WRDC-TR-89-2034

COMPATIBILITY OF FUEL SYSTEM COMPONENTS WITH HIGH DENSITY FUEL

A. F. Grenich and A. M. Johnson
Boeing Advanced Systems
P.O. Box 3707
Seattle, WA 98124-2207

May 1989

Final Report: April 1987 to January 1989

Approved for public release; distribution unlimited.

AERO PROPULSION AND POWER LABORATORY
WRIGHT RESEARCH AND DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 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.

Royce P. Bradley
ROYCE P. BRADLEY, Project Engineer

Charles L. Delaney
CHARLES L. DELANEY, Chief
Fuels Branch
Fuels and Lubrication Division

FOR THE COMMANDER

Benito P. Botteri
BENITO P. BOTTERI, Chief
Fuels and Lubrication Division
Aero Propulsion and Power 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 WRDC/POSF, W-PAFB, OH 45433 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.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

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)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
WRDC-TR-89-2034

6a. NAME OF PERFORMING ORGANIZATION
Boeing Advanced Systems

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
Aero Propulsion & Power Laboratory (WRDC/POSF)
Wright Research and Development Center

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
Aero Propulsion & Power Laboratory

8b. OFFICE SYMBOL (If applicable)
WRDC/POSF

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F33615-87-C-2711

8c. ADDRESS (City, State and ZIP Code)
Wright Research and Development Center
Wright-Patterson AFB, OH 45433-6563

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
63216F	2480	10	00

11. TITLE (Include Security Classification)
~~Fuel System Component Tests in High Density Fuel~~ See Cover

12. PERSONAL AUTHOR(S)
A. F. Grenich

13a. TYPE OF REPORT
Final

13b. TIME COVERED
April 1987 TO Jan 1989

14. DATE OF REPORT (Yr., Mo., Day)
May 1989

15. PAGE COUNT
180

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.
21	04	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
High Density Fuel, Fuel System Components, Boost Pumps, Valves; Environmental Temperature Extremes; Endurance Tests; ~~Fuel System~~ Life Cycle Costs. (edc)

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

Environmental and endurance tests were conducted to evaluate the performance of typical fuel system components when exposed to high density aviation turbine engine fuel. The environmental tests simulated the extreme high and low temperatures encountered in hot and cold day missions. The results revealed that the high density fuel (HDF) would not have any fuel boiling or freezing problems but the pump power required for HDF was higher than for JP-4 fuel as was expected and the lower heat capacity of HDF resulted in noticeably higher heat exchanger discharge temperatures. The endurance tests revealed that the HDF would not cause abnormal wear or component leakage. Nothing in the test results suggested that current inputs to fuel system life cycle cost models should be modified if HDF is used.

Jet engine fuels, [illegible]
Jet fighters, [illegible]

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

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Royce Bradley

22b. TELEPHONE NUMBER (Include Area Code)
(513) 255-6814

22c. OFFICE SYMBOL
WRDC/POSF

DD FORM 1473, 83 APR

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

SS534S/J/144-9

0030A-1618

SUMMARY

Alternative fuels with higher energy per unit volume are of interest because they could significantly increase the range of airplanes that are fuel volume limited with few, if any, airplane modifications. To be viable such fuels must be producible at reasonable prices and have little or no negative impact on airplane performance or maintenance. With these factors in mind, the Air Force evaluated various candidate high density fuels and concluded that a highly naphthenic fuel, which could be produced from existing refinery by-product streams, was worthy of engine and airframe fuel system compatibility evaluations. Subsequently, the Air Force awarded contracts to Allison and General Electric to study the effects of high density fuel on engine components and to Boeing to study the effects on airframe fuel system components. Since the Air Force was interested in the impact of high density fuel across its entire fleet of airplanes, considerations of fuel systems typical of both large and small airplanes were required. The KC-135 tanker and F-4 fighter airplanes were selected as representative of large and small airplanes respectively and their fuel systems and components were subjected to environmental performance and endurance tests. The test results are presented and discussed in this report.

About 5000 gallons of high density fuel and an equivalent amount of JP-4 fuel were obtained for the fuel system simulation tests required. The high density test fuel was obtained from the Exxon Corporation by blending existing refinery streams produced in one of their large refineries. Two types of fuel system simulation tests were conducted: (1) response of high density fuel to extremes in environmental temperatures and (2) durability of typical fuel system components when exposed to high density fuel for extended time periods.

None of the results from the environmental or endurance tests suggested that the high density fuel would adversely impact airplane operations. Neither fuel boiling nor fuel freezing was a problem in the

environmental tests, but the tests revealed that the indicated volume for a fuel gauging system calibrated for JP-4 fuel would be about 8% high for high density fuel at all temperatures. The environmental tests did confirm that the lower heat capacity of the high density fuel resulted in somewhat higher, but acceptable, heat exchanger discharge temperatures with a 1.5 kw simulated thermal load. The lower heat capacity of HDF and its predicted lower thermal stability limit may be significant disadvantages because fuel is becoming increasingly important for aircraft thermal management.

The endurance tests focused on boost pump performance and component leakage. Boost pump performance was of concern because significant changes in the fuel's density and viscosity affect the pump's performance and because boost pumps rely on the fuel for lubrication. Component leakage was of concern for two basic reasons: (1) Past field experience has shown that leakage can occur when switching between JP-4 and JP-8 fuels. (2) The aromatic content of the high density fuel was high (about 35%) and seal and sealant problems are usually assumed to become greater as the aromatic content increases. Based on the test results, however, these concerns may be dismissed. Boost pumps operating with both high density and JP-4 fuels for 480 hours and typical valves and switches operating with these fuels for 264 hours performed satisfactorily and exhibited no leakage. The components tested all had new seals; whether used seals would have changed these results is not known. One factor to be considered is that the electrical pump power required for the high density fuel increased in proportion to the fuel density, as would be predicted. This might be an issue if pump motor, circuit breaker or generator capacities are marginal.

Results from the Boeing tests agreed with results from the material compatibility test program on seals and sealants conducted by the University of Dayton. Fuels from the same batches were used in both test programs.

A related objective of these tests was to predict changes in component failure rates and maintenance cycles when high density fuel was used. However, based on these test results, life cycle costs based on operating with JP-4 and JP-8 fuels would be valid for high density fuel.

PREFACE

This is the final report of work conducted under AFWAL Contract F33615-87-C-2711 which was awarded to Boeing Advanced Systems (a division of the Boeing Company) in June 1987. Program sponsorship and guidance were provided by the Fuels Branch, Aero Propulsion and Power Laboratory, Wright Research and Development Center, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. The work was conducted under Project 2480, Task 10, and Work Unit 00 and Royce Bradley was the Project engineer.

Boeing wishes to especially acknowledge the leadership and judgement provided throughout the program by Royce Bradley, the technical expertise provided by Ed Binns (WRDC/POSF) in evaluating component wear and performance anomalies, and the cooperation of the Exxon Corporation in blending and supplying the high density fuel. The excellent cooperation of the Air Logistics Center Laboratory (SA-ALC/SFTLD) in performing quality control testing of the test fuels during the endurance testing is also gratefully acknowledged.

CONTENTS

CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

1.0 INTRODUCTION

Selecting a fuel that totally optimizes an airplane's performance is usually not practical because of fuel economic considerations and logistics constraints. An excellent example is a typical Air Force fighter airplane, which is fuel volume rather than weight limited. The range of such airplanes could be immediately increased simply by using a fuel with a higher energy on a volumetric basis, provided that the fuel was compatible with the airplane. The Air Force has identified several potential sources of higher density fuels that could increase the range of a typical fighter by 10 to 15 percent. Since other fuel properties besides density would be noticeably different, the Air Force awarded contracts to GE Aircraft Engines and to the Allison Gas Turbine Division of General Motors to study the impact of the high density fuel on engine performance, and to the Boeing Company to evaluate the impact of this fuel on airframe fuel system performance. The results of the GE and Allison studies are presented in Refs. 1 and 2 respectively; the results of the Boeing study are presented in this report.

The airframe studies were based on comparing fuel system performance between the standard Air Force fuel, JP-4, and a high density naphthenic fuel derived from existing oil refinery by-product streams. The high density test fuel was obtained from product streams in a large Exxon Corporation refinery. The alternative, making the test fuel in a pilot plant, would have consumed a major fraction of the contract resources.

Both environmental and endurance tests were performed. The environmental tests focused on the behavior of high density fuel (HDF) when exposed to the extremely high and low environmental temperatures that could be encountered in actual airplane operations. The endurance tests focused on the potential for HDF to cause abnormal wear or failure, or leakage in typical airframe fuel system components. To provide a frame of reference for evaluating the HDF test results, similar tests were performed using JP-4 fuel.

In addition to identifying fuel system performance problems with HDF, the results were also intended to provide a basis for updating fuel system life cycle costs such as those discussed in Refs. 3 and 4. Currently, the values used for untested fuels are estimates based on engineering judgement. To reach firm conclusions on the potential for more frequent scheduled and unscheduled maintenance, higher airplane downtime, and higher component costs, test data for the fuel in question must be obtained. Then one can tradeoff the benefits offered by a fuel against any negative side effects.

The primary purpose of this study was to evaluate the impact of using HDF in Air Force fleet operations by performing tests on fuel system components of a typical large and small airplane. The KC-135 and F-4 airplanes were selected because of Boeing's experience with these airplanes in development and modification activities. (Note that even though the KC-135 is a weight limited airplane, it would carry HDF because of its role in refueling fighter aircraft.)

2.0 DISCUSSION OF TEST PROGRAM

Behavioral differences between HDF and JP-4 were studied experimentally by comparing the performance of the two fuels at extremes in aircraft operating temperatures and when exposed to typical fuel system components for extended periods of time. Additional details of the test program and rationale used in selecting test conditions are discussed below.

2.1 Comparison of HDF and JP-4 Fuels

Some of the key differences in physical properties between HDF and JP-4 fuels are quantified in the following table:

Property	High density fuel	JP-4 Fuel
Density (lb/ft^3) @ 41^oF	53.5	47.5
Viscosity @-40^oF (cSt)	20.2	2.24
Freezing Point (^oF)	<-100	-87
Hydrogen Content (wt%)	13.08	14.55
Aromatic Content (vol%)	35	9.7
Net Heat of Combustion (BTU/Gal)	129,600	117,500
Specific Heat @59^oF (BTU/lb/^oF)	0.425	0.492

The values shown were extracted from measurements by Pratt and Whitney Aircraft under an Air Force fuels analysis contract and the Energy Management Laboratory at WPAFB; their complete reports are presented in Appendix A. Corrosion inhibitor/lubricity improver (DuPont DCI-4A) was added to the HDF to levels equivalent to those found in turbine engine fuels in the fleet. The lubricity of the fuel was monitored throughout the test program to ensure that sufficient additive was present.

To ensure that overall fuel quality was maintained, daily samples of the test fuels were taken for analysis by an Air Force laboratory at Mukilteo, Washington. The tests included fuel lubricity, vapor pressure flash point, peroxide number and specific gravity.

The fuel property differences between HDF and JP-4 have a number of possible ramifications to the design of the fuel system and the performance of the airplane. On the positive side (and the reason that high density fuel is of interest) is simply that more Btu's can be loaded on fuel volume limited airplanes, i.e., about 129,000 Btu/gallon for high density fuel compared with about 117,000 Btu/gallon for JP-4. However, the other property differences could create fuel system problems and/or necessitate system modifications as discussed in Section 2.3.

2.2 Environmental Temperature Exposures

The initial and boundary conditions of interest for simulating worst case environmental temperatures are usually extreme but realistic temperatures that could be encountered in actual ground and flight operations. One method for estimating these extreme temperatures is to impose a statistical distribution on atmospheric temperature data and establish extremes by analyzing the tails of the frequency distribution curve. Another approach, and the one used in this study, is to extract the worst case temperatures from a data base of actual atmospheric temperature measurements. The atmospheric temperatures for the data base were obtained from the National Center for Atmospheric Research (NCAR). The data base covered the period from 1966 through 1982 (excluding 1971 and 1972) and contained twice-daily records of temperature at various altitudes to 53,000 feet at each of 1,977 grid points covering most of the Northern Hemisphere (Figure 1). The high and low temperature extremes were extracted from the data base by identifying the worst case exposures for a given airplane

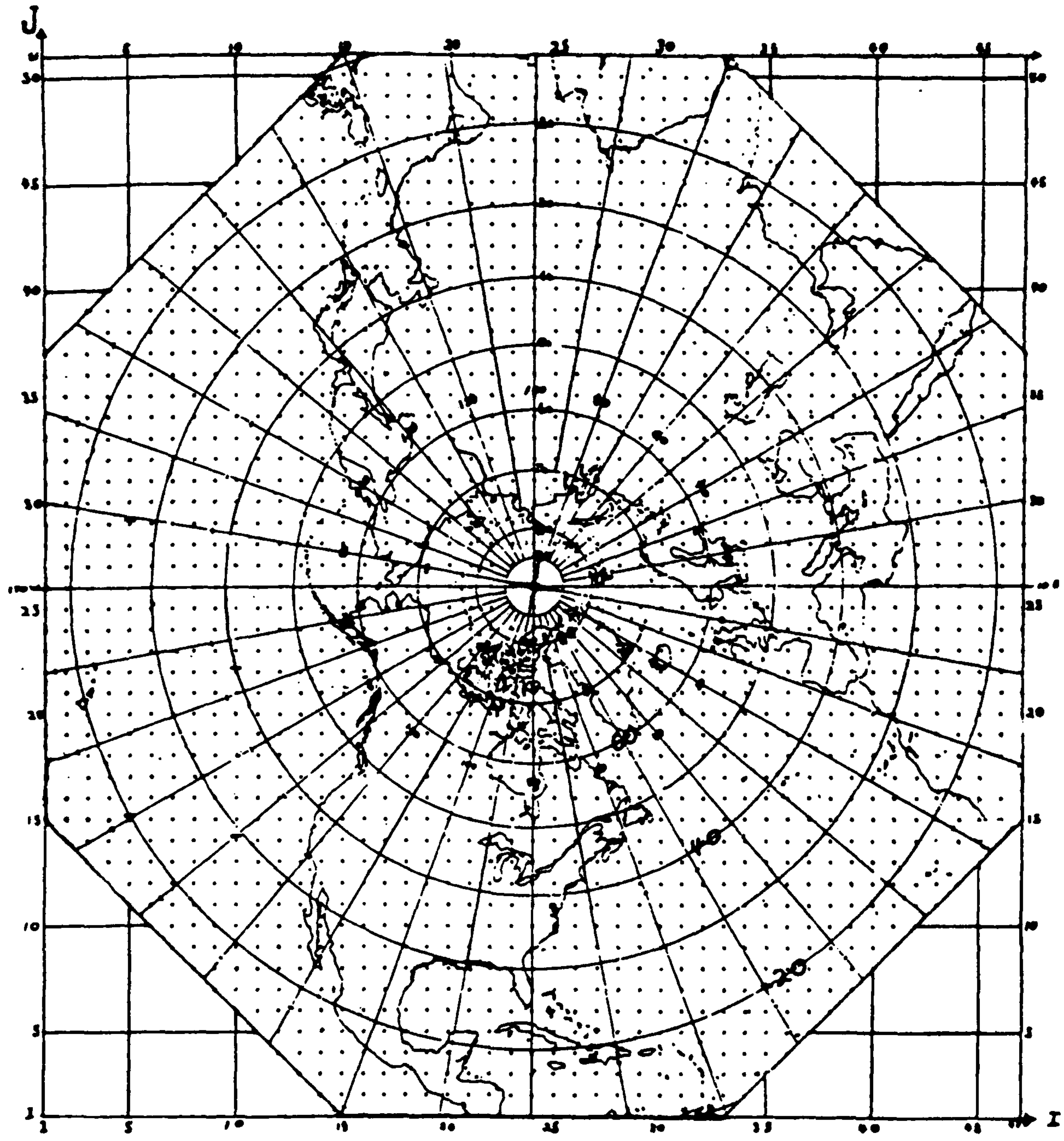


Figure 1. NCAR Meteorological Grid

route (longitude, latitude, altitude and air speed). The time averaged worst case temperatures along each route were used to define worst case hot and cold day missions for KC-135 and F-4 airplanes.

Ground temperature exposures are also important because military airplanes are often refueled shortly after landing but not flown again for many hours. Exposure to extremely high or low temperatures during this waiting period could produce unacceptably high temperatures or fuel freezing depending on the type of fuel and loading temperatures. Ground temperature extremes were based on the data base obtained from the USAF Environmental Technical Applications Center (ETAC) in Asheville, North Carolina. A computer code was used to identify the worst case ground temperature exposures. The program searched the multi-year data base, which contained temperatures recorded at 1-hour intervals, and identified the ten lowest temperature 24-hour periods on a time-averaged basis. The time period covered included either 14 or 15 years. (Data were not readily available for the years 1971 and 1972 in some cases.)

Another important consideration was simulating the fuel tanks of the KC-135 and F-4 airplane that would be most sensitive to temperature extremes. The KC-135 fuel system (Figure 2) is characterized by four main tanks for tank to engine feed, two outboard reserve tanks, a center wing tank, and body tanks for aerial refueling. The KC-135 tanks most vulnerable to temperature extremes are the reserve tanks because these tanks are not used until late in the mission and are relatively small. The F-4 fuel system (Figure 3) is composed of right- and left-hand integral wing tanks, three external tanks and seven fuselage fuel cells. The wing tanks of the F-4 are the most sensitive to extreme temperatures because they have a large surface to volume ratio and are more directly exposed to the outside thermal environment.

The extreme temperature exposures were found by identifying the missions and operating bases flown by the KC-135 and F-4 that resulted in the worst case thermal environments. The worst case low temperature exposures for the KC-135 airplane were established in a previous study

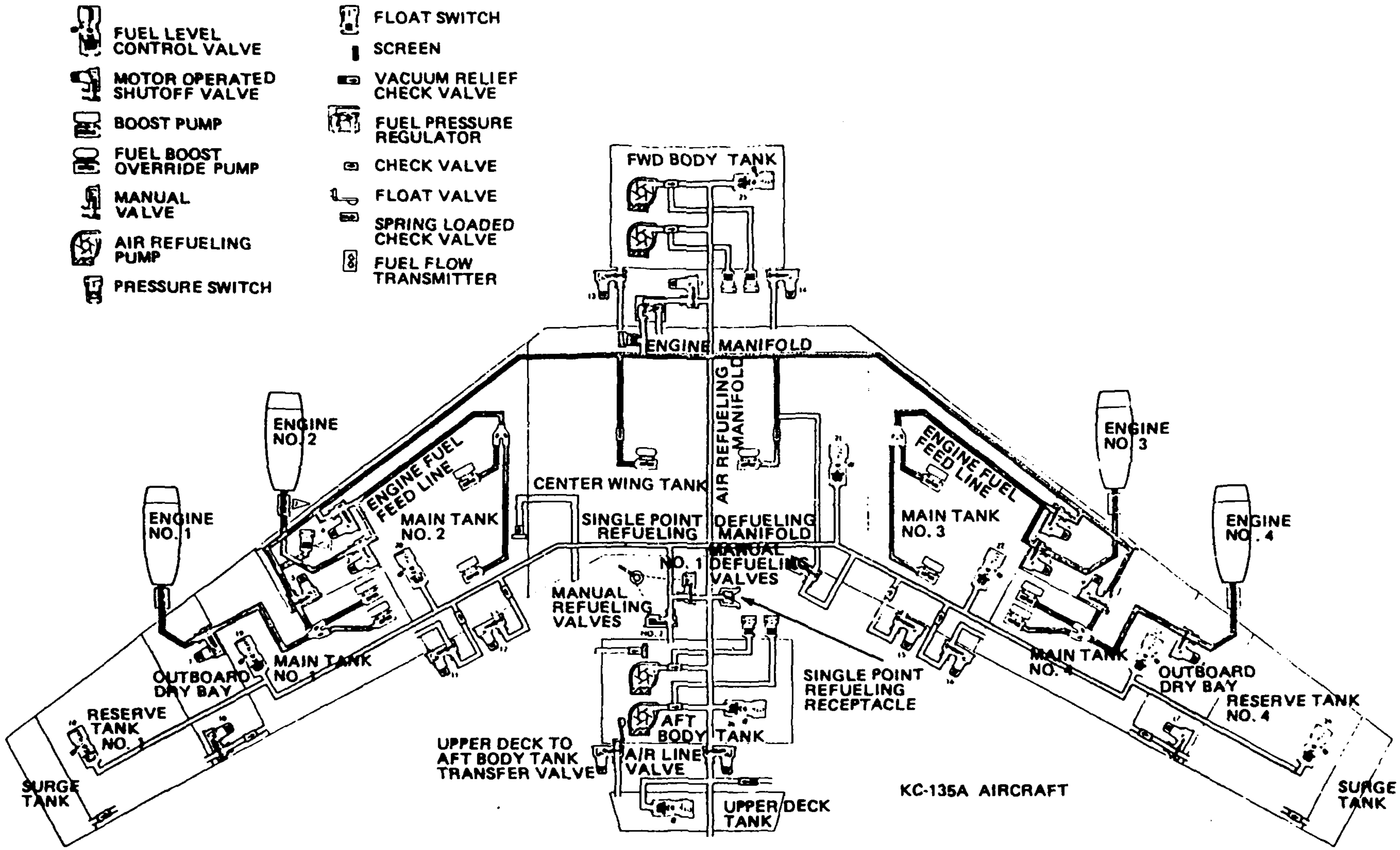


Figure 2. KC–135 Fuel System Schematic

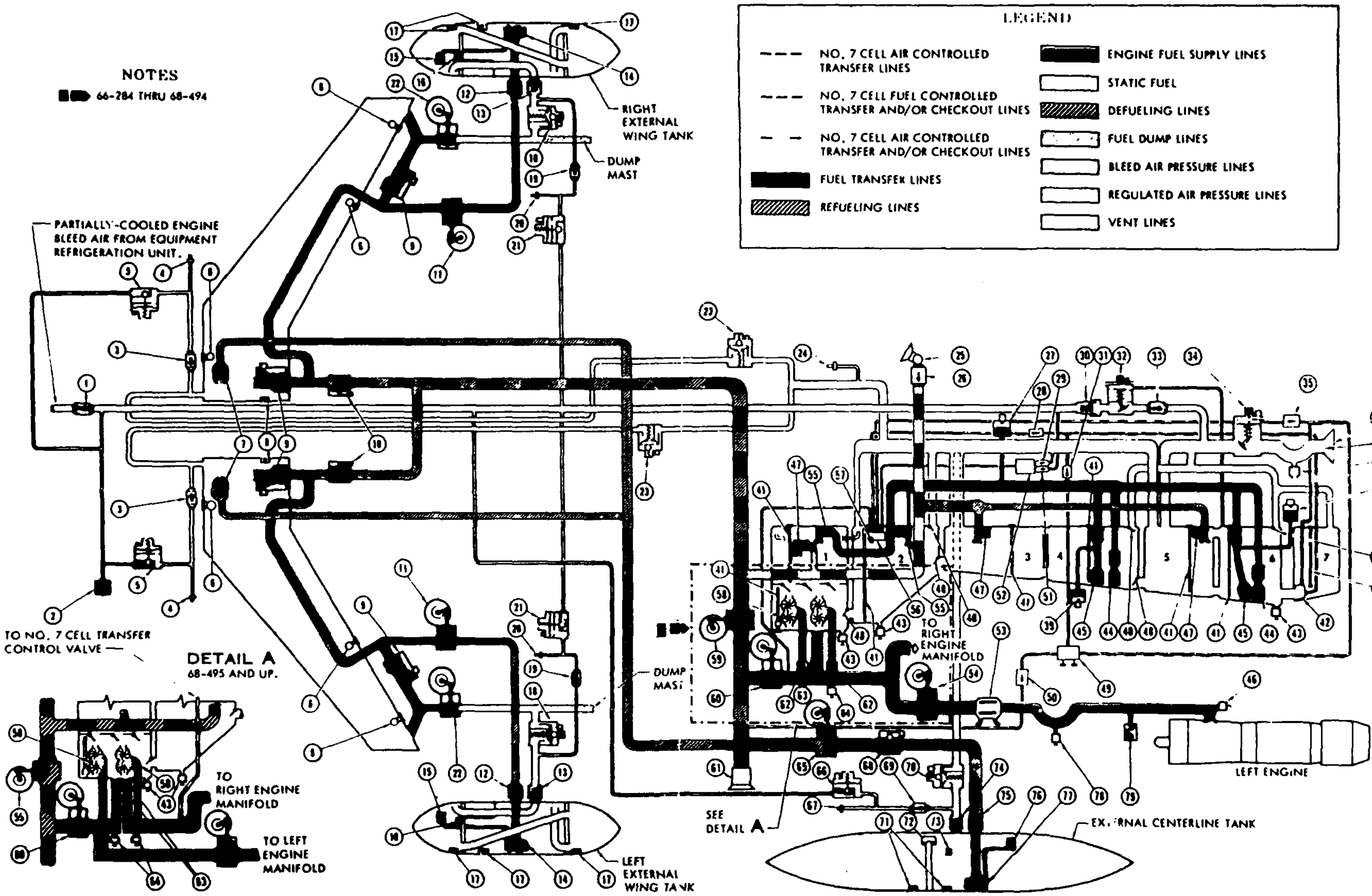


Figure 3. F–4 Fuel System Schematic

(Ref. 5). The lowest ground or surface temperatures were at Eielson AFB, Alaska, where temperatures could remain at about -58°F for a 24 hour period. The lowest temperatures inflight for the KC-135 were for a polar refueling mission from Eielson and return; the skin and bulk fuel temperatures for this mission are shown in Figure 4. Surprisingly, the ground temperatures were lower than the inflight exposure due to the recovery temperature effect inflight. (Recall that the recovery temperature and not the ambient temperature is the driving force for aerodynamic heating or cooling. Since the recovery temperature is a measure of the percentage of total temperature recovered in the boundary layer due to viscous dissipation, the recovery temperature is always higher than the ambient temperature.)

Worst case environmental temperatures for F-4 hot and cold day operations and KC-135 hot day operations were established with the aid of the Operational Analysis organization of Boeing Advanced Systems. The hot and cold day missions, examined for the F-4 airplane were strike missions, combat air patrol (CAP)/escort missions and ferry missions. The KC-135 hot day mission was based on refueling support requirements for the F-4 missions. All missions were defined in terms of recovery temperatures and fuel consumption rates for the given altitude, longitude and latitude, and air speed histories. The mission profiles were referenced to current F-4 operational bases that were determined, from review of ground temperature data, to represent extremes in high and low temperature exposures.

Based on surveys of F-4 operational bases and ground temperature environments, Luke AFB in Arizona presented the worst case hot day exposures for strike and CAP/escort missions. For this study these missions were based on flights from Luke AFB directly south and return. The worst case F-4 hot day ferry identified was from Cairo, Egypt to Rijadh, Saudi Arabia. This ferry mission was much shorter than most ferry missions but had the highest temperature exposure. Ground and in-flight air temperatures for the three F-4 hot day missions are shown in Figure 5. During ground standby, temperatures from 110°F to 120°F could be encountered. During flight (based on a cruise altitude of 25,000 feet),

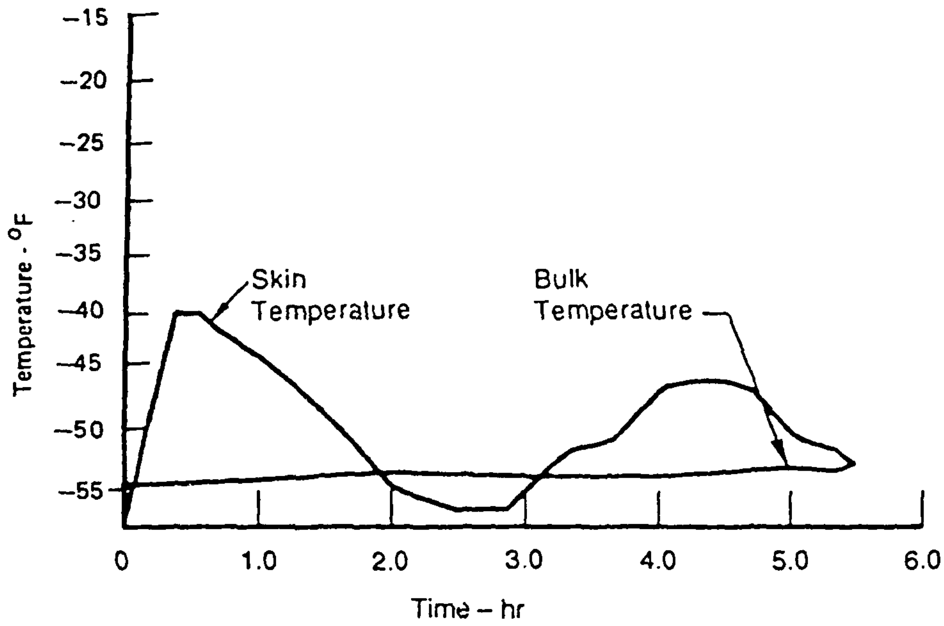


Figure 4. KC–135 Worst Case Cold Day Skin and Bulk Fuel Temperatures

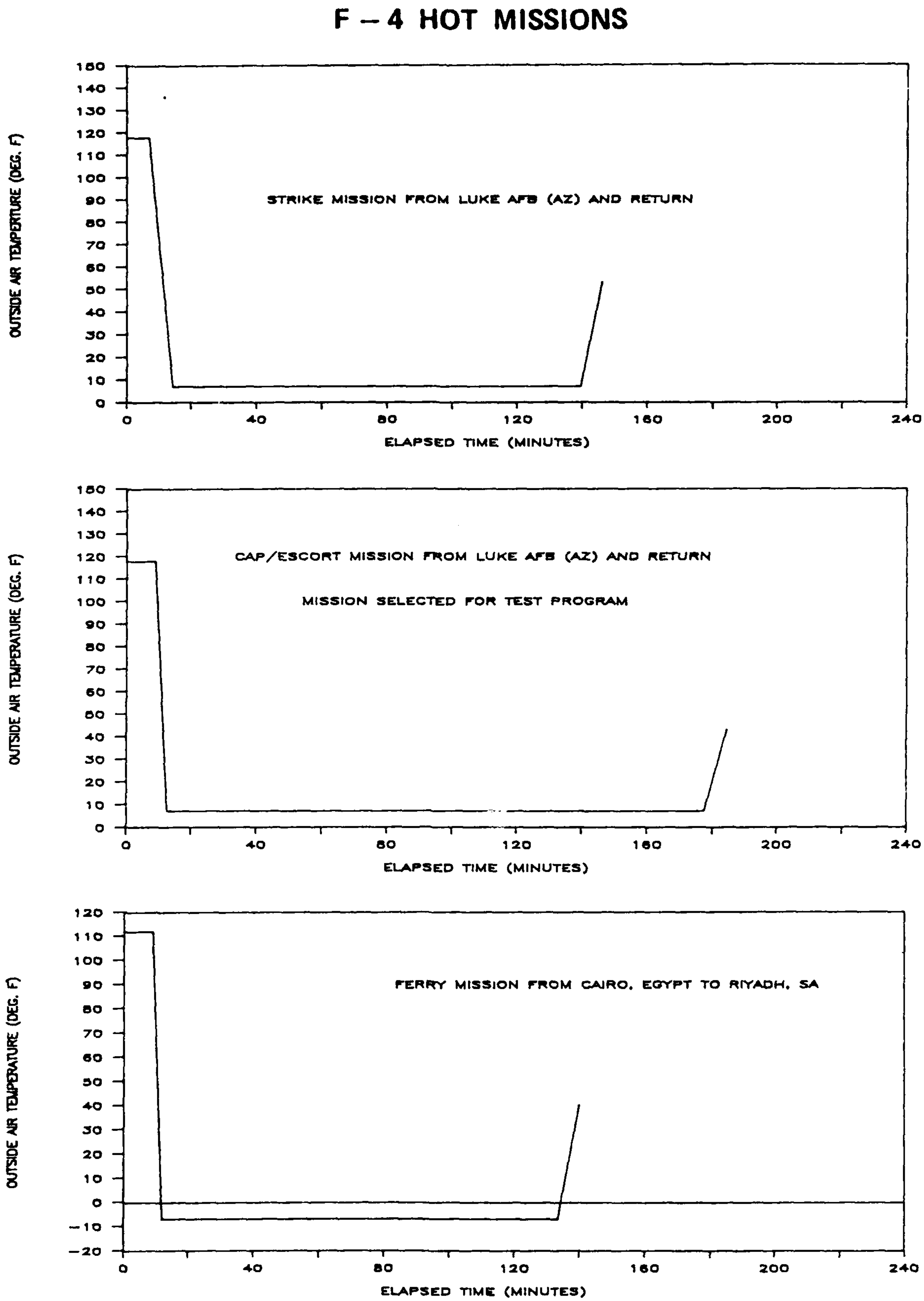


Figure 5. F-4 Hot Day Mission Temperatures

the maximum temperature was about 0°F. (This temperature was based on the 15 highest in-flight temperatures in the data base for a cruise altitude of 25,000 ft. These temperatures fall within a narrow band as shown in Figure 6, and justified the choice of a constant ambient temperature at cruise.) The other important variable in selecting the mission for thermal simulation testing is usually fuel usage, since this determines the exposure time to extreme temperatures. The fuel usage from the Navy tanker for the three F-4 hot day missions is shown in Figure 7. Periods of aerial refueling are evident in the figure. On the basis of exposure the CAP/escort mission would be the mission of choice for thermal analysis and was chosen for the study. However since the ambient temperature decreases during flight, no adverse hot day effects should be anticipated for any of the missions.

Worst case F-4 cold day missions were selected based on a survey of northern latitude operating basis and ferry missions. Elmendorf AFB in Alaska was found to have the worst case ground exposure temperatures for the strike and CAP/escort missions. Worst case in-flight low temperature exposures were based on flying these missions directly north from Elmendorf and return. The worst case cold day F-4 ferry mission was from Spangdahlem, Germany to Seymour - Johnson AFB, North Carolina. The ground and in-flight temperatures for these three missions are shown in Figure 8. During ground standby, temperatures as low as -28°F can be encountered. During flight, outside air temperatures approaching -70°F can be encountered. Assuming the same fuel usage as for the hot day missions (Figure 7), the CAP/escort mission was the appropriate mission and the one used for F-4 worst case cold day thermal simulation testing.

The ground and in-flight temperatures for a KC-135 airplane supporting the worst case hot day F-4 CAP/escort mission are shown in Figure 9. These were the basis for KC-135 hot day thermal simulation tests.

All of the hot and cold day F-4 and KC-135 missions considered and the missions selected for thermal simulator testing are summarized in Table 1.

