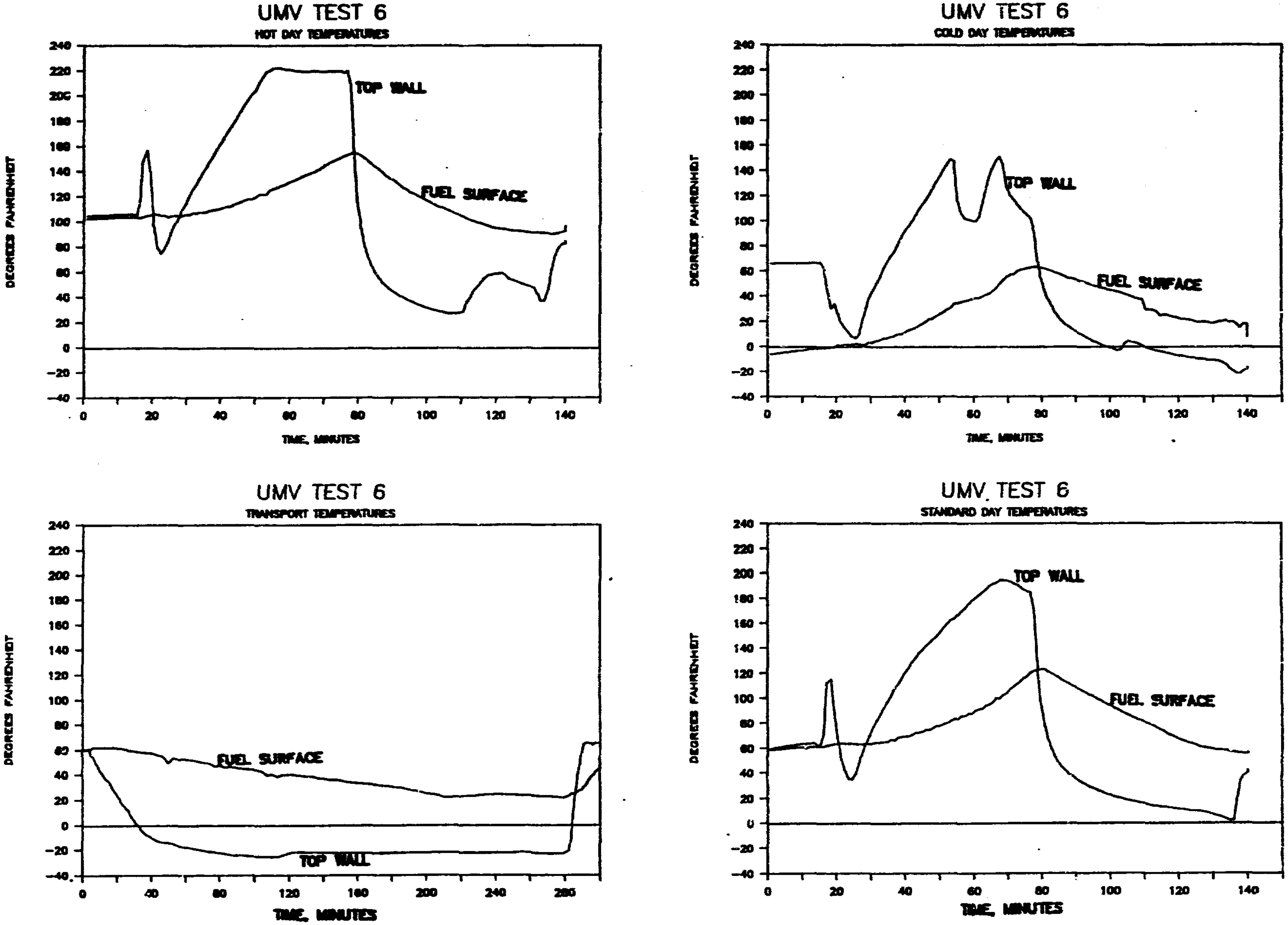


Figure 33. Top Wall and Fuel Surface Temperatures

Altitude pressure vs. time is plotted for both fighter and transport missions (Figure 34). During transport mission profiles, the test tank was vented to the altitude tank, therefore test tank pressure equaled altitude tank pressure. Fighter mission profiles utilized the climb valve/demand regulator apparatus described in Section 3.2. In the fighter cold day, standard day and hot day mission profiles, the climb valve was set to open when test tank pressure was 6.3 psi above altitude tank pressure. The demand regulator was set to inlet mixing valve product gas (NEAx) into the test tank when test tank $P <$ altitude tank $P + 4.7$ psi. By using the climb valve and demand regulator, test tank pressure was controlled between 4.7 psi and 6.3 psi above altitude tank pressure during fighter mission profiles.

Ullage height vs. time are plotted (Figure 35). Two different initial fuel levels were used in the fighter mission profiles, 86% full and 97% full. However, fuel withdrawal rates for all fighter mission profiles were identical. The ullage size schedule for the transport missions is also shown in Figure 35. It is evident that the fuel withdrawal rate during transport missions was much lower than during fighter missions.

Demand gas was fuel tank make-up gas that was supplied to the fuel tank during descent or fuel withdrawal. In the fighter mission profiles, this occurred when test tank $P <$ altitude tank $P + 4.7$ psi. Then NEAx demand gas flowed through the demand regulator and into the test tank. During cold day, hot day and standard day runs #1 and #2, the demand gas was NEA_5. For standard day run #3, NEA_{12} was used as the demand gas throughout while standard day run #4 employed NEA_{12} as the demand gas at peak make-up gas demand times during descents and used NEA_5 as a low flow rate fuel withdrawal make-up gas. Since the test tank was vented to the altitude tank during transport missions, air was used as the demand gas during the transport missions.

Fuel for all missions was air saturated and in equilibrium with the ullage at the beginning of the mission. After the mission began, no scrub was utilized during the transport missions. However, an NEA_5 scrub was used for all fighter mission profiles from t=0 to t=19 minutes. Scrub flow rate was 0.228 lb/min and a ground scrub was performed from t=0 to t=15 minutes. Scrub during climb occurred between t=15 and t=19 minutes and then scrub flow was shut off when an altitude pressure of 2.5 psia was reached (Figure 34).