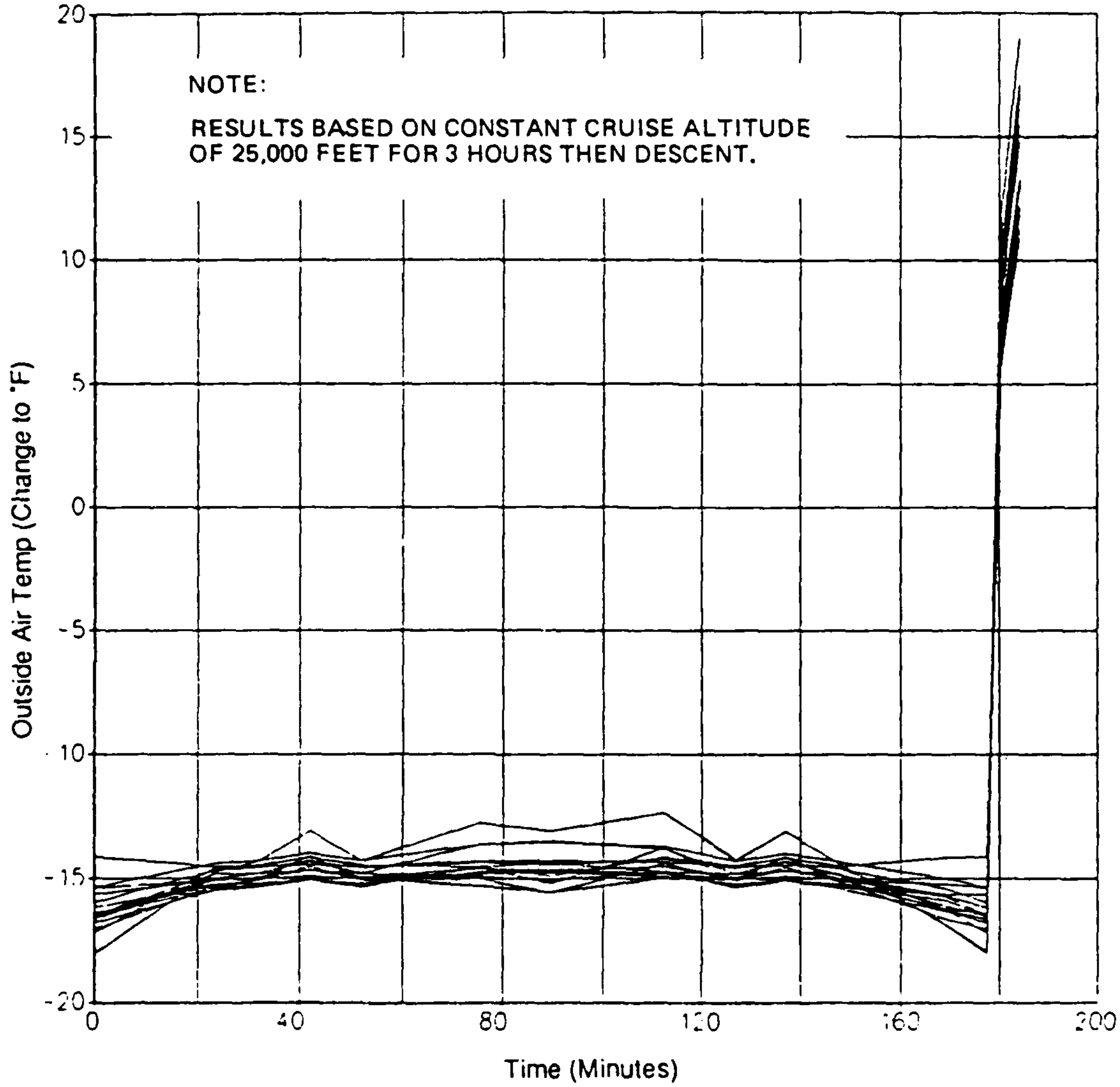


Figure 6. 15 Worst Case Hot Day Temperatures

F – 4 HOT MISSIONS

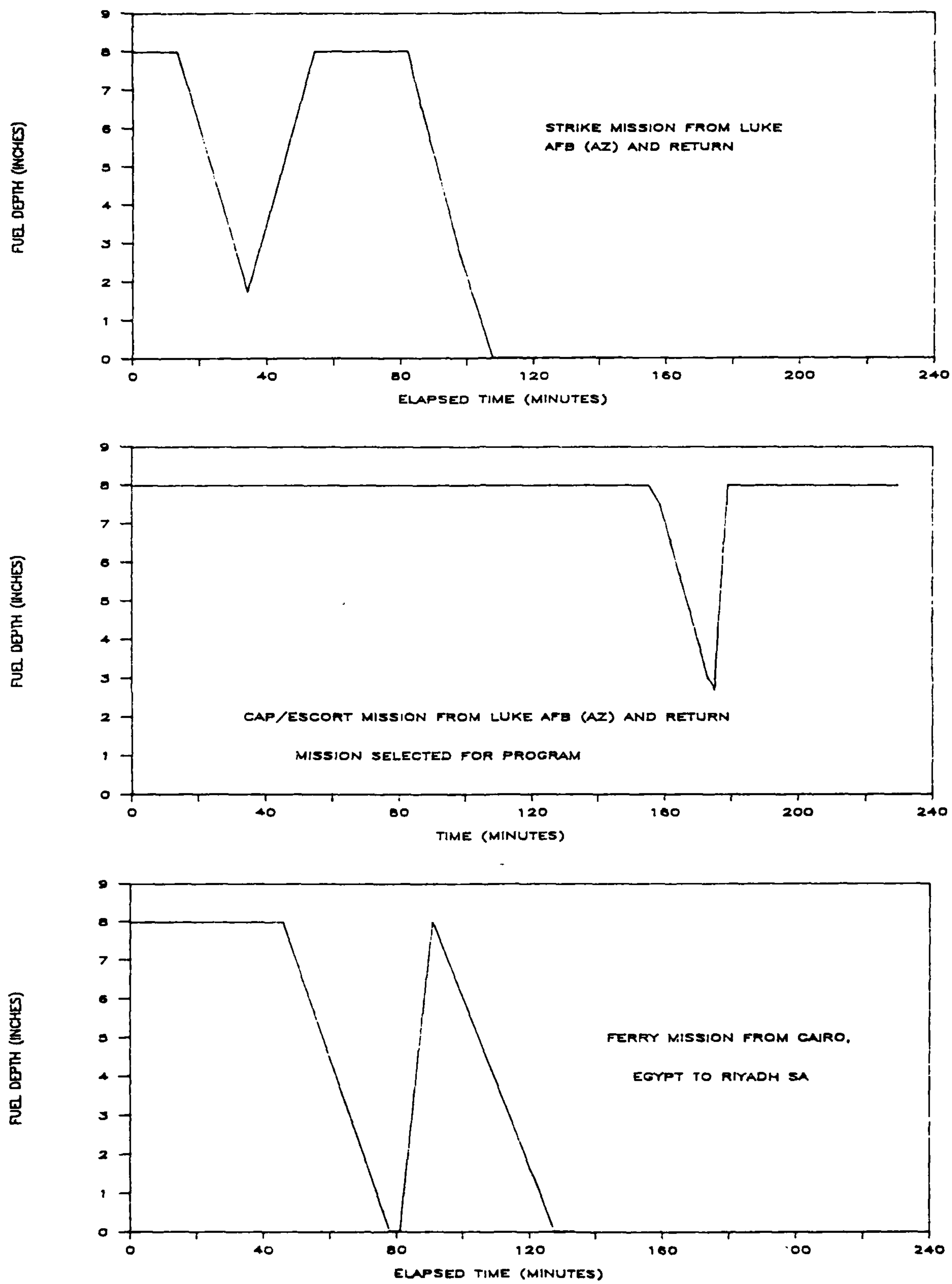


Figure 7. Fuel Depletion for F–4 Hot Day Missions

F – 4 COLD MISSIONS

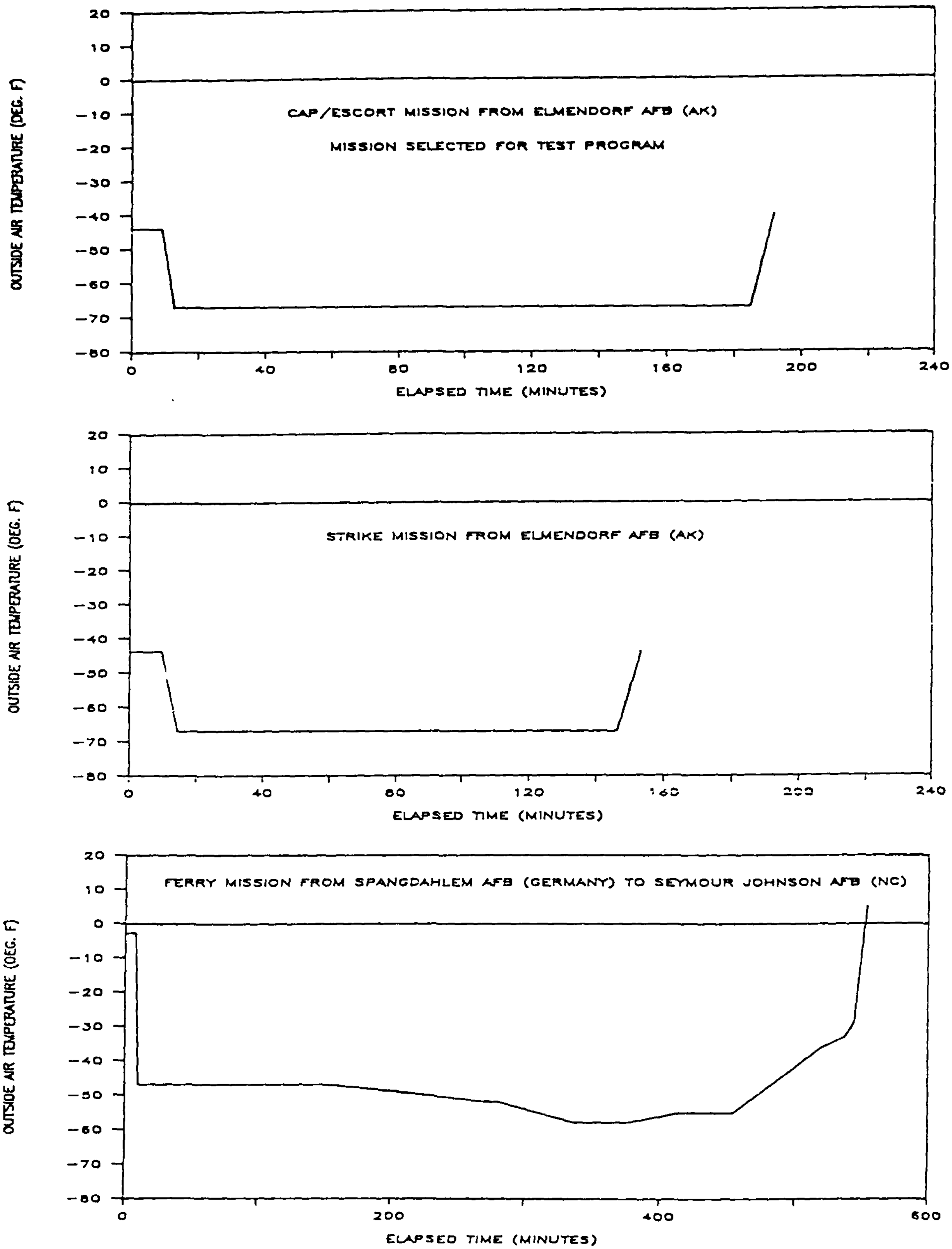


Figure 8. F–4 Cold Day Mission Temperatures

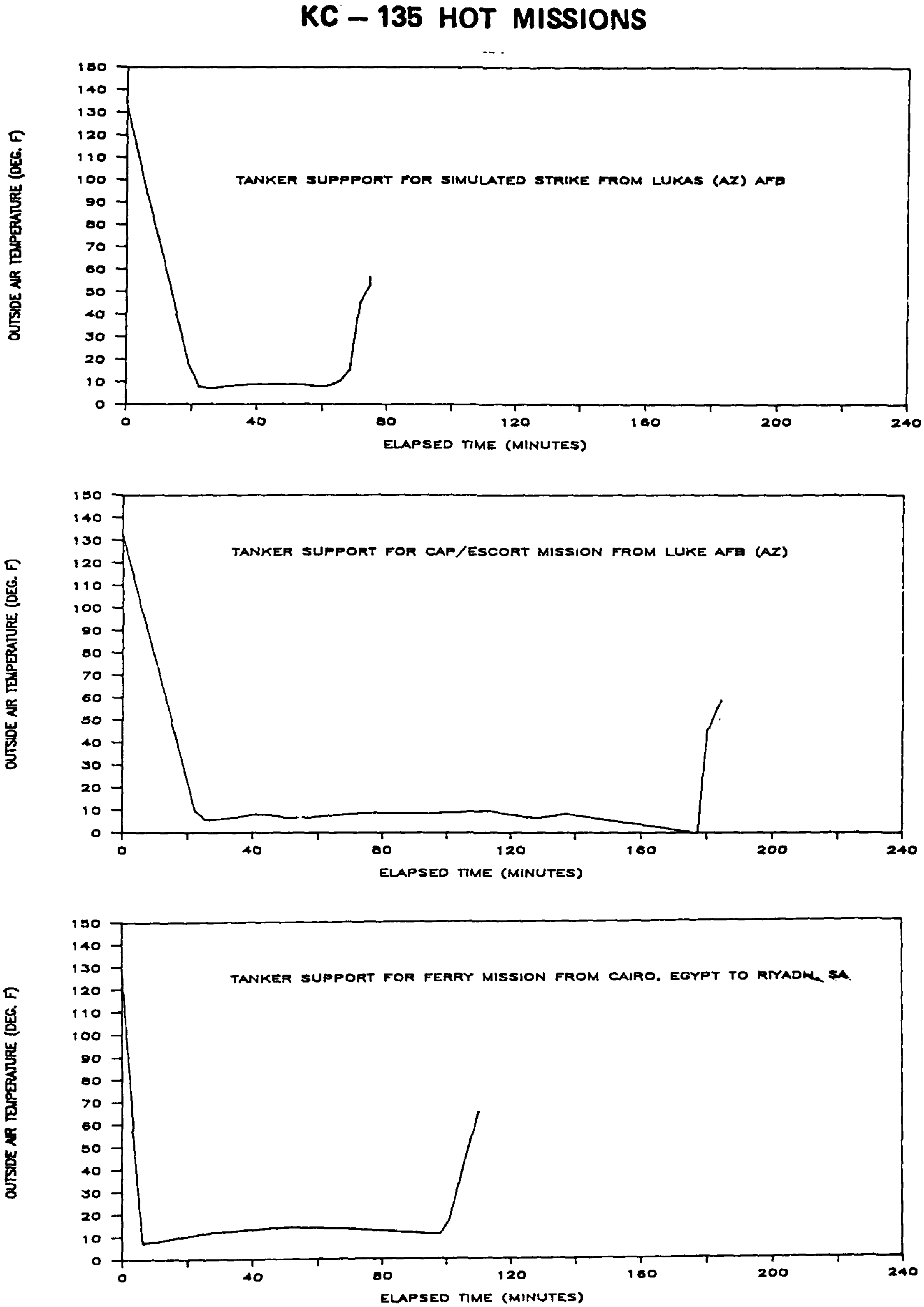


Figure 9. KC–135 Hot Day Mission Temperatures

Table 1. KC–135 and F–4 Missions Simulated in Environmental Tests

AIRPLANE	MISSION TYPE	TAKEOFF BASE	DESTINATION BASE	WORST CASE MISSION
F–4	HOT	LUKE AFB, AZ	LUKE AFB, AZ	
F–4		LUKE AFB, AZ	LUKE AFB, AZ	←
F–4	HOT	CAIRO, EGYPT	RIYADH, SA	
F–4	COLD	ELMENDORF AFB, AK	ELMENDORF AFB, AK	
F–4	COLD	ELMENDORF AFB, AK	ELMENDORF AFB, AK	←
F–4	COLD	SPANGDHLEM AFB, GERMANY	SEYMOUR JOHNSON AFB, NC	
KC–135	HOT	LUKE AFB, AZ	LUKE AFB, AZ	
KC–135	HOT	LUKE AFB, AZ	LUKE AFB, AZ	←
KC–135	HOT	CAIRO, EGYPT	RIYADH, SA	
KC–135	COLD	EIELSON AFB, AK	EIELSON AFB, AK	←

2.3 Component Durability

The durability of the fuel system may be crucial in airplane operations, especially in an hostile environment, since the fuel system contains critical components such as fuel tanks, boost pumps, feed lines, valves, fuel shut off switches and transfer pumps. The durability of this system also affects the operational readiness and maintenance costs of the airplanes. For these reasons, major fuel system components must satisfy stringent performance and durability criteria. Usually, the components are subjected to rigorous testing with standard test liquids and procedures prior to airworthiness qualification to qualify them for use with conventional fuels such as JP-4, JP-5 and JP-8. However, if a new fuel with differing properties is introduced, it is necessary to thoroughly understand the performance variation and durability impacts. In this program typical fuel components were exposed to relatively long duration tests with HDF under severe conditions of operation. Most of the components contained elastomer seals that could expand or contract if exposed to fuels with differing chemical compositions. To investigate this aspect, durability tests were conducted using HDF and JP-4 fuels alternately.

Critical components of the KC-135 and F-4 airplane fuel systems were identified; the major components fell under the following categories:

- Centrifugal boost pumps or transfer pumps
- Shut off valves
- Check valves
- Transfer valves
- Level control valves

Some valves falling under a given category may differ somewhat in details of construction and operation. However, the designs and materials in the components selected for testing were sufficiently broad to be representative of most components in the Air Force fleet. In evaluating the performance of the fuel system components, the following fuel properties and their effects were considered:

Fuel Density - In addition to influencing the airplane's operating range, fuel density may affect the pressure losses in plumbing arrangements. This is because at a constant mass flow rate a higher density fuel has a lower flow velocity and lower frictional losses. However, the losses also depend on the viscosity (see below) of the fuel. Both of these factors were investigated in the test program.

Viscosity - The viscosity of fuel affects the frictional losses in the fuel feed system and pumping capabilities. Since viscosity is a strong function of temperature, the performance of boost pumps can vary significantly at different temperatures. High viscosity can produce unacceptably high pressure losses in fuel lines restricting refueling operation or failing to deliver fuel at the required pressure to the engine driven fuel pump.

Aromatics - The aromatic content of the fuel (both level and chemical types) can cause seals and sealants to deform resulting in unacceptable fuel leakage. The increase in the specification limit of aromatics from 20 percent to 25 percent in Jet A fuel was a highly contentious issue because of seal leakage concerns. Since the high density test fuel had an aromatics level of 35%, seal leakage tests were emphasized in this study.

Dielectic Constant - The dielectric constant of the fuel is important because nearly all fuel gauging systems use capacitance probes to infer fuel height and the probe signal is a direct function of the fuel's dielectric constant. Since gauging systems are designed to be as accurate as possible (usually in the 1 to 2 percent range) even small changes in dielectric constant may be significant and its effect on the gauging system accuracy requires assessment.

In view of these fuel property issues, the environmental and endurance tests included the following features.

- o Instrumentation to measure pump power and discharge flow rates as a function of fuel type and temperature
- o Leakage testers to sense leakage rates of both valve seats and component bodies
- o A capacitance gauging unit mounted in the fuel tank thermal simulator to compare the response between HDF and JP-4 fuels as a function of fuel level and temperature.

2.4 Components Tested

The fuel system components tested, which were Government Furnished Equipment, are listed in Tables 2 and 3 for the F-4 and KC-135 airplanes fuel systems respectively. Note that many of the components required adapters, packings, couplings and similar interface hardware to install the components in the simulator. All of the parts were obtained from Government Stores and most were rebuilt as opposed to new parts. Although a complete check of the parts was not made, it is fairly certain that all of the components contained new seals.

Table 2. F-4 Fuel System Components Tested

COMPONENT	NSN	P/N	TOTAL REQUIRED
SHUTOFF VALVE	2915-00-816-4502	AV16B1358B	3
ADAPTER	4730-00-799-6504	32-58148	1
BOLT	5306-00-182-2015	AN4H4A	1
BOOST PUMP	2915-00791-3950	60-0576	3
BOLT-BP ELBOW	5306-00-815-7218	32-58258	1
ELBOW PUMP OUTLET	4730-01-052-7386	13659-7	1
VALVE BOOST PUMP	4820-00-815-9270	312700	1
COUPLING	5340-00-159-4562	MS27114-18R	1
HOUSING	4730-01-052-7385	13659-5	1
COUPLING	4730-00-787-3897	3655-48D	1
PACKING	5330-00-251-9368	MS2913-337	3
LEVEL CONTROL VALVE	2915-00-938-4206BF	2660414	3
PACKING	5330-00-599-2537	MS29513-223	3
CHECK VALVE	2915-00-815-9270	312700	3
COUPLING	5340-00-159-4562	MS27114-18R	1
TRANSFER VALVE	2915-00-853-5633BF	30140	3
LINE ASSEMBLY	N/A	32-58137-57	1
CLAMP	5340-00-597-4601	MS21919F5	2
UNION	4730-00-052-0589	MS24487D5	1
PACKING	5330-00-263-8029	MS29512-05	2
NUT	5310-00-282-7832	32-57058-17	1
FITTING	4730-00-897-7674	32-581584-3	1
STAT-O-SEAL	5330-00-171-8367	600-015 1-2	2
FITTING	1560-00-088-8935	32-581583-3	1
STAT-O-SEAL	5330-00-599-7725	600-015 7-16	1
NUT	5310-00-138-3624	32-57058-9	1
LINE ASSEMBLY	N/A	32-58137-61	1
UNION	4730-00-045-4869	MS24487D4	1
PACKING	5330-00-263-8028	MS29512-04	2

Table 3. KC-135 Fuel System Components Tested

COMPONENT	NSN	P/N	TOTAL REQUIRED
BOOST PUMP	2915-00-003-5602	60367-2	3
FITTING	4730-01-009-3309	35-33010-1	1
BOLT	5306-00-282-9859	MS20074-06-50	1
GASKET SEAL	5330-00-584-1097	BACG10AE-24	2
HOSE ASSEMBLY	4720-00-555-3826	147-51032-9	1
LEVEL CONTROL VALVE	2915-00-349-2159	1321-546967	3
SUPPORT	1560-00-333-6697	5-89848-2	1
PACKING	5330-00-717-3981	MS29513-226	2
BOLT	5306-00-151-1421	AN4-13A	1
PACKING	5330-00-263-8031	MS29512-8	2
UNION	4730-00-239-3638	AN815-8D	1
GASKET	5330-00-263-8033	MS29512-12	2
PACKING	5330-00-291-3310	MS29513-242	2
UNION	4730-00-928-3478	AN815-12D	1
COVER	1560-00-441-6753	32-58183-301	1
BOLT	5306-00-292-8252	AN4H7A	1
WASHER	5310-00-791-8501	AN960D416	1
SHUTOFF VALVE #1	2915-00-639-9711	AV16B1248C	3
FITTING ASSY	4730-00-906-6568	5-95878-9	2
PACKING	5330-00-260-9338	MS29513-227	3
SHUTOFF VALVE #2	2915-00-556-0584	119075	3
SLEEVE CRES WIRE	N/A	1191-4CNX 1/2	1
CONNECTOR	4730-00-639-9023	MS20760D24	6
PACKING	5330-00-599-25379	MS29513-223	2
FITTING	4730-00-104-6273	9-62539-1	1
BOLT	5306-00-182-1966	AN4H20A	1
CHECK VALVE	4820-00-639-9133	1111-558458	3

3.0 TEST FACILITIES

The tests were conducted at two different Boeing test sites. The environmental temperature effects tests were performed in an existing facility at North Boeing Field in Seattle. The endurance tests were conducted at the Boeing hazardous material test site at Tulalip, Washington in test rigs specifically developed for component endurance testing.

3.1 Environmental Tests

Extremes in environmental temperature were simulated in the Boeing Fuel tank Thermal Simulator (FTTS). The heart of the FTTS is an insulated rectangular fuel tank constructed from typical aircraft integral fuel tank materials and equipped with typical aircraft fuel system components. Two interchangeable sections allowed simulation of portions of a thick wing (such as on the KC-135) or a thin wing (such as on the F-4) airplane. The thick and thin wing tank simulators are shown in Figures 10 and 11 respectively.

The internal tank construction consisted of typical integral aircraft fuel tank materials. The upper and lower stringers were constructed from two 6061-T6 aluminum alloy angle extrusions bolted together to form a Z section to simulate the tank heat transfer paths. The overall stringer height was set at 3.0 inches for both the KC-135 and the F-4 simulations.

A weigh tank, sized to hold about 60 gallons of fuel, was located adjacent to the FTTS. This tank was suspended from a 0- to 500- pound load cell in a frame work that allowed it to be elevated so that the FTTS could be gravity filled or lowered to the floor to allow access for manual filling. A small 28-Vdc aircraft boost pump was installed below the FTTS to transfer fuel from the test tank to the weigh tank. Each Z stringer in the FTTS tank had a 0.75-by 1.75-inch elliptical fuel transfer opening to allow fuel flow to the boost pump bell mouth inlet. A 1-inch diameter tank vent tube with an inlet near the upper skin of the tank was routed through

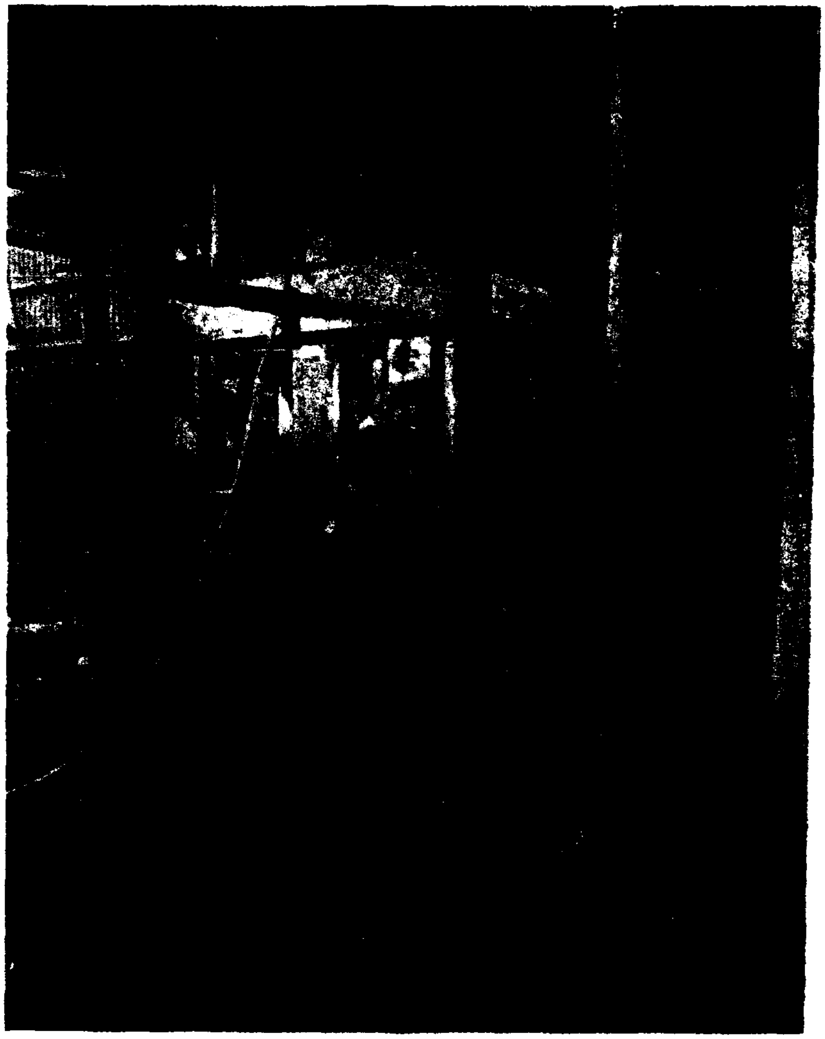


Figure 10. Thick Wing Fuel Tank Thermal Simulator

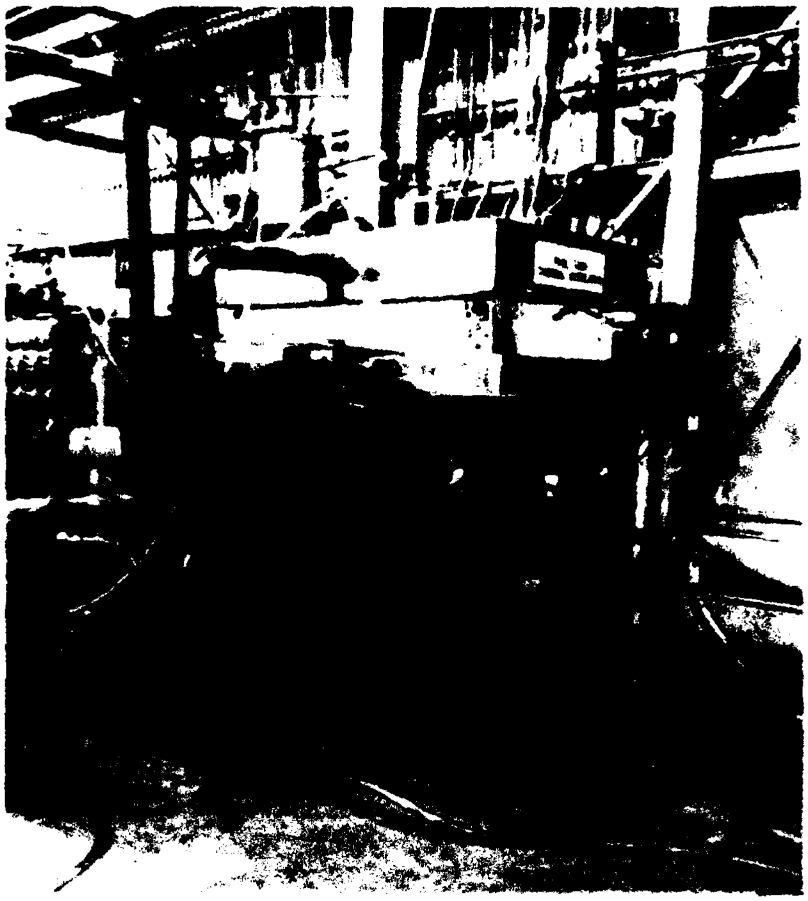


Figure 11. Thin Wing Fuel Tank Thermal Simulator

the side of the tank to a point above the highest fuel level of the tank. Two double pane viewing ports made of Lexan were located on opposite vertical sides of the tank.

The extremes in environmental temperatures were simulated by cooling or heating the tank by passing a water/methanol solution through two flat plate heat exchangers, the inner surfaces of which formed the top and bottom surfaces of the tank. The outer surfaces of the heat exchangers were insulated to minimize heat transfer to the surroundings. The water/methanol solution was either chilled using liquid nitrogen or heated by a steam heat exchanger. A schematic of the FTTS heating and cooling systems is shown in Figure 12.

The temperature conditioning solution was distributed uniformly over the entire heat transfer surfaces by internal flow straighteners. The inlet and outlet manifolds were designed to provide nearly uniform temperatures on the tank skins. The flow rate past each skin was controlled by throttleable valves and measured by turbine flowmeters.

In the cooling mode, an air-driven vane-type pump circulated the water/methanol mixture in closed Loop A over the upper and lower outside tank surfaces and then through a conventional double-pass stainless steel shell and tube heat exchanger. Coolant Loop B absorbed heat rejected by the simulator system. Coolant Loop B flowed through the same double pass heat exchanger and was cooled by liquid nitrogen in an intimate contact vat-type heat exchanger. The liquid nitrogen was introduced directly into the coolant where it absorbed energy as it changed phase. The nitrogen vapor passed out of the heat exchanger to the atmosphere. Again an air driven pump circulated the coolant solution through this loop. Both the liquid nitrogen and the coolant flow rates were controlled with throttling valves. In the heating mode a steam heat exchanger was incorporated into loop A and throttling valves controlled the upper and lower surface temperatures.

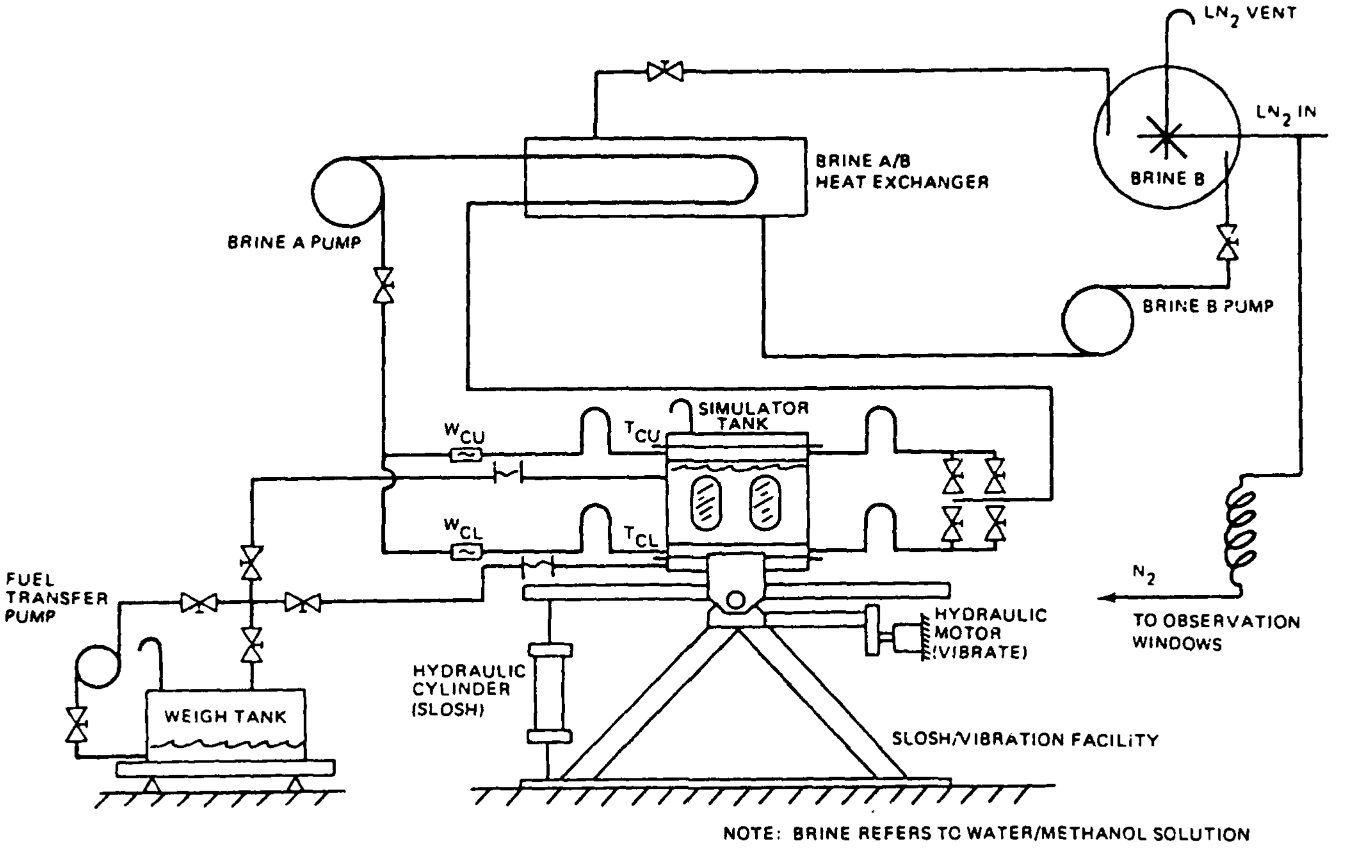


Figure 12. Fuel Tank Thermal Simulator Schematic

A hydraulic motor and a hydraulic actuator provided vibration and slosh simulation to the simulator tank. The vibrator eccentric weights were set to displace the simulator approximately ±0.002 inch at 83.3 hertz (1-1/2 g's acceleration). The slosh table had a maximum travel of ±15 degrees at 0.33 hertz.

An external fuel heating system (Figure 13) was incorporated into the FTTS to simulate heat addition to the fuel from on-board airplane sources. The main component of the system was a lubricating oil-to-fuel, shell and tube heat exchanger. A secondary heat exchanger was used to heat the oil using electrical cartridge elements. For fuel heat transfer tests, fuel was pumped from the simulator tank and circulated through the oil-fuel heat exchanger. Recirculated fuel was distributed back to the fuel tank through a perforated manifold or "piccolo" tube with holes facing downward. Fuel and oil flow rates were measured by turbine flowmeters and governed by control valves. The electrical heat input rate was controlled by cycling the power on and off. The system allowed regulated heat input rates up to 1500 watts; fuel and oil flow rates were controllable from 0 to about 1 gallon per minute.

3.1.1 Instrumentation

The FTTS was equipped with standard instrumentation to measure temperature, pressure, flow rate, acceleration and electric power consumption during a test. The thermocouple assemblies for the temperature measurements included commercially available probes, shields, wires and connectors. Thermocouple accuracy of $\pm2^{\circ}F$ was maintained by regular calibration checks. The flowmeters were a turbine type with a calibrated accuracy within $\pm1\%$ of full scale. The pressure transducers were a strain gauge type with an accuracy of $\pm0.5\%$ of full scale based on calibrations by standard dead weight testers.

Tests using the external fuel heating system to simulate heat loads from onboard equipment were included because the role of fuel in thermal management is sharply increasing. Fuel is the natural choice for cooling

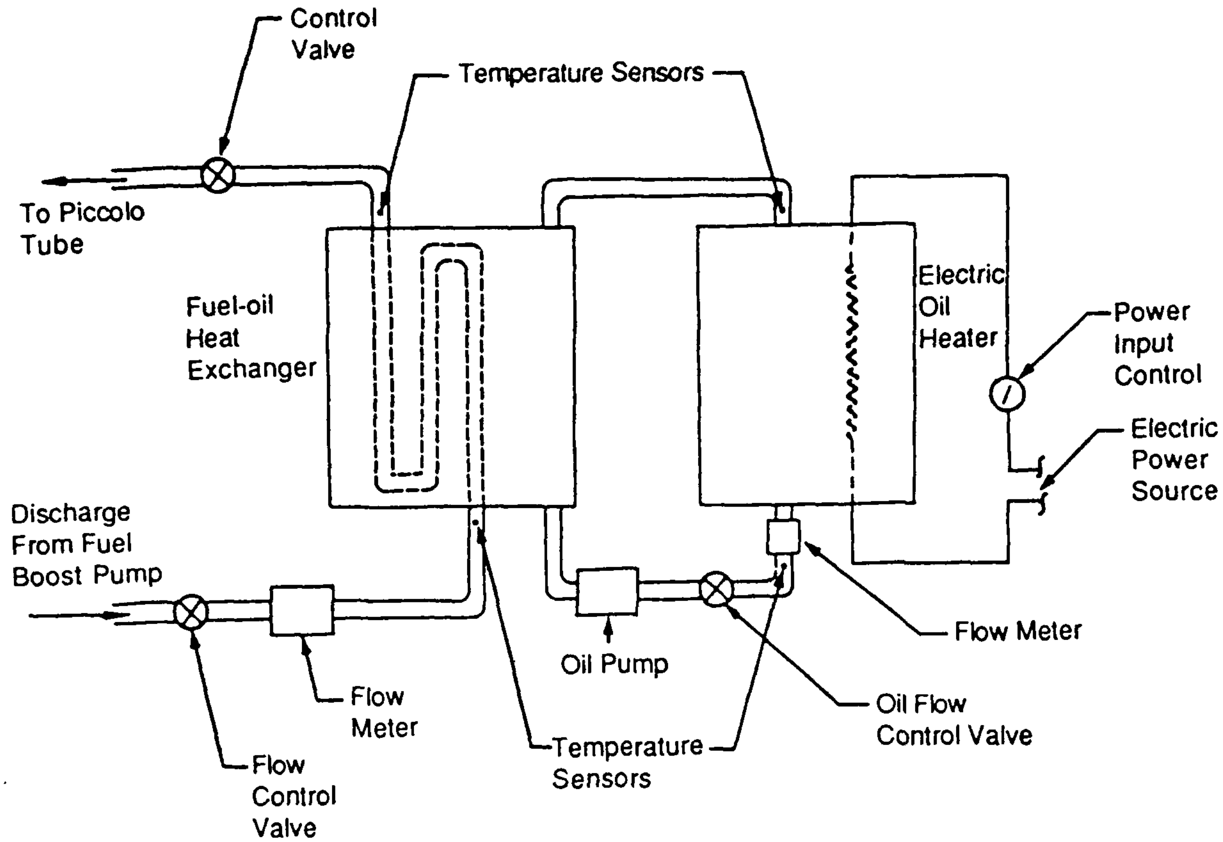


Figure 13. External Fuel Heating System Schematic

supersonic airplanes and equipment since the fuel is the only convenient heat sink at those speeds. Furthermore, fuel is being used much more extensively as a heat sink for subsonic airplanes as well because ram air scoops increase airplane drag and may increase the detectability of stealthy airplanes.

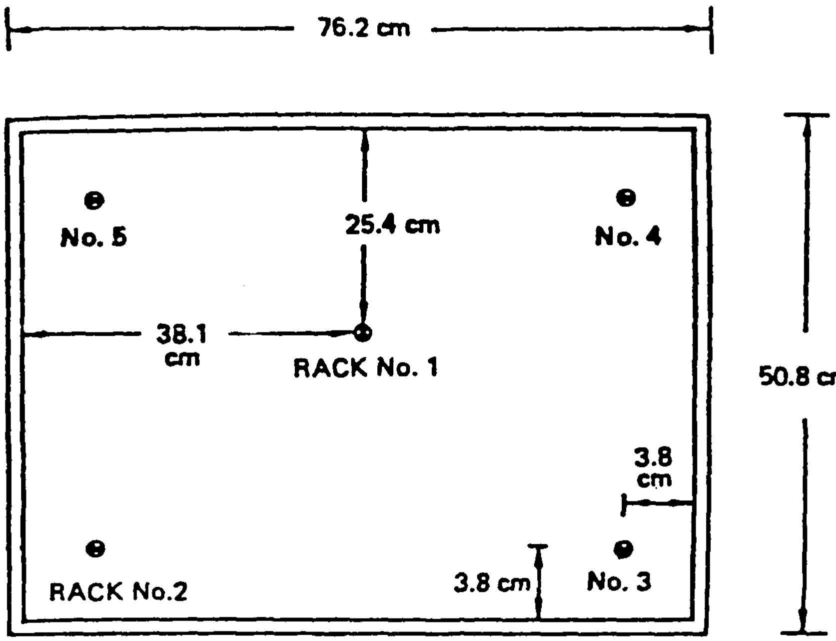
Thermocouples were used to measure in-tank fuel temperatures, tank wall temperatures, and heat exchanger coolant temperatures. The FTTS had 48 thermocouples to map the in-tank fuel temperature behavior (Figure 14). Thermocouples on the upper and lower surfaces were used to monitor and control the skin temperatures. Control was achieved by comparing the measured skin temperature with the desired simulated flight temperature and regulating coolant flow until the differences were nulled out. The FTTS control system allowed tank upper and lower surface temperatures to vary as desired over the entire duration of a simulated mission.

Pressure, flow rate, displacement, and electrical power measurements were made to control the FTTS or measure component performance. Flowmeters measured coolant flow rates in the FTTS heat exchangers. Four accelerometers were placed on the outside of the fuel tank to monitor vibration displacements. Boost pump performance data (discharge pressure and flow rate) and electrical data (voltage, current and power) were recorded to assess its performance.

3.1.2 Data Acquisition

The data acquisition system for the FTTS was a Hewlett Packard 3052A. This system provided near real-time display of any two selected test variables in engineering units on a Lear Siegler terminal. Continuous stripchart records of two selected test variables (usually tank top and bottom skin temperatures) were obtained for each test.

The most relevant data for this program were the 48 channels of fuel temperature data and the upper and lower skin temperature and the weigh



Thermocouple Locations Height Above Bottom		Thermocouple Identifiers				
Cm.	In.	Rack 1	Rack 2	Rack 3	Rack 4	Rack 5
0	0	1	13	21	29	39
0.6	0.25	2			30	40
1.27	0.50	3	14	22	31	41
2.54	1.00	4	15	23	32	42
5.08	2.00	5				
10.16	4.00	6	16	24	33	43
25.4	10.00	7	17	25	34	44
40.64	16.00	8	18	26	35	45
45.72	18.00	9				
48.26	19.00	10	19	27	36	46
49.53	19.50	11			37	47
50.80	20.00	12	20	28	38	48

Figure 14. Fuel Tank Simulator Thermocouple Locations

tank data when fuel depletion was simulated. Proper facility operation was verified by monitoring heat exchange temperatures and flow rates. Capacitance data for the fuel quantity probe were recorded manually.

3.2 Endurance Tests

The component endurance tests were performed in an outdoor hazardous test cell at the Boeing test site in Tulalip, Washington. The test facility consisted of an insulated test chamber with temperature control, and nitrogen inerting systems (Figure 15). Separate boost pump and valve test rigs were developed specifically for this test program. Each test rig had a network of tanks, pumps, valves, heat exchangers, tubing and instrumentation to simulate desired elements of an airplane fuel system. Figure 16 shows the flow diagram of the boost pump test apparatus and Figure 17 shows the valve test apparatus. Each test apparatus was mounted on a structural floor assembly, allowing it to be installed or removed from the test chamber. When inside the chamber the floor rested on a catch basin that was sized to contain all of the fuel in the system in the event of a gross leak.

Test Chamber

The test chamber was a 13-foot by 13-foot by 10-foot high insulated cell. The chamber facilities included a hot water heater and water/fuel heat exchanger for fuel heating and a nitrogen cooled Dowtherm tank and a Dowtherm/fuel heat exchanger for fuel cooling. The chamber also had an electrical power panel for all the test rig power requirements (voltage, frequency, and single or three phase). The thermal control system controlled the fuel temperature within $\pm$ 2°F over the 160°F to -50°F temperature range. A photograph of the boost pump test rig installed in the test chamber is shown in Figure 18.