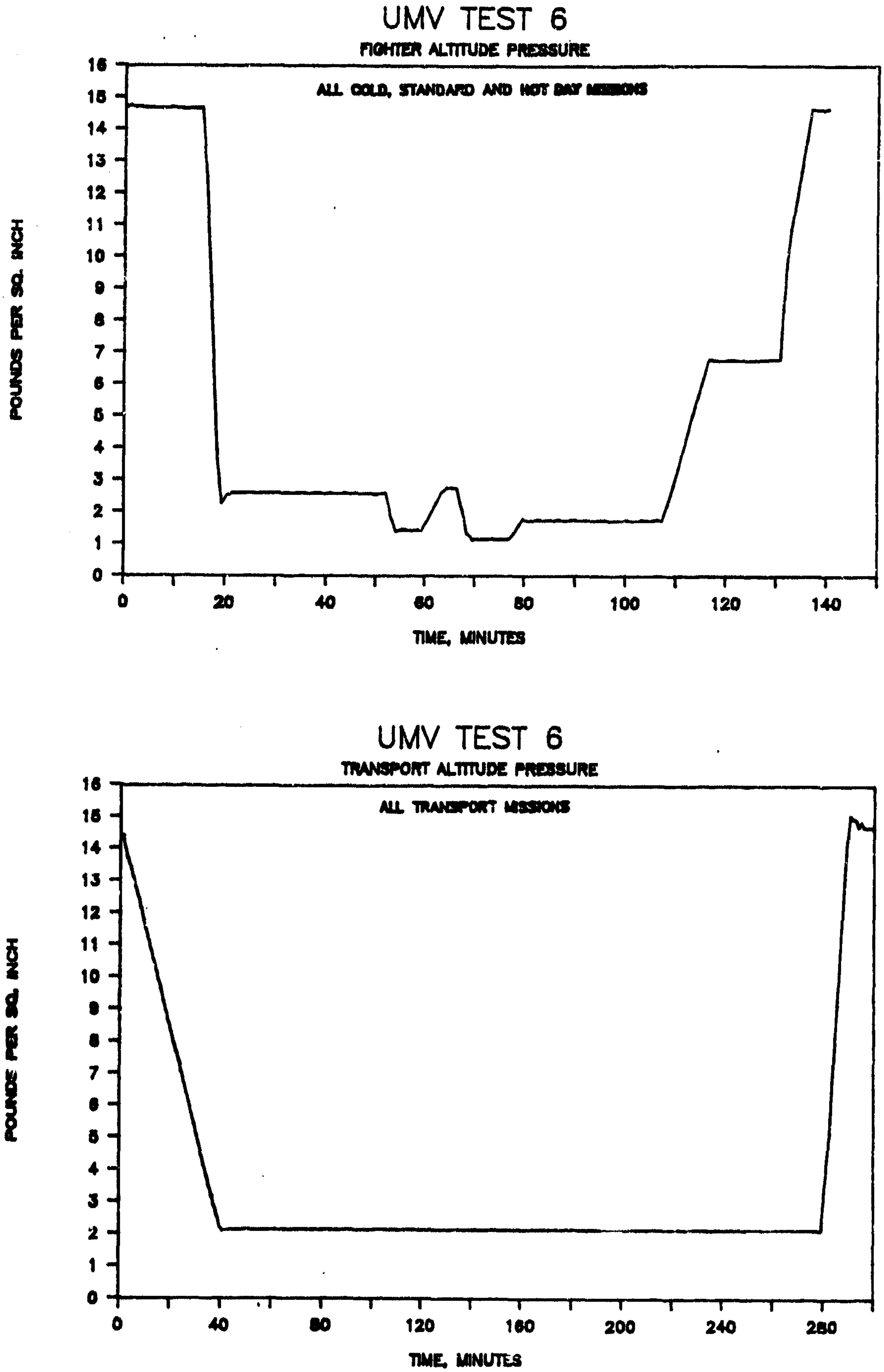


Figure 34. Altitude Pressures

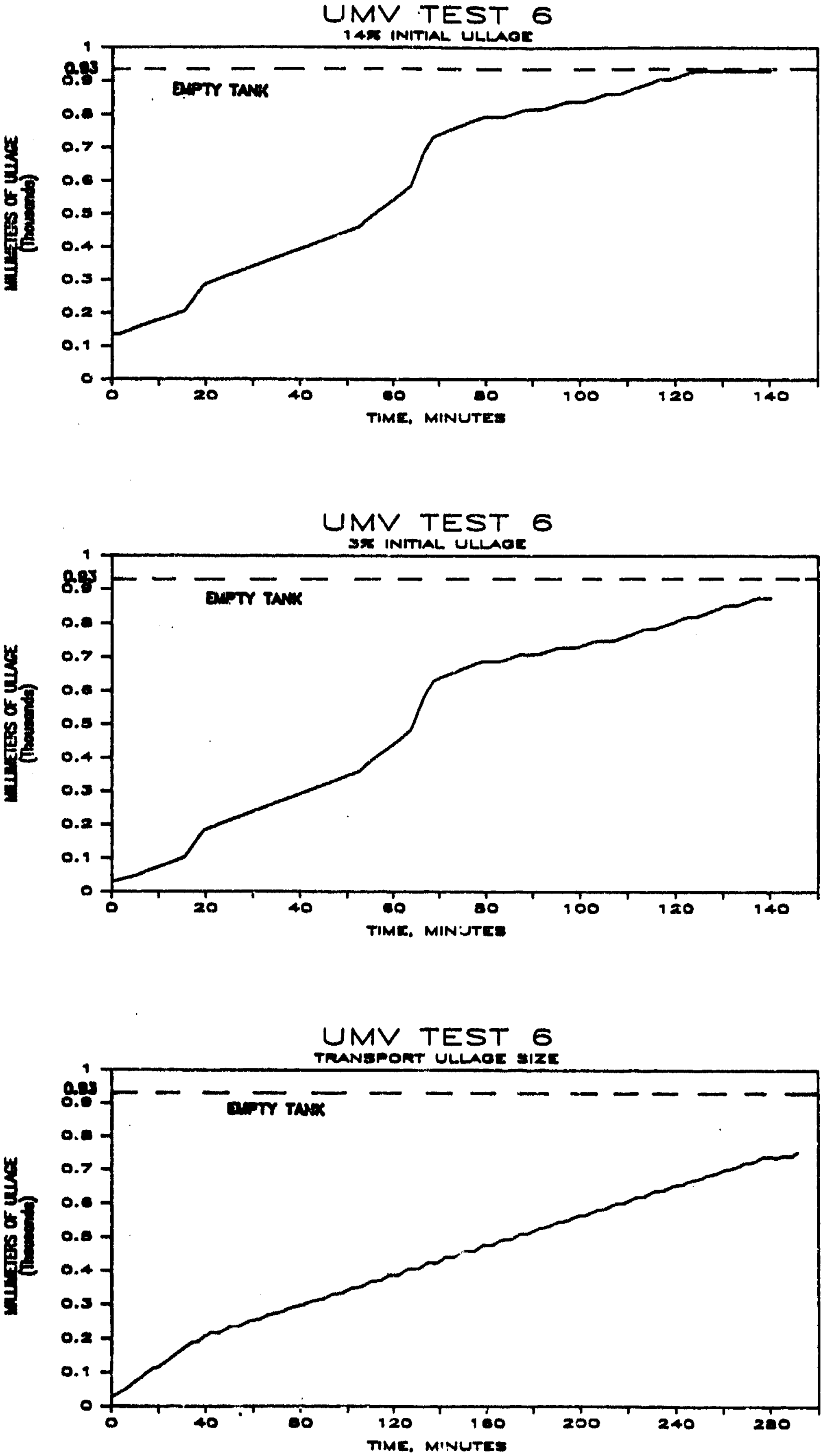


Figure 35. Ullage Sizes

6.2 Results

6.2.1 Fighter Missions

Figures for %O_2 and %HC vs. time are presented for mass spectrometer probes that were located at the tank top wall and at 50 mm above fuel surface (Figure 36) for cold day, standard day and hot day temperatures. These three runs had identical mission variables (such as fuel type, scrub, dive gas (NEA_5) and initial fuel level) except for wall and initial bulk fuel temperatures. Top and bottom wall temperatures and bulk fuel temperature were set initially according to day temperature. Top and bottom wall temperatures were controlled during the mission simulation by the computer and side wall temperatures and the fuel temperature were allowed to float. It was observed during UMV Test 6 that bulk fuel temperature was virtually equal to fuel surface temperature, due to the recirculation pump running throughout the test. An inverse relationship between % hydrocarbon and % oxygen (as %HC increases, %O_2 decreases) is evident in these plots. Hot day %HC was greater than standard day %HC which in turn was greater than cold day %HC. This was due to the vapor pressure of JP-4 increasing with temperature. Because of the %O_2 - %HC inverse relationship, %O_2 decreased with increasing day temperature. At low altitude pressure, t = 80 minutes and 50 mm above fuel surface, hot day %O_2 approached zero as %HC approached 90%.

The effect of the NEA_5 scrub during the first 19 minutes of the mission is apparent in the steep negative slope of the %O_2 vs. time plots. The scrub was used only during the first climb in each mission and did an effective job of lowering %O_2 in the ullage, in spite of the oxygen that evolved from the air saturated fuel during climb (UMV Test 4 - Section 5.3).

Stratification appeared to be present in the standard and hot day missions. There is a 47% hydrocarbon difference (87% to 40%) between 50 mm above fuel surface and the top wall at t=80 minutes for the hot day mission profile. The 50 mm - top wall %HC difference for standard day = 35% and cold day (t=80 min.) %HC difference was only about 5%. Stratification appeared to be most pronounced for the hot day mission, but this was due to the values of %HC being very large (because of high fuel vapor pressure).

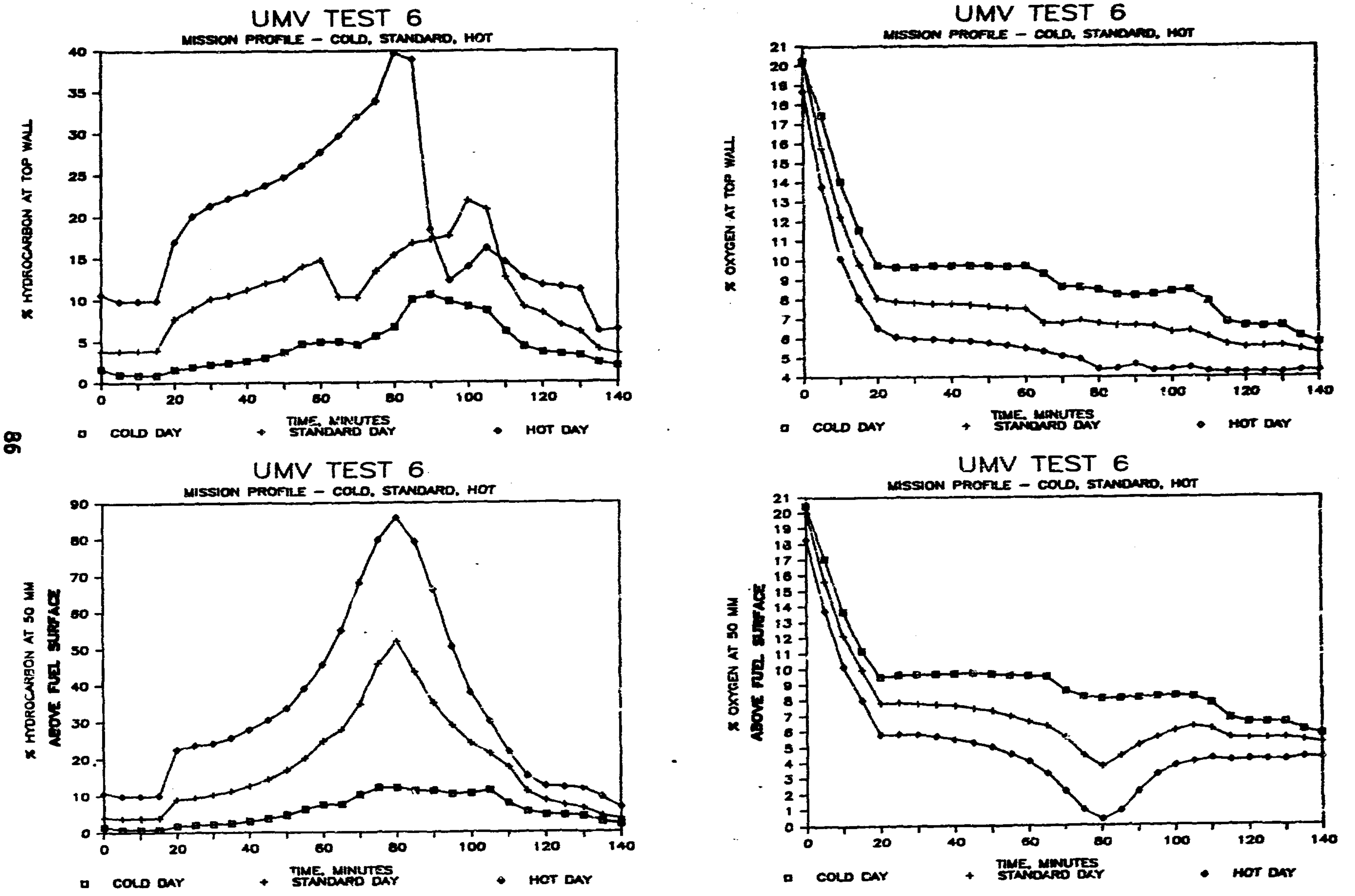


Figure 36. Cold, Standard and Hot Day Fighter Mission Ullage Oxygen and Hydrocarbon

Normalization of %HC must be performed on the hot, standard and cold day mission profiles to eliminate the temperature effect on %HC and give a true picture of the degree of ullage stratification. Normalizing means dividing the difference %HC at 50 mm (above fuel surface) - %HC at top wall by %HC at equilibrium. However, since ullage pressure and fuel temperature was changing throughout the mission, %HC at equilibrium was non-constant. A first order approximation was to set %HC at equilibrium = %HC at 50 mm. The formula for normalization in this case is:

$$\begin{array}{l} \text{normalized top wall to} \\ \text{50 mm above fuel surface} \\ \text{HC concentration differential} \\ \quad (\text{"bottom" - "top"}) \end{array} = \frac{\%\text{HC at 50 mm} - \%\text{HC at top wall}}{\%\text{HC at 50 mm}}$$

Plots of this normalized HC concentration differential (Figure 37) show a similar degree of significant stratification commencing at t = 30 minutes for cold, standard and hot JP-4 missions and ullage mixing after t = 80 minutes. As noted from the top wall temperature and fuel surface temperature vs. time plots (Figure 33), hot top wall (top wall T > fuel surface T) stratification conditions existed between t = 30 and t = 80. Natural convection occurred after t = 80 due to a cold top wall relative to the fuel surface temperature and this is reflected in the decrease in stratification.

As seen in the altitude pressure vs. time plots for fighter mission profiles (Figure 34), the airplane descended at t > 110 minutes and make-up gas (NEA_5) was supplied to the fuel tank. The ullage vent gas heat exchanger wasn't used during UMV Test 6 and as a result, fuel tank demand gas temperature was approximately $70^{o}F$ regardless of top wall temperature. Vent gas was cold relative to hot day and standard day ullages. Vent gas was hot relative to the cold day ullage. The temperature difference between vent gas and ullage was much greater than the $25^{o}F$ difference tested in UMV Test 2 (Forced Convection). This large temperature difference in the hot day mission led to forced convection mixing, rather than inlet gas stream stratification as seen in UMV Test 2.

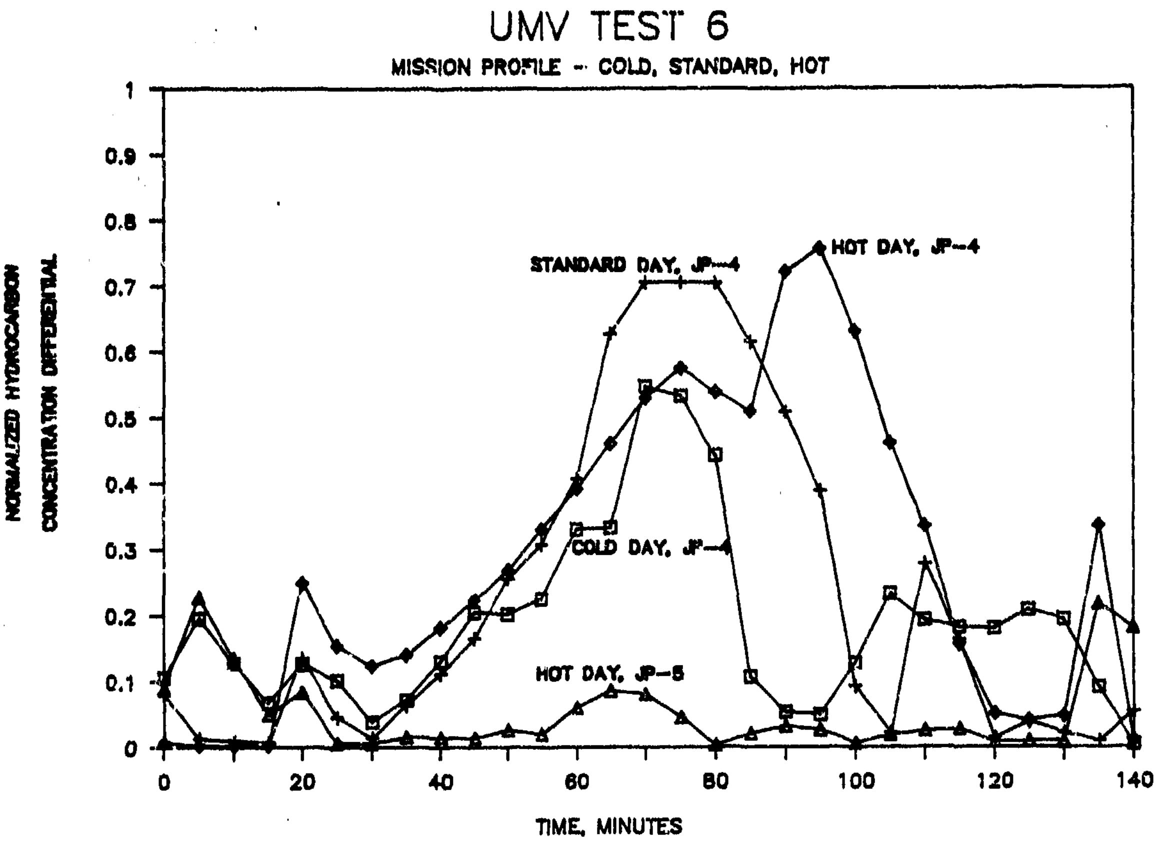


Figure 37. Cold, Standard and Hot Day Fighter Mission Normalized Hydrocarbon Concentration Differential