Boost Pump Test Apparatus

The boost pump test rig had two 975-gallon test tanks for holding test

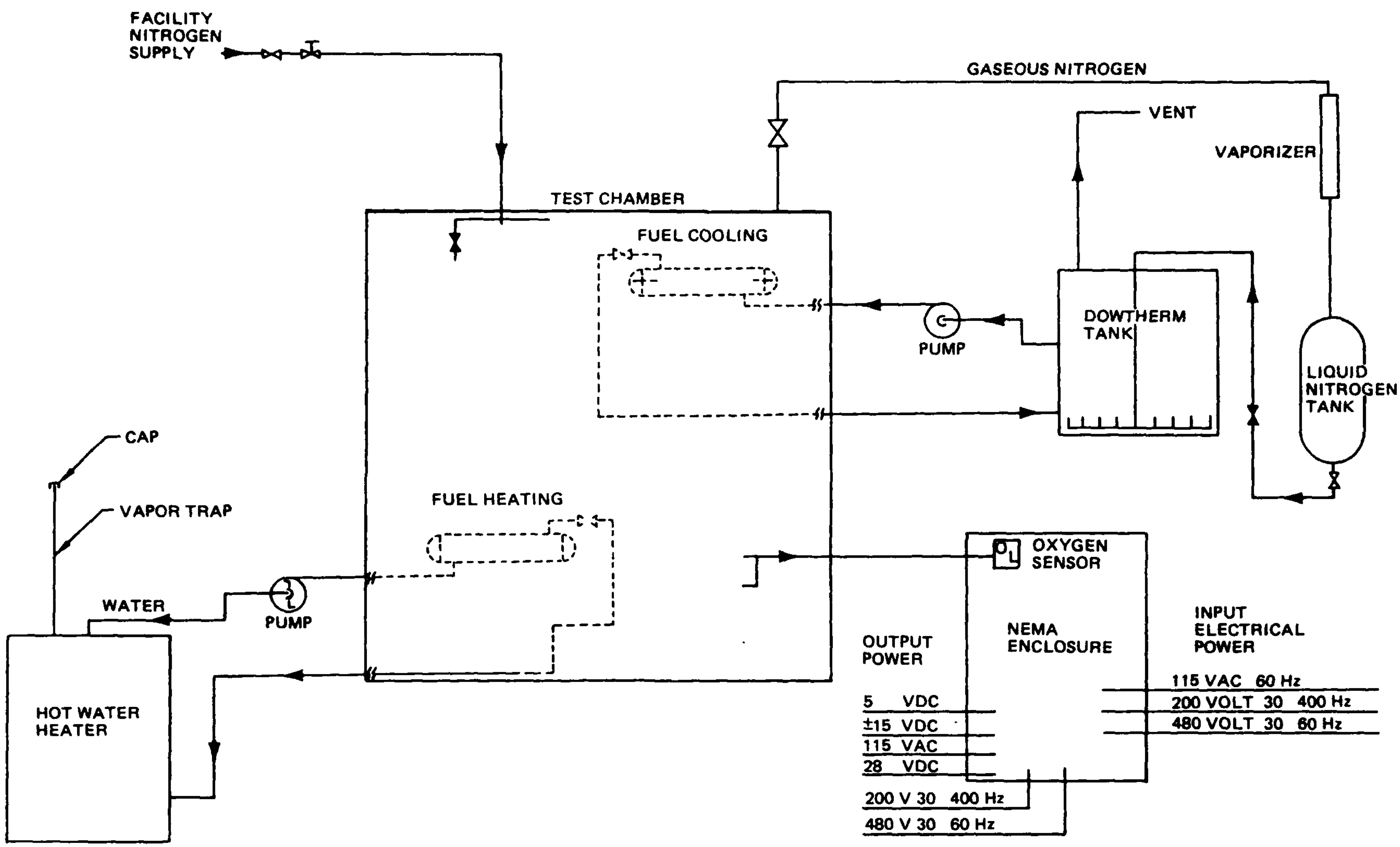


Figure 15. Schematic of Endurance Test Facility

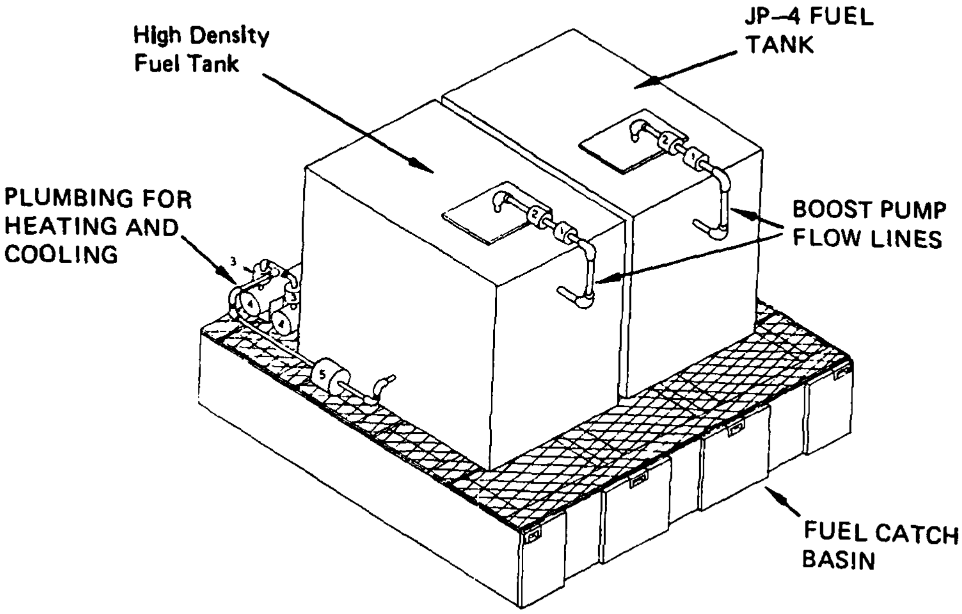


Figure 16. Automated Boost Pump Endurance Test Rig

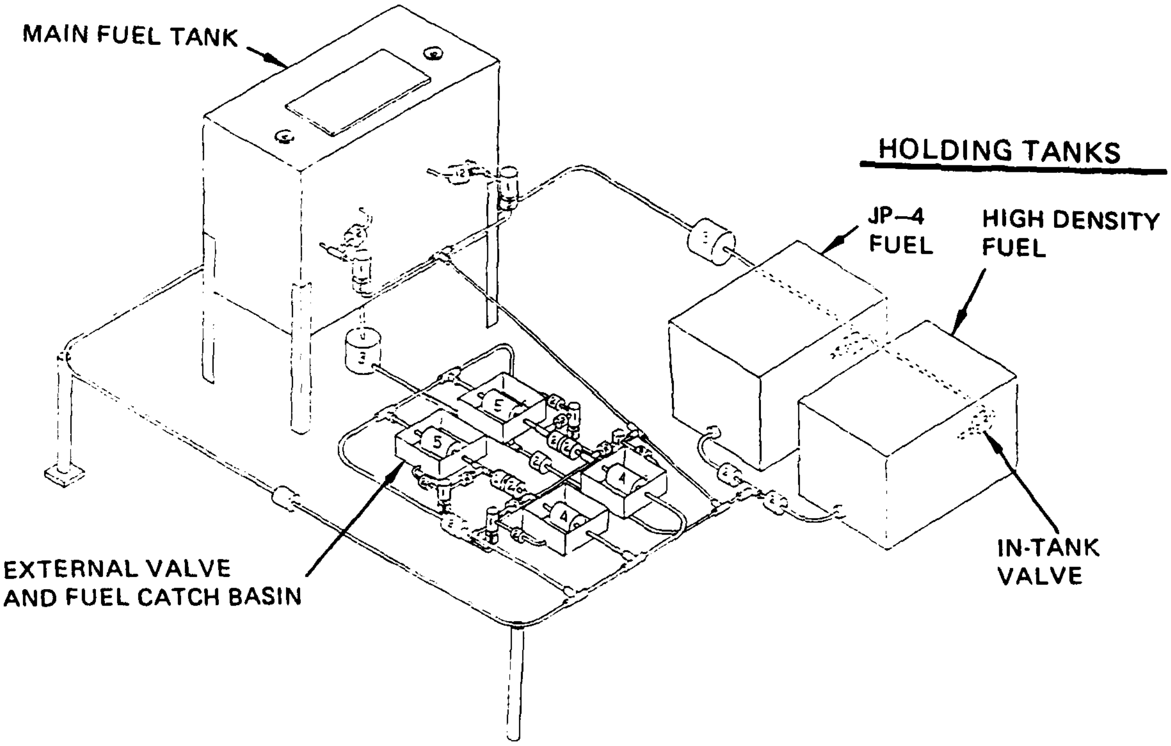


Figure 17. Automated Valve Endurance Test Rig

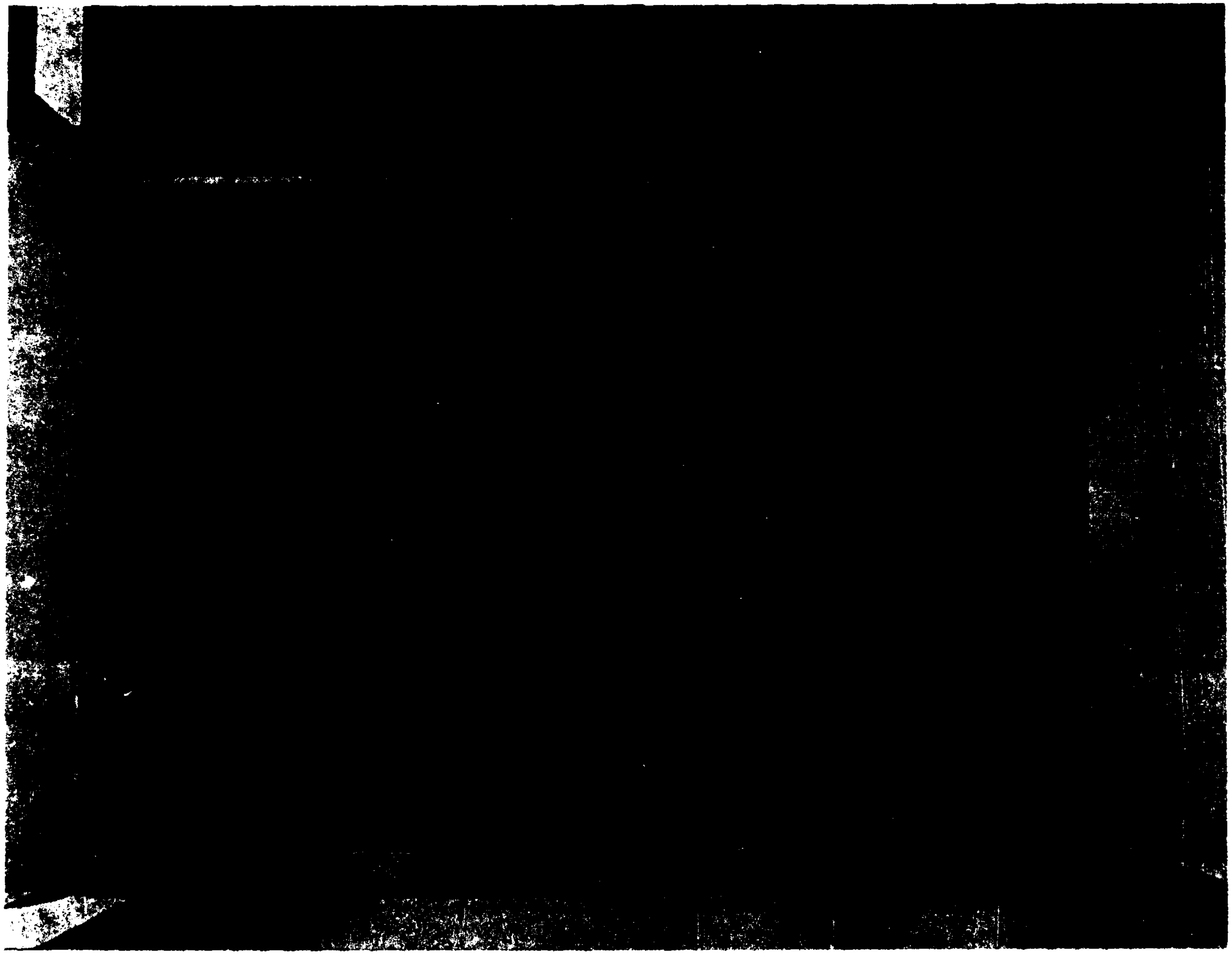


Figure 18. Boost Pump Endurance Test Rig Installed in Test Chamber

fuels, temperature control equipment, and instrumentation (Figure 16). An aircraft boost pump was submerged and tested inside each tank. Fuel on the discharge side of the pump was transported out the top of the tank, through a turbine flowmeter and a pressure control valve, and then back into the tank. Temperature, pressure, and flow rate of this test loop were continuously monitored. Both test tanks had their own thermal conditioning loop.

Valve Test Apparatus

The valve test apparatus consisted of a valve test tank, two fuel holding tanks, pumps, valves, level indicators, heat exchangers, tubing, and fittings (Figure 17). Eight of the airplane fuel system test components were mounted in the system. The shutoff valves and check valves were mounted such that fuel flowing through the main test loop would flow through them. The level control valves and the fuel transfer valve were located inside the valve test tank to simulate their aircraft application. All aircraft components were tested for functionality and leakage as fuel was circulated out of the valve test tank through the valves and back into the tank. A temperature control loop was included in this test apparatus also. Two fuel holding tanks were provided to allow alternating fuel types during the test.

3.2.1 Instrumentation

Boost Pump Test Instrumentation

The boost pump test instrumentation consisted of flowmeters, float switches, pressure transducers and thermocouples (Table 4). The flowmeters were used to measure the fuel flow rates through the HDF and JP-4 boost pump flow loops. Float switches were provided to detect excessive fuel leakage. The pressure transducers measured static pressure inside the HDF and JP-4 test tanks and the discharge pressures from the boost pumps. Thermocouples provided a number of temperature measurements including fuel

Table 4. Boost Pump Test Instrumentation

37 Analog Data Channels

Variable	Description
FM1A	HDF test loop flowmeter
FM1B	JP-4 test loop flowmeter
O2	Chamber oxygen content
PT1A	HDF tank pressure
PT1B	JP-4 tank pressure
PT2A	Test pump tank A discharge pressure
PT2B	Test pump tank B discharge pressure
T-1A	HDF tank temperature #1
T-1B	JP-4 tank temperature #1
T-2A	HDF tank temperature #2
T-2B	JP-4 tank temperature #2
T-3A	HE-HA fuel inlet temperature
T-3B	HE-HB fuel inlet temperature
T-4A	HE-HA fuel exit temperature
T-4B	HE-HB fuel exit temperature
T-5A	HE-CA fuel inlet temperature
T-5B	HE-CB fuel inlet temperature
T-6A	HE-CA fuel exit temperature
T-6B	HE-CB fuel exit temperature
T-7A	HE-HA water inlet temperature
T-7B	HE-HB water inlet temperature
T-8A	HE-HA water exit temperature
T-8B	HE-HB water exit temperature
T-9A	HE-CA Dowtherm inlet temperature
T-9B	HE-CB Dowtherm inlet temperature
T10A	HE-CA Dowtherm exit temperature
T10B	HE-CB Dowtherm exit temperature
T11A	Dowtherm tank temperature #1
T11B	Dowtherm tank temperature #2
T12A	NEMA enclosure temperature #1
T12B	NEMA enclosure temperature #2
T14A	Tank A pump discharge temperature
T14B	Tank B pump discharge temperature
T15A	Chamber temperature #1
T15B	Chamber temperature #2
TPAP	Tank A pump power
TPBP	Tank B pump power
	HE-XY is Heat Exchanger where: X is Hot or Cold and Y is Loop A or B

2 Discrete Data Channels

Variable	Description
LS-5	Catch basin gross leakage float switch
CONPRES	Gaseous Nitrogen pressure switch

pump inlet and discharge temperatures, water and Dowtherm temperatures in the fuel heating and fuel cooling heat exchangers, and the temperatures at two locations inside the test chamber.

Valve Test Instrumentation

The valve test instrumentation also included flowmeters, float switches, pressure transducers and thermocouples but for somewhat different purposes (Table 5). The flowmeters measured the fuel flow rates through the HDF and JP-4 valve test flow circuits. The float switches were used to detect excessive leakage rates from valve seats and valve bodies (see Section 4.2.2). Pressure transducers measured pressures inside the two valve test flow circuits.

Thermocouples provided temperature data for fuel, water and Dowtherm at the inlets and exits of the fuel/water and fuel/Dowtherm heat exchangers, inside the two test tanks and at two locations inside the test chamber.

An oxygen sensor was also used throughout the test program to monitor the oxygen concentration in the test chamber. For unattended operation the oxygen concentration was required to be less than 9% prior to initiating any of the endurance tests.

3.2.2 Data Acquisition

The data acquisition and test facility control system for the component tests consisted of a personal computer with a hard disk and a modem and employed an Intellution Inc. firmware package called FIX. The instrumentation was interfaced to the control system by OPTO22 signal conditioning equipment. All active endurance test instrumentation was monitored continuously and the data were stored on a hard disk every 15 seconds. The data were reduced and plotted using standard graphics packages and personal computers.

Table 5. Valve Test Instrumentation

20 Analog Data Channels

Variable	Description
FM2	Main loop flowmeter
O2	Chamber oxygen temperature
PT-3	Test loop pressure #1
PT-4	Test loop pressure #2
T-3C	HE-HC fuel inlet temperature
T-4C	HE-HC fuel exit temperature
T-5C	HE-CC fuel inlet temperature
T-6C	HE-CC fuel exit temperature
T-7C	HE-HC water inlet temperature
T-8C	HE-HC water exit temperature
T-9C	HE-CC Dowtherm inlet temperature
T10C	HE-CC Dowtherm exit temperature
T11A	Dowtherm tank temperature #1
T11B	Dowtherm tank temperature #2
T12A	NEMA enclosure temperature #1
T12B	NEMA enclosure temperature #2
T13A	Valve test tank temperature #1
T13B	Valve test tank temperature #2
T15A	Chamber temperature #1
T15B	Chamber temperature #2
	HE-XC is Heat Exchanger where: X is Hot or Cold and C is Valve test heat exchanger

14 Discrete Data Channels

Variable	Description
CONPRES	Gaseous Nitrogen control pressure switch
LS-1A	Leak check F4 shutoff valve
LS-1B	Leak check F4 check valve
LS-1C	Leak check KC shutoff valve #2
LS-1D	Leak check KC shutoff valve #1
LS-1E	Leak check KC check valve
LS-1F	Leak check KC level control valve
LS-1G	Leak check F4 fuel transfer valve
LS-1H	Leak check F4 level control valve
LS-2A	Leak detection F4 shutoff valve
LS-2B	Leak detection F4 check valve
LS-2C	Leak detection KC shutoff valve #2
LS-2D	Leak detection KC shutoff valve #1
LS-2E	Leak detection KC check valve
LS-5	Catch basin gross leakage float switch
	LS = level switch

4.0 TEST RESULTS

Results of the environmental and endurance tests are presented and discussed in this section. The objective of the environmental tests was to identify significant differences between HDF and JP-4 fuel when operating in severe thermal environments. The objective of the endurance tests was to predict significant changes in operational performance or maintenance requirements of fuel system components using HDF.

4.1 Environmental Tests

From Section 2.2 the selected missions for thermal environmental tests were:

- F-4 hot day - CAP/escort mission from Luke AFB and return
- F-4 cold day - CAP/escort mission from Elmendorf AFB and return
- KC-135 hot day - tanker support mission for F-4 hot day mission
- KC-135 cold day - B-52 refueling mission from Eielson AFB and return

The simulator was controlled to the recovery temperatures for these mission for in-flight temperature simulations.

Strictly speaking, the simulator should be controlled to the appropriate wall temperature adjusted for heat transfer rather than the recovery temperature. However, for fuel heating or cooling in subsonic airplanes, the difference between the recovery and wall temperature is only a few degrees. Furthermore, the results using the recovery temperature are conservative, i.e., using the recovery temperature produces higher heat transfer rates to or from the fuel.

The recovery temperature profile for the selected F-4 hot day mission is shown in Figure 19. The changes in recovery temperature during cruise

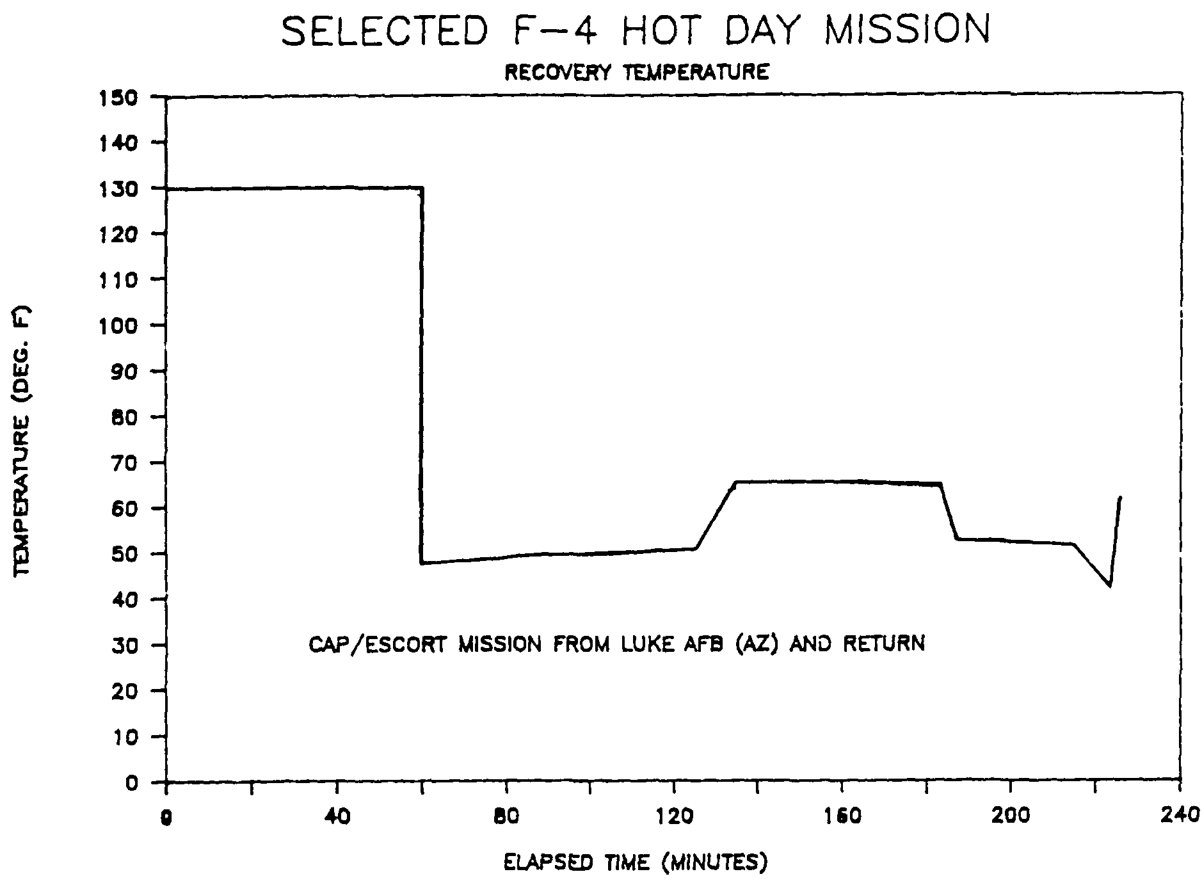


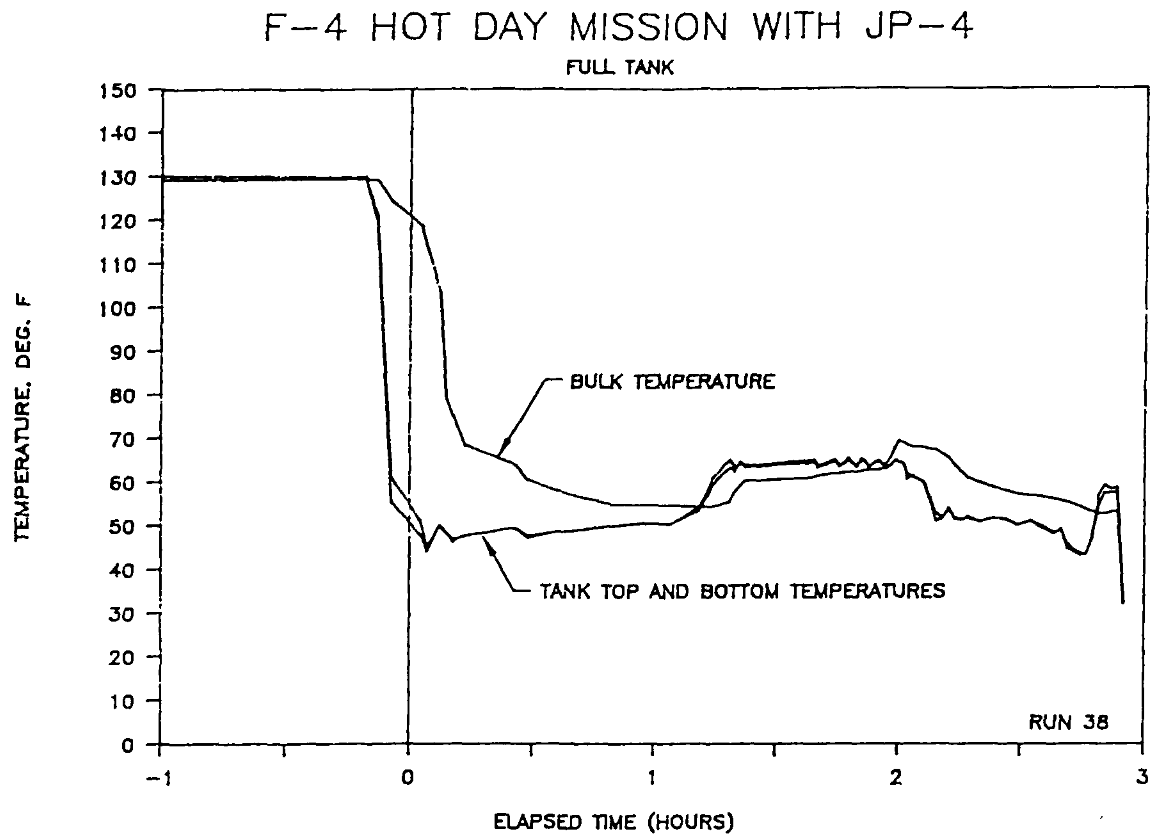
Figure 19. Recovery Temperature for Selected F-4 Hot Day Mission

correspond to Mach number variations during the mission. The resulting fuel temperatures for a full tank are shown in Figure 20, and for a nearly full tank in Figure 21. (Differences in heat transfer rates between full and nearly full tanks are sometimes significant because the air space in a nearly full tank reduces the heat transfer rate from the tank to the fuel.) No particular significance should be attached to the zero point on the elapsed time axis. The point where the temperatures begin to decrease rapidly corresponds to airplane takeoff. Obviously, the differences between full and nearly full tanks and between JP-4 and HDF on fuel bulk temperature variations for the conditions tested are quite small.

The recovery temperature profile for the selected F-4 cold day mission is shown in Figure 22. Again, both full and partially full tanks were tested for both JP-4 and HDF (Figures 23 and 24). As is evident, the influence of these variables on the fuel bulk temperature was quite small. Fuel freezing would not be an issue since the freezing point is below -100^{o}F, but flowability may. Proper engine fuel feed may be a problem at temperatures below -30^{o}F where the viscosity of HDF reaches 12 cS; the maximum engine design viscosity.

Prior to discussing the KC-135 thermal simulator results in detail, same general comments are appropriate.

The KC-135 mission simulations included comparisons between full and nearly full fuel tanks, the effects of slosh and vibration and the effects of heat addition to the fuel as well on bulk HDF and JP-4 fuel temperatures. Natural convection currents are driven from the top of the tank when cooling and from the bottom of the tank when heating. Therefore, differences in heat transfer rates between full and nearly full tanks are much lower when heating since the fuel is always in contact with the heat transfer surface that drives the convection currents. Slosh and vibration of course promote fuel mixing that leads to higher heat transfer rates to or from the fuel. The slosh and vibration frequencies and amplitudes used are discussed in Section 3. Changes of fuel temperature due to heat



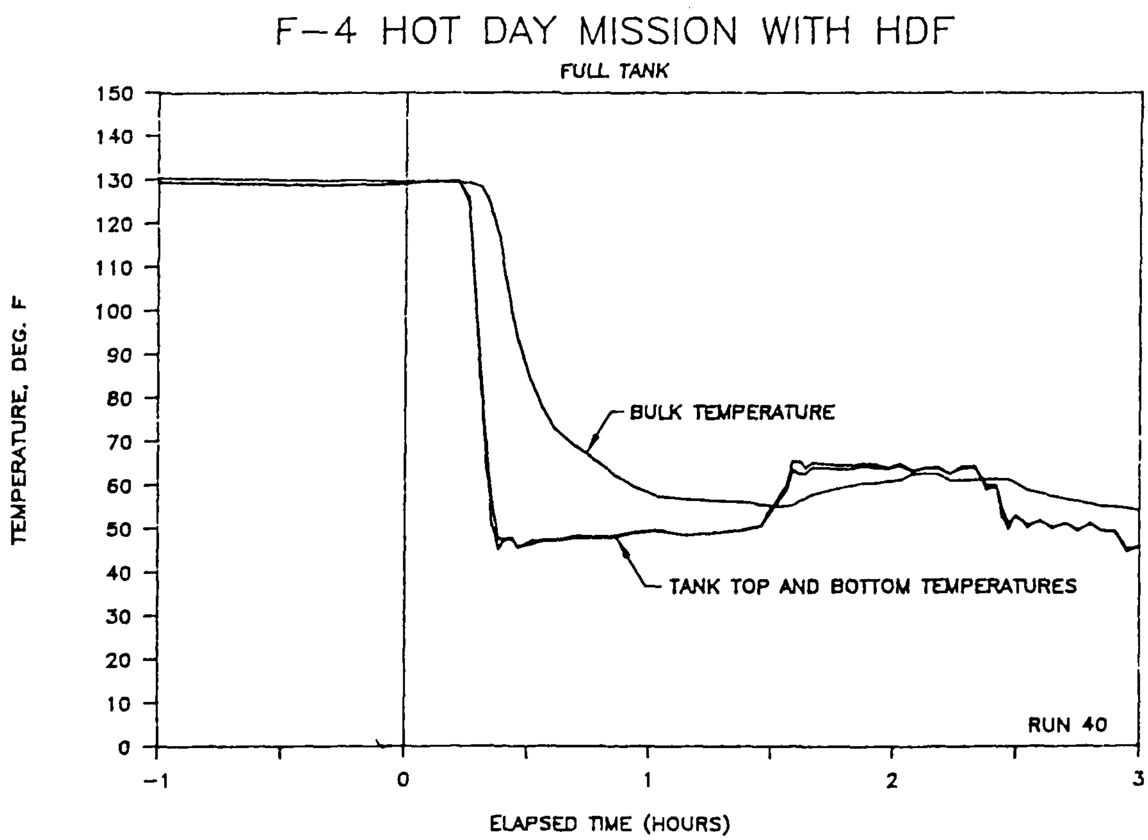
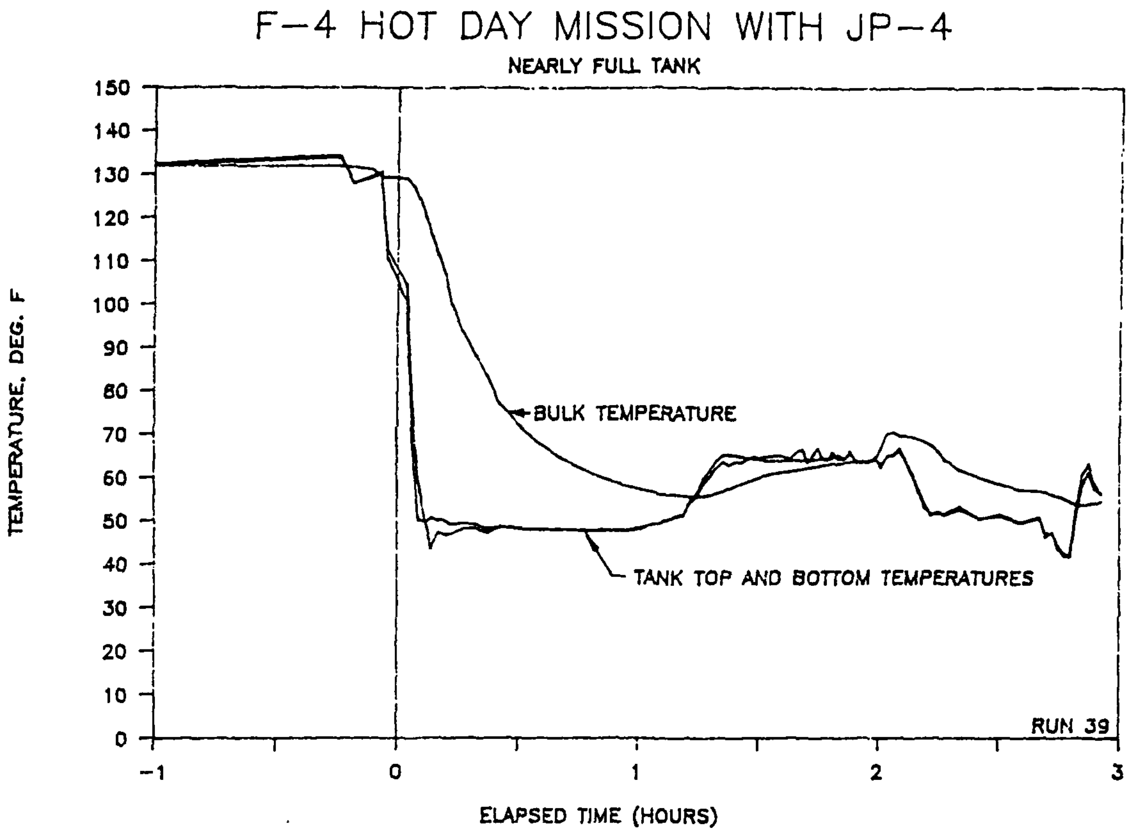


Figure 20. Fuel Temperature of JP-4 and HDF for F-4 Hot Day Mission withFull Tank



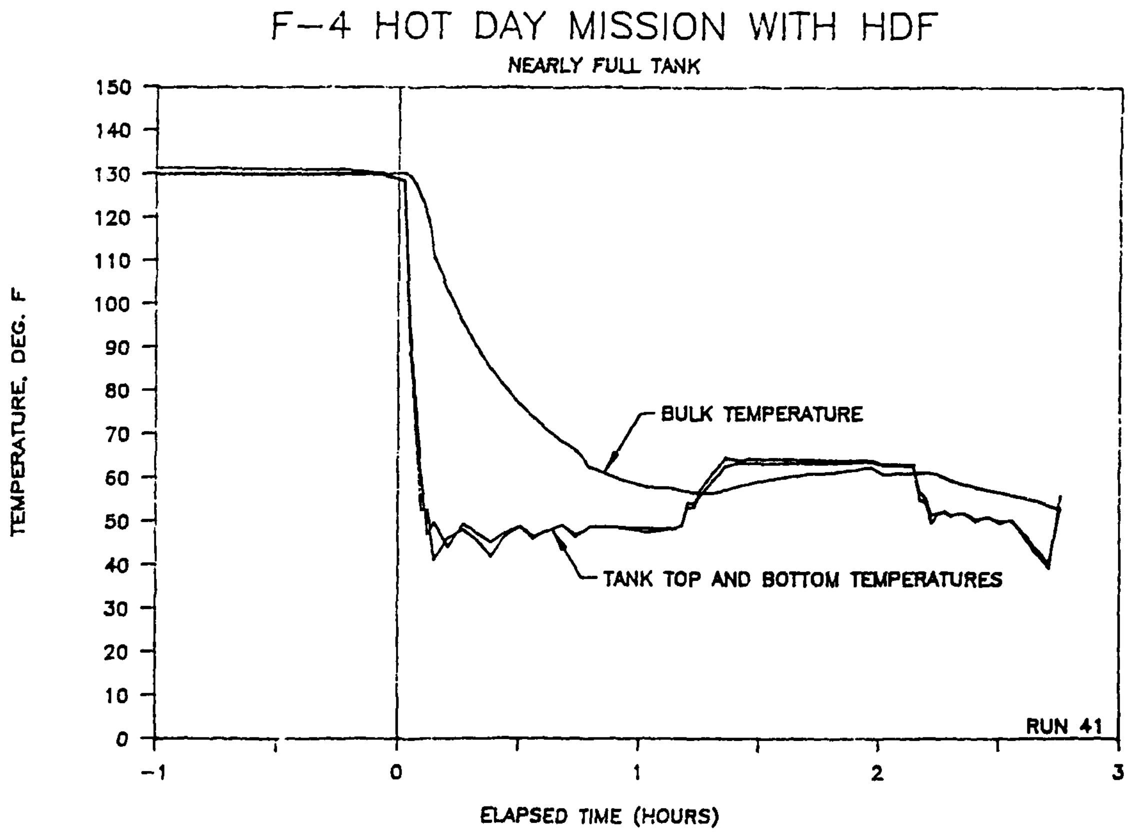


Figure 21. Fuel Temperatures of JP-4 and HDF for F-4 Hot Day Mission with Nearly Full Tank

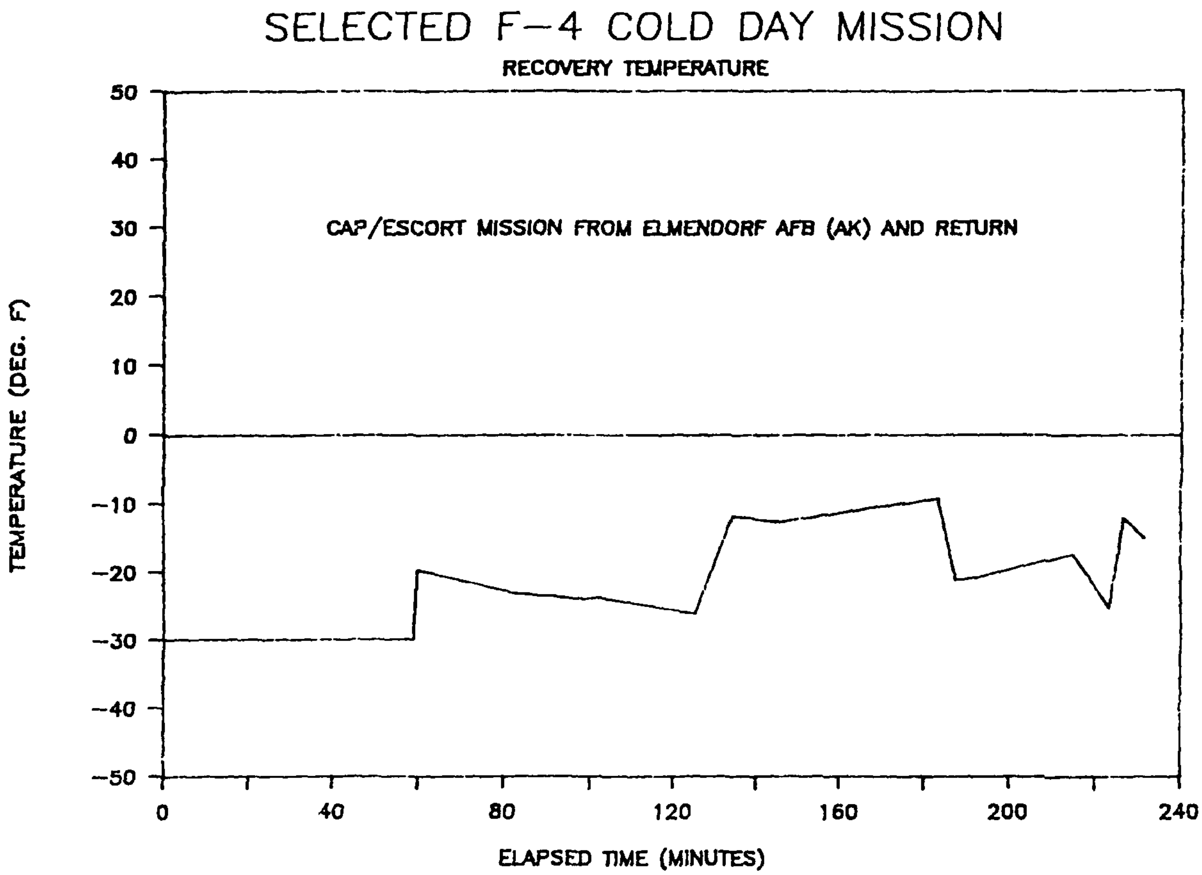
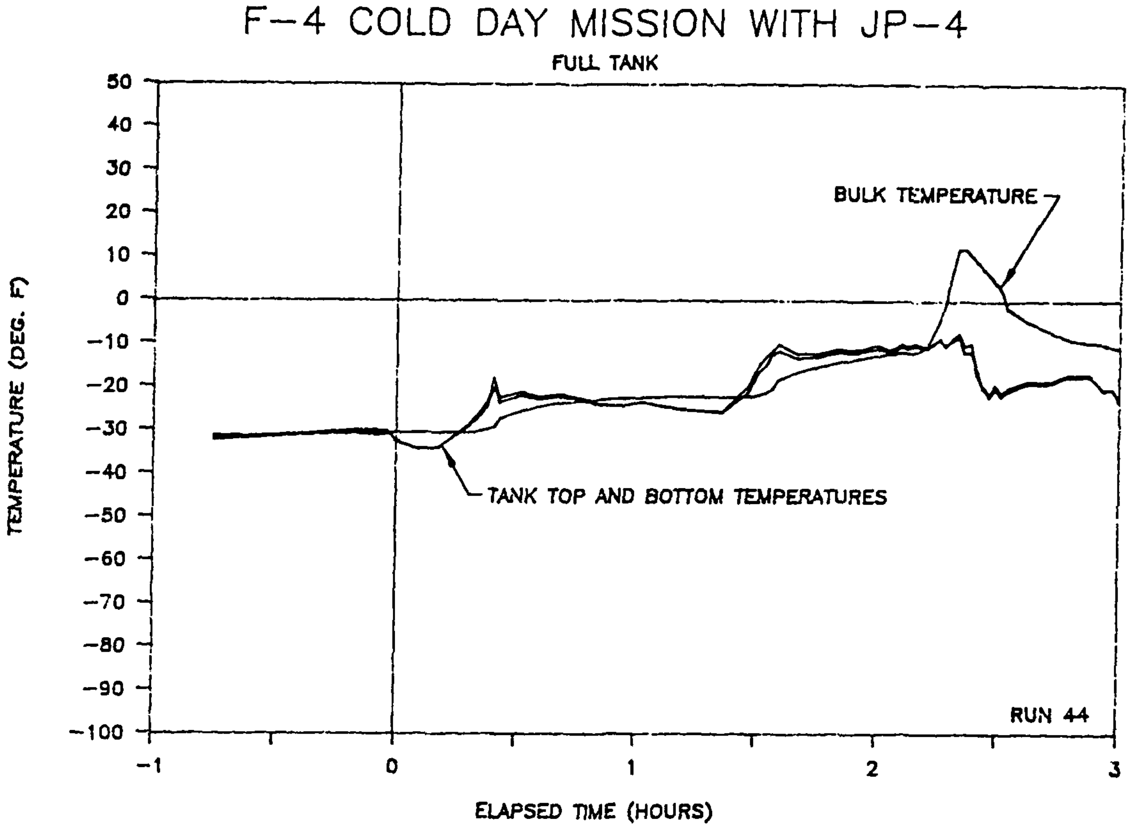


Figure 22. Recovery Temperatures for Selected F-4 Cold Day Mission



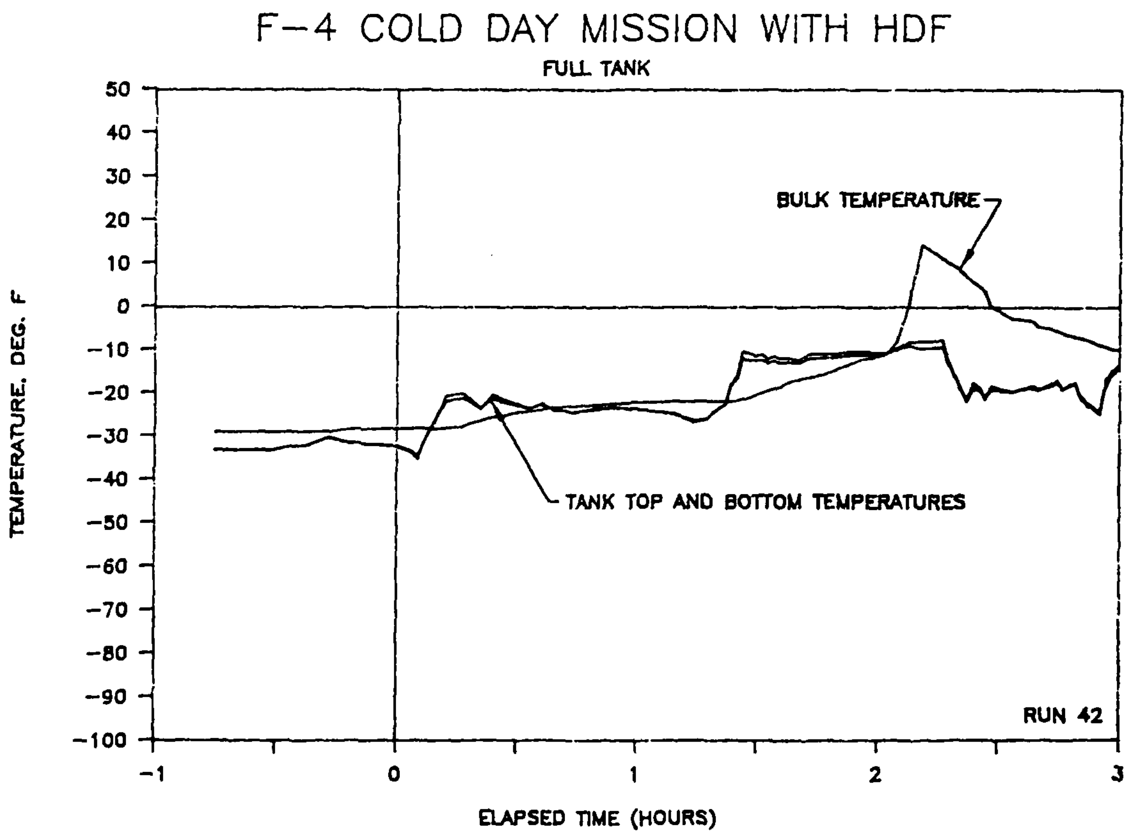
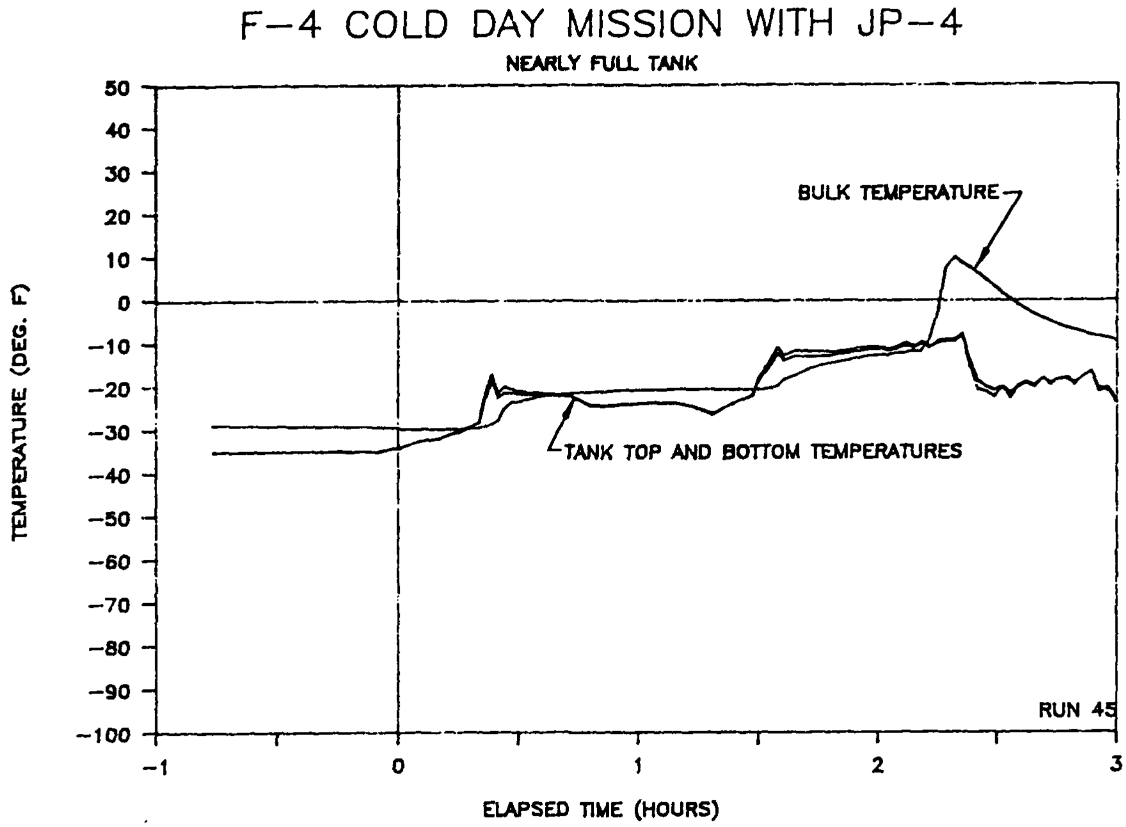


Figure 23. Fuel Temperatures of JP-4 and HDF for F-4 Cold Day Mission with Full Tank



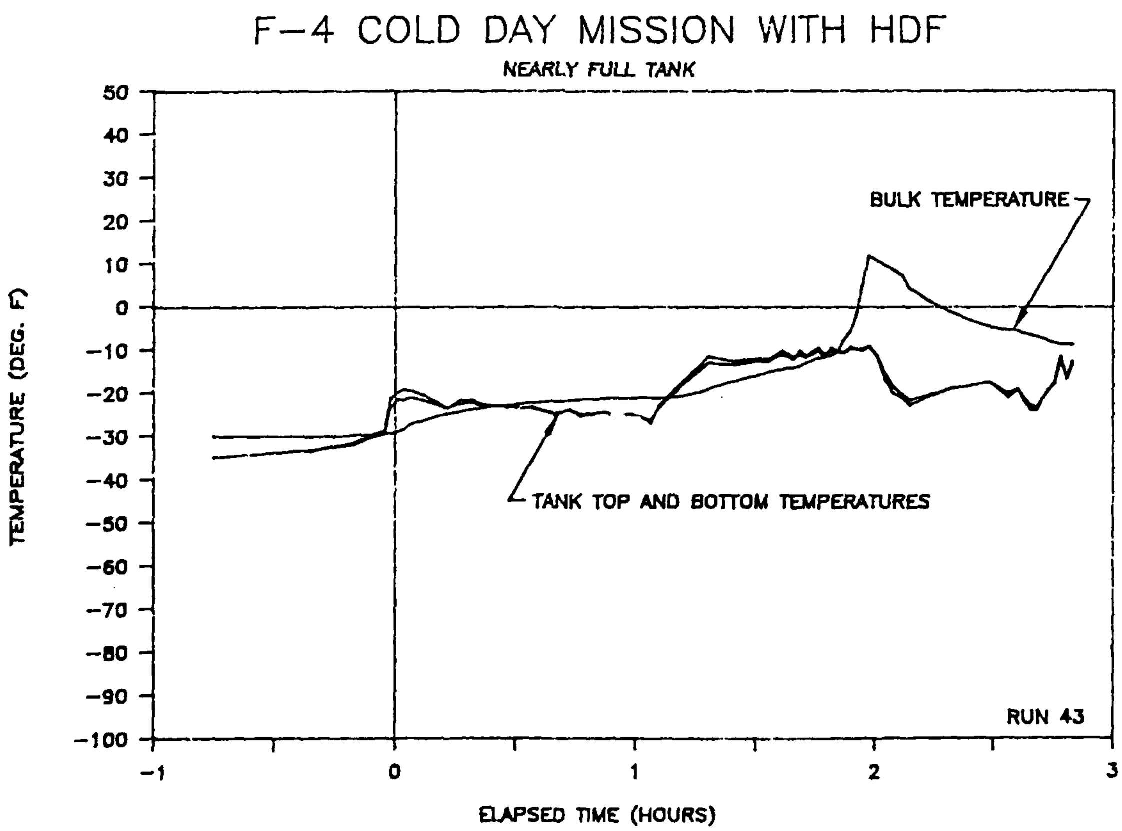


Figure 24. Fuel Temperatures of JP-4 and HDF for F-4 Cold Day Mission with Nearly Full Tank

addition were of particular interest in this study because the HDF had a lower heat capacity than JP-4. Tests were made with and without a heat exchanger that transferred a 1.5-kW thermal load into the fuel.