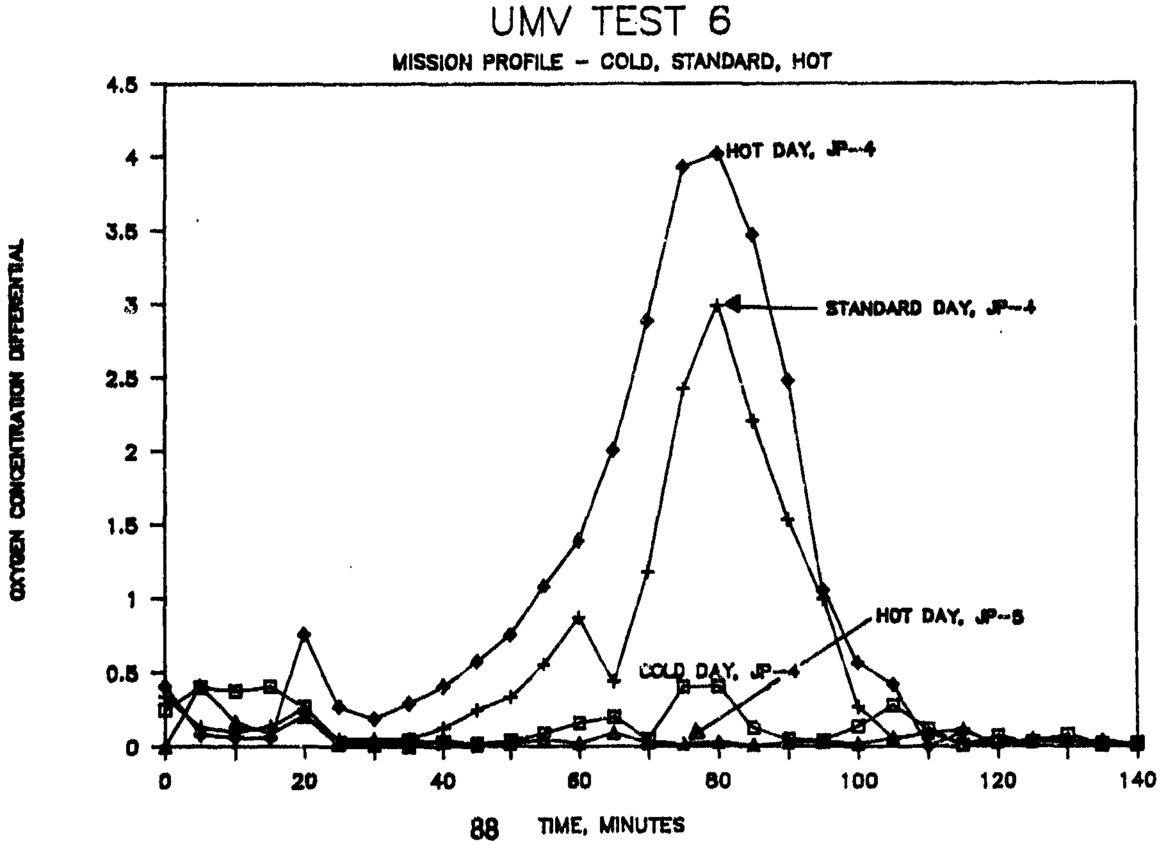
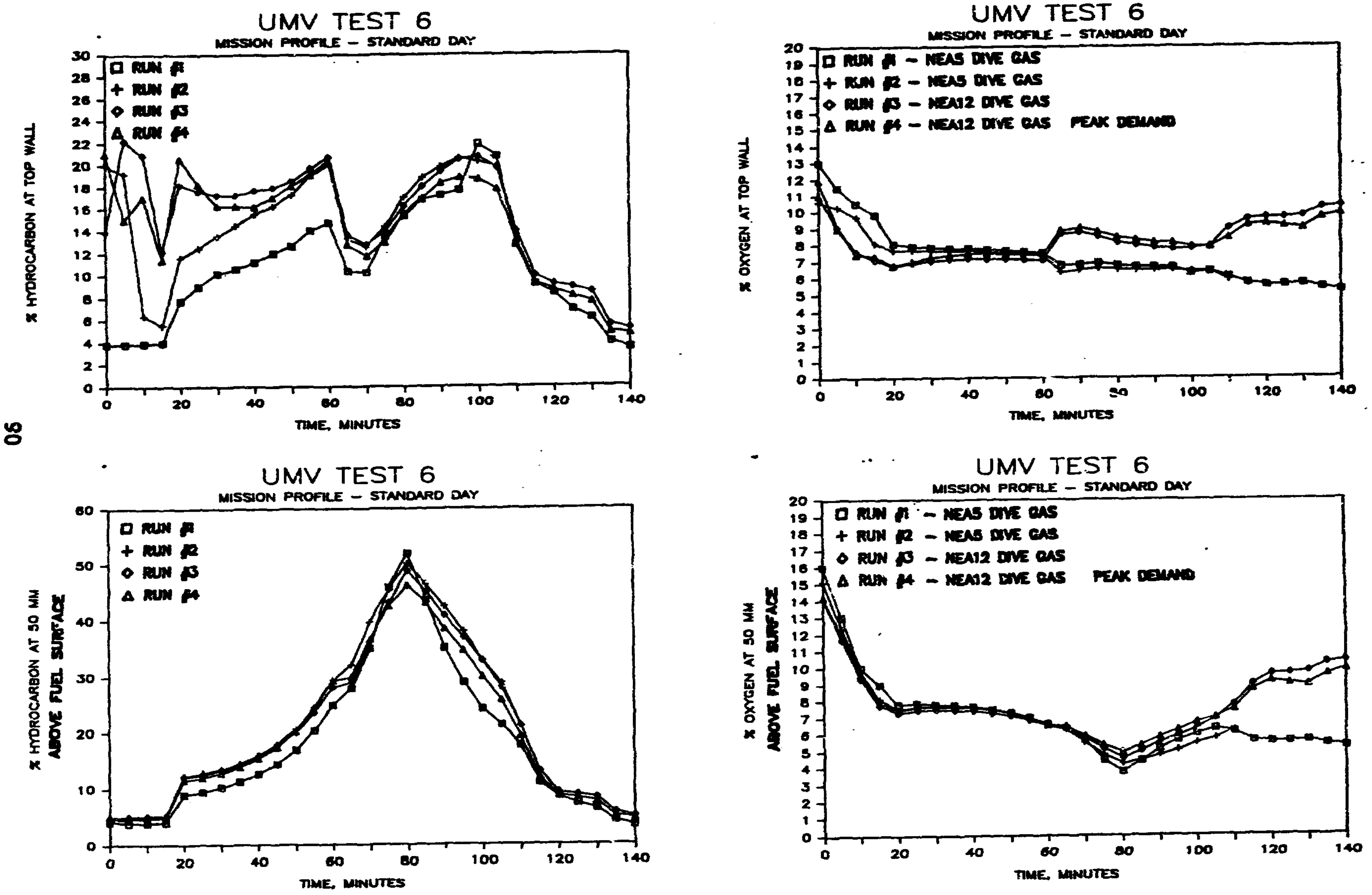


Figure 38. Cold, Standard and Hot Day Fighter Mission Oxygen Concentration Differential

In spite of having a very similar top wall temperature and fuel surface temperature profile, the hot day mission using JP-5 didn't stratify nearly as much as the JP-4 missions, even after normalization (Figure 37). The reasons for the well stirred ullage during the JP-5 hot day mission are not known. Non-normalized top to bottom $\%O_2$ differences for cold, standard and hot days are apparent (Figure 38). Cold day $\%O_2$ appears to be well mixed but this is due only to the low vapor pressure of JP-4 at cold day temperatures, which limited the maximum possible $\%O_2$ difference to a very small value. Likewise, hot and standard days appear to be stratified but this is due to the higher vapor pressure of JP-4, causing larger magnitude of difference in $\%O_2$. Normalization of $\%O_2$ would show equal stratification for hot, standard and cold days as in Figure 37.

The effect of NEA_{12} vs. NEA_5 demand gas was next examined (Figure 39). As expected, %HC was not affected at all by the difference in $\%O_2$ in the vent demand gas. The difference between NEA_{12} and NEA_5 make-up and dive gas is evident only on the $\%O_2$ vs. time plots. Standard day Run #4 used NEA_{12} during peak demand, that is, NEA_{12} during descent and used NEA_5 during low flow, fuel withdrawal make-up. Standard day run #3 used NEA_{12} throughout the test for both descent and fuel withdrawal make-up. These two tests (3 and 4) show a higher ullage $\%O_2$ starting at about t=60 minutes. Final descent at t=110 minutes, which called for a large amount of dive gas, emphasized the difference in ullage $\%O_2$ that NEA_{12} vs. NEA_5 demand gas made. However, overall there was only a small effect due to changes in the $\%O_2$ in the demand gas.

Different fuel types have an effect on $\%O_2$ and %HC in the ullage (Figure 40). The higher hydrocarbon vapor pressure of JP-4 is immediately apparent in the lower initial $\%O_2$ in ullage in equilibrium with air saturated fuel. Likewise the inverse relationship of $\%O_2$ and %HC is demonstrated. The ullage concentration of hydrocarbon during the JP-4 hot day mission was quite high and this forced $\%O_2$ in the ullage to be lower than $\%O_2$ ullage for the JP-5 hot day mission. JP-5 has a low vapor pressure even at high temperatures and $\%O_2$ during the JP-5 mission was greater than $\%O_2$ during the JP-4 mission. The 19 minute NEA_5 scrub has a similar effect on both JP-4 and JP-5, rapidly reducing $\%O_2$ in the ullage in spite of O_2 evolution during climb. The difference in slope for the two $\%O_2$ vs. time curves during scrub for JP-4 and JP-5 is probably due to the difference in the Ostwald coefficients for the fuels (Section 5.1, Scrub Test).


UMV TEST 6
MISSION PROFILE – STANDARD DAY

UMV TEST 6
MISSION PROFILE – STANDARD DAY

UMV TEST 6
MISSION PROFILE – STANDARD DAY

UMV TEST 6
MISSION PROFILE – STANDARD DAY

Figure 39. Effect of Demand Gas on Ullage Oxygen and Hydrocarbon Concentrations

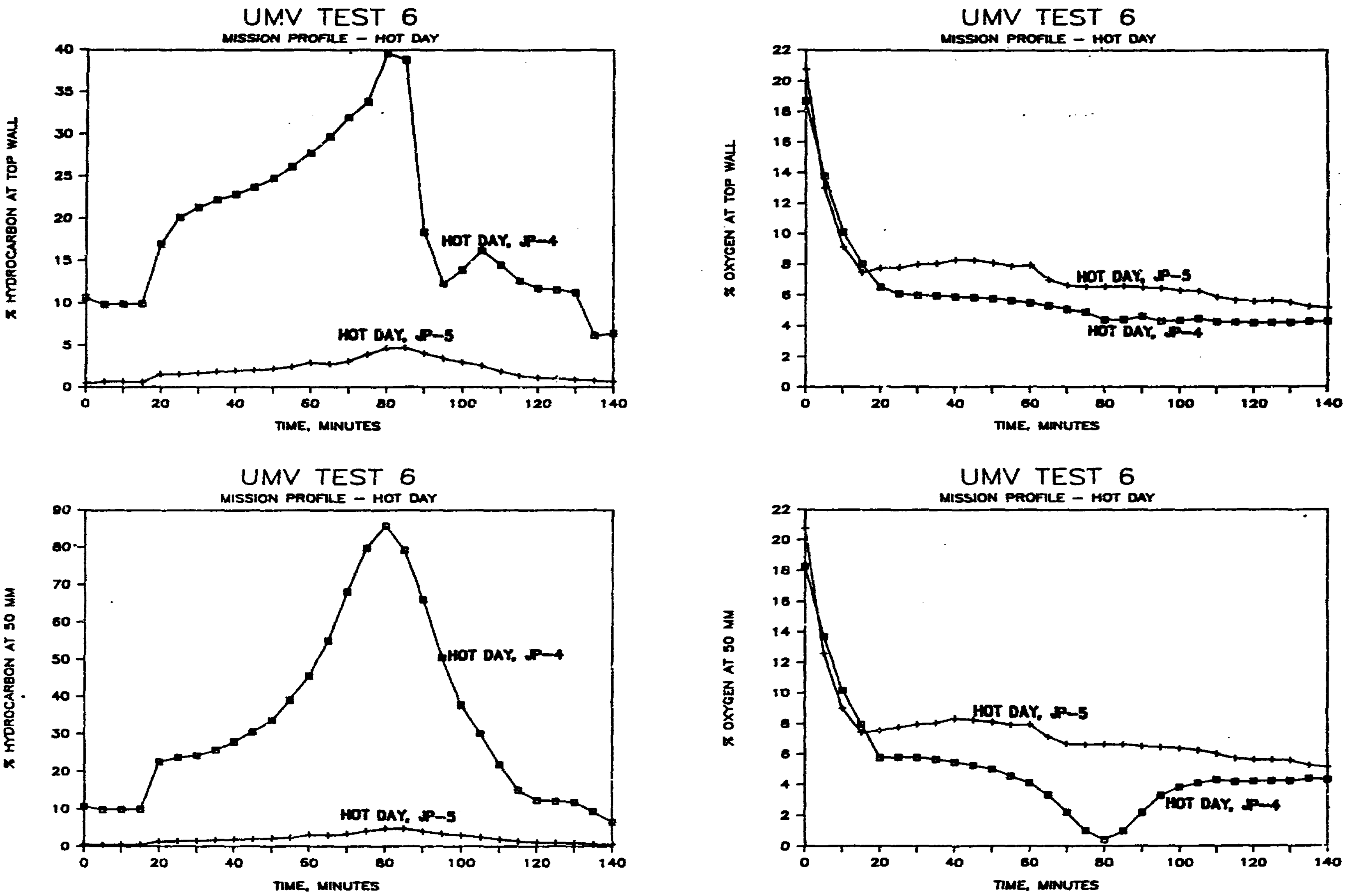


Figure 40. Effect of Fuel Type on Ullage Oxygen and Hydrocarbon Concentrations

6.2.2 Transport Missions

The transport mission profiles were much simpler than the fighter mission profiles. There wasn't a scrub during climb and the fuel tank was vented to the altitude tank. By opening the manual bypass valve, the climb valve/demand regulator apparatus was not used and fuel tank P = altitude P. As a result of venting to the altitude tank, air was used as the fuel withdrawal make-up gas and as the descent gas. See Figure 33 for plot of top wall and fuel surface temperatures vs. time. Note that fuel surface temperature exceeded top wall temperature for the entire 300 minute mission except for the last 15 minutes. As expected, this temperature scheme led to natural convection, mixing the ullage.

The %HC at top wall and at 50 mm above fuel surface vs. time and shows that the ullage was well mixed (Figure 41). Even the non-normalized %HC differences between top wall and 50 mm above fuel surface for the JP-4 mission are small.