The recovery temperature profile for the KC-135 hot day mission is shown in Figure 25. Differences in average fuel temperatures of HDF between a full and nearly full tank for this mission can be seen by comparing Figures 26 and 27. Note that the average temperature with a full tank decreases more rapidly than for a nearly full tank as would be expected. Note also fuel cooling occurs throughout the simulated flight since the ground temperatures were much higher than the in-flight recovery temperatures.

The recovery temperature profile for the KC-135 cold day mission is shown in Figure 28. The converse of the hot day mission was true for this mission as the data for full versus partially full tanks (Figures 29 and 30). Since the ground temperatures were lower than the in-flight recovery temperatures, the fuel was undergoing heating even though a cold day mission was simulated. As discussed above, the effect of a wetted upper surface is less pronounced with heating than with cooling. This is evident in Figures 29 and 30 since the average fuel temperatures are about the same for both cases.

The effect of slosh and vibration on the simulated KC-135 hot day mission with HDF and full tanks can be seen by comparing Figures 26 and 31. Basically, slosh and vibration caused the fuel to cool more rapidly but had little effect on the final temperature level. The effect of slosh and vibration on the simulated KC-135 cold day mission is seen by comparing Figures 29 and 32. In this case the average fuel temperature with slosh and vibration was about $4^{o}F$ higher throughout the simulated missions. Comparison tests were made for the selected KC-135 hot and cold day missions with and without 1.5-kW heat input to a full tank of HDF. The resulting temperature differences for the hot day mission can be seen by comparing Figures 26 and 33. The difference increases throughout the mission reaching about $10^{o}F$ by the end of the mission.

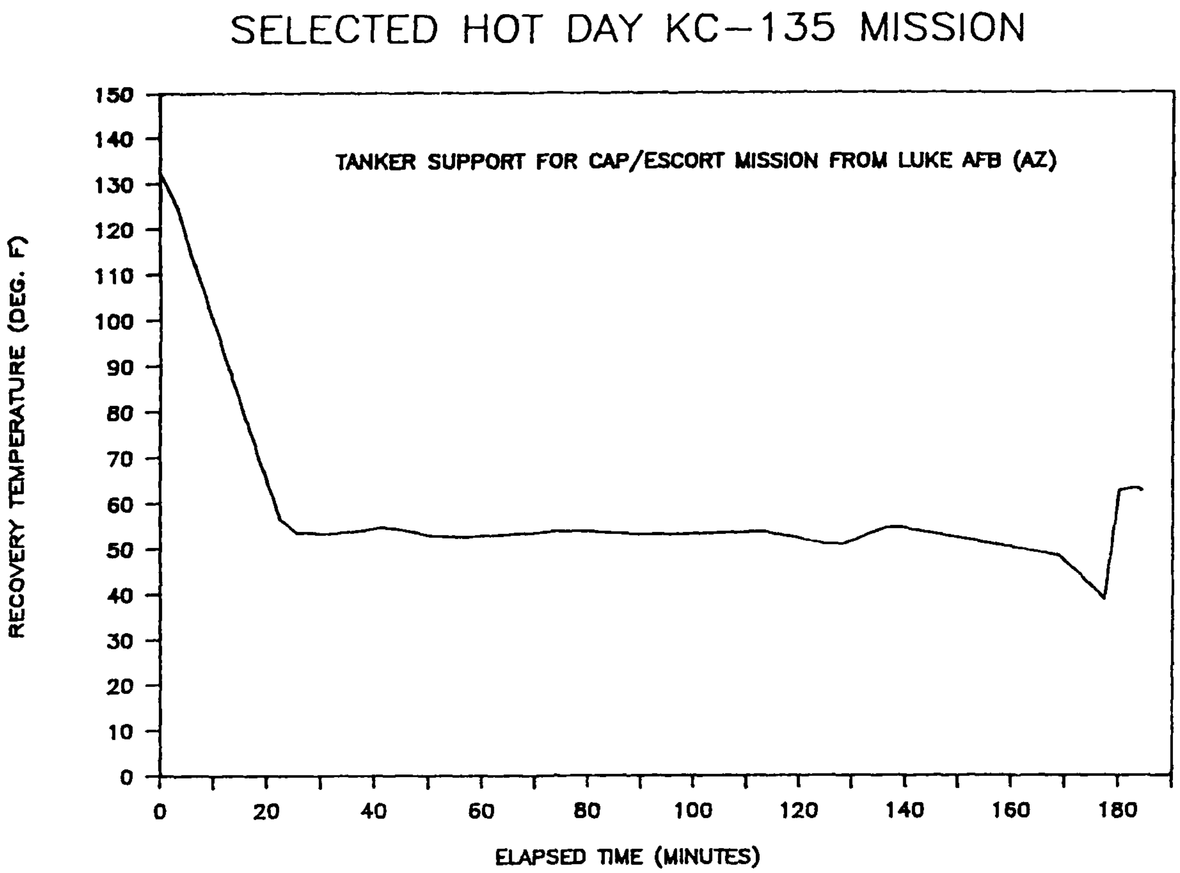
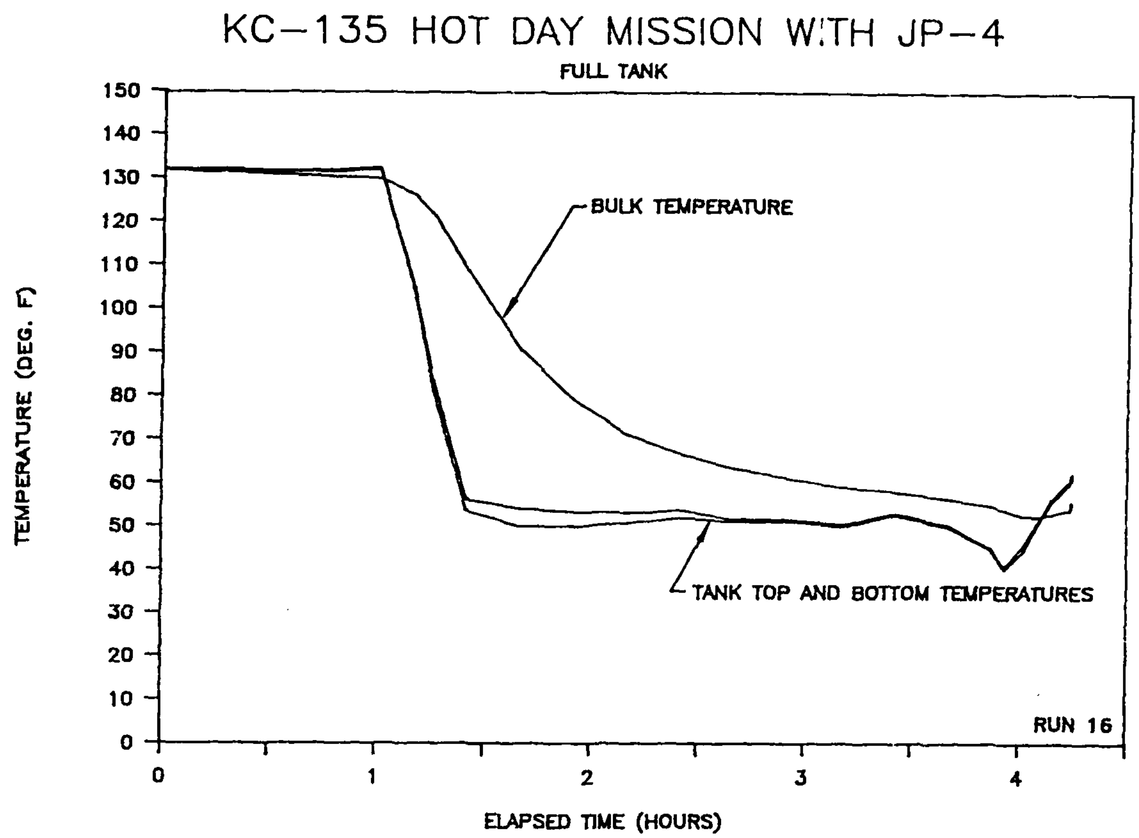


Figure 25. Recovery Temperature for Selected KC-135 Hot Day Mission



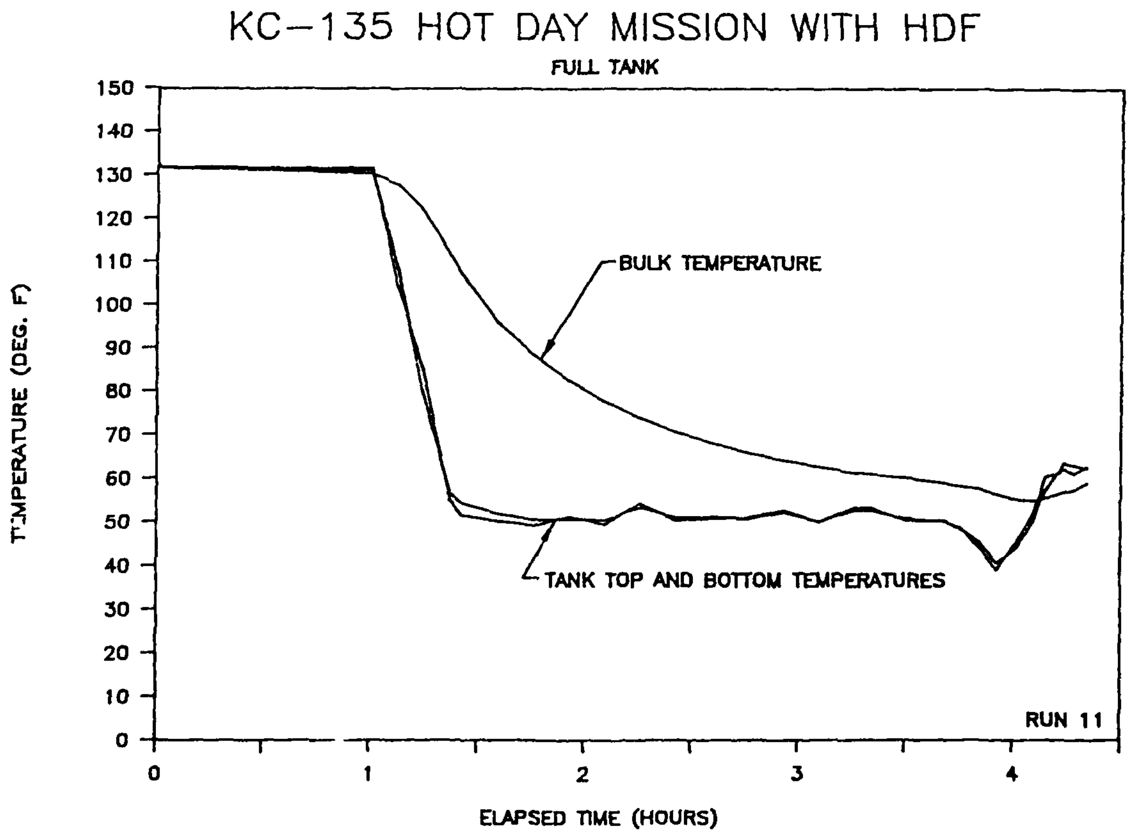


Figure 26. Fuel Temperatures of JP-4 and HDF for KC-135 Hot Day Mission with Full Tank

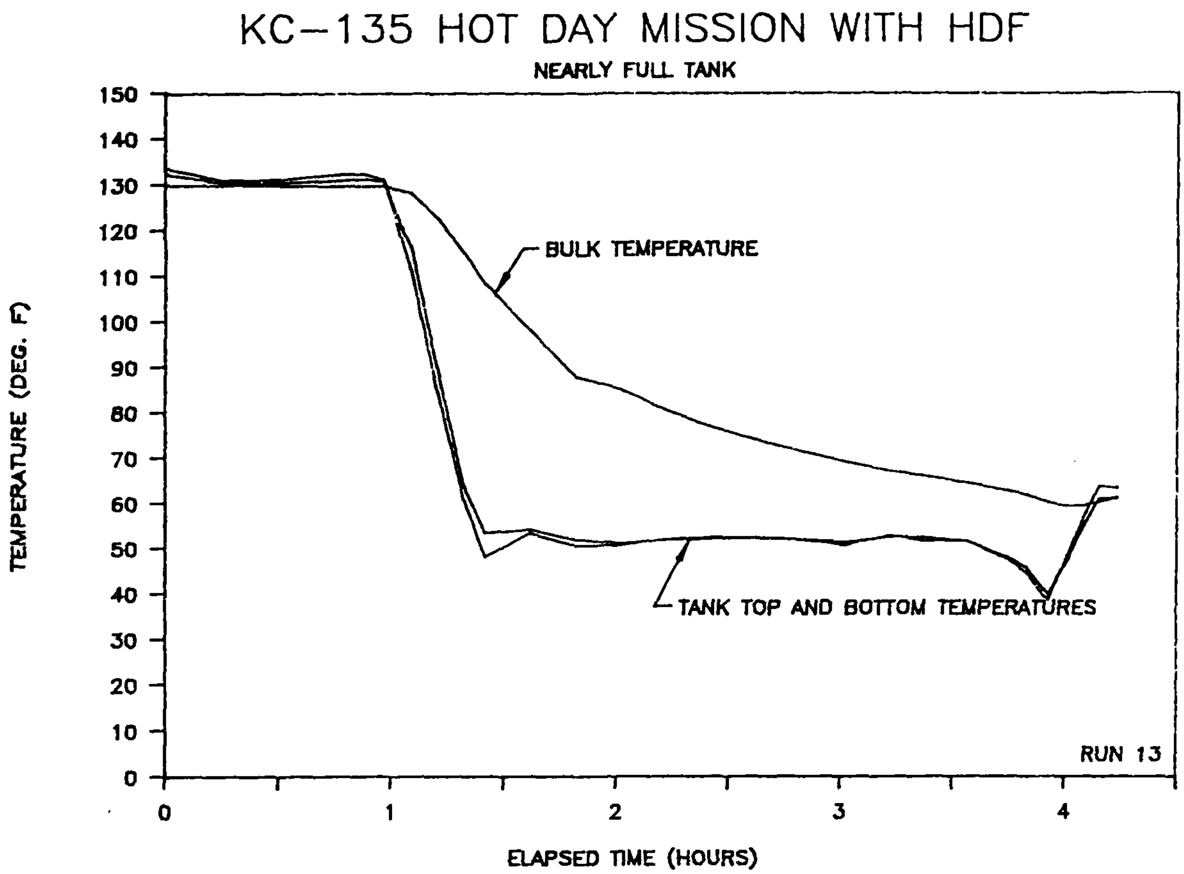


Figure 27. Fuel Temperature of HDF for KC-135 Hot Day Mission with Nearly Full Tank

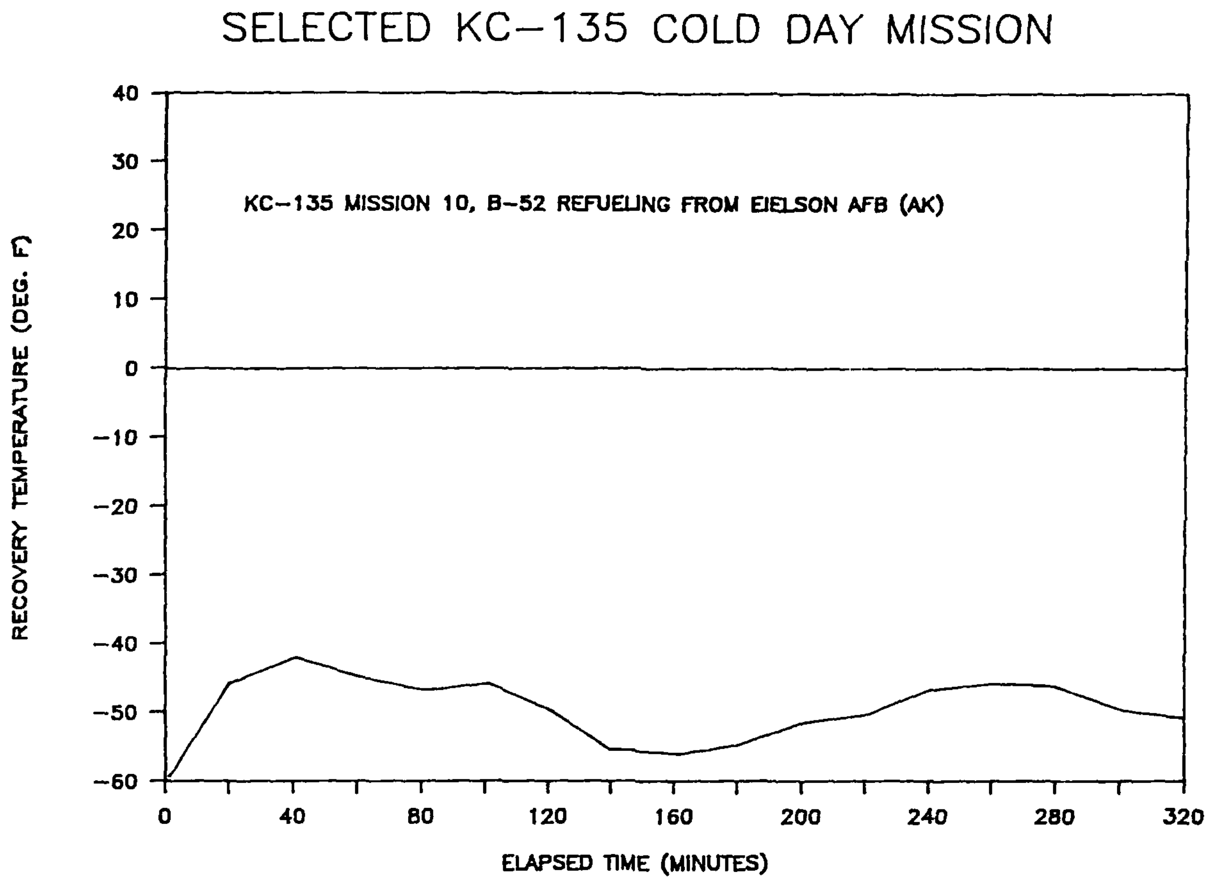
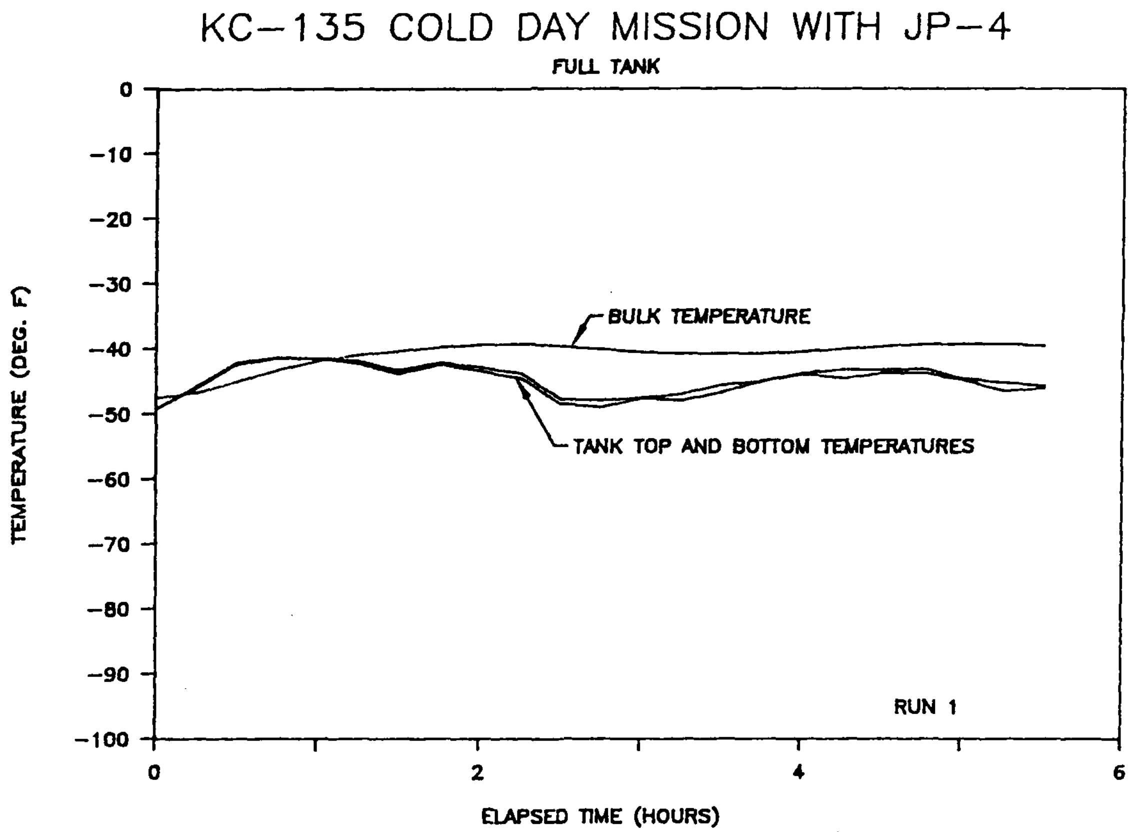


Figure 28. Recovery Temperature for Selected KC-135 Cold Day Mission



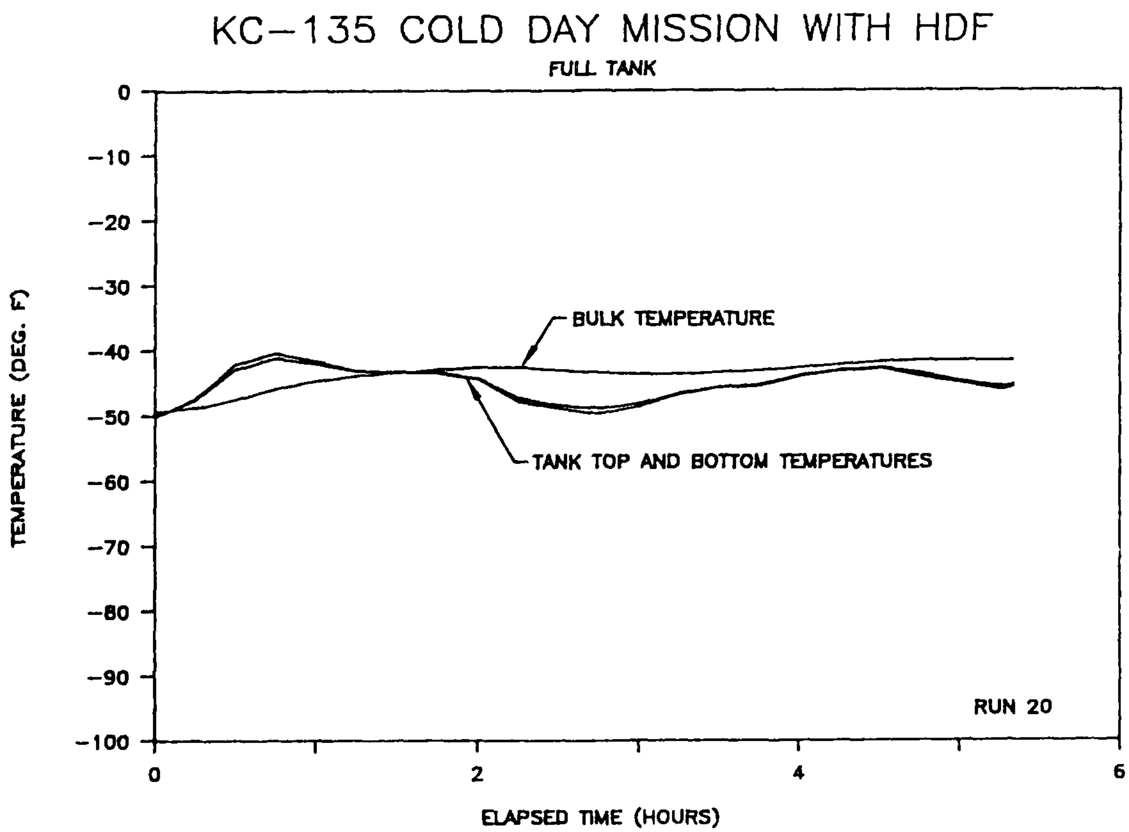


Figure 29. Fuel Temperatures of JP-4 and HDF for KC-135 Cold Day Mission with Full Tank

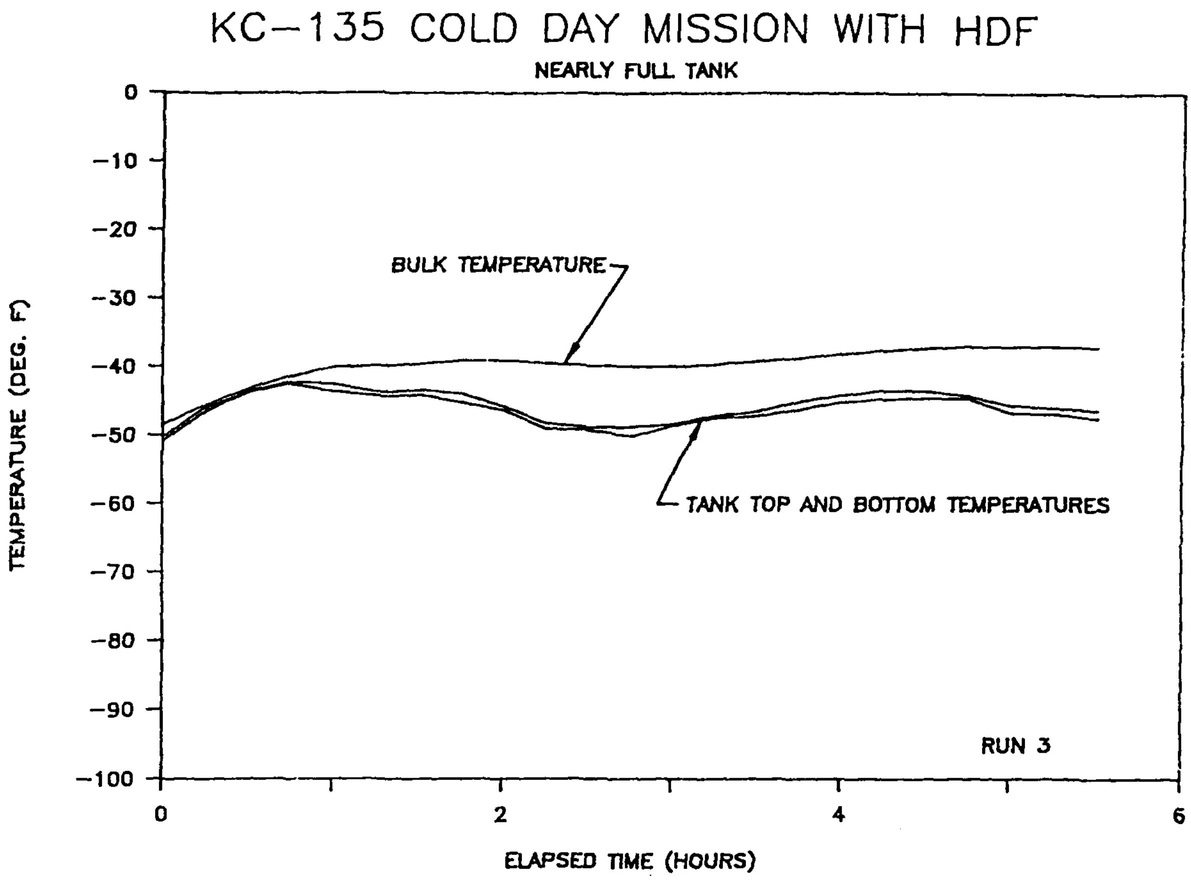


Figure 30. Fuel Temperature of HDF for KC-135 Cold Day Mission with Nearly Full Tank

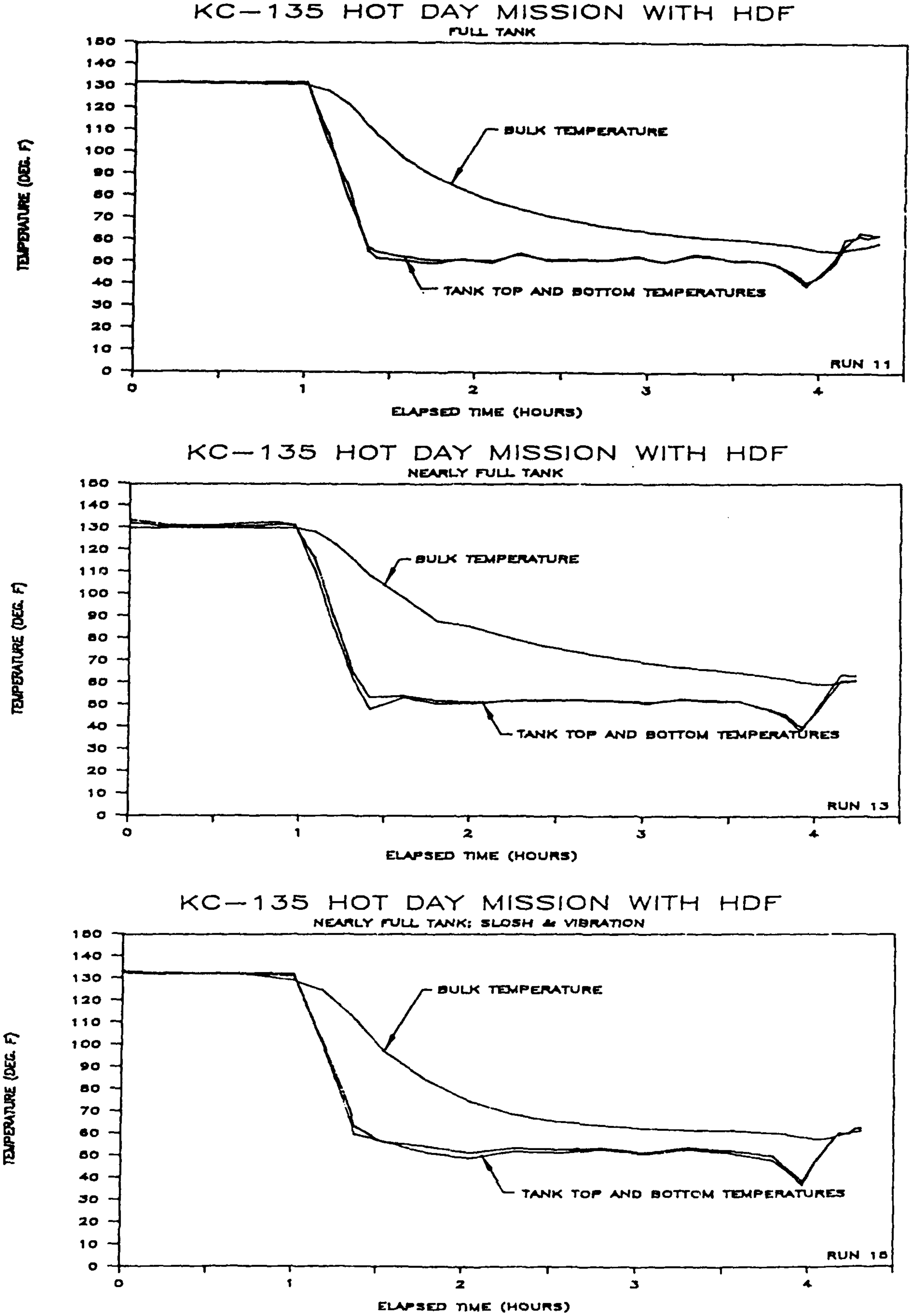


Figure 31. Effect of Fuel Level and Slosh and Vibration on Fuel Temperature for KC-135 Hot Day Mission with HDF

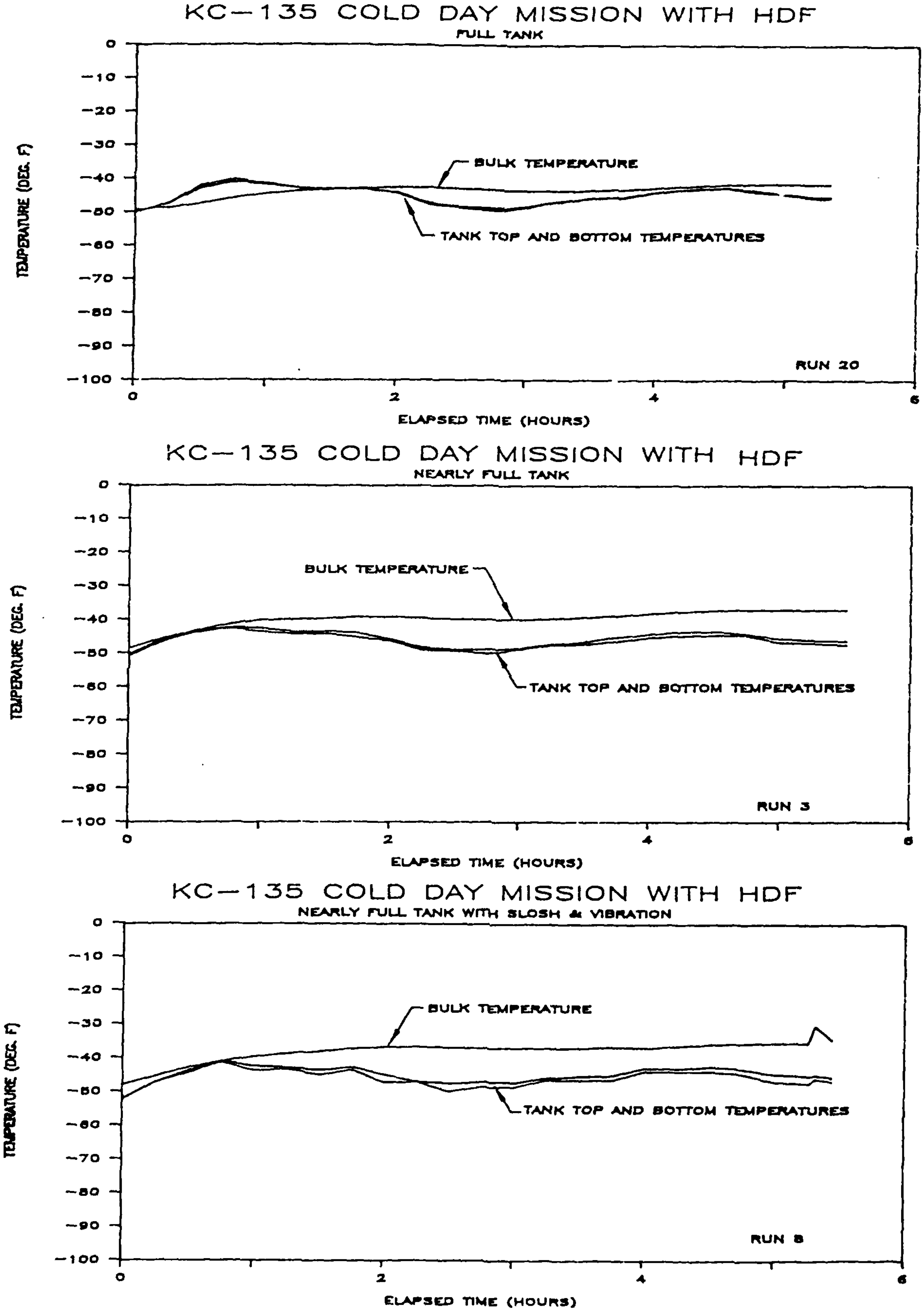
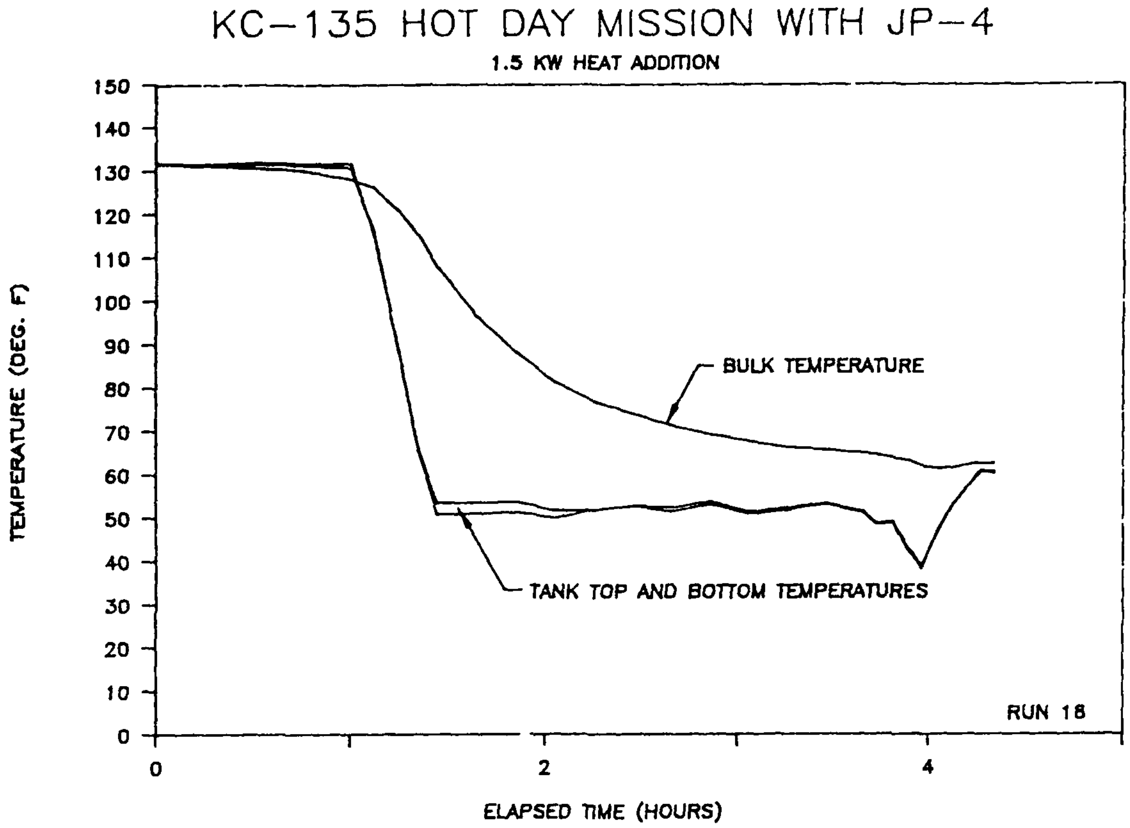


Figure 32. Effect of Fuel Level and Slosh and Vibration on Fuel Temperatures for KC-135 Cold Day Mission with HDF



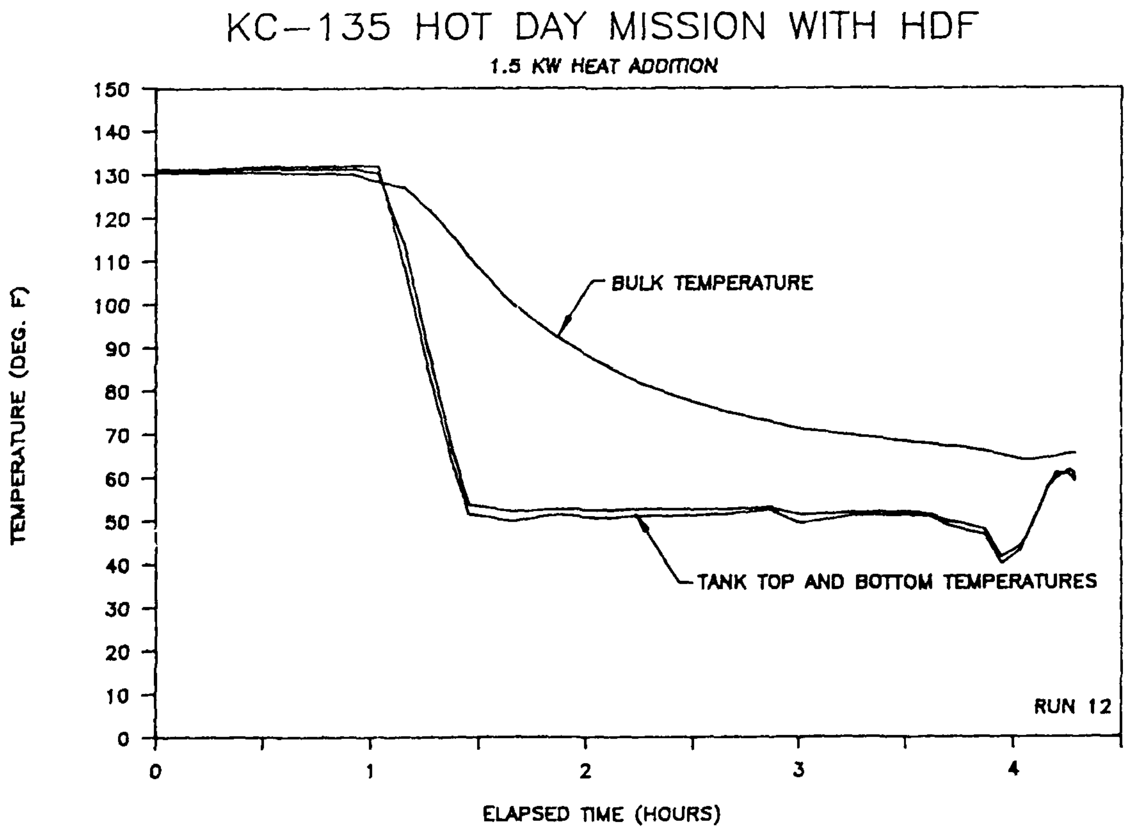
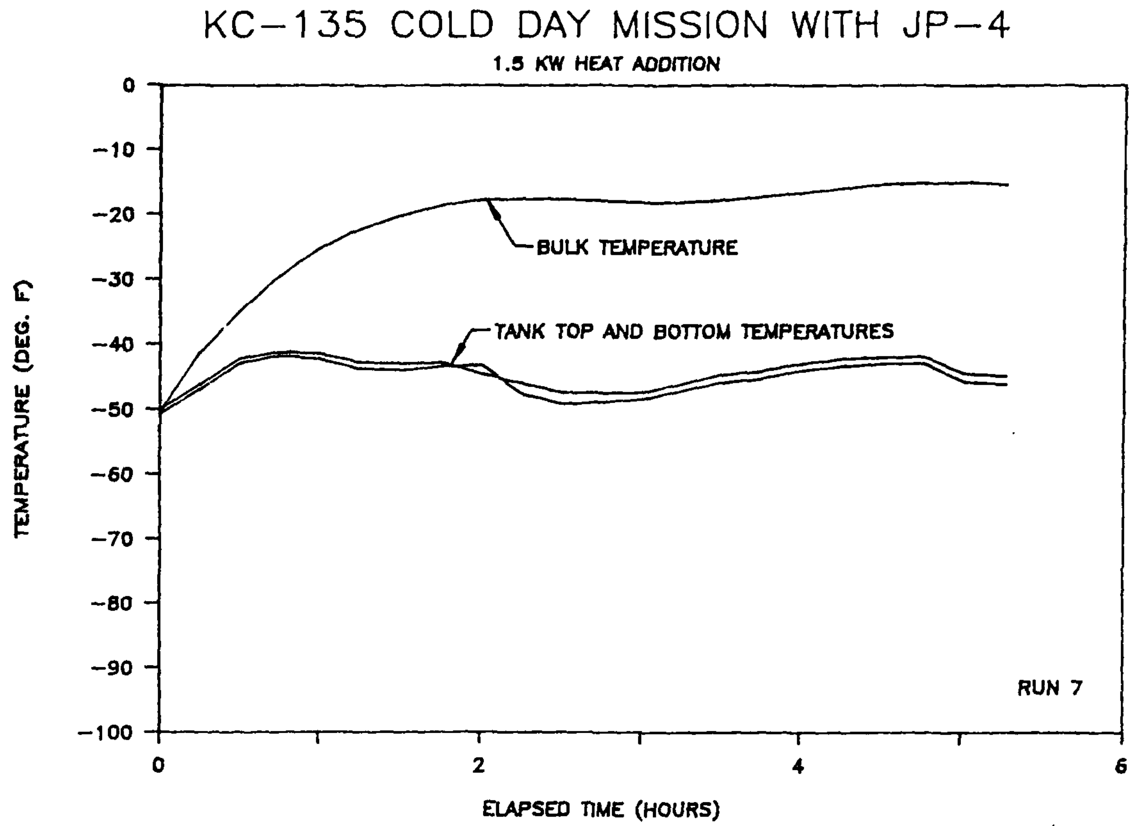


Figure 33. Fuel Temperatures of JP-4 and HDF for KC-135 Hot Day Mission with Heat Addition

Of considerable interest are the differences in temperature response to fuel heating between HDF and JP-4 fuels. These results for the KC-135 hot day mission are also shown in Figure 33. The effect of the lower heat capacity of HDF results in HDF temperatures that are about 8°F higher by the end of the mission. The response of the average temperature of HDF with and without heating for the KC-135 cold day missions was much more significant (Figures 29 and 34). The temperatures with heat addition was about 27°F higher with heat addition by the end of the mission. The larger temperature difference was due to the lower heat transfer from the tank walls for the cold day simulations, allowing the heat input from the external heat exchanger to have a larger effect on the average fuel temperature. Comparing average temperatures of HDF and JP-4 for KC-135 cold missions with heat input (Figures 32 and 33) the lower heat capacity of HDF is again evident in the data. The temperature of the HDF was as much as 9°F higher than JP-4 under very similar test conditions.

The heat loads generated by aircraft subsystems such as avionics, hydraulics, and environmental control systems are increasing significantly as overall weapon system capability is improved. The primary resource for cooling these subsystems is the fuel. At the same time, there are indications that the cycloparaffins inherent in the production of this type of high density fuel results in reduced thermal stability. The data in Appendix A indicate that the JFTOT breakpoint of the high density fuel used in this program was 440°F. The combination of low heat capacity and low thermal stability could limit the use of high density fuel.

Nearly all airplanes use capacitance-type fuel gauging probes. These devices yield fuel quantity by measuring fuel height and converting the height to volume through height-volume relationships for the tank geometry involved. The fuel height measurement is based on the differences in dielectric constant between the fuel (usually around 2) and air (which is 1 by definition). In this program the output of a typical capacitance gauge was measured and recorded as a function of fuel level for JP-4 and HDF (Figure 35 and 36). The readings for an empty tank were the same, as they obviously should be. With higher fuel levels the difference between the



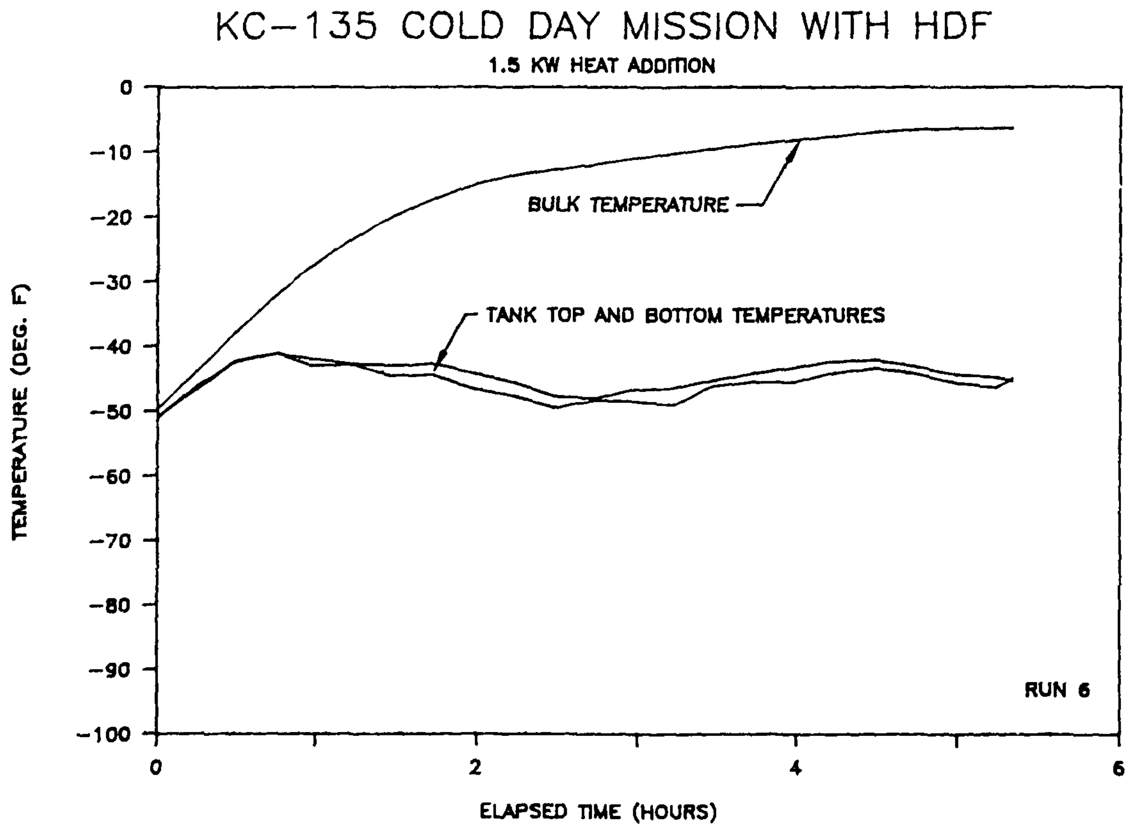


Figure 34. Fuel Temperatures of JP-4 and HDF for KC-135 Cold Day Mission with Heat Addition

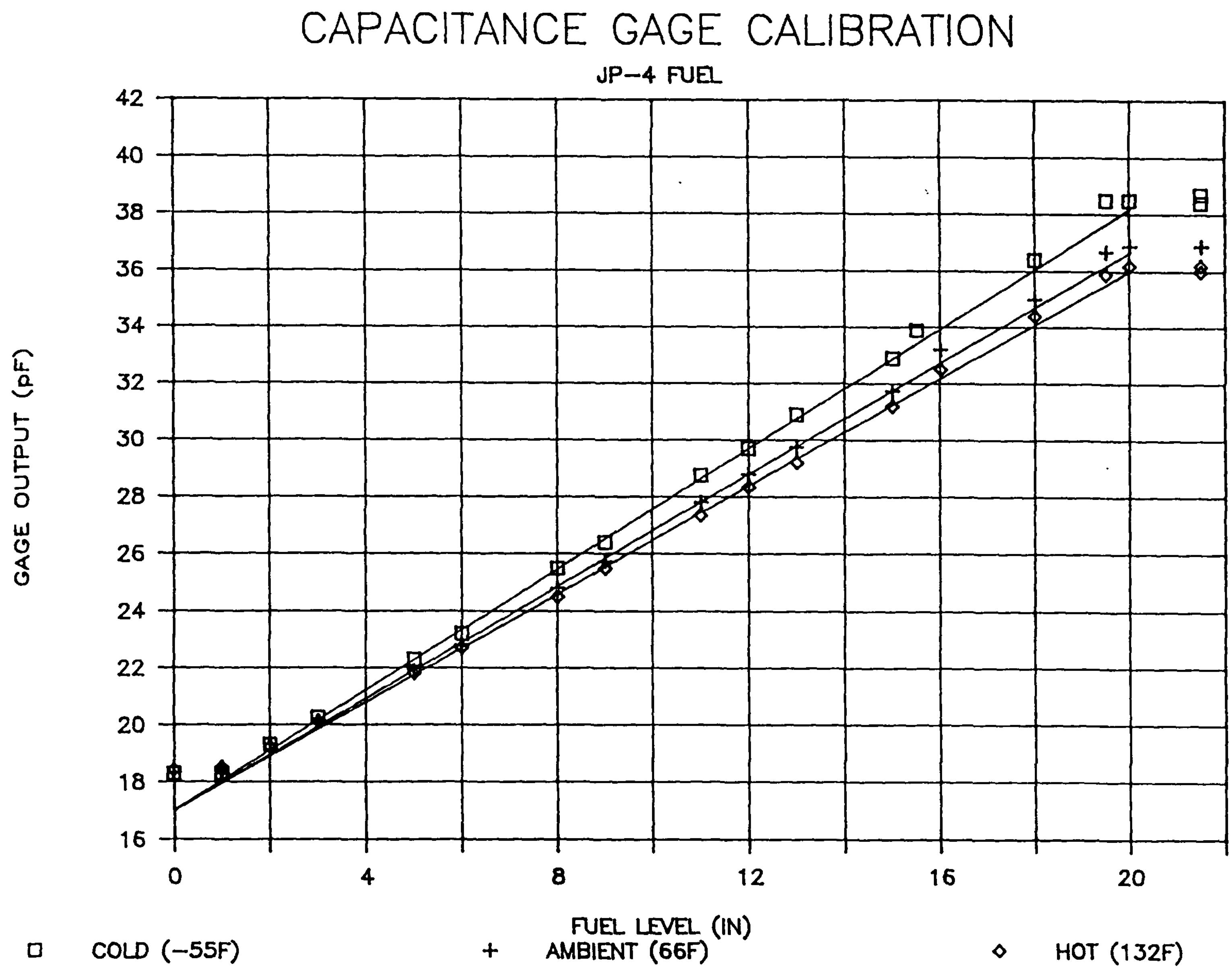


Figure 35. Capacitance Gauge Response with JP-4 Fuel

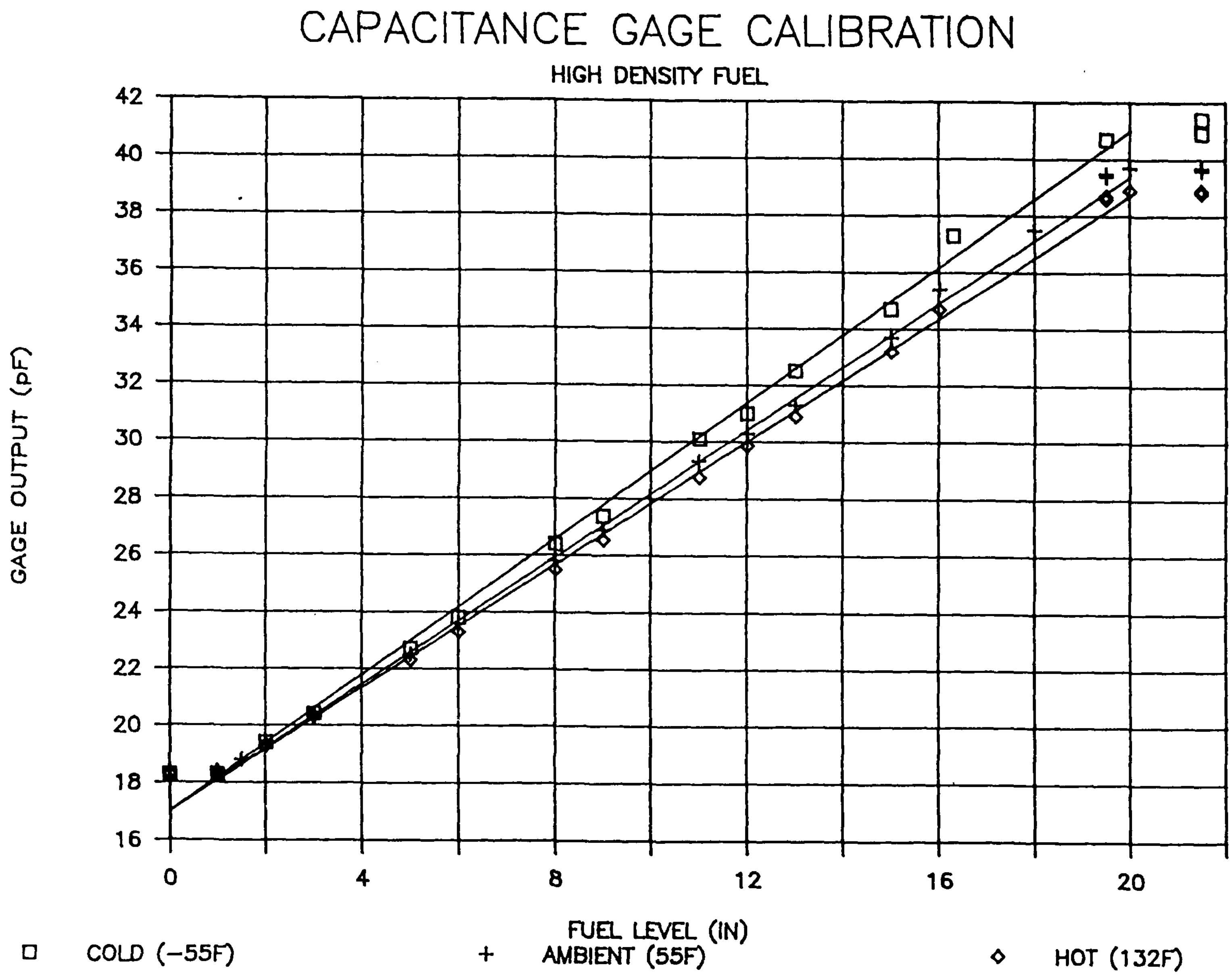


Figure 36. Capacitance Gauge Response with HDF

readings increased (Figure 37). The difference in capacitance readings was about 8% which is about the difference in dielectric constants of the two fuels. Hence, a gauging system designed for JP-4 would read about 8% high on a volumetric basis if HDF was used. However, on a mass basis the system would read low as explained in the following example.

Assume that a fuel tank with a 200 gallon capacity is 50% full (contains 100 gallons) of HDF. A gauging system calibrated for JP-4 would read 8% high on volumetric basis (would indicate 108 gallons). However, since the system is based on the density of JP-4, a fuel mass of 108x47.5/7.48 or 687 pounds of HDF would be indicated. The actual mass of HDF would be 100x53.5/7.48 or 715 pounds. (The density values of 47.5 and 53.5 lb/ft^3 are from Section 2.1 and 7.48 is the conversion factor from gallons to cubic feet.) Therefore, the indicated mass of fuel would be about 4% less than the actual value. In summary, HDF could be safely used in a JP-4 fuel calibrated system since the mass and not the volume of fuel is the key to airplane performance and the mass indicated gauging system would read low (be conservative) for HDF.

4.2 Endurance Tests

Since endurance tests require long hours of testing with relatively minor changes in test conditions, an automated facility that operated unattended was developed. After the appropriate test unit and test fuels were installed in the test chamber, the only manpower required was to load the appropriate test conditions into the control system computer, initiate the test, and collect daily fuel samples. The automated control system included an auto-dialer to alert test engineers of anomalies in system performance and allow tests to be monitored, changed or interrupted from remote terminals.

4.2.1 Boost Pump Tests

The boost pumps testing consisted of two phases. The first phase was run with HDF only; the second phase was run with alternating HDF and JP-4

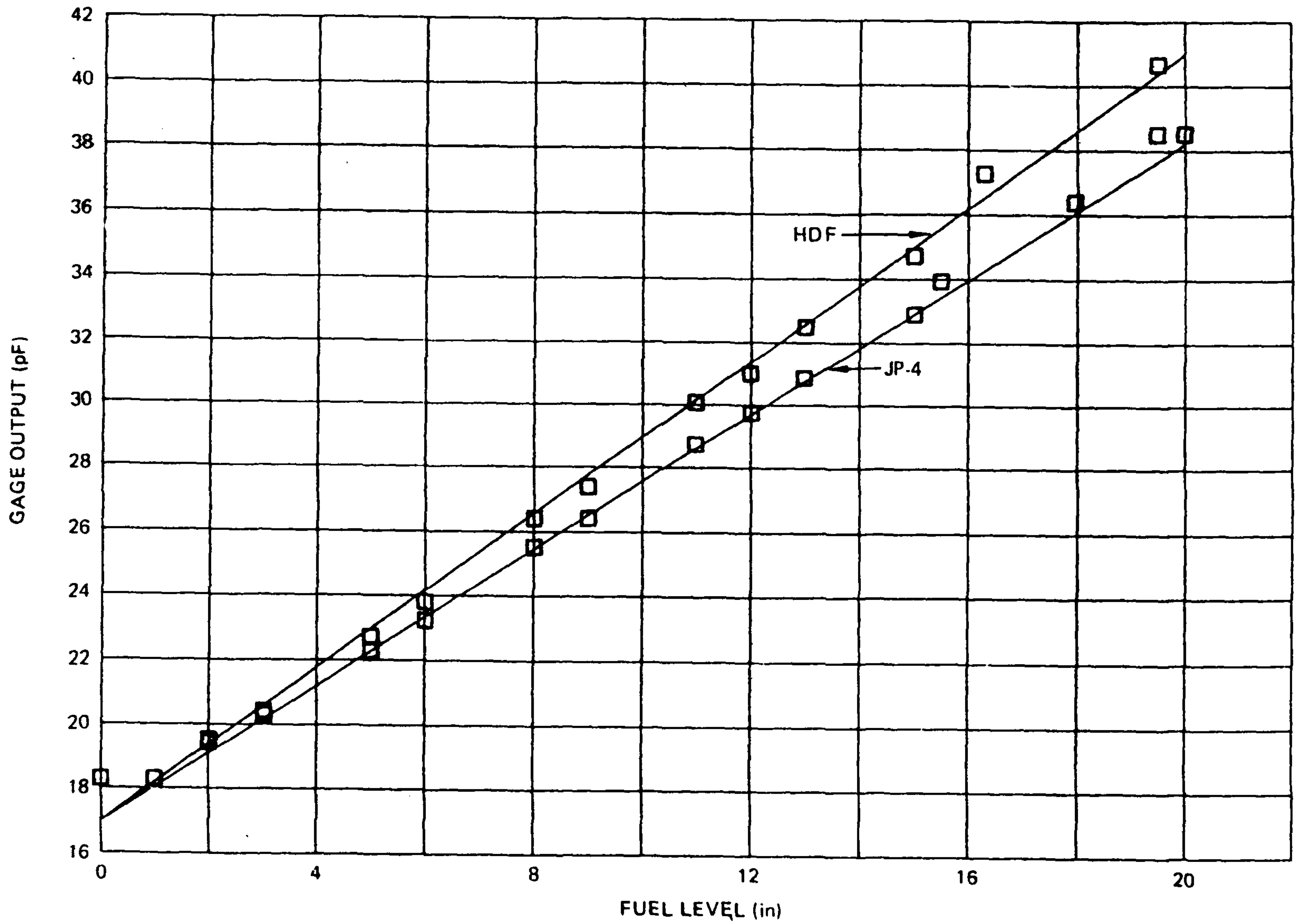


Figure 37. Comparison of Capacitance Gauge Response Between JP-4 and HDF at the Same Temperature

fuel. During both phases the boost pump discharge rate and fuel temperature were varied independently in a sequence of 72 different test conditions (Table 6). In general the discharge flow rates were set at 0 (deadhead), 50 and 95% of the rated flow, except as noted. Fuels at temperature extremes of about -40°F and 135°F were used in the testing. The total duration was 480 hours of which 240 hours were with HDF fuel only and the last 240 hours were with alternating HDF and JP-4 fuel. The manner in which the fuels were alternated is shown in Table 6. The lubricity, specific gravity, viscosity, flash point (HDF), vapor pressure (JP-4), and peroxide number of the HDF and JP-4 fuels were monitored throughout the testing. There was no measurable change in any of the properties with the exception of an increase in the peroxide number for JP-4. The peroxide number was less than 0.3 ppm by wt for HDF and increased from 0.2 to 0.8 ppm by wt for JP-4, which is still very low. The lubricity of HDF and JP-4, as determined by the Ball-On-Cylinder Lubricity Evaluator (BOCLE) using a 500 gm wt, was 0.55 and 0.57 mm, respectively.

The performance of an F-4 boost pump during 240 hours of operation in HDF is summarized in Figure 38. The pump power was higher at low fuel temperatures as would be expected. However, the pump discharge pressure as a function of fuel mass flow rate was essentially independent of fuel temperature. The trends for the KC-135 boost pump were very similar (Figure 39), although the actual pump pressures, discharge flow rates and electrical power requirements were quite different.

The performance of the boost pumps before and after the alternating fuels tests were compared to check for any deterioration in performance. Neither the results for the F-4 pump (Figure 40) nor the KC-135 pump (Figure 41) revealed any loss of performance due to pumping HDF.

The most significant results were the pump electrical power and discharge pressure data. The electrical power for the F-4 pump was about 15% higher for the HDF but the discharge pressures for HDF and JP-4 were about the same (Figure 42). Similar results were obtained for the KC-135 pump (Figure 43). The higher electrical power required for HDF was

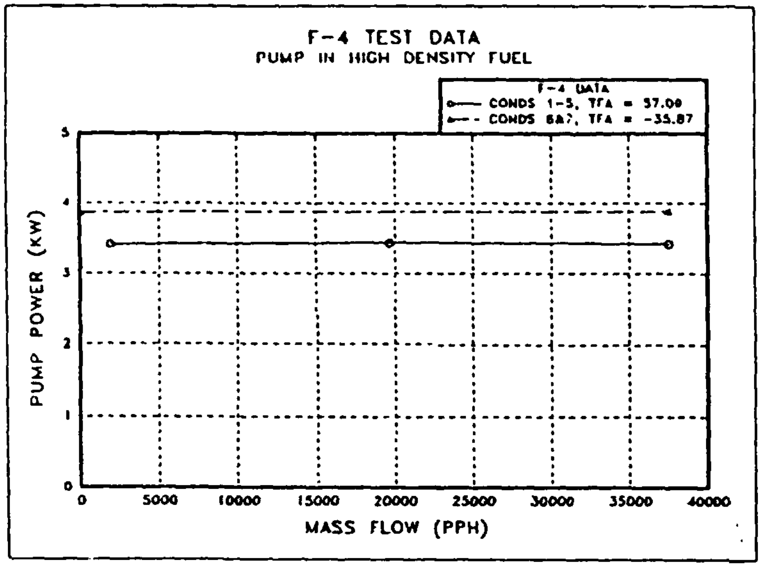
Table 6. Boost Pump Endurance Test Conditions

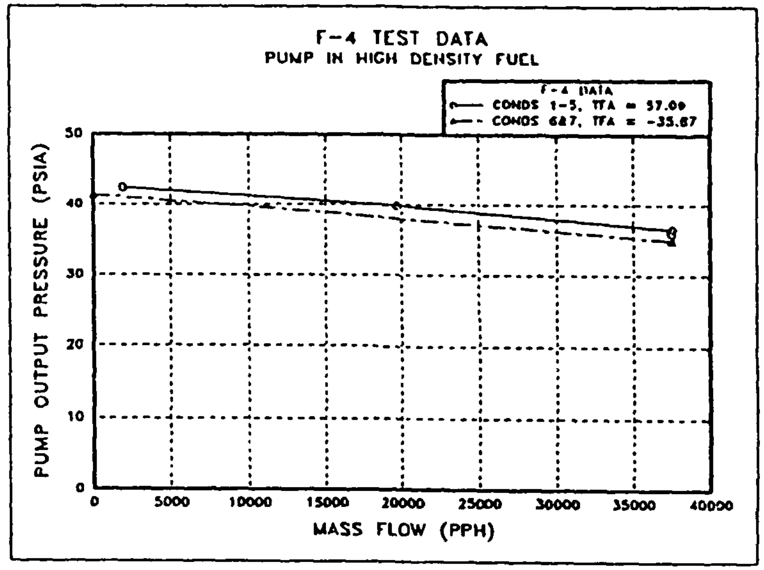
TEST CONDITION	HOURS	START TIME	TEMP DEG. F	FLOW PERCENT	TANK A	TANK B	DESCRIPTION
1	24	0	135	95	F-4	KC-135	THE F-4 PUMP IS CAPABLE OF
2	24	24	135	50	"	"	REACHING 100% OF ITS RATED
3	20	48	135	5	"	"	FLOW. THEREFORE FLOW RATE IS
4	4	68	135	0	"	"	PERCENT OF RATED FLOW
5	24	72	135	95	"	"	
6	20	96	-50	95	"	"	
7	4	116	-50	0	"	"	THE KC-135 PUMP IS NOT CAPABLE
8	24	120	135	95	"	"	OF REACHING 100% RATED FLOW.
9	24	144	135	50	"	"	THE 95% CONDITION HAS BEEN SET
10	20	168	135	5	"	"	TO 14250 PPH. THE 50%, 5% AND 0%
11	4	188	135	0	"	"	CONDITIONS ARE BASED ON RATED FLOW.
12	24	192	135	95	"	"	
13	20	216	-50	95	"	"	
14	4	236	-50	0	"	"	END HOF ONLY TEST. END TIME 240 HRS
15	X		AMB	A	"	"	POST-TEST CALIBRATION RUNS
16	X		AMB	B	"	"	
17	X		AMB	C	"	"	
18	X		AMB	A	"	"	POST-INSPECTION TESTS IN HOF
19	X		AMB	B	"	"	
20	X		AMB	C	"	"	
21	X		AMB	A	"	"	PRE-ALTERNATING FUELS TEST
22	X		AMB	B	"	"	CALIBRATION IN JP-4
23	X		AMB	C	"	"	
24	12	240	135	95	"	"	CYCLE 1 - START OF ALTERNATING
25	12	252	135	50	"	"	FUELS TEST
26	10	264	135	5	"	"	
27	2	274	135	0	"	"	
28	12	276	135	95	"	"	
29	10	288	-50	95	"	"	
30	2	298	-50	0	"	"	END TIME = 300 HRS
31	X		AMB	A	"	"	POST CYCLE 1 CALIBRATION RUNS
32	X		AMB	B	"	"	
33	X		AMB	C	"	"	
34	X		AMB	A	KC-135	F-4	PRE CYCLE 2 CALIBRATION RUNS
35	X		AMB	B	"	"	
36	X		AMB	C	"	"	
37	12	300	135	95	"	"	CYCLE 2
38	12	312	135	50	"	"	
39	10	324	135	5	"	"	
40	2	334	135	0	"	"	
41	12	336	135	95	"	"	
42	10	348	-50	95	"	"	
43	2	358	-50	0	"	"	END TIME = 360 HRS
44	X		AMB	A	"	"	POST CYCLE 2 CALIBRATION RUNS
45	X		AMB	B	"	"	
46	X		AMB	C	"	"	
47	X		AMB	A	F-4	KC-135	PRE CYCLE 3 CALIBRATION RUNS
48	X		AMB	B	"	"	
49	X		AMB	C	"	"	
50	12	360	135	95	"	"	CYCLE 3
51	12	372	135	50	"	"	FUELS TEST
52	10	384	135	5	"	"	
53	2	394	135	0	"	"	
54	12	396	135	95	"	"	
55	10	408	-50	95	"	"	
56	2	418	-50	0	"	"	END TIME = 420 HRS
57	X		AMB	A	"	"	POST CYCLE 3 CALIBRATION RUNS
58	X		AMB	B	"	"	
59	X		AMB	C	"	"	
60	X		AMB	A	KC-135	F-4	PRE CYCLE 4 CALIBRATION RUNS
61	X		AMB	B	"	"	
62	X		AMB	C	"	"	
63	12	420	135	95	"	"	CYCLE 4
64	12	432	135	50	"	"	
65	10	444	135	5	"	"	
66	2	454	135	0	"	"	
67	12	456	135	95	"	"	
68	10	468	-50	95	"	"	
69	2	478	-50	0	"	"	END TIME = 480 HRS
70	X		AMB	A	"	"	POST TEST CALIBRATION IN JP-4
71	X		AMB	B	"	"	
72	X		AMB	C	"	"	

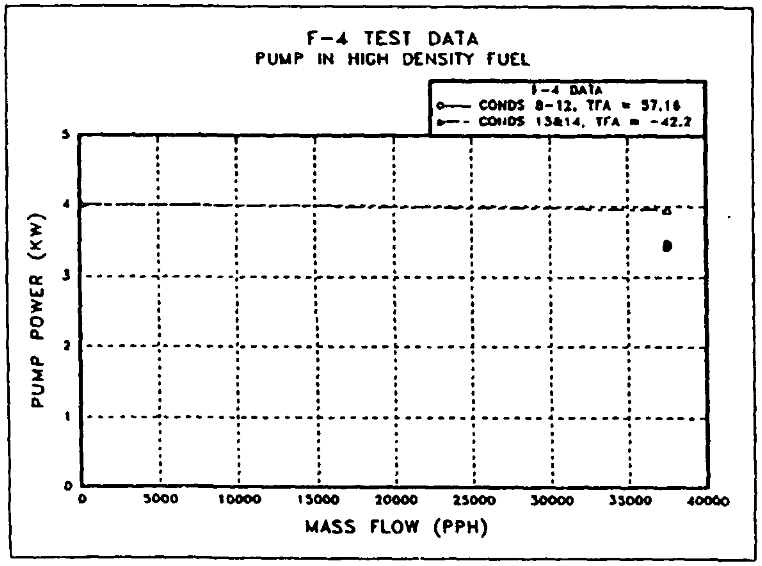
NOTES:

X - CALIBRATION RUN TIMES WILL BE APPROXIMATELY 10 MINUTES
A - 0 PPH FOR F-4 AND KC-135
B - 34000 PPH FOR F-4; 10000 PPH FOR KC-135
C - 39500 PPH FOR F-4; MAXIMUM OBTAINABLE FOR KC-135

DURING CONDITIONS 1 TO 17 BOTH TANKS HELD HOF
DURING CONDITIONS 18 TO 72 TANK A HELD JP-4 AND TANK B HELD HOF







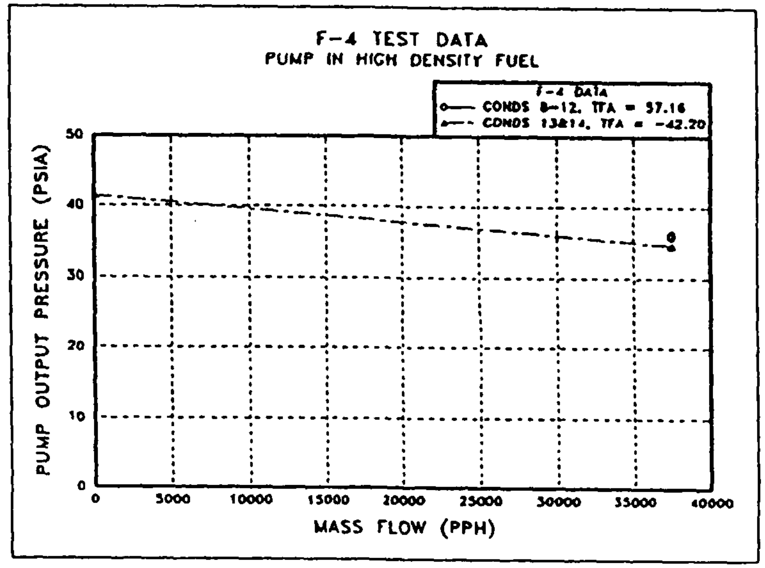


Figure 38. F–4 Pump Performance During the High Density Fuel Test

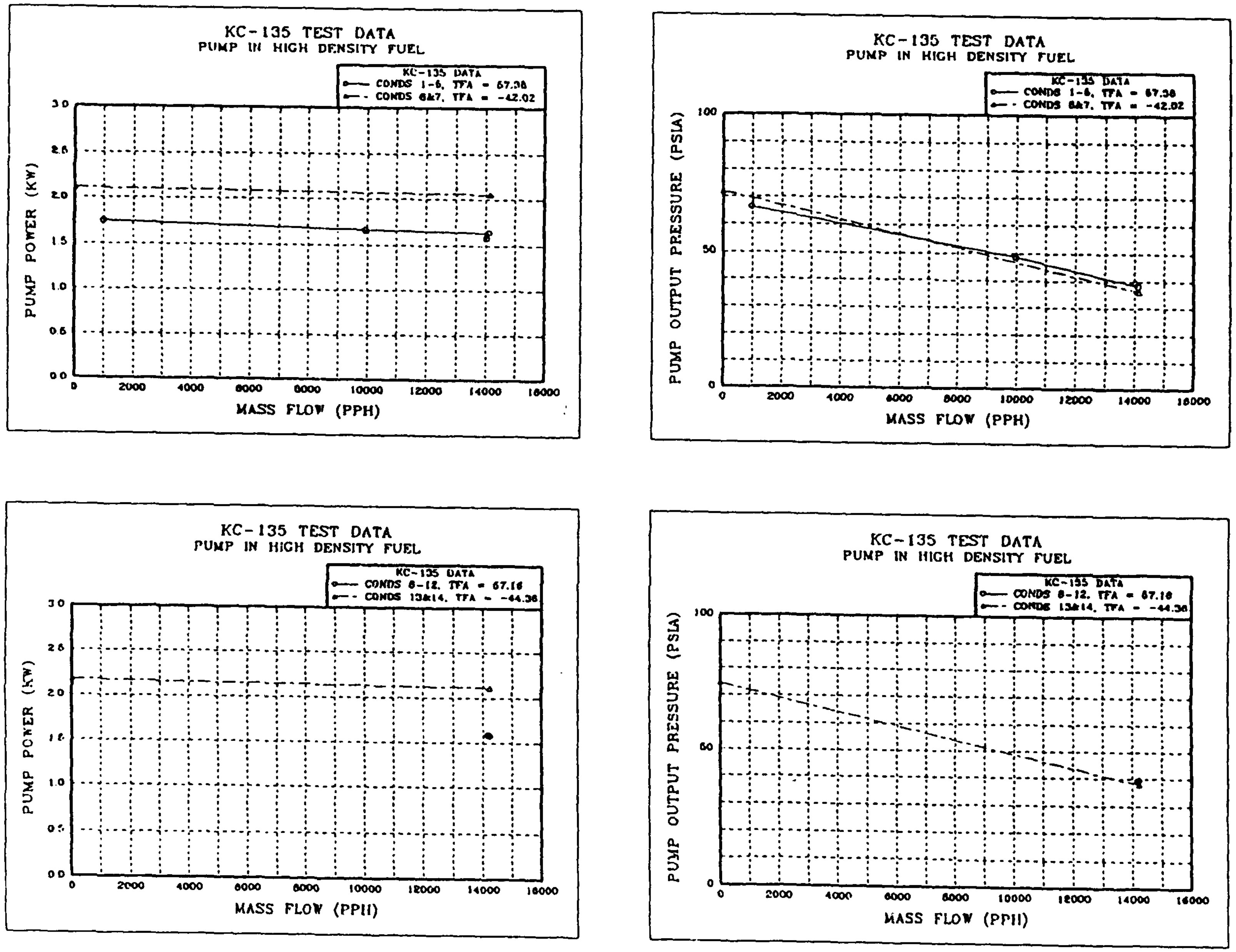
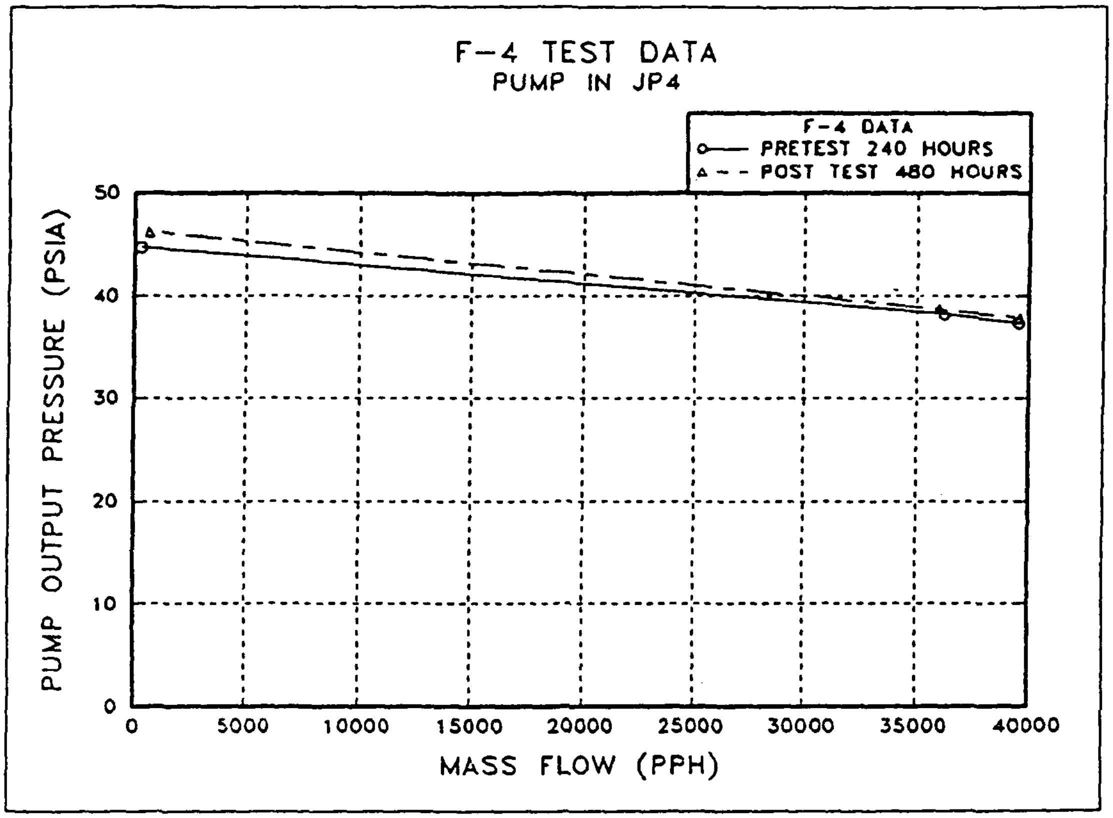