Also, $\%O_2$ at top wall and at 50 mm above fuel surface is plotted for transport missions (Figure 41). The lack of an NEA_5 scrub is evident in the sharp rise in $\%O_2$ during climb for JP-5 transport missions. $\%O_2$ during climb for the JP-4 transport mission didn't dramatically increase because of the $\%O_2$ - %HC inverse relationship. O_2 is evolved from JP-4 during climb but the high JP-4 vapor pressure caused a high percentage of hydrocarbons in the ullage during the JP-4 mission. This high %HC forced $\%O_2$ in the ullage to remain at relatively low levels, even during climb.

The slight negative slope of %HC vs. time plots for JP-4 between 40 and 260 minutes shows the effect cooling fuel had on %HC in the ullage. Top and bottom wall temperatures were held at -25°F by the ModComp and the wall temperature conditioning system for the duration of the high altitude subsonic cruise. This cruise cooled off the fuel, lowering the bulk and surface temperature. Accordingly, the vapor pressure of the fuel decreased, leading to a lower %HC in the ullage.

The similar shape of the $\%O_2$ vs. time plots for JP-5 between 40 and 260 minutes demonstrates the effect fuel withdrawal make-up gas (air, $\%O_2 = 20.9$) had on $\%O_2$ in the ullage when $\%O_2$ at t=40 minutes was about 28%.

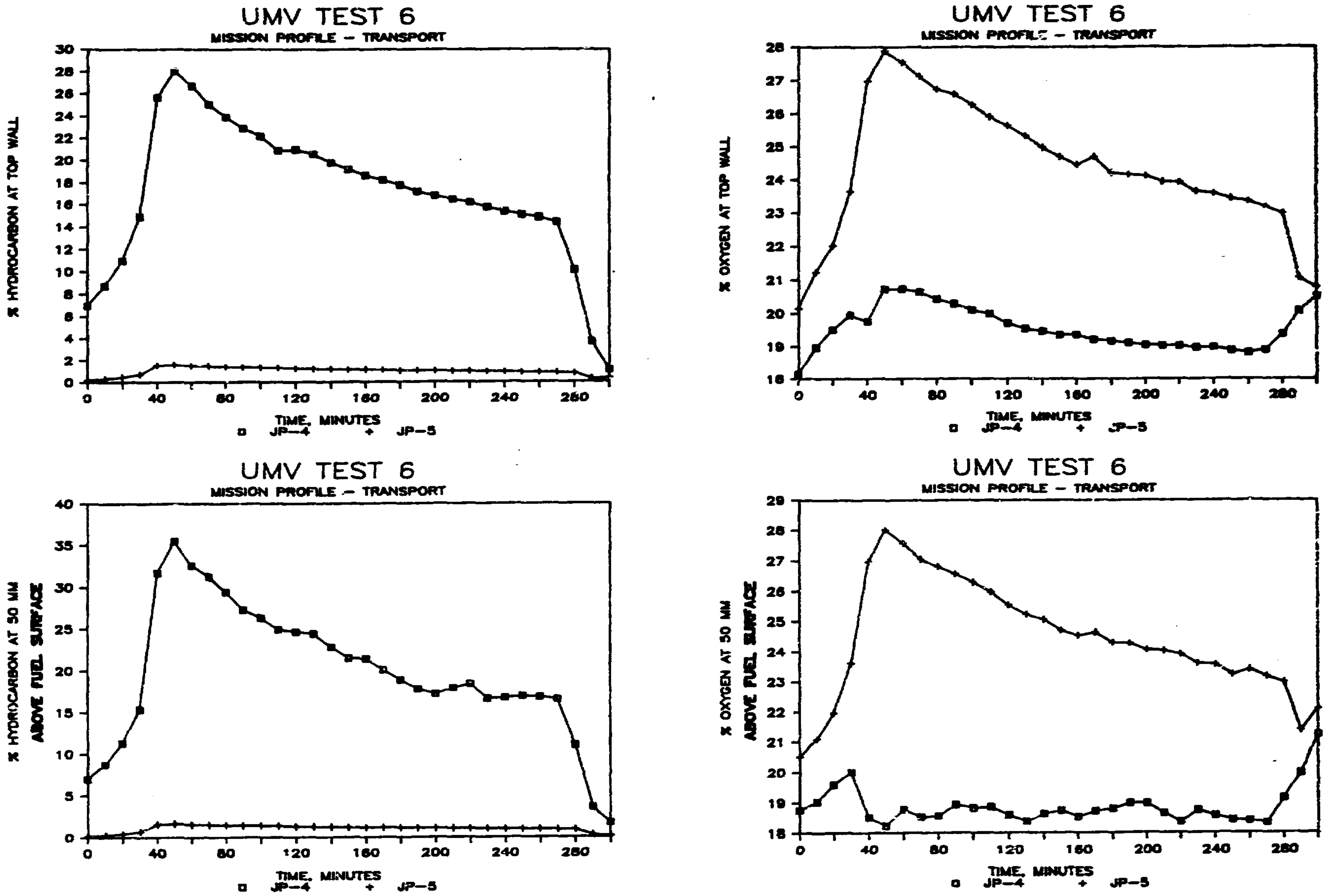


Figure 41. Transport Mission Ullage Oxygen and Hydrocarbon Concentrations

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Under certain fuel tank wall temperature conditions such as hot top wall or cold fuel, fuel tank ullage mixing will be diffusion dominated and any hydrocarbon concentration gradients will relax approximately according to Fick's second law.

In contrast, a cold top wall or hot fuel in a fuel tank will cause natural convection and the ullage will be well stirred.

Both diffusion and natural convection are mixing forces which tend to eliminate any concentration gradients but natural convection mixes the ullage much faster than diffusion which is a very slow process.

A fuel withdrawal vent gas make-up stream was observed to stratify the ullage where mixing was diffusion dominated. A higher vent gas flowrate was required to stratify the ullage if natural convection currents existed in the tank. The stratification effect of the vent gas stream was observed in all configurations of the vent gas stream (cold/ambient/hot and horizontal/vertical vent).

The effect of slosh mixing was observed to depend on the violence of the slosh event. Significant mixing was only observed when the tank was sloshed at its natural frequency.

A viable analytical scrub model was derived that accurately predicted $\%O_2$ in the ullage during NEA_5 or air scrub.

The phenomenon of oxygen evolution into the ullage during climb or during refuel was seen as a result of the difference in oxygen partial pressures in the fuel and the ullage. The refuel scenario was successfully analytically modeled as well.

Oxygen non-equilibrium conditions were observed in Dissolved Oxygen Evolution During Climb tests when agitation of the fuel was not present. It was found that vibration or recirculation (scrub) provided sufficient agitation so that oxygen in the fuel was always at or nearly at equilibrium with the oxygen in the ullage.

It was observed in UMV Test 4 that, provided the fuel was being agitated (via vibration), NEA_5 wash reduced the ullage $\%O_2$ below 9 percent faster than NEA_5 scrub.

UMV Test 5 (Oxygen Evolution During Refuel) showed that an airplane can remain inert for extended periods of time (days) on a runway with oxygen rich fuel in non-equilibrium with a nitrogen rich ullage if there is no agitation. This scenario could exist subsequent to refueling an airplane with air saturated fuel if the tanks are initially inert.

An inverse relationship between hydrocarbon and oxygen in the ullage was observed in UMV Test 6. High fuel vapor pressure and low altitude pressure causes hydrocarbon to be high which in turn displaces oxygen and lowers $\%O_2$.

A vent gas stream was observed in UMV Test 6 that did not stratify the ullage. This gas stream was very cold relative to the ullage and at a very high flow rate, conditions that were not examined in UMV Test 2 (Forced Convection).

7.2 Recommendations

The following recommendations can be made for further work:

1. $25^{o}F$ was the standard temperature difference used throughout UMV Tests 1 and 2. Ullage mixing probably occurs faster if the top wall is colder than in those tests. Test utilizing wall temperature differences other than the $25^{o}F$ temperature difference should be run to examine various natural convection mixing "speeds".