Figure 39. KC–135 Pump Performance During the High Density Fuel Test



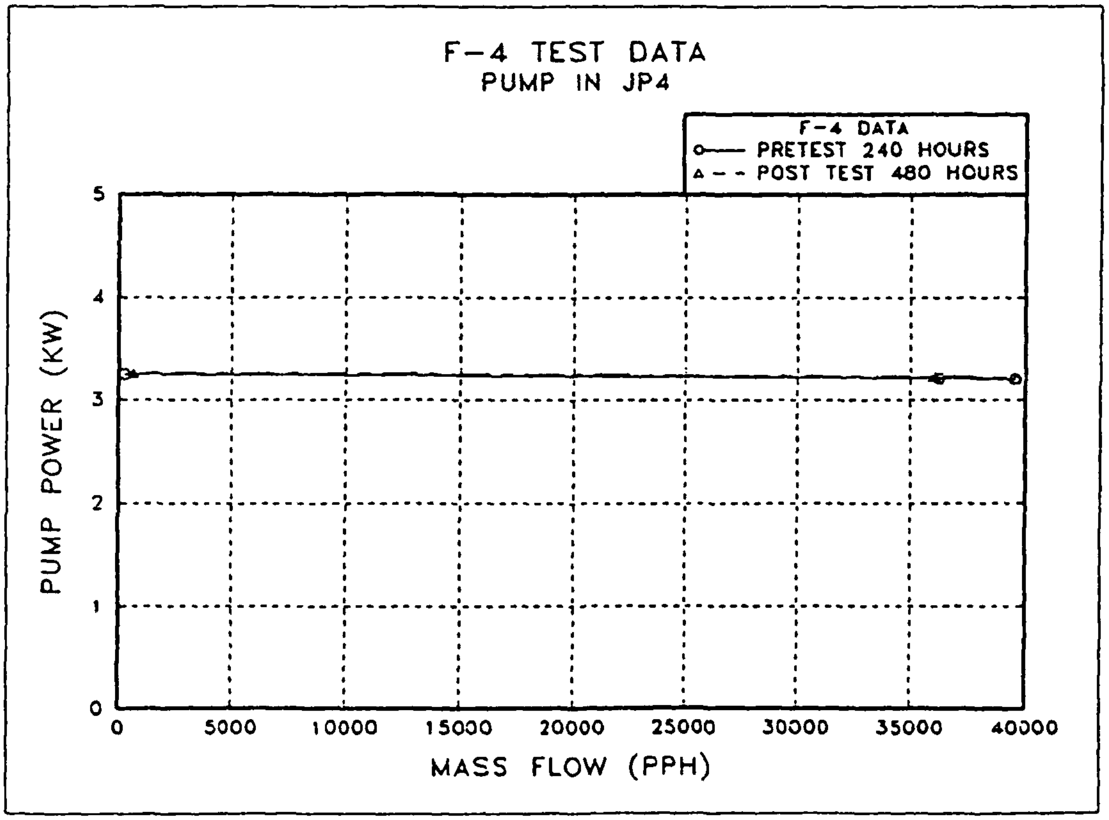
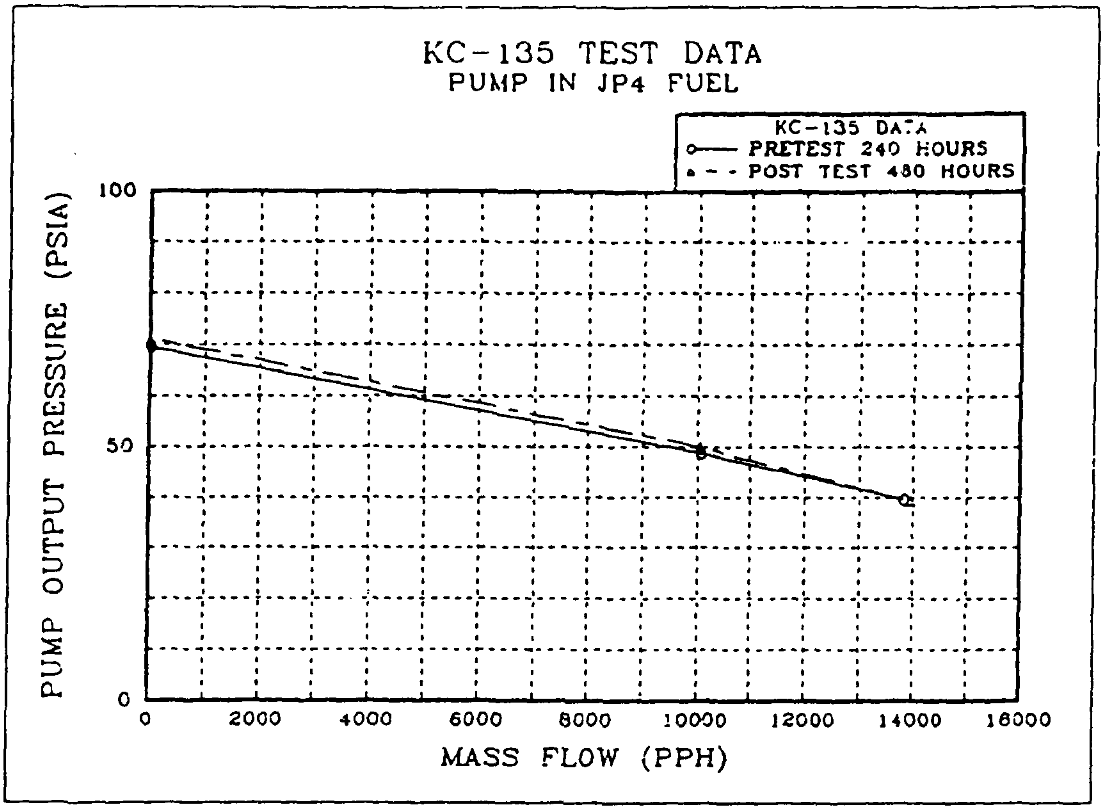


Figure 40. F-4. Pump Performance Before and After the Alternating Fuel Test



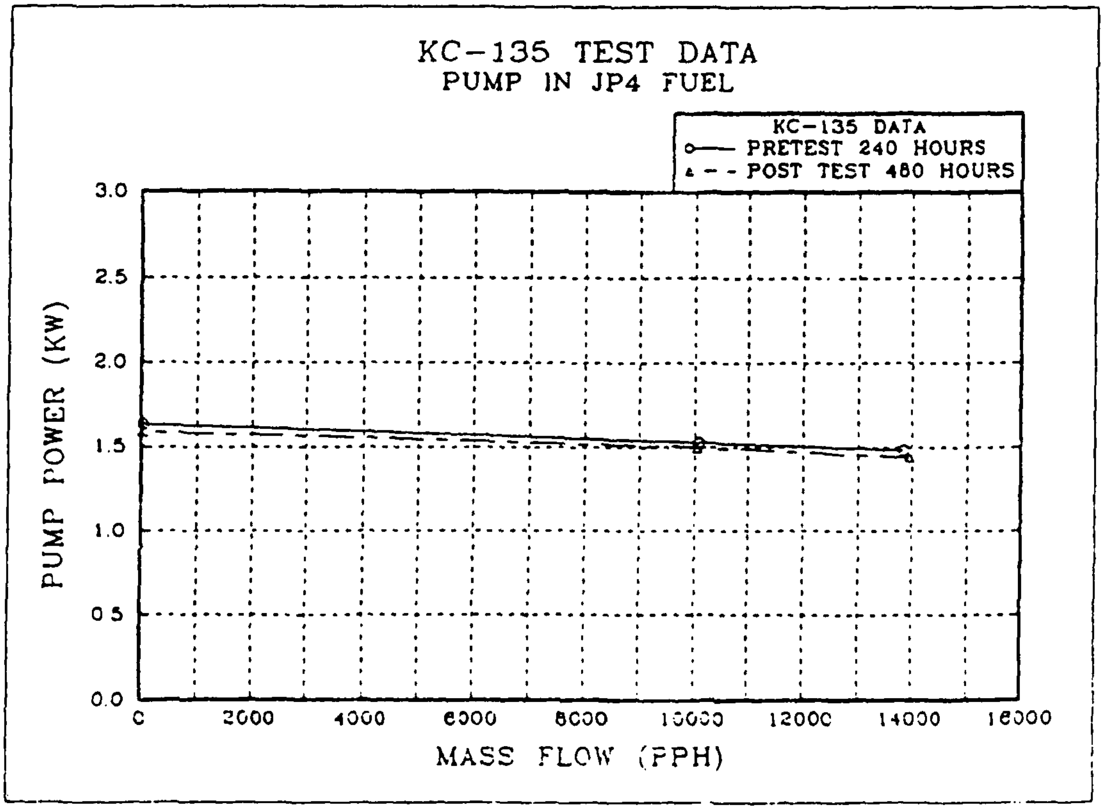


Figure 41. KC-135 Pump Performance Before and After the Alternating Fuel Test

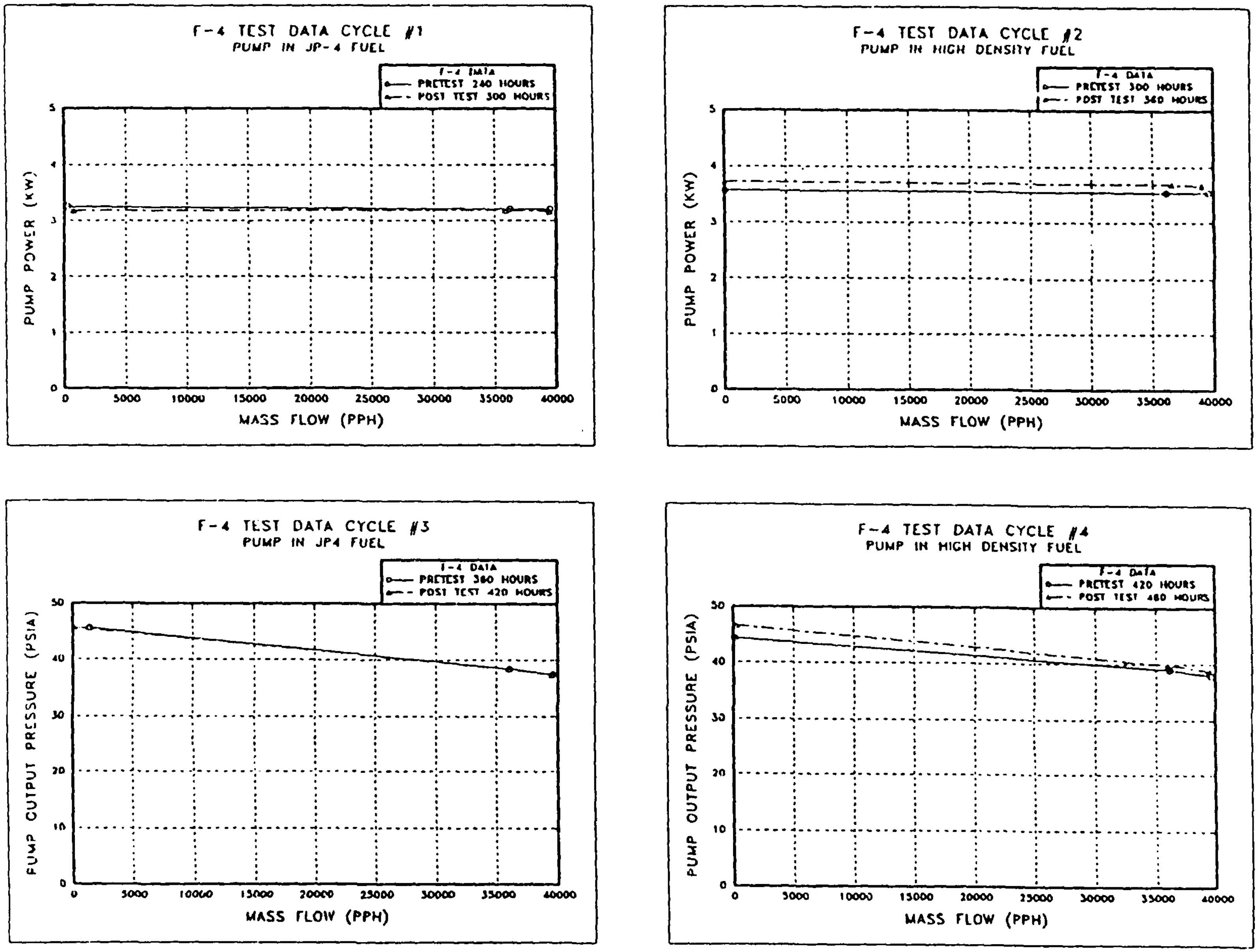


Figure 42. F–4 Pump Power and Discharge Pressure for JP–4 and HDF

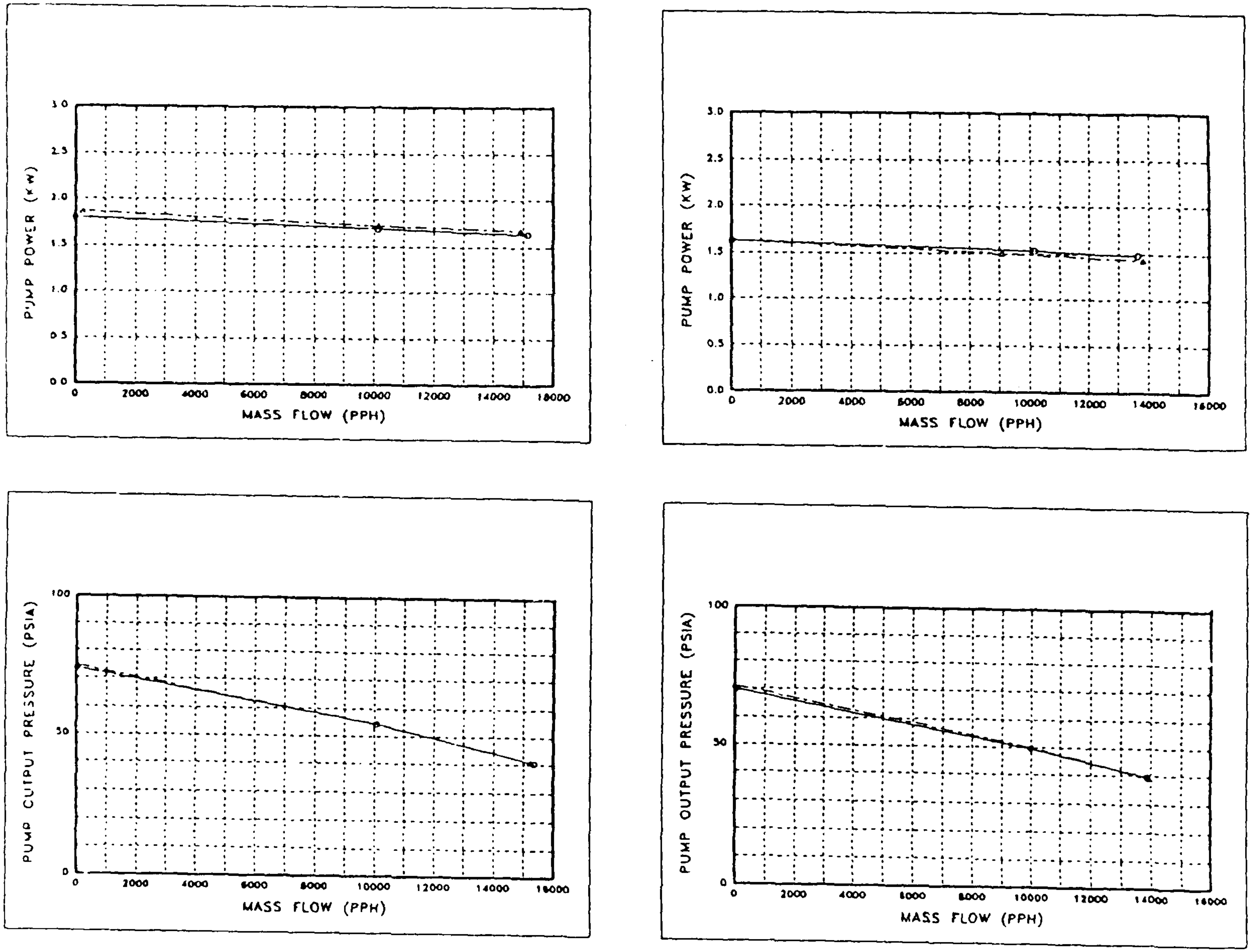


Figure 43. KC–135 Pump Power and Discharge Pressure for JP–4 and HDF

predictable since according to centrifugal pump theory (Ref 6) the pump power is directly proportional to fluid density. The effect of HDF on discharge pressure is much more difficult to predict. The higher viscosity of the HDF tends to lower the discharge pressure but the higher density tends to raise the discharge pressure. Furthermore pump efficiencies may not be as high for HDF as JP-4, the fuel for which the pump was designed. All things considered, equivalent discharge pressures for HDF and JP-4 for the pumps tested were not unreasonable.

The boost pumps were partially disassembled and visually inspected by Air Force personnel prior to testing, between the HDF and alternating fuels testing and after the testing was completed. The results of these inspections are shown in Appendix B. Nothing was found to suggest that the HDF had any adverse effects on the pumps. The only anomaly was the scoring of an impeller housing on an F-4 boost pump. Discussions with pump experts revealed that even one small particle of foreign matter can cause such damage. Care was taken to clean and add a protective coating to all the tanks and the fuel was always filtered when refueling the system. However, no filters were installed in the boost pump discharge flow circuit.

4.2.2 Valve Tests

The valve and float switch tests were conducted in two phases. The first phase was run with HDF only; the second phase with HDF and JP-4 fuel used alternately (Table 7). A total of 264 hours of testing was completed with 132 hours in each phase. Fuel temperature extremes of 158°F and -47°F were used in the testing. The lubricity, specific gravity, viscosity, flash point (HDF), vapor pressure (JP-4), and peroxide number of the HDF and JP-4 fuels were monitored throughout the testing. There was no measurable change in any of the properties. The peroxide number was 0.2 ppm by wt for HDF and 1.1 ppm by wt for JP-4; an acceptable level. The lubricity of HDF and JP-4, was determined by the BOCLE using a 500 gm wt, was 0.55 and 0.53 mm, respectively.

Table 7. Value Endurance Test Procedure

VALVE TEST AND SWITCH SCHEDULE H PHASE 1				
CONDITION	TIME (hrs)	TEMPERATURE (deg F)	FUEL (type)	ACTION
1	0-96	158	HDF	Cycle Every 6 hours Leak Check all valves
2	96-114	158	HDF	Check every 32 seconds Leak Check all valves
3	114-132	-47	HDF	Cycle every 130 Seconds Leak Check all valves
4	Teardown, Inspect, and Photograph all Valves			

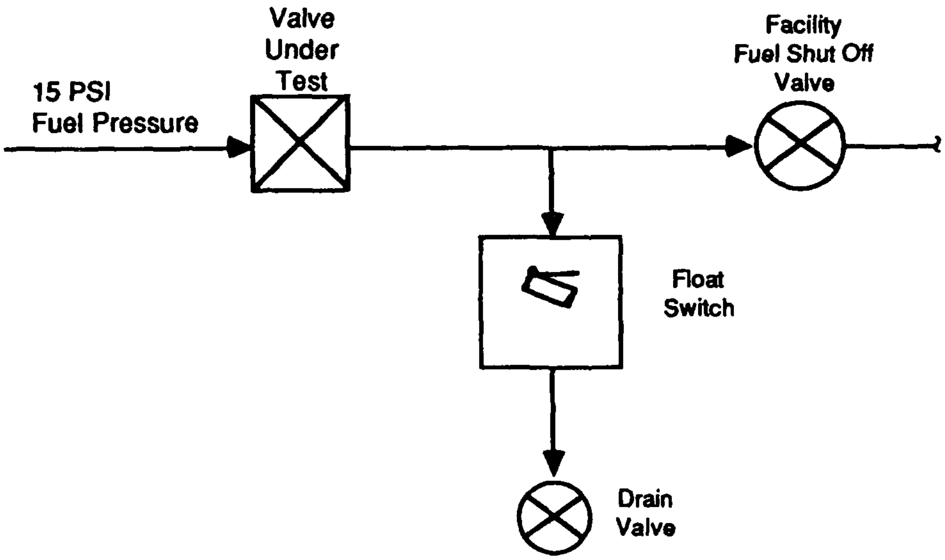
VALVE TEST AND FLOAT SWITCH SCHEDULE PHASE 2				
CONDITION	TIME (hrs)	TEMPERATURE (deg F)	FUEL (type)	ACTION
1	0-48	158	HDF	Cycle Every 6 hours Leak Check all valves
2	48-96	158	JP-4	Cycle Every 6 hours Leak Check all valves
3	96-105	158	JP-4	Cycle every 32 seconds Leak Check all valves
4	105-114	158	HDF	Cycle every 32 seconds Leak Check all valves
5	114-123	-47	HDF	Cycle every 130 Seconds Leak Check all valves
6	123-132	-47	JP-4	Cycle every 130 Seconds Leak Check all valves
7	Teardown, Inspect, and Photograph all Valves			
Notes: All tests at ambient pressure				

During the tests the valves were cycled periodically to verify their functionality. The shutoff valves were opened and closed by actuating their motors. The check valves were closed by backpressuring the downstream side of each valve. Level control valves and fuel transfer valves, which are normally open valves, were closed by raising the fuel level at the discharge of each valve.

The valve tests were not intended to provide quantitative performance data; rather the basic issues were whether the valves showed abnormal wear or had excessive leakage rates after exposure to HDF. The valves and switches were tested for leakage both through the fuel flow path (past the valve seat) and external leakage from the valve body using leakage testers designed for these applications (Figure 44). The shutoff and check valves were leak tested by an in-line leak detector as sketched in Figure 44a. To make a leak test, the valve was closed; the valve on the leak detector was opened to drain residual fuel and then closed; the fuel on the upstream side of the shutoff or check valve was pressurized and leakage was monitored. If the leakage exceeded leakage rates given in the appropriate Air Force Technical Orders, a float switch on the leak detector device would close indicating a failure condition. If no signal was received, the leakage was less than the maximum limit.

The level control valves and fuel transfer valves were tested somewhat differently. Since these valves were mounted inside the fuel tank, each one was enclosed within its own catch tank (Figure 44b). To conduct a leak test, the drain valves in the bottom of a catch tank were closed, causing the fuel to rise. If the level control or transfer valves functioned properly, float switches placed in the catch tank at a calibrated level above the normal valve shut off level would be actuated to indicate a failure condition.

The third type of leak detector consisted of a catch tank surrounding each of the components that were external to the fuel tanks (Figure 45). Each of these catch tanks contained a float switch (Figure 44c) to indicate



<u>TEST PROCEDURE:</u>

1. Close valve under test and facility valve.

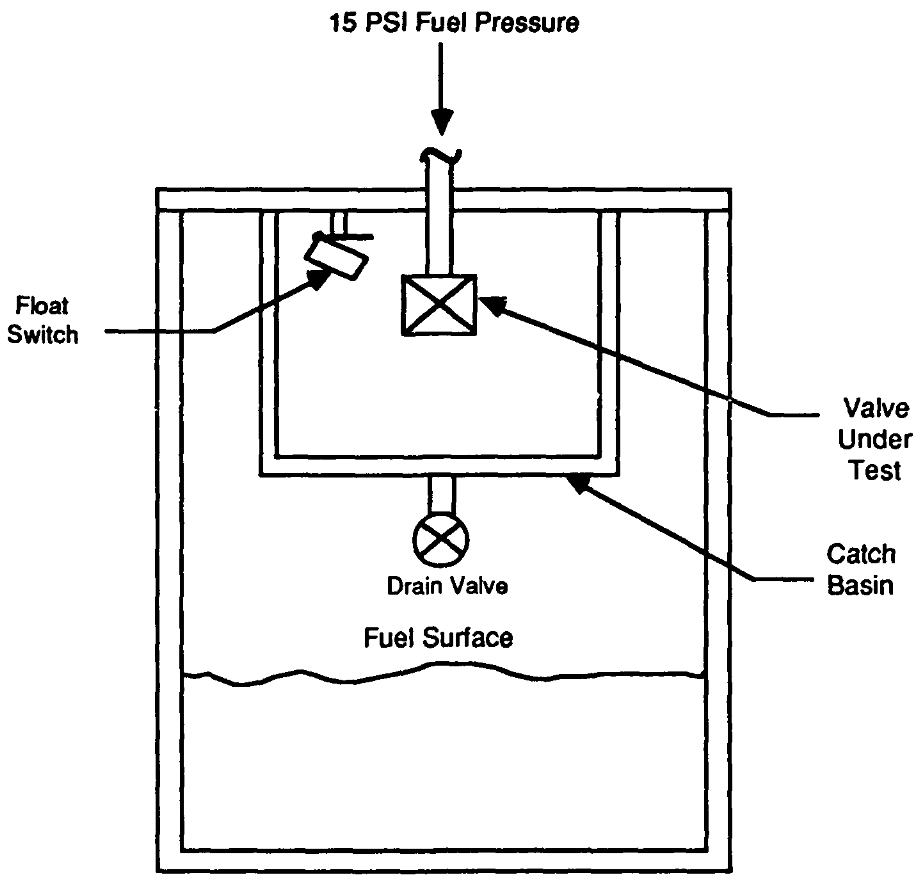
2. Open drain valve to drain residual fuel.

3. Close drain valve and observe leakage rate – if float switch is actuated leakage rate is unacceptably high.

FG03–1

a. In-Line Component Leakage Test

Figure 44. Component Leakage Testers



TEST PROCEDURE:

1. Close drain valve and monitor filling of catch basin for a preselected time interval.

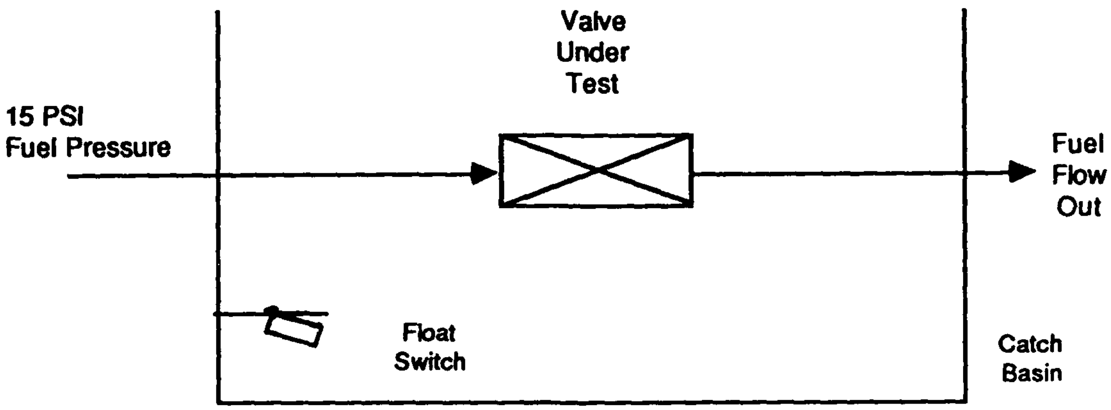
2. If float switch is not actuated, valve is statisfactory.

3. If float switch is actuated, leakage from valve seat and/or valve body is unacceptably high.

FG03-3

b. In-Tank Component Leakage Test

Fig'ıre 44. Component Leakage Testers (Continued)



TEST PROCEDURE:

Test was qualitative and was used for leakage of motor operated gate valves and check valves.

1. Float switches monitored throughout endurance tests.

2. If float switch was activated, control system went into alarm mode.

FG03-2

c. Valve Body Leakage Test

Figure 44. Component Leakage Testers (Continued)

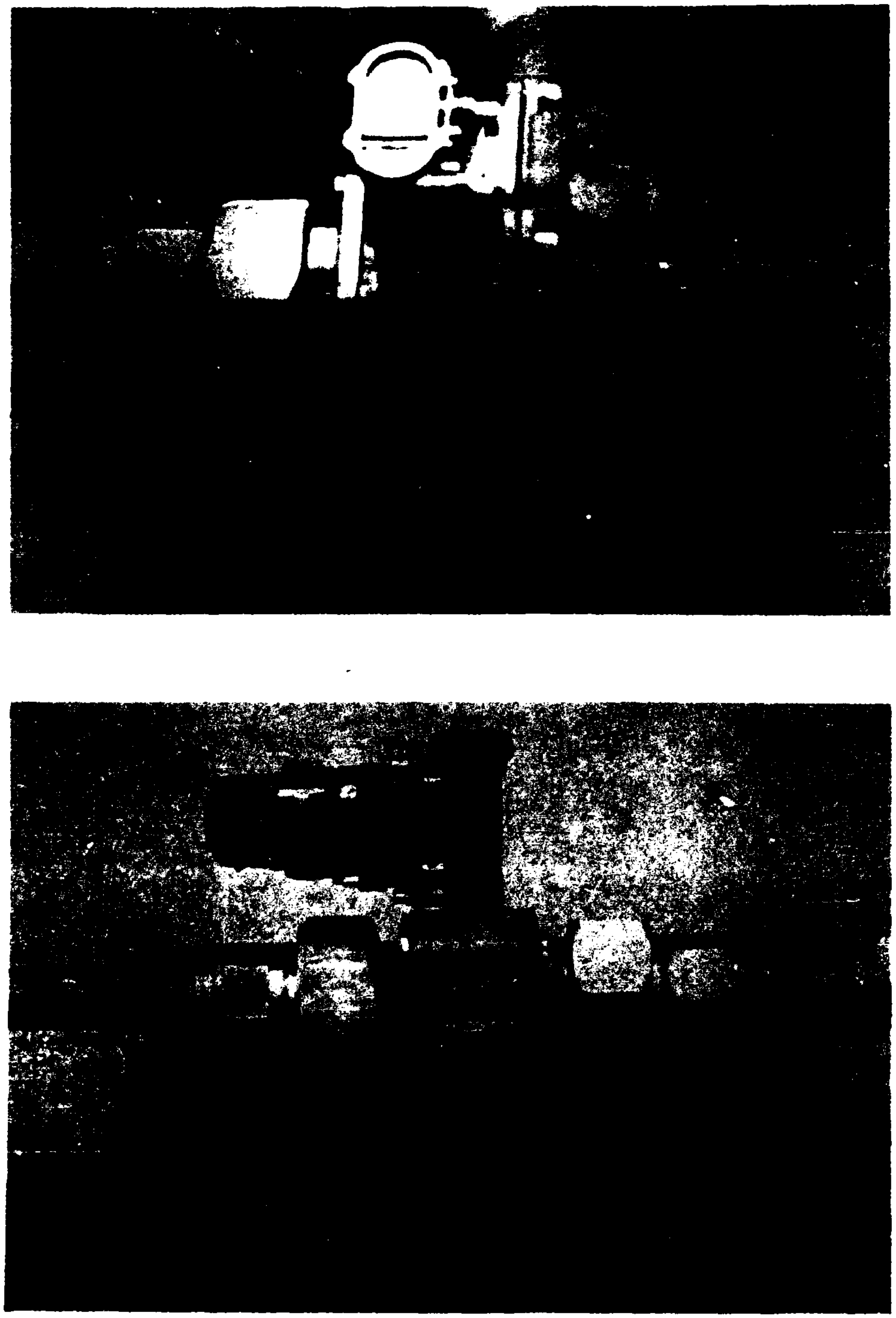


Figure 45. In-Line Valve Leak Detector

excessive leakage from a valve body or plumbing connections. These float switches were simply monitored throughout the testing to signal the test engineer that an abnormal leak had been detected.

Nothing about the valve tests suggested that the HDF had any adverse effects. All valve leakage rates were below the allowable rates which are listed in Table 8. The only anomaly was excessive leakage from an F-4 level control valve. However, subsequent disassembly and inspection revealed a small particle of foreign matter lodged on the valve seat. When the particle was removed the leakage rate of this valve was also well within specification limits.

Table 8. Allowable Component Fuel Leakage Rates

COMPONENT	ALLOWABLE LEAKAGE RATE	* MAXIMUM UNDETECTED LEAKAGE RATE
F-4 Check Valve PART # 31270	.30 ml/min	.23 ml/min
F-4 Float Valve PART # 30140	.164 ml/min	.0636 ml/min
F-4 Level Control Valve PART # 2660414	130 ml/min	21.7 ml/min
F-4 Shut Off Valve PART # AV16B1358B	.30 ml/min	.30 ml/min
KC-135 Check Valve PART # 111-558458	.33 ml/min	.23 ml/min
KC-135 Level Control Valve PART # 1321-546967	49.16 ml/min	46.8 ml/min
KC-135 Shut Off Valve PART # AV16B1247D	.30 ml/min	.265 ml/min
KC-135 Shut Off Valve PART # AV16B1248C	.30 ml/min	.247 ml/min

* The maximum undetected leakage rate is the volume of leakage to lift the level switch divided by the hold time. The hold time was long enough to determine that each component had a leakage rate less than the allowable.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Environmental and endurance tests were performed on typical airframe fuel system components of KC-135 and F-4 airplanes to identify any adverse effects of using a high density fuel. This fuel was a highly naphthenic fuel blended from conventional oil refinery product streams. In addition to having a density about 13% higher than JP-4, the high density fuel had other property differences that merited investigation. Differences in viscosity as well as density caused pump discharge pressure, flow rates and electrical power requirements to be of interest. The much higher aromatics content of high density fuel (35% versus 9% for JP-4) caused component leakage tests to be emphasized. Differences in dielectric constants between the two fuels prompted a study of fuel gauging systems errors with high density fuel since nearly all gauging systems rely on capacitance gauging units.

Environmental testing focused on the extreme high and low temperatures that the KC-135 and F-4 airplanes could encounter in fleet operations. Mission simulations were conducted to identify the worst case exposures and the recovery temperature profiles were used as boundary conditions for tests with HDF and JP-4 in a fuel thermal simulator. No unusual behavior was noted during these tests. Since the measured freeze point of the HDF was less than $-100^{o}F$, fuel freezing and fuel holdup would not occur even under the most extreme atmospheric conditions. The only low temperature effect of note was the higher electrical power required to pump HDF and the possible effect of the higher viscosity on engine starting. Airplanes that currently operate near the limit of power consumption could have a pump power problem with HDF. It might be necessary to limit the use of HDF to bases where the fuel temperature to the engine is above $-30^{o}F$; the temperature at which the viscosity of HDF reaches 12 cS. The only real issue at high temperatures was the temperature the fuel could reach during hot soak while on ground standby. These temperatures could be as high as 130°F. After takeoff the fuel temperature decreased rapidly even when exposed to upper limits of outside air temperatures.

Typical KC-135 and F-4 airplane boost pumps and valves were endurance tested for 480 and 264 hours, respectively. These components were operated with HDF fuel alone for the first half of the test program and with alternating HDF and JP-4 fuel for the last half. Pre-, mid-, and post-test pump performance checks revealed no basic performance changes. Similarly, regular checks of valve leakage rates revealed that none of the rates exceeded the specified allowable rates at any time. In summary, nothing in the test data suggested any significant problems would accompany switching to the type of high density fuel used in this test program.

Leakage past elastomers sometimes occurs when switching fuel types due to swelling and shrinking of the elastomers. It was originally thought that high total aromatic content caused this swelling. Based on this assumption, one would predict that switching from the high density fuel (total aromatics content of 35%) to JP-4 (total aromatics content of 9.7%) would have resulted in leakage during the durability testing. However, field experience has shown that fuel system component leakage may occur when switching from JP-4 to JP-8 fuel even though the aromatic level of the JP-8 is approximately 22% compared to approximately 15% for JP-4 (Ref. 7). This may indicate that the molecular structure of the aromatics is also important. The similar behavior of the two fuels in this program is probably due to equivalent swell producing characteristics produced by both the type and total aromatics present in the fuels. Another possible factor is that only new seals were used in this program.

These results are in agreement with the results from the materials compatibility test program that was concurrently conducted by the University of Dayton Research Institute using the same two fuels (Appendix C). Four representative O-ring and gasket materials were evaluated and it was concluded that exposure to HDF and alternating between HDF and JP-4 did not have any detrimental effect on the materials. Of the thirty-seven materials included in the compatibility testing, the only material more adversely affected by HDF than by JP-4 was a non-curing type tank sealant identified as PR 703 Polysulfide which showed a highly negative swell and a large decrease in pressure rupture. Late model aircraft, such as the F-15 and the B-1, use a tank sealant identified as 94-031 which did not show a problem in the compatibility testing.

Two anomalous results occurred: one of the boost pump impeller housings was scored and one of the level control valves failed to close properly. Both of these irregularities were traced to small particles of foreign material in the fuel. Even though the fuel tanks were carefully cleaned and coated, and the fuel was filtered each time it was pumped into the test tanks, the foreign materials still appeared. In retrospect, a fuel filter probably should have been installed in the recirculating fuel loop.

A fuel gauging system calibrated for JP-4 would read about 8% high in fuel volume but would read 4% low in fuel mass, the much more significant variable in airplane performance. Therefore, HDF could be safely used in an airplane with a gauging system calibrated for JP-4 fuel.

5.2 Recommendations

The fact that components do leak when switching from JP-8 to JP-4 fuel in the fleet but no leakage was experienced in these tests with HDF and JP-4 fuel suggests that tests with "used" components might have yielded different results. Even though most of the components tested were rebuilt rather than new components, new seals were common throughout all components. Therefore, tests should be run on components with seals that have been partially aged.

Historically, engine starting must be demonstrated on Air Force airplanes at $-65^{\circ}F$ or at the fuel temperature where the fuel viscosity is 12 centistokes. No such tests for HDF are known, but they should be conducted due to the observed flowability problems at low temperature.

One key objective of this test program was to identify changes to the Air Force's fuel system life cycle cost model. However, no evidence surfaced to justify any changes to the model to account for switching to HDF, and continuing the life cycle cost model based on current failure rates and maintenance cycles is recommended.

REFERENCES

1. T. L. Oller and T. F. Lyon, "High Density Fuel Effects," AFWAL-TR-88-2059, August, 1988.

2. N. K. Rizk, V.L. Oechsle, P.T. Ross, and H.C. Mongla, "High Density Fuel Effects," AFWAL-TR-88-2046, August, 1988.

3. G. Beal, B. McCallum and F. Grenich, "Fuel-Engine-Airframe Optimization Study," AFWAL-TR-84-2028, April, 1984.

4. T. F. Lyon and B.A. Anderson, "Fuel-Engine-Airframe Optimization Study," AFWAL-TR-86-2025, May, 1986.

5. L. A. Desmarais and F. F. Tolle, "Fuel Freeze Point Investigations," AFWAL-TR-84-2049, July, 1984.

6. F. M. White, Fluid Mechanics, McGraw-Hill Book Company, 1979.

7. C. L. Dickson and P.W. Woodward, "Aviation Turbine Fuels," 1987, NIPER-154-PPF 88-2, March 1988.

APPENDIX A

MEASURED FUEL PROPERTIES

Pratt and Whitney Aircraft, who was under Air Force contract for fuel analyses, and the Energy Management Laboratory at WPAFB measured the physical properties of the HDF and JP-4 fuels used in this program. Their reports are presented in this appendix.

UNITED TECHNOLOGIES
PRATT&WHITNEY

400 Main Street
East Hartford, Connecticut 06108

P.O. Box 109600
West Palm Beach, FL 33410-9600

Engineering Division

TO: Steve Anderson, AFWAL/POSF
FROM: Tedd Biddle, Fuels & Lubricants Grp. - P&W
Subj: Characterization of JP-4 and JP-8X Fuel Samples

DATE: 31 March 1988

Enclosed are the test results for two fuel samples received for characterization. The samples were identified as 87-POSF-2611 (JP-4) and 87-POSF-2612 (JP-8X). Tests performed as a function of temperature included vapor pressure, surface tension, density, thermal conductivity, viscosity, dielectric constant, and specific heat. The data from tests performed as a function of temperature were plotted and are enclosed for your review. In addition, hydrocarbon type determinations were conducted according to ASTM D2789 and ASTM D1319. Net heat of combustion was determined according to ASTM D2382 and hydrogen content by ASTM D3701. The lubricity properties of the fuel samples were characterized at 500 and 1000 gram loads using the Ball-On-Cylinder Lubricity Evaluator (BOCLE). The Jet Fuel Thermal Oxidation Tester (JFTOT) breakpoint temperature was determined for the JP-8X sample as a measure of its thermal stability.

SAMPLE: 87-POSF-2612 **FUEL TYPE:** JP-8X **DATE:** 3/25/88

Fuel History: Task Order Number 15

1. Hydrocarbon Type

Mass Spectroscopy (ASTM D2789)	Percentage	FIA (ASTM D1319)	Percentage
paraffins	33.6	saturates	64.1
monocycloparaffins	27.9	aromatics	35.0
dicycloparaffins	11.5	olefins	0.9
alkylbenzenes	14.8		
indans and tetralins	7.5		
naphthalenes	2.6		
olefins (ASTM D1319)	0.9		

2. Gross and Net Heats of Combustion (P&W FLP 6)

a) Hydrogen, wt % 13.08
b) Sulfur, wt% 0.05
c) Gross Heat of Combustion, MJ/kg (Btu/lb) 45.371 (19506)
d) Net Heat of Combustion, MJ/kg (Btu/lb) 42.595 (18312)
e) Volumetric Heat of Combustion, MJ/L (Btu/gal) 36.130 (129623)

3. Specific Heat, kJ/kg/K (DSC)

a) 0C (32F) 1.73
b) 15C (59F) 1.78
c) 30C (86F) 1.83
d) 45C (113F) 1.88
e) 60C (140F) 1.93
f) 75C (167F) 1.98

4. Kinematic Viscosity, cSt (ASTM D445)

a) -40C (-40F) 20.15
b) -20C (- 4F) 7.79
c) 25C (77F) 2.28
d) 40C (104F) 1.75

5. Density, g/mL (ASTM D4052)

a) -20C (- 4F) 0.87428
b) 5C (41F) 0.85506
c) 40C (104F) 0.83055
d) 75C (167F) 0.80488

6. Dielectric Constant (ASTM D924)

a)	0C (32F)	2.23
b)	30C (86F)	2.20
c)	50C (122F)	2.18
d)	75C (167F)	2.14

7. True Vapor Pressure, kPa (psia) (ASTM D2879)

a)	-30C (-22F)	0.0067 (0.00097)
b)	0C (32F)	0.063 (0.0091)
c)	40C (104F)	0.60 (0.087)
d)	75C (167F)	2.75 (0.40)

8. Surface Tension, dynes/cm (ASTM D1331)

a)	-10C (14F)	27.9
b)	0C (32F)	24.1
c)	40C (104F)	22.9
d)	75C (167F)	20.1

9. Thermal Conductivity, W/m/K (ASTM D2717)

a)	0C (32F)	0.119
b)	30C (86F)	0.117
c)	50C (122F)	0.116
d)	75C (167F)	0.114

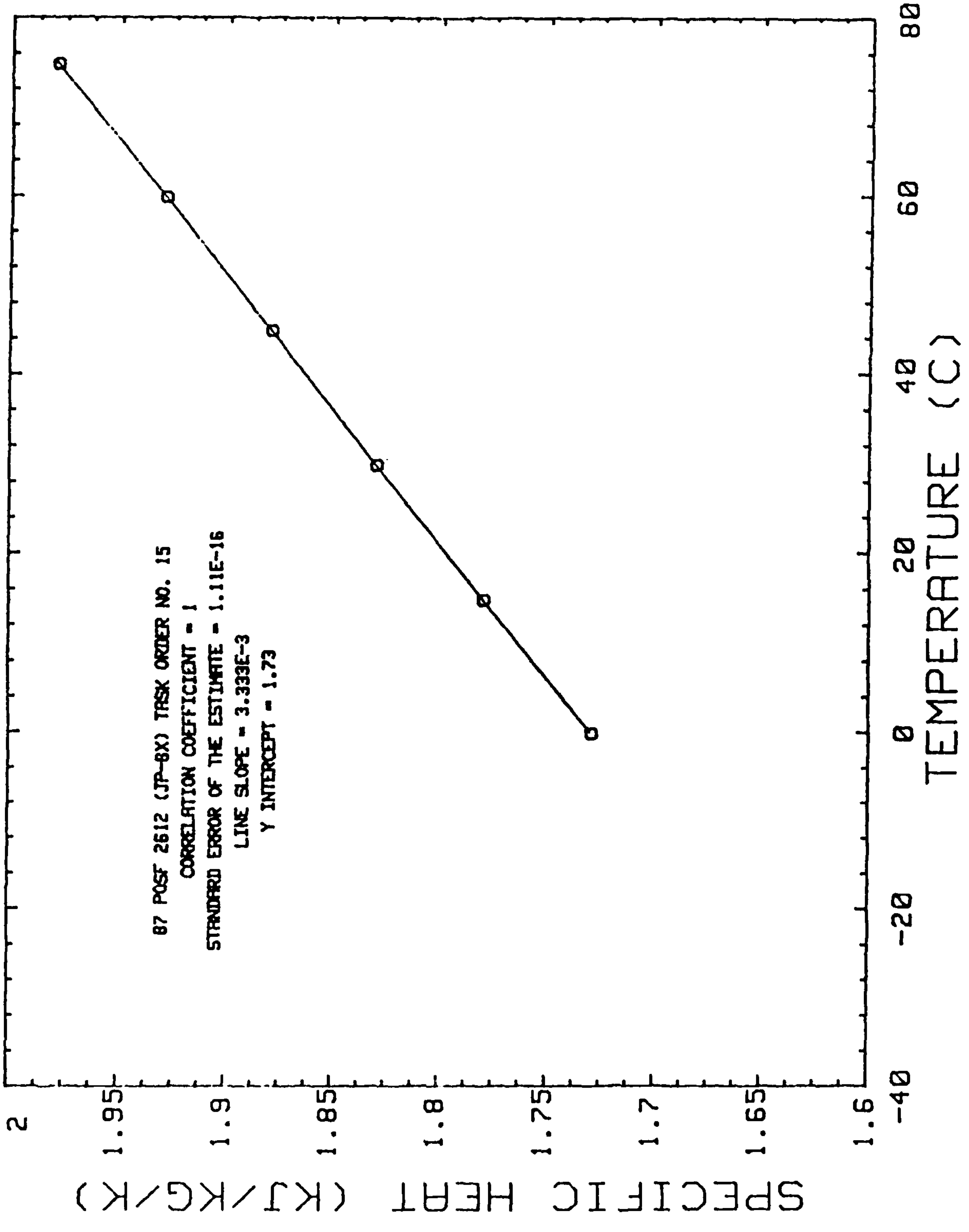
10. Ball-On-Cylinder Lubricity Evaluator (BOCLE) (CRC-DRAFT 10)

a)	500g Load: WSD, mm	0.50
b)	1000g Load: WSD, mm	0.59

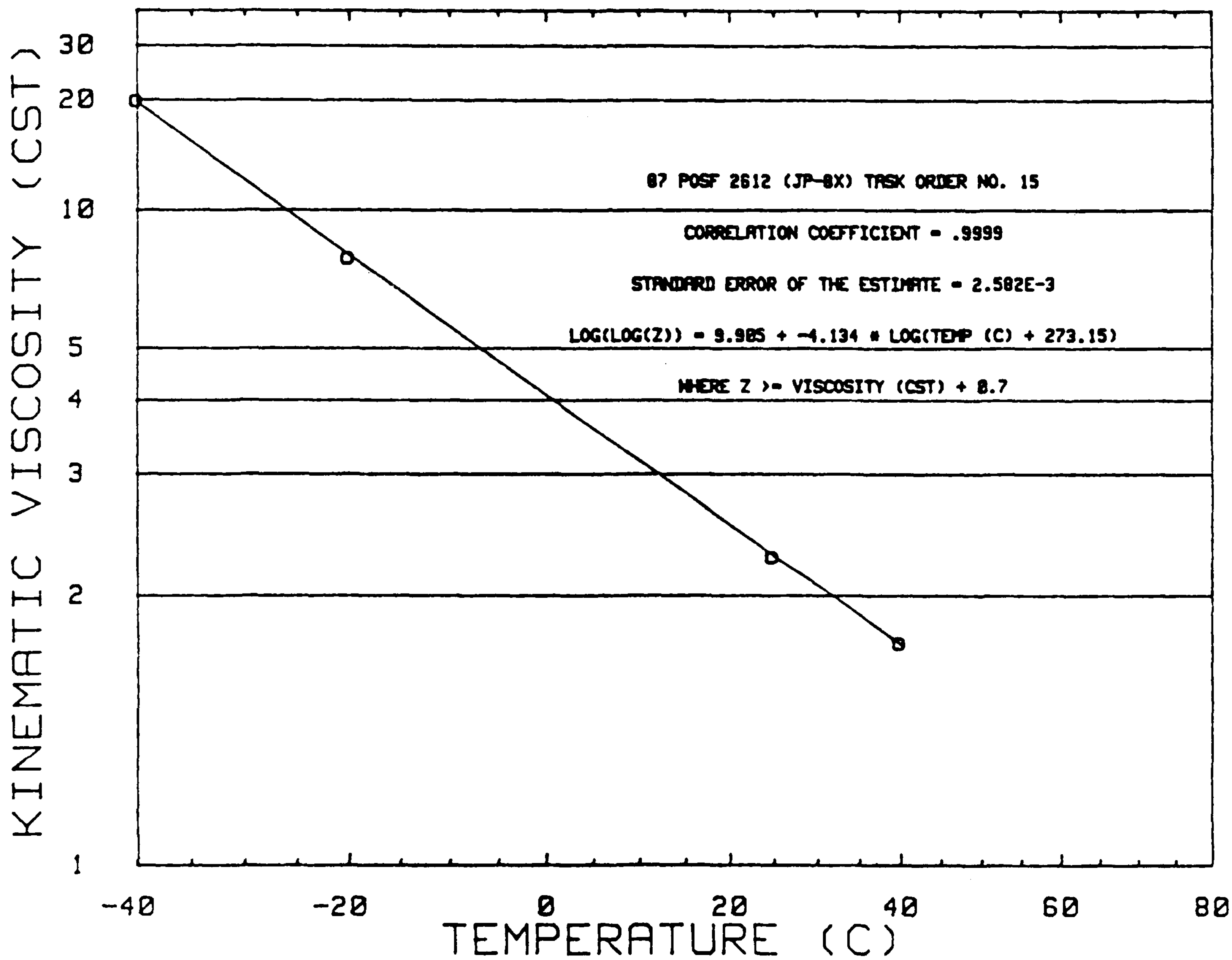
11. Thermal Stability Breakpoint
As Determined By JFTOT (ASTM D3241) To Within 2C (5F)

Highest Temperature Yielding Passing Result 227C (440F)

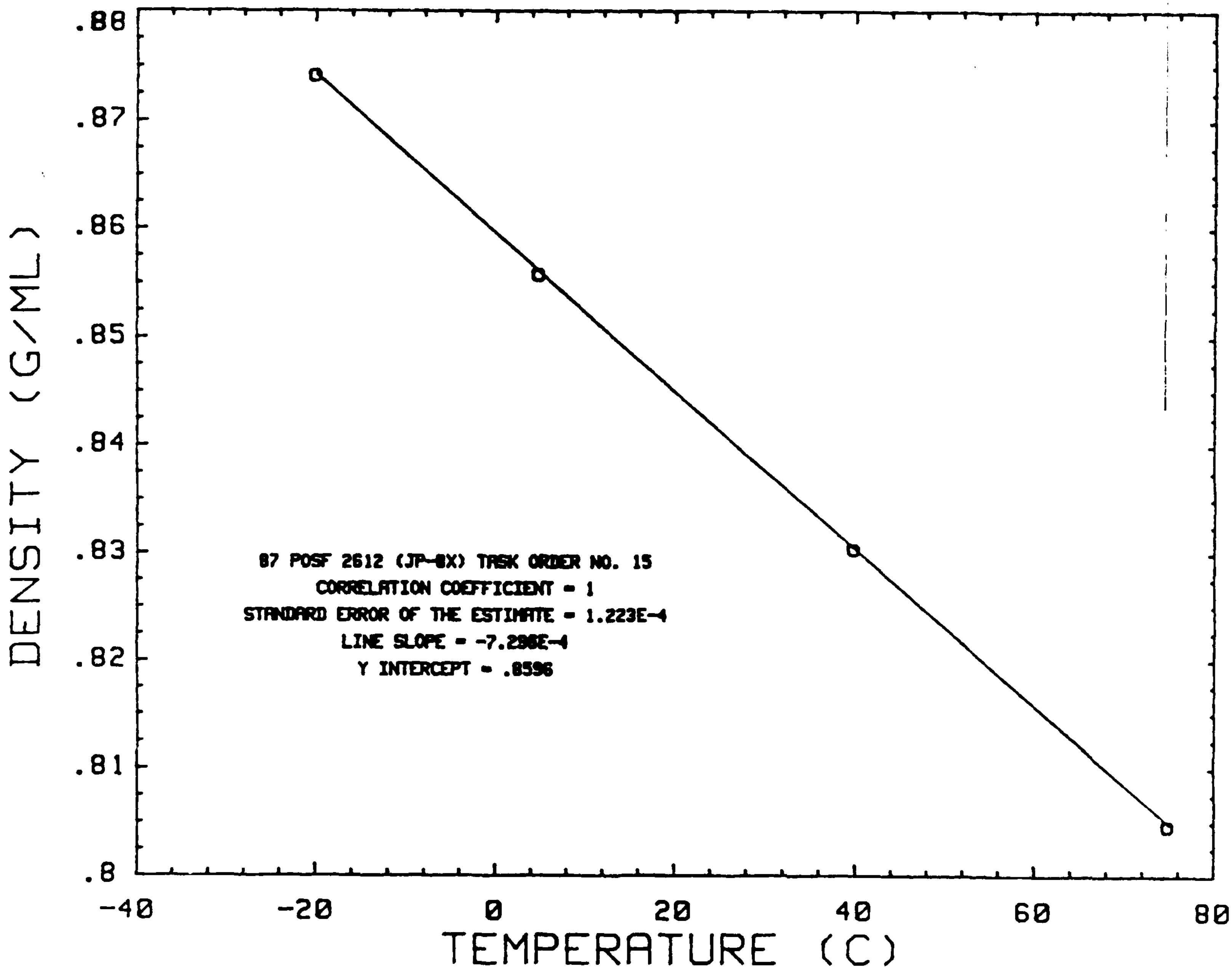
Test No.	Test Temperature	Pressure Drop,^P (mm Hg, min.)	Max ^ TDR	Visual Tube Rating
1	274C (525F)	270, 60	0	>4
2	246C (475F)	55, 90	0	3
3	232C (450F)	0, 150	3	>4
4	227C (440F)	0, 150	0	<3
5	224C (435F)	0, 150	0	2
6	218C (425F)	0, 150	0	<2



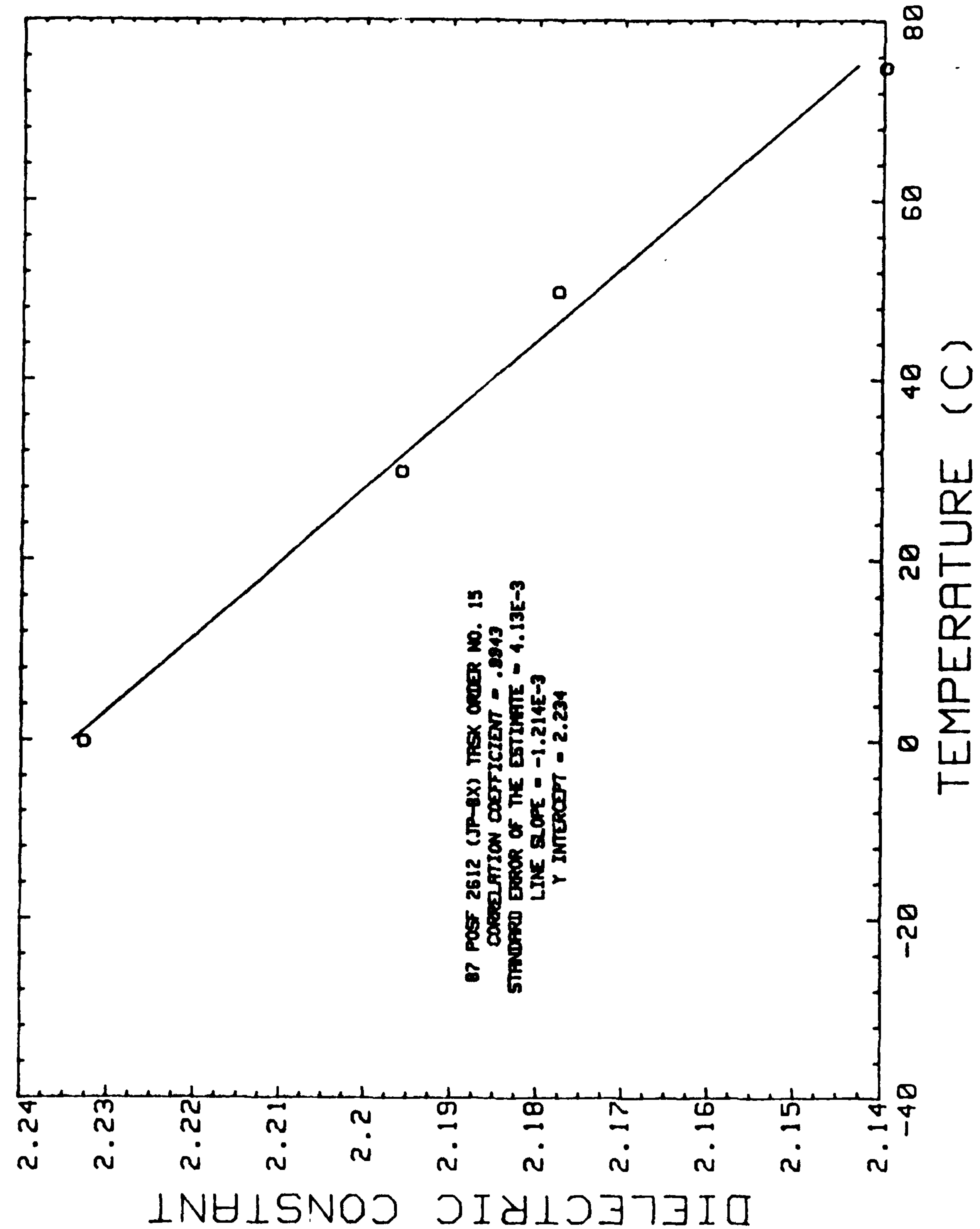
SPECIFIC HEAT (KJ/KG/K) AS A FUNCTION OF TEMPERATURE (C)



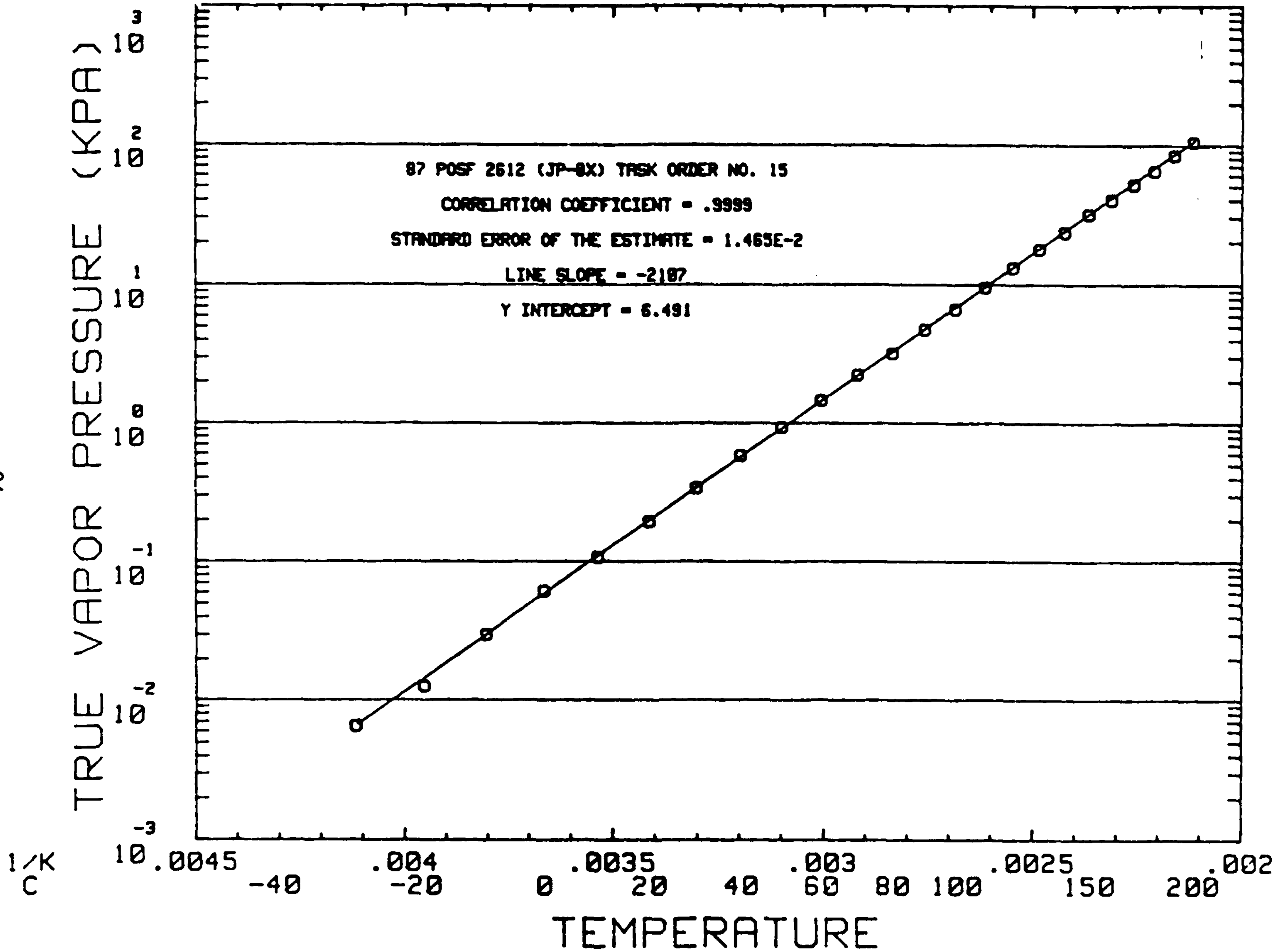
KINEMATIC VISCOSITY (CST) AS A FUNCTION OF TEMPERATURE (C)



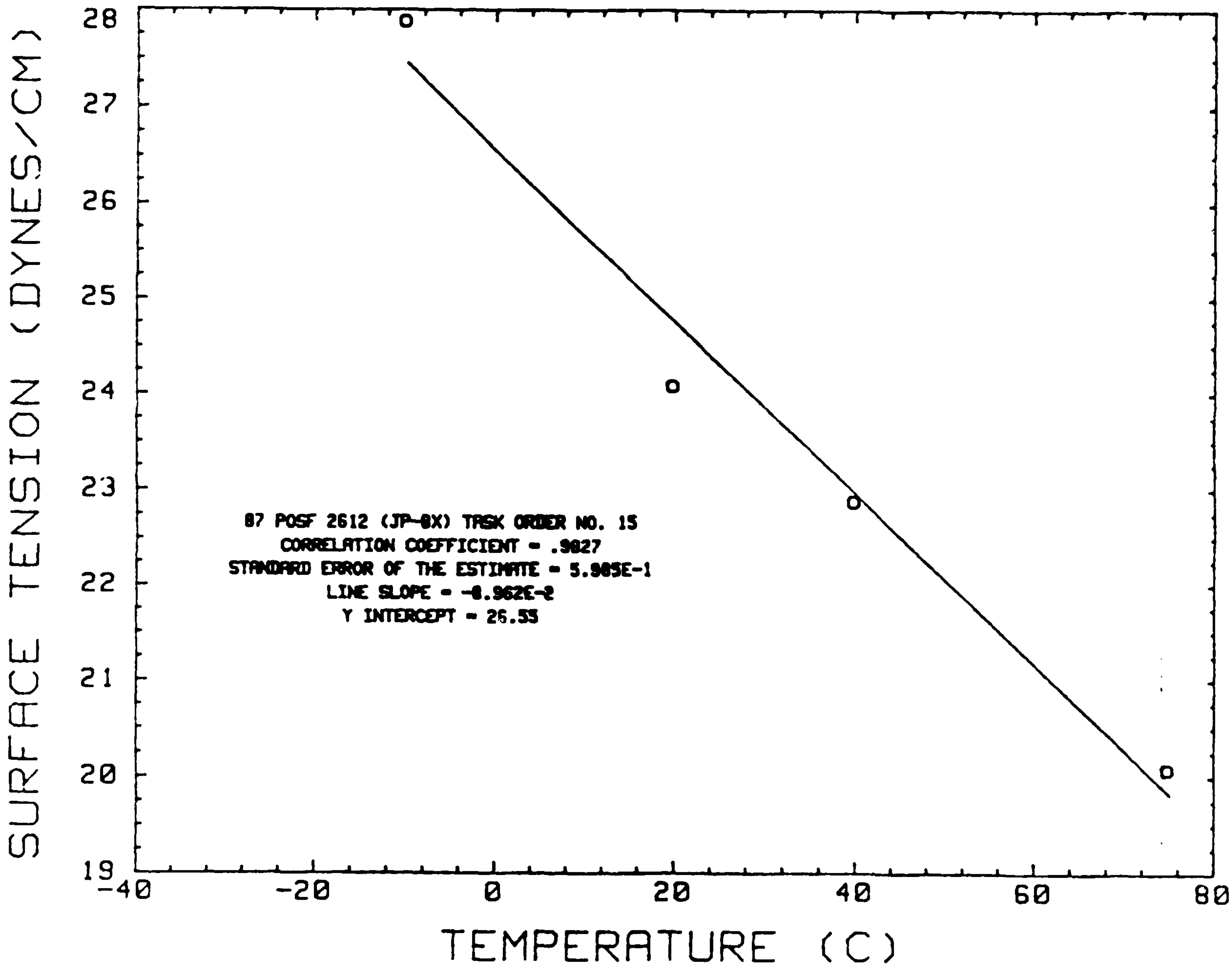
DENSITY (G/ML) AS A FUNCTION OF TEMPERATURE (C)



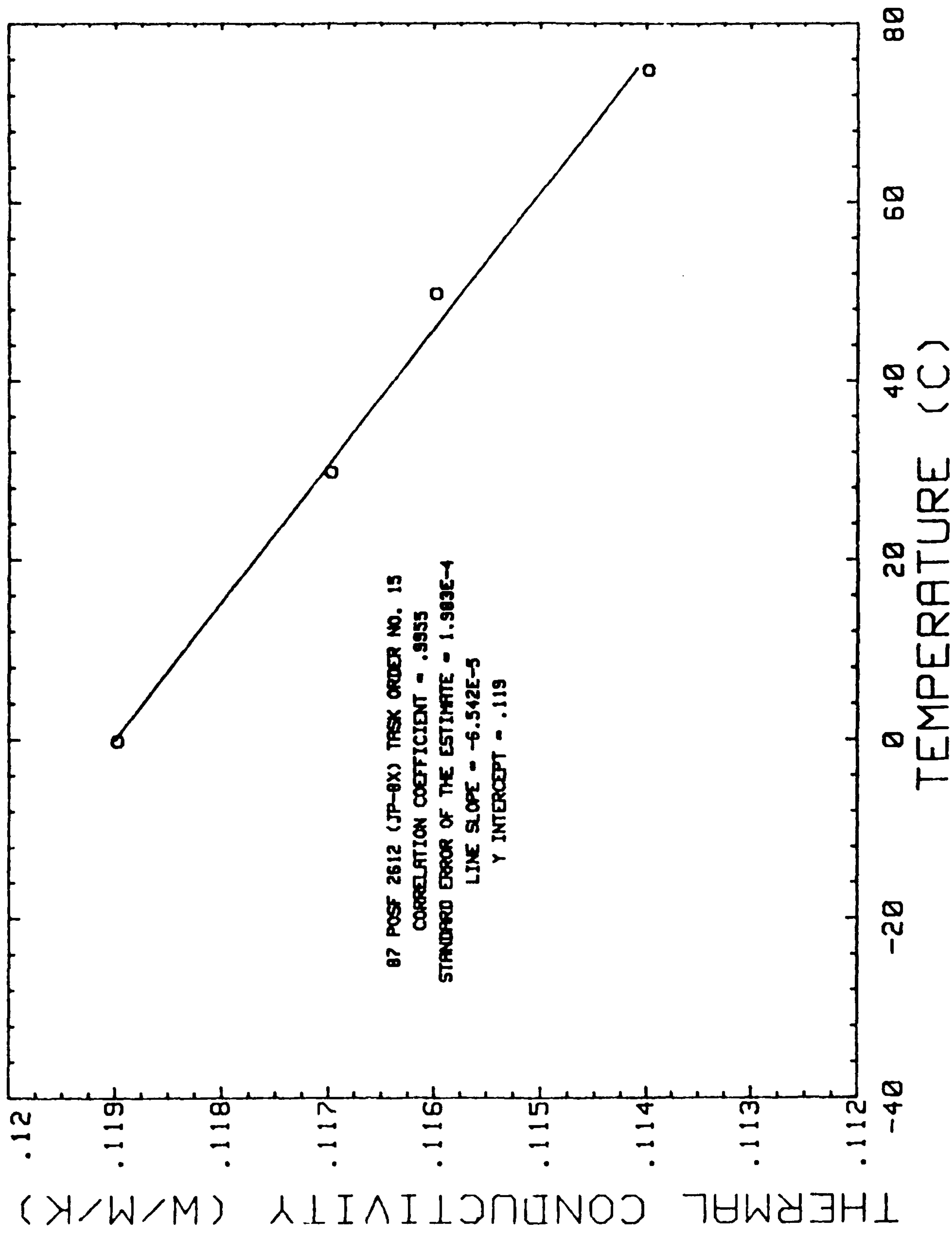
DIELECTRIC CONSTANT AS A FUNCTION OF TEMPERATURE (C)



TRUE VAPOR PRESSURE (KPA) AS A FUNCTION OF TEMPERATURE (C)



SURFACE TENSION (DYNES/CM) AS A FUNCTION OF TEMPERATURE (C)



THERMAL CONDUCTIVITY (W/M/K) AS A FUNCTION OF TEMPERATURE (C)

SAMPLE: 87-POSF 2611 FUEL TYPE: JP-4 REV: 3/25/88

Fuel History: Task Order Number 15

1. Hydrocarbon Type

Mass Spectroscopy (ASTM D2789)	Percentage	FIA (ASTM D1319)	Percentage
paraffins	62.5	saturates	90.1
monocycloparaffins	25.1	aromatics	9.7
dicycloparaffins	1.7	olefins	0.2
alkylbenzenes	7.7		
indans and tetralins	1.0		
naphthalenes	0.8		
olefins (ASTM D1319)	0.2		

2. Gross and Net Heats of Combustion (P&W FLP 6)

a) Hydrogen, wt % 14.55
b) Sulfur, wt% 0.08
c) Gross Heat of Combustion, MJ/kg (Btu/lb) 46.729 (20090)
d) Net Heat of Combustion, MJ/kg (Btu/lb) 43.642 (18763)
e) Volumetric Heat of Combustion, MJ/L (Btu/gal) 32.759 (117535)

3. Specific Heat, kJ/kg/K (DSC)

a) 0C (32F) 1.97
b) 15C (59F) 2.06
c) 30C (86F) 2.12
d) 45C (113F) 2.18
e) 60C (140F) 2.26
f) 75C (167F) 2.31

4. Kinematic Viscosity, cSt (ASTM D445)

a) -40C (-40F) 2.24
b) -20C (- 4F) 1.50
c) 25C (77F) 0.80
d) 40C (104) 0.68

5. Density, g/mL (ASTM D4052)

a) -20C (- 4F) 0.77970
b) 5C (41F) 0.75952
c) 40C (104F) 0.73099
d) 75C (167F) 0.70126

6. Dielectric Constant (ASTM D924)

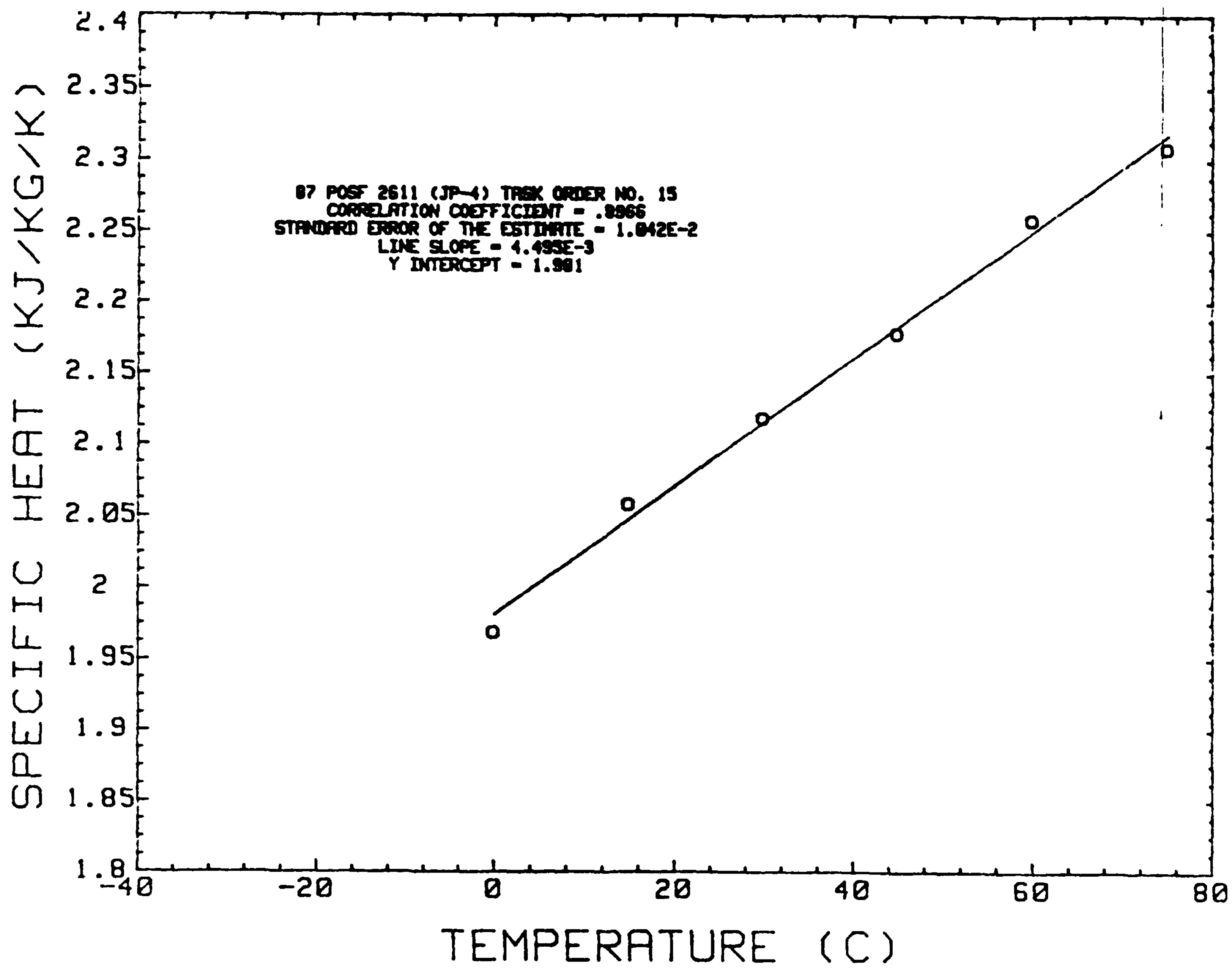
a)	0C (32F)	2.08
b)	30C (86F)	2.03
c)	50C (122F)	2.00
d)	75C (167F)	1.96

7. Surface Tension, dynes/cm (ASTM D1331)

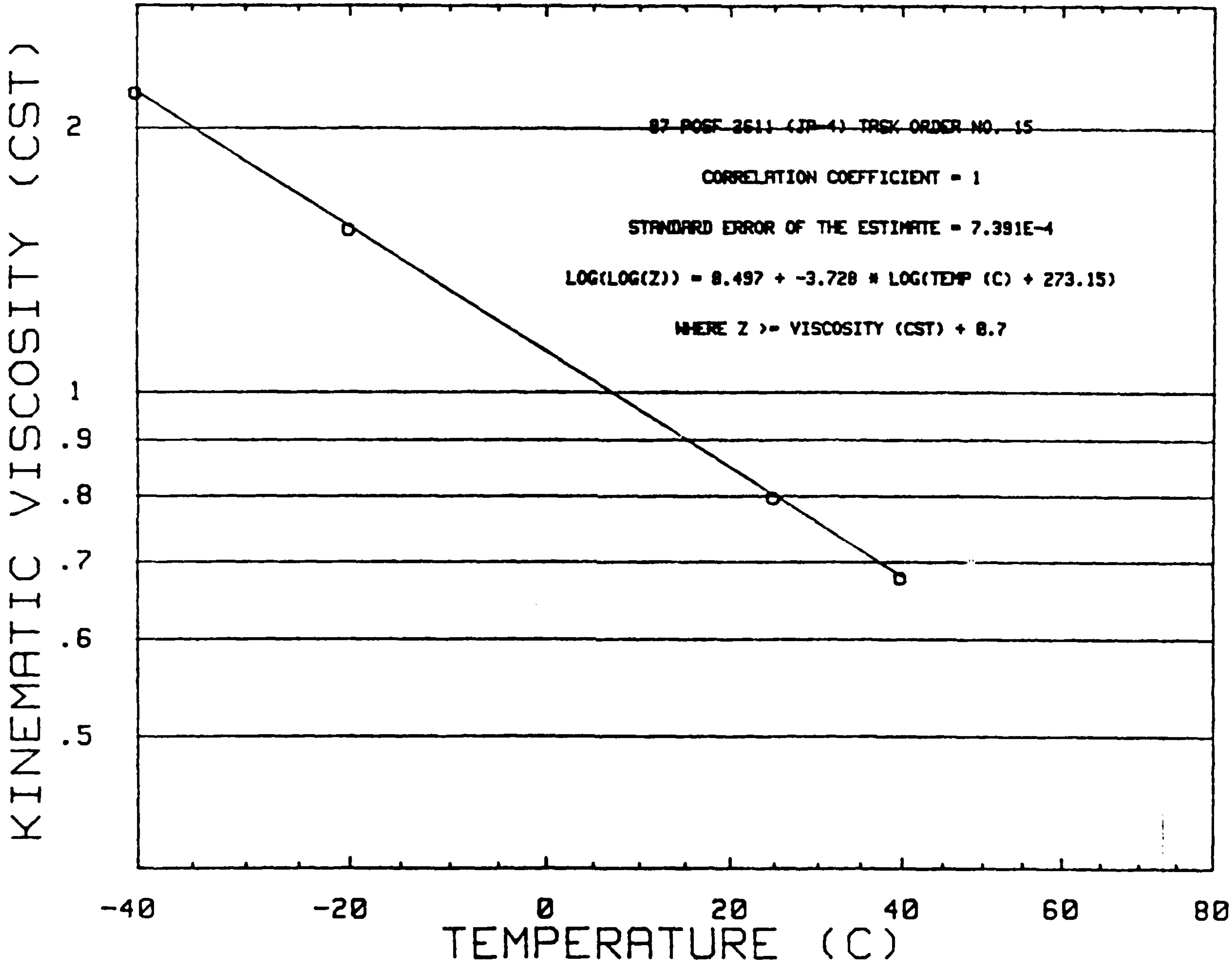
a)	-10C (14F)	22.6
b)	20C (68F)	19.9
c)	40C (104F)	18.1
d)	75C (167F)	16.1

8. Ball-On-Cylinder Lubricity Evaluator (BOCLE) (CRC-DRAFT 10)

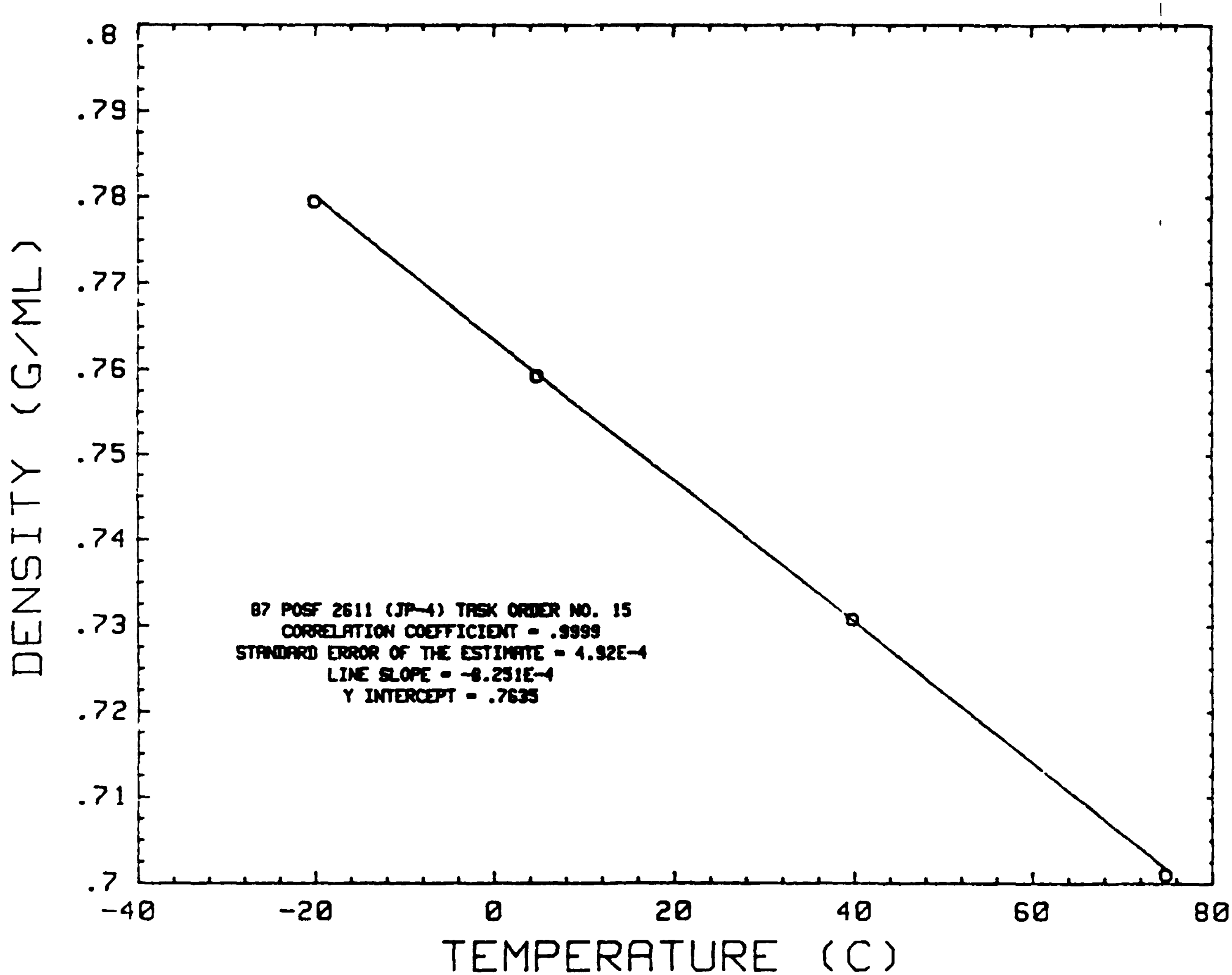
a)	500g Load: WSD, mm	0.56
b)	1000g Load: WSD, mm	0.68



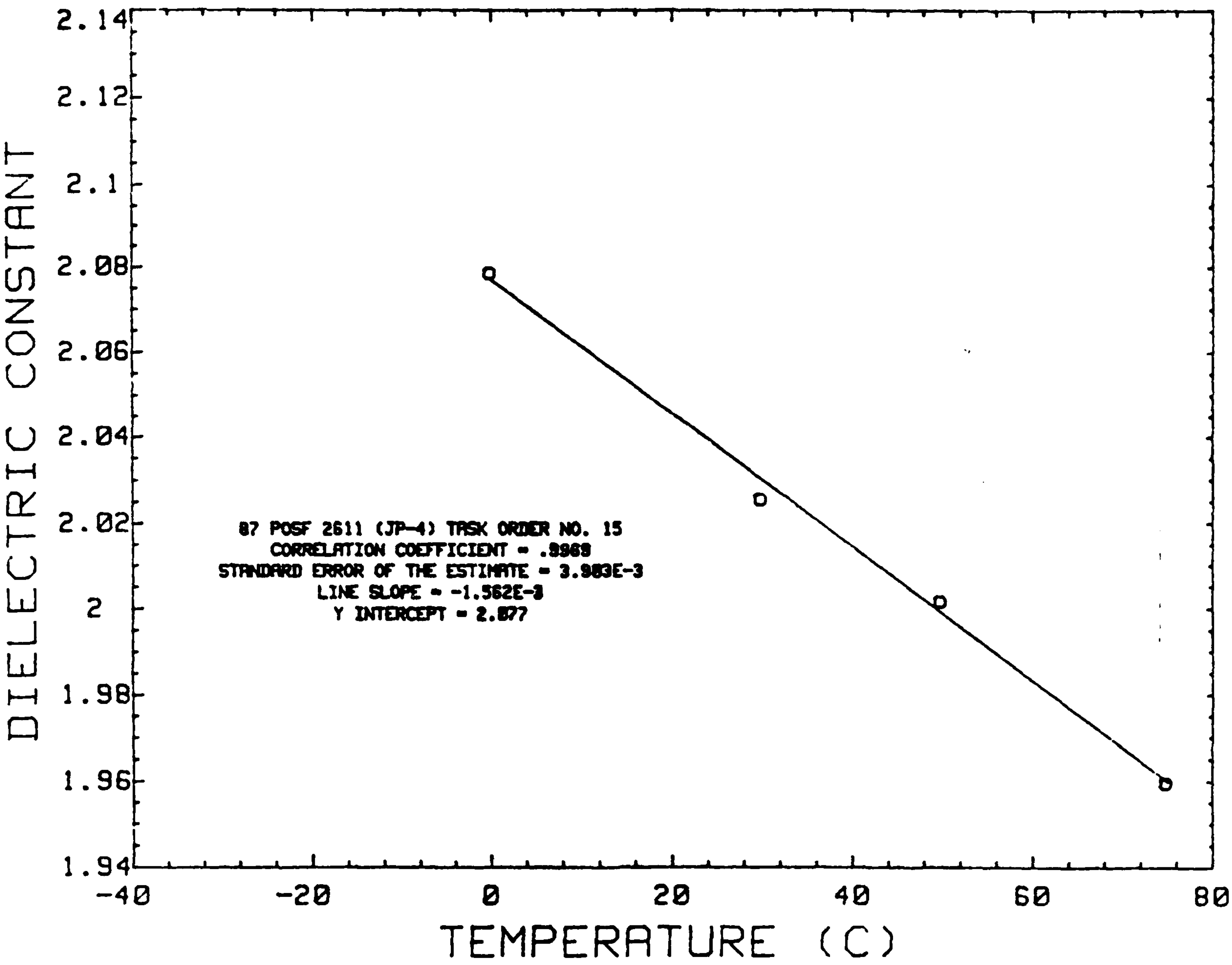
SPECIFIC HEAT (KJ/KG/K) AS A FUNCTION OF TEMPERATURE (C)