2. As shown in UMV Test 6, under the proper conditions a vent gas stream is not a stratifying force. Using UMV Test 2 procedures, forced convection should be re-examined under greater temperature differences and also using descent instead of fuel withdrawal to add vent gas to the ullage.

3. Slosh was observed to mix the ullage. The effect of vibration on ullage stratification is unknown and is a possible area for further study.

4. It was seen in UMV Test 4 that wash may be a more efficient inerting scheme that scrub. Work can be done in this area to determine the conditions where wash is more efficient than scrub.

REFERENCES

1. McConnell P. M., et al, Volume III, Part 2, "Fuel Scrubbing and Oxygen Evolution Tests," AFWAL-TR-85-2060, January 1986.

2. Anderson, C. L., "C-17 O_2 Evolution Test Data Report," Interim Report, Contract F33615-84-C-2431, June 1985.

3. Mahood, L., et al, "Fuel Tank Fire-Explosion Computer Model," JTCG/A-78-V-010, Contract F33615-74-C-2057, May 1978.

4. Coordinating Research Council, Inc., Handbook of Aviation Fuel Properties, Contract DAAK70-81-C-0128, 1983.

5. Anderson, C. L., Williamson, R., "SAFTE Operating Manual," Contract F33615-78-C-2063, November 1984.

6. Welty, J.R., et al, Fundamentals of Momentum, Heat, and Mass Transfer, John Wiley and Sons, 1976 second edition.

7. Jakob and Hawkins, Elements of Heat Transfer.

ACRONYMS AND ABBREVIATIONS

amb	ambient temperature
CPM	cycles per minute, min^{-1}
GPM	gallons per minute
Hz	hertz, sec^{-1}
mil	one thousandth of an inch (0.001")
ModComp	Modular Computer Systems, real-time computer
MS	mass spectrometer
NEA_x	nitrogen enriched air, x is $\%O_2$
OBIGGS	on-board inert gas generator system
%HC	percent hydrocarbon by volume
psia	pounds per square inch, absolute
psig	pounds per square inch, gauge
Re-Circ	recirculation fuel flow
RVP	reid vapor pressure
SAFTE	simulated aircraft fuel tank environment
TDF	test direction file
UMV	ullage model verification
UIS	ullage instrumentation system
Vib	vibration of SAFTE tank

APPENDIX A

MASS SPECTROMETER DESCRIPTION

The mass spectrometer used to analyze the composition of ullage gas from the SAFTE tank was designed and constructed by Analog Technology Corporation (ATC Model 2001). The unit is relatively small and was intended for measuring trace constituents in air and other gases. This instrument was developed under a contract from the Langley Research Center of NASA, and the sensor design is based on a two-inch hyperbolic-rod quadruple mass filter.

The instrument has a mass range of 2 to 200 AMU, and a detection limit of 0.1 parts per million. It has three operating modes, which provide (1) a conventional mass spectrum scan, (2) continuous monitoring of a single mass peak, or (3) automatic analysis for determination of selected concentrations of compounds or compound types. The automatic analysis mode uses peak-switching to measure up to 40 mass peaks and provides a digital readout of concentration in percent by volume units after correction for spectral interferences. The application for the SAFTE tank involves only the automatic analysis mode for the measurement of four peaks to determine the percent by volume of nitrogen, oxygen, argon, and hydrocarbons. This information is continuously transmitted to the ModComp computer at the rate of one measurement every two seconds as well as displayed on a CRT in real time.

The particular novelty of this instrument is its capability, in a relatively small and inexpensive configuration, to make rapid, repetitive measurements with a measurement time much shorter than can be accomplished in a gas chromatograph-mass spectrometer system, and to provide analysis results directly in concentration units with corrections for any spectral interferences that may be present. The limitation of the method is that the identity of the possible interfering compounds must be predicted at the calibration stage. However, spectral interference and calibration do not present any difficulty for the SAFTE tank application.

The instrument package consists of (1) a vacuum envelope (ion pumped) containing a quadruple mass spectrometer, (2) vacuum and gas-inlet components associated with the vacuum envelope, (3) electronic circuits required to operate the mass spectrometer (located behind the vacuum envelope), and (4) a computer that controls the operation of the mass spectrometer and processes the data obtained.

The entire instrument package occupies 30" of vertical space in a standard 19" rack.

The inlet system is a conventional continuous "flow by" system which requires that the sample pressure be reduced to the 2 to 6 Torr range (2 Torr is used for this application) so that a molecular-flow leak can be used. The leak is mounted in the seat of a solenoid valve that automatically closes in the event of loss of power or on any occasion when unacceptably large pressure increases occur in the mass spectrometer.

Sample gas continuously flows past the molecular leak to a large mechanical pump. The leak valve is located within a temperature-controlled oven. The molecular-flow leak is a 0.0003" pin-hole in a gold foil. This is mounted in the solenoid valve with a very small entrapped volume (0.15 microliter) between the leak and the valve seat so that the pressure rise in the vacuum system resulting from loss of power is small and the system returns to operation immediately on restoration of power. A very small portion of the gas sample actually flows through this molecular-flow leak into the mass spectrometer for analysis.

In addition to providing analog display of a spectrum, the CRT also provides an alphanumeric display. This alphanumeric display permits recovery of any information in the computer memory representing the status of the instrument based on commands given from the keyboard, housekeeping measurements of operating parameters, and monitoring of circuits that detect malfunctions. It also permits display of concentrations and of all values measured or calculated by the computer, with selection of the information to be displayed provided by a display selector key.

The measured concentrations and other digital information stored in computer memory can also be sent to an auxiliary device via an RS232 interface. This RS232 interface is used to transmit concentration data to the data acquisition system for disk logging.

In the automatic analysis mode, the computer causes the instrument to measure integrated ion currents for a set of up to 40 selected mass peaks, with individually selected integration times. Concentrations are obtained in the automatic analysis mode by solving simultaneous equations with coefficients representing the sensitivity of each of the compounds expected at each of the mass peaks measured. The coefficients can be measured automatically by use of standard samples with known concentrations, after keyboard entry of the concentration. Alternatively, the coefficients can be manually entered using the mass number and constituent number keys to identify the coefficient to be entered. After all of the required coefficients have been entered, the computer inverts the matrix and is then ready to perform automatic analyses using these inverted matrix coefficients to calculate concentrations. The peaks used for the SAFTE application are as follows:

Constituent	Peak (AMU)
N_2	14
O_2	32
Ar	40
All HC's	43

Sensitivity coefficients are determined automatically by measuring sensitivities as a ratio to the mass-14 peak which represents nitrogen, so that correction is made for any variations of sensitivity during the calibration. The calculated concentrations are normalized by dividing by the sum of all of the measured concentrations, again correcting for drifts in sensitivity. Measurements can also be corrected for drifts in relative sensitivity at different masses, using the same reference compound that is used for mass calibration, and then measuring the variation in the spectral pattern for this compound between the time of the original calibration and the time an analysis is made.

APPENDIX B

Fick's Second Law - Diffusion Model

$$\frac{dC}{dt} = \frac{Dd^2C}{dx^2}$$

where D = diffusion coefficient, cm^2/sec
C = concentration, mol/cm^3
x = distance above fuel, cm
t = time, seconds

$\frac{dC}{dx}$, concentration gradient (fixed time)

$\frac{dC}{dt}$, rate of change of concentration (fixed x)

$\frac{d^2C}{dx^2}$, change of conc. gradient w/ x (fixed time)

Boundary and Initial Conditions

$C(0,h) = 0$ where h = distance above fuel
$C(t,0) = Ceq = 1$ t = time

find C(t,h)

use finite approximation

$$\frac{C(j+1,k)-C(j,k)}{\Delta t} = \frac{D\ (C(j,k+1)-2C(j,k)+C(j,k-1))}{\Delta h^2}$$

$$C(j+1,k) = C(j,k) + \frac{D\Delta t}{\Delta h^2}\ (C(j,k+1)-2C(j,k)+C(j,k-1))$$

step size rule for convergence $\Delta t < = \frac{\Delta h^2}{2D}$

See below for derivation of diffusivity D for JP-4 in air and an IBM PC Basic code for Fick's law computation.

From Reference 7, this is an empirical method for determining diffusivity, D, for JP-4 in air.

$$D = 0.0043 \frac{T^{3/2}}{P(V_A^{1/3} + V_B^{1/3})^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}}$$

where : D = diffusion coefficient, cm^2/sec

T = temperature in degrees Kelvin

P = total pressure, atm

M_A = molecular weight of air

M_B = molecular weight of JP-4 = 78.5 gm/mol

V_A, V_B = molecular volumes at normal b.p.

$V_A = 29.9$ (air)

V_B is determined as follows:

Average formula for JP-4 is: $C_{5.491}H_{12.391}$

Sum of atomic volumes:

$$\begin{aligned} 5.491 \times C &= 5.491 \times 14.8 = 81.27 \\ 12.391 \times H &= 12.391 \times 3.7 = \underline{45.85} \\ &\qquad 127.11 \end{aligned}$$

Deduct 30 for ring $\quad \underline{-30}$

$97.11 = V_B$ (JP-4)

Plugging above values into the equation,

$D = 0.07946\ cm^2/sec = 0.307\ ft^2/hr$

Compare to D for n-Octane in air (Reference 5) = $0.233\ ft^2/hr$

Fick's Diffusion Law Program (BASIC) calculates hydrocarbon concentrations throughout ullage at selected time intervals

```
10 REM   FINITE DIFFERENCE METHOD FOR COMPUTING HYDROCARBON
20 REM   DIFFUSION THROUGH AIR USING FICK'S SECOND LAW
30 DIM C(500,20), TIME(500), HEIGHT(20)
40 INPUT "enter height step size, mm   ",DELH
50 INPUT "enter ullage height, mm   ",ULLHT
60 INPUT "enter diffusivity, ft2/hr   ",D
70 INPUT "enter endtime, minutes   ",ENDT
80 INPUT "enter time step size, minutes   ",DELT
90 INPUT "enter begin time, minutes  ",BEGT
100 REM  CONVERT UNITS AND COMPUTE # OF STEPS FOR TIME AND HEIGHT
110 ENDT =(ENDT-BEGT)/60
120 NONE = INT(ULLHT/DELH)
130 IF NONE>99 THEN NONE = 99
140 DELH = (DELH/25.4)/12
150 DELT = DELT/60
160 IF DELT > (DELH^2)/(2*D) THEN DELT = (DELH^2)/(2*D)
170 LPEND = INT(ENDT/DELT)
180 REM  SET INITIAL AND BOUNDARY CONDITIONS
190 FOR K = 1 TO NONE+1
200 H = K*DELH*12*25.4
210 PRINT "enter initial concentration at", H
220 INPUT INCON
230 C(0,K)=INCON
240 NEXT K
250 FOR J = 0 TO LPEND
260 C(J,0) = 1
270 NEXT J
280 REM  COMPUTE AND PRINT NEW VALUES OF C(J,K)
290 HEIGHT(0) = 0
300 TIM = BEGT
310 MDELH = 12*25.4*DELH
320 MDELT = 60*DELT
330 FOR K = 1 TO NONE
340 HEIGHT(K) = HEIGHT(K-1) + MDELH
350 NEXT K
```

```
360 FOR J = 0 TO LPEND
370 FOR K = 0 TO NONE
380 PRINT TIM, C(J,K), HEIGHT(K)
390 NEXT K
400 TIME(J) = TIM
410 TIM = TIM + MDELT
420 FOR K = 1 TO NONE
430 C(J+1,K) = C(J,K) + ((D*DELT)/(DELH^2))*(C(J,K+1)-2*C(J,K)+C(J,K-1))
440 NEXT K
450 C(J+1,NONE+1) = C(J+1,NONE)
460 NEXT J
470 REM  TRANSMIT DATA FILE TO DISKETTE B FOR LOTUS 1-2-3
480 OPEN "b:DIFF1.prn" FOR OUTPUT AS 1
490 PRINT #1, USING "##";13;
500 FOR K = 0 TO NONE
510 PRINT #1, USING " ###.#";HEIGHT(K);
520 NEXT K
530 PRINT #1,""
540 FOR J = 0 TO LPEND
550 PRINT #1, USING " ###.###"; TIME(J);
560 FOR K = 0 TO NONE
570 PRINT #1, USING " #.####"; C(J,K);
580 NEXT K
590 PRINT #1, ""
600 NEXT J
610 CLOSE
620 END
```

DEPARTMENT OF THE AIR FORCE
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES (AFSC)
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6563

REPLY TO ATTN OF: POSF 25 November 1987

SUBJECT: Reports Distribution List

TO: DISTRIBUTION LIST (FIRE PROTECTION)

1. The attached report describes experimental work conducted using a fuel tank simulator to investigate the composition of airplane fuel tank ullage spaces. The investigations included ullage mixing by diffusion and convection, oxygen evolution during simulated climbs and refueling and complete mission simulation.

2. AFWAL-TR-87-2060, Volume 1, "Development and Evaluation of an Airplane Fuel Tank Ullage Composition Model (Airplane Fuel Tank Ullage Computer Model)", is restricted by the Arms Export Control Act. A detailed mathematical description of the model as it relates to the physical processes governing the ullage of an airplane fuel tank is included in Volume 1, along with user instructions and examples. Extensive comparisons of computer model predictions to experimental data are included. The model is interactive and can be used on a variety of computers including personal computers.

3. In order to receive Volume 1, the attached form, "Statement of Terms and Conditions Release of Air Force-Owned or Developed Computer Software Packages", must be submitted to me within two weeks of receipt of this letter. DOD components may also use this form to request Volume 1.

4. During Aug 87 you received the report "Fighter Aircraft OBIGGS Study", AFWAL-TR-87-2024. Supplementing this report are two software reports: (1) "Fighter Aircraft Fuel Tank Inerting Mission Analyses and OBIGGS Design User's Manual" and (2) "Life Cycle Cost Analysis for Fighter Aircraft Fuel Tank Explosion Protection System User's Manual". These reports are also restricted. A limited number of these reports are available, with each requiring a separate release form.

ROBERT G. CLODFELTER
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

2 Atch
1. AFWAL-TR-87-2060, Vol 2
2. Release Forms

STATEMENT OF TERMS AND CONDITIONS RELEASE OF AIR FORCE-OWNED OR DEVELOPED COMPUTER SOFTWARE PACKAGES

Date ____________

1. Release of the following US Air Force software package (computer programs, systems descriptions, and documentation) is requested:

2. The requested software package will be used for the following purpose:

Such use is projected to accrue benefit to the government as follows:

3. I/we will be responsible for assuring that the software package received will not be used for any purpose other than shown in paragraph 2 above; also, it will not be released to anyone without prior approval of the Air Force. Further, the release of the requested software package will not result in competition with other software packages offered by commercial firms.

4. I/we guarantee that the provided software package, or any modified version thereof, will not be published for profit or in any manner offered for sale to the government; it will not be sold or given to any other activity or firm, without the prior written approval of the Air Force. If this software is modified or enhanced using government funds, the government owns the results, whether the software is the basis of, or incidental to a contract. The government may not pay a second time for this software or the enhanced or modified version thereof. The package may be used in contract with the government but no charge may be made for its use.

5. The US Air Force is neither liable or responsible for maintenance, updating or correcting any errors in the software provided.

6. I/we understand that no material subject to national defense security classification or proprietary rights was intended to be released to us. I/we will report promptly the discovery of any material with such restrictions to the Air Force approving authority. I/we will follow all instructions concerning the use or return of such material in accordance with regulations applying to classified material, and will make no further study, use, or copy such material subject to security or proprietary rights marking.

7. I/we understand that the software package received is intended for domestic use only. It will not be made available to foreign governments nor used in any contract with a foreign government.

____
Signature of Requestor

____
Name of Requestor

____
Organization/Address

____
City, State and Zip Code

____
Signature of Air Force Approving Authority

____
Name/Title of Air Force Approving Authority

____
Organization/Location

★ U.S. GOVERNMENT PRINTING OFFICE: 1987 — 548-054-80583