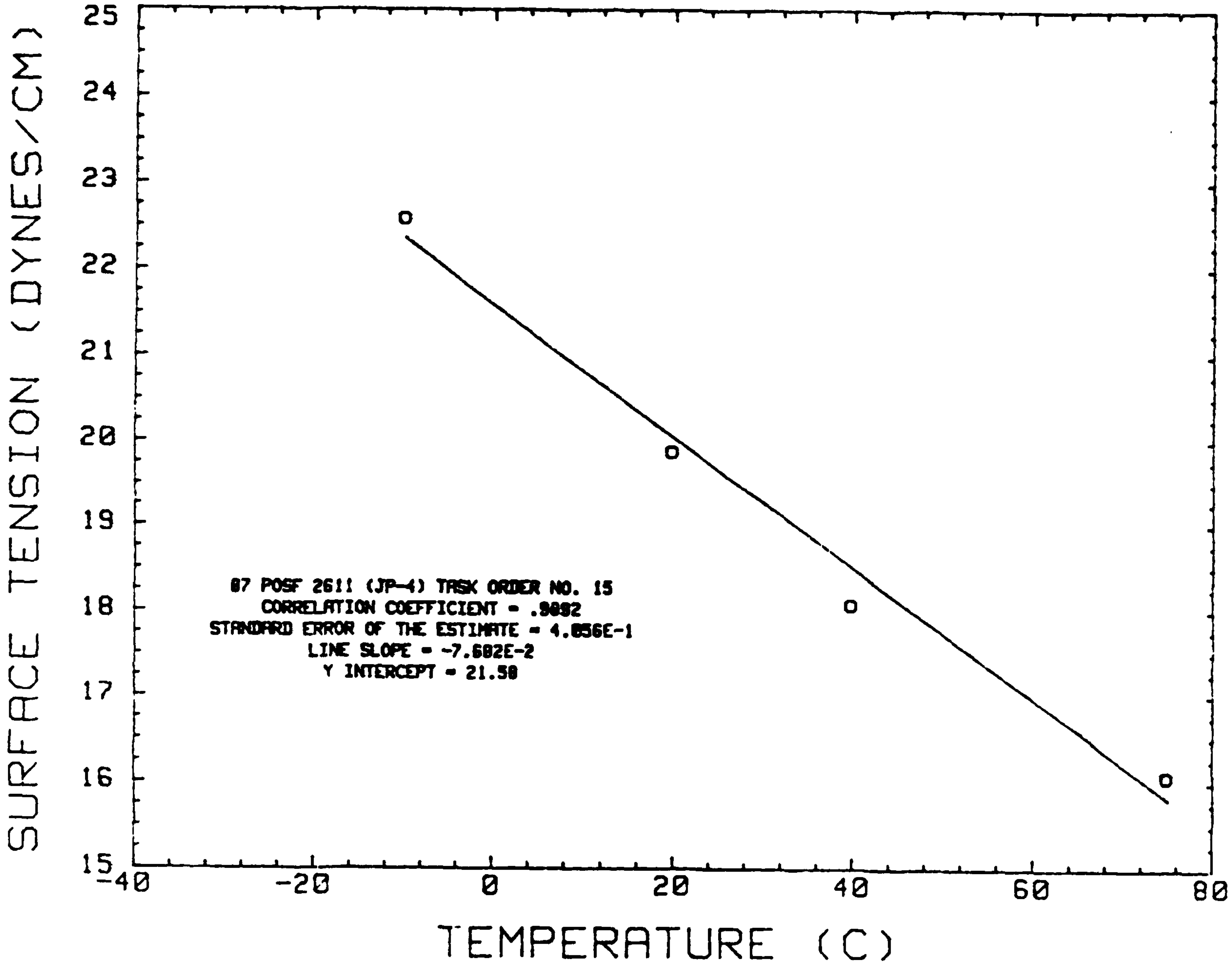
KINEMATIC VISCOSITY (CST) AS A FUNCTION OF TEMPERATURE (C)



DENSITY (G/ML) AS A FUNCTION OF TEMPERATURE (C)



DIELECTRIC CONSTANT AS A FUNCTION OF TEMPERATURE (C)



SURFACE TENSION (DYNES/CM) AS A FUNCTION OF TEMPERATURE (C)

ENERGY MANAGEMENT LABORATORY
DET 13, SA-ALC/SFTLA
WRIGHT-PATTERSON AFB, OH 45433-5000

LAB SAMPLE NBR: 87-F-1400
REPORT DATE: 03 DEC 87

TURBINE FUEL TEST REPORT - HIGH DENSITY FUEL

REASON FOR SUBMISSION:
AFWAL/POSF

SUBMITTED BY:

AFWAL/POSF
WRIGHT-PATTERSON AFB, OH 45433-5000

SUPPLIER:

Insufficient information
Data required:
Company Name
Address
City, State Zip Code

DATE RECEIVED: 30 NOV 87
SUBMITTER'S NBR: 87-POSF-2612

TEST RESULTS:-

(SEE PAGE TWO FOR ALL TEST DATA)

REMARKS:

Data reported for information purposes only.
TEST Ball on Cylinder, Wear Scar Dia., mm. 0.41

L. VAREE RYALS
QUALITY INSPECTION SPECIALIST

THOMAS J. O'SHAUGHNESSY
CHIEF, ENERGY MANAGEMENT LABORATORY
DIRECTORATE OF ENERGY MANAGEMENT

(This is a copy of the original signed version)

ENERGY MANAGEMENT LABORATORY
DET 13, SA-ALC/SFTLA
WRIGHT-PATTERSON AFB, OH 45433-5000

LAB SAMPLE NBR: 87-F-1400
REPORT DATE: 03 DEC 87

TURBINE FUEL TEST REPORT - HIGH DENSITY FUEL

TEST RESULTS:-

D156	Color, Saybolt	+20
D3242	Total Acid Number, mg KOH/g	0.005
D1319	Aromatics, Vol %	32.6
D1319	Olefins, Vol %	1.5
D3227	Mercaptan Sulfur, Wt %	0.002
D2622	Sulfur, Total Wt %	0.1
D2887	Distillation Initial Boiling Pt. Deg C	111
D2887	Distillation 10 % recovered, Deg C	166
D2887	Distillation 20 % recovered, Deg C	182
D2887	Distillation 50 % recovered, Deg C	233
D2887	Distillation 90 % recovered, Deg C	278
D2887	Distillation End Point, Deg C	356
D86	Distillation Initial Boiling Pt. Deg C	169
D86	Distillation 10 % recovered Deg C	191
D86	Distillation 20 % recovered Deg C	201
D86	Distillation 50 % recovered Deg C	232
D86	Distillation 90 % recovered Deg C	270
D86	Distillation End Point, Deg C	296
D86	Distillation Residue, Vol %	1.0
D86	Distillation Loss, Vol %	1.0
D1298	Density, kg/l	0.849
D93	Flash Point, Deg C	58
D2386	Freezing Point, Deg C	BELOW -73
D445	Viscosity @ -20 Deg C, cs	7.8
D3338	Net Heat of Combustion, MJ/kg	42.7
D3343	Hydrogen Content, Wt %	12.8
D130	Copper Strip Corrosion	1a
D381	Existent Gum, mg/100 ml	8.0
D1094	Water Reaction Interface	1b
D1094	Water Reaction Volume Change, ml	0
D3948	Water Separation Index Modified	32
D1322	Smoke Point, mm	13

ENERGY MANAGEMENT LABORATORY
DET 13, SA-ALC/SFTLA
WRIGHT-PATTERSON AFB, OH 45433-5000

LAB SAMPLE NBR: 87-F-1399
REPORT DATE: 03 DEC 87

TURBINE FUEL TEST REPORT
MIL-T-5624L TURBINE FUEL, AVIATION GRADE JP-4

DATE RECEIVED: 30 NOV 87
SUBMITTER'S NBR: 87-POSF-2611

TEST RESULTS:-

D3242	Total Acid Number, mg KOH/g	0.003
D1319	Aromatics, Vol %	11.0
D1319	Olefins, Vol %	0.7
D3227	Mercaptan Sulfur, Wt %	0.001
D2622	Sulfur, Total Wt %	0.08
D2887	Distillation Initial Boiling Pt. Deg C	37
D2887	Distillation 10 % recovered, Deg C	88
D2887	Distillation 20 % recovered, Deg C	93
D2887	Distillation 50 % recovered, Deg C	111
D2887	Distillation 90 % recovered, Deg C	225
D2887	Distillation End Point, Deg C	296
D86	Distillation Initial Boiling Pt. Deg C	76
D86	Distillation 10 % recovered Deg C	94
D86	Distillation 20 % recovered Deg C	98
D86	Distillation 50 % recovered Deg C	113
D86	Distillation 90 % recovered Deg C	218
D86	Distillation End Point, Deg C	241
D86	Distillation Residue, Vol %	1.0
D86	Distillation Loss, Vol %	1.0
D1298	Density, kg/l	0.751
D2551	Vapor Pressure, kPa	14
D2386	Freezing Point, Deg C	-66
D3338	Net Heat of Combustion, MJ/kg	43.6
D3343	Hydrogen Content, Wt %	14.6
D130	Copper Strip Corrosion	1a
D381	Existent Gum, mg/100 ml	0.2
D1094	Water Reaction Interface	1
TEST	Ball on Cylinder, Wear Scar Dia., mm.	0.48

REMARKS:
Data reported for information purposes only.
D445 Viscosity @ -20 Deg C, cs 1.53

L. VAREE RYALS
QUALITY INSPECTION SPECIALIST

THOMAS J. O'SHAUGHNESSY
CHIEF, ENERGY MANAGEMENT LABORATORY
DIRECTORATE OF ENERGY MANAGEMENT

(This is a copy of the original signed version)

APPENDIX B

AIR FORCE BOOST PUMP INSPECTIONS

The F-4 and KC-135 boost pumps were sent to WPAFB for Air Force inspection before, after 240 hours and at the conclusion of the fuel system component effects test program. There resulting inspection reports, which are included in this appendix, are tabulated below:

1. Pretest Inspection of KC-135 Pump Serial No. 1577, 14 March, 1988.

2. Pretest Inspection of F-4 Pump Serial No. 7577, 11 April, 1988.

3. Inspection KC-135 Pump Serial No. 1577 at 240 hrs, 28 June, 1988.

4. Inspection of F-4 Pump Serial No. 7577 at 240 hrs, 29 June, 1988.

5. Inspection of F-4 Pump Serial No. 7577 at 480 hrs, 18 November, 1988.

6. Inspection of KC-135 Pump Serial No. 1577 at 480 hrs, 28 November, 1988.

14 Mar 88

MEMO TO: File

SUBJECT: Pretest Inspection of KC-135 Pump Serial No. 1577

1. The subject pump was received from Boeing on 10 Mar 88 to enable us to disassemble and inspect the pump. The pump was manufactured by Hydro-Aire, Model No. 60-367-2. The pump was disassembled by Al Turner and inspected by Ed Binns and Royce Bradley. T.O. 6J10-3-96-3 was used as a guide and the Key Numbers referred to in the following comments are from Figure 2-2 of the T.O. The following observations were made:

a. The adaptor (Key No. 3) has two circumferential scratches. One scratch is 1/8-in. long and is located 1 in. from the inlet. The other scratch is 1/4-in. long and is located 1 3/8 in. from the inlet. Otherwise, the adaptor is in excellent condition.

b. The impeller (Key No. 5) has several circumferential scratches or machining marks on the O.D. of the impeller, two of which may match two of the marks on the adaptor. There is a small ding on the leading edge (outside corner) of one of the blades that was probably caused by something passing through the pump. The impeller is considered to be in very good condition.

c. No wear was evident on the rotor assembly shaft (Key No. 14).

d. The bearing (Key No. 17) that rides on the rotor shaft appears to be made of carbon. There is a step in the bearing material located approx. 1/3 of the way from the inlet end. The remainder of the bearing, the actual bearing surface, appears to be porous, with some evidence of wear. There is one circumferential mark on one lobe and part of a second lobe that is 3/16 in. from the impeller end of the bearing. It appears that something has passed through the pump making its mark on the bearing. The lobe that has the full mark also has a spiral mark starting 5/32 in. from the impeller side of the bearing and passing completely across the lobe. In addition, to these marks, there is limited wear on the bearing as indicated by polishing of the surface. It is considered that the bearing is in acceptable condition.

e. Difficulty was encountered in reinstalling the holder (Key No. 16). There appears to be a mismatch between the alignment tabs on the holder and the slots on the bearing. It is also noted that both the bearing and holder were more difficult to remove from this pump then they were from pump Serial No. 539X1

2. The other bearing (Key No. 23) was not inspected as that would have required removal of the rotor assembly and it appears that the bearings were replaced during overhaul.

Royce Bradley

Royce Bradley
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

11 Apr 88

MEMO TO: File

SUBJECT: Pretest Inspection of F-4 Pump Serial No. 7577

1. The subject pump was received from Boeing on 4 Apr 88 to enable us to disassemble and inspect the pump. The pump was manufactured by Hydro-Aire, Model No. 60-057-C-HY. The pump was disassembled by Al Turner and inspected by Ed Binns and Royce Bradley. T.O. 6J10-3-111-3 was used as a guide and the Key Numbers referred to in the following comments are from Figure 8-1 of the T.O. The following observations were made:

a. The adaptor (Key No. 43) has circumferential scratch or rub marks as the result of impeller contact throughout the entire area where the two could come together. However, prior to disassembly, the clearance between the two parts was measured and it was found that the clearance was acceptable per the T.O., although the clearance was on the low side of the allowable. In addition, there was no evidence that the impeller in this pump had rubbed the adapter. In addition to the rub marks, there were at least five pits that appear to be the result of casting defects. The rub marks and the pitting should not have any affect on the performance to the pump.

b. The impeller (Key No. 46) has a few shallow circumferential grooves on the O.D. of the impeller and the outer edges of the blades are shiny. However, indications are that the blades are shiny due to machining of the impeller following some prior problem. Overall, the impeller appears to be in very good condition.

c. No wear was evident on the rotor assembly shaft (Key No. 65) where bearing Key No. 56 rides.

d. The bearing (Key No. 56) that rides on the rotor shaft appears to be new. The bearing material appears to be nonporous carbon. The small marks that are on the bearing are in random directions indicating that these marks are inherent from the manufacturing process.

2. The pump was not disassembled any further since it would have involved disconnecting electrical wiring and breaking sealed connections. We do not have the required materials to reseal these connections.

Royce Bradley

Royce Bradley
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

28 Jun 88

MEMO TO: File

SUBJECT: Inspection of KC-135 Pump Serial No. 1577 at 240 hrs

1. The subject pump was received from Boeing on 27 Jun 88 after completing 240 hrs of testing using high density fuel. The pump was manufactured by Hydro-Aire, Model No. 60-367-2. The pump was disassembled by Al Turner and inspected by Ed Binns and Royce Bradley. T.O. 6J10-3-96-3 was used as a guide and the Key Numbers referred to in the following comments are from Figure 2-2 of the T.O.:

   a. The clearance between the adaptor (Key No. 3) and the impeller (Key No. 5) was measured to be between 0.003 and 0.005 in. which is in agreement with the T.O. However, the adaptor has additional circumferential scratches that evidently are the result of contact with the impeller. The scratches cover an arc of approximately 100°. Otherwise, the adaptor is in excellent condition.

   b. The impeller (Key No. 5) has several circumferential scratches or machining marks on the O.D. of the impeller, some of which are probably due to the contact with the adaptor mentioned in the previous paragraph. The impeller is considered to be in very good condition.

   c. No wear was evident on the rotor assembly shaft (Key No. 14).

   d. The bearing (Key No. 17) is in excellent condition. No change was evident except for polishing of the wear surface.

2. The other bearing (Key No. 23) was not inspected as that would have required removal of the rotor assembly.

3. It was concluded that the condition of the pump is satisfactory and that it should be used for the second phase of the testing; i.e., durability testing alternating between JP-4 and high density fuel.

Royce Bradley

Royce Bradley
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

29 Jun 88

MEMO TO: File

SUBJECT: Inspection of F-4 Pump Serial No. 7577 at 240 hrs

1. The subject pump was received from Boeing on 27 Jun 88 after completing 240 hrs of testing using high density fuel. The pump was manufactured by Hydro-Aire, Model No. 60-057-C-HY. The pump was disassembled by Al Turner and inspected by Ed Binns and Royce Bradley. T.O. 6J10-3-111-3 was used as a guide and the Key Numbers referred to in the following comments are from Figure 8-1 of the T.O.:

a. The clearance between the adaptor (Key No. 43) and the impeller (Key No. 46) was determined to be 0.007 in. which is in agreement with the Technical Order. There was no evident change in the condition of the adaptor.

b. There was no evident change in the condition of the impeller (Key No. 46).

c. No wear was evident on the rotor assembly shaft (Key No. 65) where bearing Key No. 56 rides.

d. Except for polishing, there is no evident change in the condition of the bearing (Key No. 56) that rides on the rotor shaft beneath the impeller.

2. The pump was not disassembled any further since it would have involved disconnecting electrical wiring and breaking sealed connections. We do not have the required materials to reseal these connections.

3. It was concluded that the condition of the pump is satisfactory and that it should be used for the second phase of the testing; i.e., durability testing alternating between JP-4 and high density fuel.

Royce Bradley

Royce Bradley
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

18 Nov 88

MEMO TO: File

SUBJECT: Inspection of F-4 Pump Serial No. 7577 at 480 hrs

1. The subject pump was received from Boeing on 6 Sep 88 after completing 480 hrs of testing. The first 240 hrs of testing used only high density fuel. The second 240 hrs alternated between JP-4 and high density fuel. The pump was manufactured by Hydro-Aire, Model No. 60-057-C-HY. The pump was disassembled by Al Turner and inspected by Ed Binns and Royce Bradley. T.O. 6J10-3-111-3 was used as a guide and the Key Numbers referred to in the following comments are from Figure 8-1 of the T.O.:

a. The clearance between the adaptor (Key No. 43) and the impeller (Key No. 46) on the end of the pump opposite the mounting flange was determined to be 0.008 in. which is acceptable based on the requirement in the Technical Order (0.006 to 0.008 in.). Visual inspection indicates that the degree of wear on both parts has increased since the 240-hr inspection. There is observable wear of the impeller from contact with the adaptor. The edges of the impeller are sharp indicating significant wear. No evidence was found that would indicate how the two parts could come in contact with each other. A rough calculation indicates that the axial movement of the impeller would have to be 0.057 in. to produce contact. There was no evidence that this movement was due to wear. It is concluded that the axial play that was inherent in the pump was sufficient to allow the contact under load and the fuels used in the program did not contribute to the wear.

b. The clearance between the adaptor (Key No. 43) and the impeller (Key No. 46) on the mounting flange end of the pump was determined to be >0.008 in. which is greater than the requirement of the Technical Order. Although the measuring device required to accurately measure the clearance was not available, it is estimated that the clearance was between 0.008 and 0.010 inches. Wear is evident on the inside of the adaptor from contact with the impeller. However, examination of the impeller indicates that it has been machined since the last time it made contact with the adaptor. Therefore, it is concluded that the wear on the adaptor did not take place during the endurance test program.

c. No wear is evident on the rotor assembly shaft (Key No. 65) where the two shaft bearings (Key No. 56) ride. There is a slight discoloration of the shaft at the location of the bearings. The diameter of the shaft is 0.4995 in. at both locations (0.4992 to 0.4995 in. allowed by the T.O.). The condition of the shaft is excellent.

e. The two bearings (Key No. 56) appear to be in excellent condition. The diameter of the bearing nearest the mounting flange end of the pump is between 0.5002 and 0.5003 inches. The internal diameter of the other bearing is between 0.5003 and 0.5005 inches. An internal diameter of 0.5002 to 0.5005 in. is allowed by the Technical Order. Therefore, the level of wear is acceptable.

f. The condition of both thrust plates (Key No. 59) is excellent. There is no visible wear. The thickness of the plate on the mounting flange end of the pump was determined to be 0.2506 in. (0.249 to 0.251 in. allowed by the T.O.). There is a small amount of debris on the edges of the plate and in the grooves of the plate. The thickness of the thrust plate on the other end of the pump is 0.2509 in. which is also within the T.O. limits.

2. It was concluded that the the problems found during the inspection are not due to the two fuels used during the durability testing.

Royce Bradley

Royce Bradley
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion Laboratory

28 Nov 88

MEMO TO: File

SUBJECT: Inspection of KC-135 Pump Serial No. 1577 at 480 hrs

1. The subject pump was received from Boeing on 6 Sep 88 after completing 480 hrs of testing. The first 240 hrs of testing used high density fuel. The second 240 hrs of testing alternated between JP-4 and high density fuel. The pump was manufactured by Hydro-Aire, Model No. 60-367-2. The pump was completely disassembled by Al Turner and inspected by Ed Binns and Royce Bradley. T.O. 6J10-3-96-3 was used as a guide and the Key Numbers referred to in the following comments are from Figure 2-2 of the T.O.:

a. The clearance between the adaptor (Key No. 3) and the impeller (Key No. 5) was measured to be between 0.003 and 0.0035 in. which is in agreement with the T.O. (0.003 to 0.005 in.). However, the adaptor has additional circumferential scratches that evidently are the result of contact with the impeller. The scratches now cover a full 360° arc, however the entire surface is not covered with scratches. An in-depth inspection did not reveal the reason for the contact between the two surfaces. There is no indication of wear on the thrust plate (Key No. 20) or shaft bearings that would allow the two surfaces to rub. Otherwise, the adaptor is in excellent condition. Due to the lack of wear on the components that would have allowed the adaptor and impeller to come into contact and after discussions between Ed Binns and experts in the area, it was concluded that the wear on the adaptor and impeller is not related to the fuel used in the test program.

b. The impeller (Key No. 5) has many circumferential scratches or machining marks on the O.D. of the impeller, some of which are probably due to the contact with the adaptor mentioned in the previous paragraph. The impeller is considered to be in good condition.

c. No wear was evident on either end of the rotor assembly shaft (Key No. 14). The diameter of the shaft where the bearing rides was measured to be 0.4995 in. on the end opposite the impeller and 0.4994 in. on the impeller end.

d. The bearings (Key Nos. 17 and 23) are in excellent condition. No change was evident except for polishing of the wear surface. The internal diameter of the bearing (Key No. 17) closest to the impeller is between

0.5004 and 0.5005 inches. The diameter of the bearing (Key No. 23) opposite the impeller end of the pump is between 0.5002 and 0.5005 inches. These diameters are within the dimensions considered acceptable by Hydro-Aire (viz., 0.5002 to 0.5005 in.). Gummy deposits and some debris were evident on the outside of bearing Key No. 23.

e. A small amount of debris was evident on the thrust plate (Key No. 20). The plate appeared to be in excellent condition. The thickness of the plate was determined to be 0.2500 inches.

2. It was concluded that the the pump is in good condition and that none of the discrepancies discussed above are due to the fuels used in the endurance testing.

Royce Bradley

Royce Bradley
Fuels Branch
Fuels and Lubrication Division
Aero Propulsion and Power Laboratory

APPENDIX C

MATERIALS COMPATIBILITY

The University of Dayton Research Institute, under contract to the Air Force Materials Laboratory, conducted materials compatibility testing on 37 typical aircraft materials that might be exposed to fuel. The same two fuels used in the Boeing testing were used in the compatibility testing. Their report is presented in this appendix.

UDR-TR-89-19

EVALUATION OF THE EFFECT OF HIGH DENSITY FUEL ON ELASTOMERIC MATERIALS, STRUCTURAL ADHESIVES, AND COATINGS

Prepared For:

Wright Research and Development Center
Wright-Patterson AFB, Ohio 45433-6533

Prepared By:

B. H. Wilt
J. N. Dues

University of Dayton
Research Institute
Dayton, Ohio 45469

February 1989

PREFACE

This technical report was submitted by the University of Dayton Research Institute, Dayton, Ohio, under Contract F33615-88-C-5437, "Quick Reaction Evaluation of Materials". The work was administered under the direction of the Wright Research and Development Center, Materials Laboratory, Materials Support Division, Wright-Patterson Air Force Base, Ohio.

This materials evaluation was initiated under Contract F33615-84-C-5130, "Quick Reaction Evaluation of Materials" in December 1987 and was completed under Contract F33615-88-C-5437 in January 1989. The authors wish to recognize Mr. John Conner of the University of Dayton and student assistants David Schoettmer, Stephen Olson, Suzanne Baker and Peter Konopinski who assisted in this program, and Mrs. Jeanne Drake and Miss Kimberly Kuhbander for organizing and typing this report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Concluded)

ABSTRACT

Nonmetallic fuel system materials that are currently used in various military aircraft were subjected to a proposed high density fuel and to conventional JP-4 for up to one year at an elevated temperature of 140°F (60°C). Comparisons of the results of selected tests were made after 7 days, 6 months, and 12 months of fuel exposure to determine the compatibility of each material with the proposed fuel.

Typical materials used in the evaluation included various O-ring elastomers, fuel tank sealants, fuel cell bladder materials, structural adhesives and coatings.

Comparisons of the test results after the respective fuel agings yielded no significant differences in materials properties for most of the materials. Thirty-four of thirty-seven materials tested had similar properties after exposure to both high density fuel and JP-4. Four materials exhibited significant changes in physical properties after exposure to the fuels. Just one material, PR 703, a non-curing groove sealant, was more adversely affected by exposure to high density fuel than JP-4.

SECTION 1
INTRODUCTION

When changes in aircraft fuel requirements or in fuel composition are proposed, the effect of any change on materials currently used in aircraft fuel systems must be evaluated. A program to determine the compatibility of typical fuel system elastomers with a high density fuel was established. These materials are commonly used in the sealing of integral fuel tanks and fuel cell cavities.

Typical nonmetallic aircraft materials were selected to establish the data base. They included elastomeric O-ring materials, fuel tank sealants, fuel bladder materials, bladder repair adhesives, fuel cell foams, structural adhesives, fuel tank coatings, wire insulation materials, and self-sealing hose. These materials were, in many cases, identical to those tested previously to determine materials compatibility to other aircraft fuel compositions. Extensive data to determine materials compatibility in shale-oil derived fuels and in petroleum fuels with varying aromatic levels and with varying fuel additives have been obtained for both the U.S. Air Force and the U.S. Navy (References 1 and 2).

SECTION 2
DISCUSSION OF THE PROGRAM

The objectives of this materials compatibility program were to determine if the high aromatic level of high density fuel (HDF) was more detrimental to fuel system elastomers than JP-4 fuel, and to investigate the effect of alternating materials exposures to JP-4 and HDF.

Baseline data were obtained for each material included in the evaluation. Physical properties of the materials were determined after agings in the respective fuels at 140°F (60°C) for 7 days, 6 months, and 12 months with monthly fuel changes where appropriate. Materials were also aged at 140°F in alternating fuels for 6 months and 12 months. The fuels were alternated at one month intervals.

For conditioning, five specimens of each material in each of the test fuels were suspended from racks placed in wide-mouth quart jars. The jars were filled with 900 ml of test fluid then sealed with lids lined with aluminum foil. Each fuel was changed every 30 days during the 6 and 12-month exposures. Prior to testing, all specimens were cooled to room temperature while suspended in the respective test fluids.

SECTION 3

TEST PROCEDURES AND RESULTS

The procedures employed and the results of testing for each of the materials evaluated are discussed in separate categories: O-ring and gasket materials; fuel tank sealants, curing type; fuel tank sealants, non-curing type; bladder materials; fire suppressant foams; structural adhesives; fuel tank coatings, wire insulation materials; and self-sealing hose.

Specific tests relating to each material category were selected to provide pertinent properties of each material after the following fuel exposures:

A. None (original properties)

B. Seven days at 140°F in JP-4

C. Seven days at 140°F in high density fuel

D. 12 months at 140°F in JP-4, changing fuel every 30 days - samples tested at the end of six months and 12 months.

E. 12 months at 140°F in high density fuel, changing fuel every 30 days - samples tested at the end of six months and 12 months.

F. 12 months at 140°F in JP-4/high density fuel alternating the type fuel every 30 days starting with JP-4 - samples tested at the end of six months and 12 months.

G. Seven days at 77°F in JP-4, followed by seven days at 77°F in high density fuel (also measured volume change when removed from the JP-4).

3.1 O-RING AND GASKET MATERIALS

Six representative O-ring and gasket materials were evaluated. Specific materials included:

MIL-P-5315, Buna-N - Parker N602-70

MIL-R-25988, Fluorosilicone - Parker L677-70

MIL-R-83248, Fluoroelastomer - Parker V747-75

AMS 7271, Buna-N - Parker N506-70

Marmon Clamp Material - Pacific Molded Products KKK-125

AMS 7261/1A, Phosphonitrilic Fluoroelastomer - Parker F953-70

O-ring evaluations included the determinations of ultimate tensile strength, percent elongation, hardness and percent volume change as a function of agings in the respective fuels. All O-ring test results are summarized in Tables 1 through 5. Marmon clamp material KKK-125 results are shown in Table 6.

Both Buna-N compounds, N602 (MIL-P-5315) and N506 (AMS 7271) underwent comparable decreases in physical properties versus time of exposure to both fuels. The N602 O-rings had approximately 30 percent volume swell in HDF, almost twice that of JP-4. HDF has, however, a much higher aromatic content than JP-4. MIL-P-5315 has an allowable volume swell of 0-50 percent in TT-S-735, Type III test fluid. The N506 O-ring compound exhibited similar volume swell properties in the two fuels, but had higher values, reaching approximately 50 percent in HDF.

Properties of L677 (MIL-R-25988) fluorosilicone, V747 (MIL-R-83248) fluoroelastomer and F953 (AMS 7261/1A) phosphonitrilic fluoroelastomer were all virtually unaffected by agings in either fuel.

The Marmon clamp material, KKK-125 showed significant decreases in tensile properties after agings in both fuel systems. Volume swell after exposure to HDF was approximately twice the values obtained in JP-4.

Additional fuel exposures and testing were included for several of the O-ring compounds. These additional requirements are described below:

A cycling test was conducted using the packing test jig assembly described by Figure 1 of MIL-P-5315B. Only the Buna-N, fluorosilicone, and phosphonitrilic fluoroelastomer were tested.

Three series of tests were also conducted on each type material in which the O-ring was exposed to the test fuel(s) for eight days at a temperature of 158°F (70°C). JP-4 was used as the test fluid in one test. The second series of tests used the high density fuel on a full time basis. The third series was conducted by alternating the two fuels after exposure to each fuel for two-day periods. The starting fuel for this series was JP-4.

Following exposure to the test fuel(s) for eight days, the test fluids were circulated through the test fixture at room temperature under 15 psig pressure. During this period, the test fixture stem was rotated a total of 5,000 revolutions at 8 to 10 RPM. The temperature was then reduced to -65°F (-54°C) and the stem was rotated 24 revolutions at 8 to 10 RPM. No leakage or damage to the O-rings occurred as a result of testing.

An additional fuel aging condition was also included for the MIL-R-83248, Type I, Class 1, Grade 75 - fluoroelastomer, only:

- o After aging 7 days at 300°F (149°C) in JP-4
- o After aging 7 days at 300°F (149°C) in high density fuel

Results of aging in both fuels at 300°F were comparable, resulting in some softening of the O-rings and in higher volume swell properties.

3.2 FUEL TANK SEALANTS - CURING TYPE

Four two-part curing type polysulfide sealants and one fluorosilicone were included in the evaluation:

MIL-S-8802, Type I, PR 1422 B-2 Dichromate cured
MIL-S-8802, Type II, PS 890 B-2 Manganese cure
MIL-S-83430, PR 1750, B-2 Manganese cured
MIL-S-7502, PR 1221, B-2 Lead dioxide cured
Q4-2817 with 1200 Primer, Fluorosilicone

Peel strength properties were determined on MIL-C-27725 substrates for all sealants except the MIL-S-7502 material, which was applied to QQ-A-250/13 clad aluminum. Volume change and low temperature flexibility were also determined for each sealant after each fuel exposure. Results of testing are presented in Tables 7 through 11.

Peel strength values for both PR 1422 (MIL-S-8802) and PR 1750 (MIL-S-8802) were similar after aging in both fuels. Both sealants passed low temperature flexibility and both exhibited some shrinkage as a result of exposures to both fuels.

PS 890 (MIL-S-8802) sealant had a lower initial peel strength than the other polysulfide sealants. Peel strength values after the respective fuel agings were, therefore, lower than the other polysulfides, but comparable for both fuels. PS 890 passed low temperature flexibility and underwent some shrinkage after agings in both fuels.

PR 1221 (MIL-S-7502) lead dioxide cured polysulfide, showed a similar loss of peel strength in both fuels, but exhibited much greater shrinkage of the sealant in both fuels. The sealant did not pass the low temperature flexibility test after exposure for 12 months to HDF.

The only fluorosilicone tested, Q4-2817, exhibited a tendency to fail adhesively after exposure to HDF. There were no low temperature flexibility failures and only slight changes in volume resulted from the fuel exposures.

3.3 FUEL TANK SEALANTS - NON-CURING TYPE

Non-curing groove injection sealants included in the test program were:

PR 703 Polysulfide

94-031 Fluorosilicone

G651 Cyanosilicone

Pressure rupture and volume change data were obtained after conditioning the materials in the respective fuels. Results of testing are shown in Tables 12 through 14.

As the data in Table 12 indicate, both fuels had a similar effect on the polysulfide, PR 703, after six months. The sealant tended to harden with a resulting increase in pressure rupture and slight decrease in volume swell. After 12 months in HDF, however, PR 703 had a highly negative swell and showed a large decrease in pressure rupture. DC 94-031 fluorosilicone sealant exhibited higher pressure rupture values after exposures to HDF than to JP-4. The sealant volume change was comparable in both fuels. G651 cyanosilicone sealant showed comparable shrinkage with increased time oi agings in both fuels.

3.4 BLADDER MATERIALS

Three fuel cell bladder materials were included in the evaluation. They were:

Goodyear 51956 Buna-N
Goodyear 80C29 Urethane
Goodyear 82C39 Urethane

Permeabilities of each bladder material to JP-4 and to HDF were obtained according to the procedure described in MIL-T-6396C, Paragraph 4.6.12. Properties of tensile strength, percent elongation and percent volume change were also determined after the respective fuel agings.

Permeability test results are contained in Table 15, and, as indicated, all three bladder construction materials were more permeable to JP-4 than to HDF. Tensile properties and volume change of all three materials are shown in Tables 16 through 18. Buna-N, 51956 underwent comparable decreases in tensile properties versus time of conditioning in both fuels and exhibited greater volume swell in HDF than in JP-4, corroborating the test results obtained on Buna-N O-ring materials.

Both urethane bladder materials, 80C29 and 82C39, showed comparable changes in tensile properties after exposures to both fuels and had slightly greater volume swell values in HDF.

3.5 SELF-SEALING BLADDER MATERIAL

Goodyear 26950, a self-sealing material, was tested for percent volume change after a single aging at 77°F (23°C) in each of the fuels. The results shown in Table 19 indicate low volume swell values for 26950 after exposure to the fuels.

3.6 BLADDER REPAIR ADHESIVES

Two bladder repair adhesives, Goodyear 1895C Buna-N and Goodyear 80C29 polyurethane adhesive were included in the materials evaluation. T-peel strength and percent cohesive failure were determined for these materials after the respective agings in JP-4 and HDF. T-peel specimens were fabricated using 1895C to create a bond on FT 136 patch material, and 80C29 to create a bond on 82C39 bladder material.

As the data in Table 20 indicate, the fuels had little effect on peel strength and all fuel aged samples exhibited at least partial adhesive failures.

3.7 FIRE SUPPRESSANT FOAMS

Two fuel cell fire suppressant foams were also evaluated after respective exposures to JP-4 and HDF. One foam was red polyester polyurethane (MIL-B-83054B, Type III). The second was a blue polyether polyurethane (MIL-B-83054B, Type V). All foam specimens were precut into either tensile specimens or 1-inch thick discs for volume resistivity measurements.

The data in Tables 21 and 22 show comparable tensile properties for both Type III and Type V foams after agings in both fuels. Both foams also had increases in volume swell versus time of exposure for both JP-4 and HDF.

No significant differences in volume resistivity measurements were noted for either foam as a function of fuel agings. Test results are shown in Table 23.

3.8 STRUCTURAL ADHESIVES

Structural adhesives that are in use on current aircraft systems were also included in the test program. Adhesives selected were:

EC3569 Epoxy/polyamide

FM47 Vinyl phenolic

AF126-2 Nitrile modified epoxy

AF143-2 Modified high temperature epoxy

EPON 828/DTA Unmodified epoxy

FM73 w/BR-127 Primer Nitrile modified epoxy

AF-10 w/EC1290 Primer Scotchweld

AF-10 w/EC3950 Primer Scotchweld

Single lap shear specimens were prepared for each fuel aging. Aluminum 2024-T3 was used as the substrates for the lap shear specimens. Lap shear data are contained in Tables 24 through 26.

EC3569, FM47, and AF126-2 were unaffected by exposures to either JP-4 or HDF. AF143-2 and FM73 were also unaffected by either fuel. EPON 828/DTA unmodified eoxy failed 100 percent adhesively under all conditions including the control specimens. Lap shear loads, however, did not vary significantly with aging in either fuel.

AF10 adhesives exhibited partial adhesive failures using both EC1290 and EC3950 primers at all conditions. No effect of fuel agings was noted.

3.9 FUEL TANK COATINGS

Three integral fuel tank corrosion prevention coatings were included:

MIL-S-4383 Buna-N

MIL-C-27725 Polyurethane

BMS 10-20 Epoxy

Pencil hardness was determined for each material fuel aging and the results are summarized in Table 27. All three coatings were unaffected by agings in either JP-4 or HDF.

3.10 WIRE INSULATION MATERIALS

Three electrically insulating sheet materials were also evaluated. The materials were:

Teflon TFE

Nylon 101

Polyethylene

Standard Die "C" tensile specimens were prepared for the determination of tensile properties as a function of fuel exposures. The data in Tables 28 through 30 show that Teflon TFE and polyethylene had virtually no effect from exposures to either fuel. The elongation of Nylon 101 was slightly greater and the material retained a higher tensile strength after fluid agings in HDF than after agings in JP-4.

3.11 SELF-SEALING HOSE

AR-184, an inner tube material used in self-sealing hoses, was also included in the materials evaluation.

Tensile properties and volume change data are shown in Table 31. Test results in both fuels were comparable after six months. After 12 months, however, AR-184 exhibited some embrittlement as a result of exposure to JP-4, as indicated by the very low value of elongation and a lower amount of volume change.

SECTION 4
CONCLUSIONS

The objective of this program was to determine the compatibility of typical aircraft fuel system materials with a proposed high density fuel (HDF). Material properties were measured after selected fuel agings in HDF and in JP-4 as a reference. Materials were also exposed to alternating fuels.

The results of testing nine different categories of fuel system materials after fuel agings of 7 days, six months, and 12 months durations are summarized in simplified form in Table 32.

Thirty-five of the thirty-seven materials exhibited similar properties after fluid conditionings in either HDF or JP-4. Of these, thirty-three were unaffected or showed only slight effects to fluid exposures at 140°F (60°C). Only four of the materials were significantly affected by exposures to one or both fuels. Materials properties were less affected by alternating the fuels.

KKK-125 marmon clamp material was equally affected by long term agings in both fuels, exhibiting a large change in volume and a loss in tensile properties.

PR 1221 B-2, one of four curing type polysulfide sealants tested, was significantly affected by both fuels. Use of this sealant, which utilizes lead-dioxide in curing, has been discontinued. PR 1221 may, however, still be found in aircraft that are more than 25 years old, and the sealant was included in the evaluation.

PR 703, a non-curing polysulfide groove sealant, was affected by long-term aging in HDF. This sealant also sees limited use as a groove sealing compound.

Nylon 101 wire insulation and AR-184 self sealing hose were affected more by long-term exposure to JP-4 than to HDF.

Based on the above observations, most nonmetallic fuel system materials are not affected by immersion in HDF to a greater degree than immersion in conventional JP-4 aircraft fuel. Only one of thirty-seven types of materials tested was more adversely affected by HDF than JP-4.

SECTION 5

REFERENCES

1. "Long Term Evaluation of the Effects of Shale Oil Produced JP-4 on Aircraft Construction Materials," AFWAL-TR-83-4046, Wilt and Dues, April 1983.

2. "Impact of Changing Fuel Composition on the Durability and Performance of Fuel System Elastomers," UDR-TR-83-109, Wilt and Dues, September 1983.

TABLE 1

N602-70 O-RING PROPERTIES

Conditioning	Tensile Strength (psi)	Elongation (%)	Hardness	Volume Change (%)
Control	1561	306	70	
7 Days @ 140F in JP-4	1379	270	52	16
7 Days @ 140F in HD	1340	281	47	29
6 Months @ 140F in JP-4	1100	214	56	13
6 Months @ 140F in HD	844	225	50	29
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	828	197	50	26
12 Months @ 140F in JP-4	211	83	50	26
12 Months @ 140F in HD	578	203	45	29
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	369	131	46	28
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	1154	259	50	14 27

TABLE 2

L677-70 O-RING PROPERTIES

Conditioning	Tensile Strength (psi)	Elongation (%)	Hardness	Volume Change (%)
Control	1038	236	70	
7 Days @ 140F in JP-4	953	243	57	11
7 Days @ 140F in HD	999	228	63	5
6 Months @ 140F in JP-4	785	198	62	9
6 Months @ 140F in HD	845	186	68	6
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	855	201	65	6
12 Months @ 140F in JP-4	876	194	64	6
12 Months @ 140F in HD	967	201	65	6
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1028	226	62	6
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	747	237	62	7
				4
7 Days @ 300F in JP-4	819	221	56	12
7 Days @ 300F in HD	148	89	59	6

TABLE 3

V747-75 O-RING PROPERTIES

Conditioning	Tensile Strength (psi)	Elongation (%)	Hardness	Volume Change (%)
Control	1718	189	75	
7 Days @ 140F in JP-4	1868	210	73	4
7 Days @ 140F in HD	1749	198	76	2
6 Months @ 140F in JP-4	1694	207	75	4
6 Months @ 140F in HD	1836	209	77	4
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1832	218	77	3
12 Months @ 140F in JP-4	2118	240	73	4
12 Months @ 140F in HD	1883	217	85	4
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1920	231	76	4
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	2094	238	75	0
				1
7 Days @ 300F in JP-4	1997	210	71	7
7 Days @ 300F in HD	1738	221	72	7

TABLE 4

N506-70 O-RING PROPERTIES

Conditioning	Tensile Strength (psi)	Elongation (%)	Hardness	Volume Change (%)
Control	1462	235	70	
7 Days @ 140F in JP-4	985	180	50	28
7 Days @ 140F in HD	999	193	49	46
6 Months @ 140F in JP-4	690	172	52	29
6 Months @ 140F in HD	607	168	45	49
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	672	169	46	47
12 Months @ 140F in JP-4	71	44	42	39
12 Months @ 140F in HD	145	161	36	53
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	77	94	40	48
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	824	186	50	23 46

TABLE 5

F953 O-RING PROPERTIES

Conditioning	Tensile Strength (psi)	Elongation (%)	Hardness	Volume Change (%)
Control	1175	137	70	
7 Days @ 140F in JP-4	1187	156	65	8
7 Days @ 140F in HD	1230	156	67	3
6 Months @ 140F in JP-4	954	135	71	7
6 Months @ 140F in HD	1171	148	73	5
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1172	155	71	5
12 Months @ 140F in JP-4	1181	156	69	5
12 Months @ 140F in HD	1160	152	69	5
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1241	159	69	5
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	1213	164	70	6
				3

TABLE 6

KKK-125 MARMON CLAMP MATERIAL

Conditioning	Tensile Strength (psi)	Elongation (%)	Hardness	Volume Change (%)
Control	1511	450		
7 Days @ 140F in JP-4	1759	255	46	65
7 Days @ 140F in HD	673	118	36	116
6 Months @ 140F in JP-4	176	166	18	153
6 Months @ 140F in HD	176	124	12	323
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	209	98	14	273
12 Months @ 140F in JP-4	36	90	*	167
12 Months @ 140F in HD	15	57	*	275
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	26	78	*	197
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	686	140	40	72
				112

* To soft to test

TABLE 7

PR 1422 B-2 FUEL TANK SEALANT - CURING TYPE

Conditioning	Peel Strength (lbs)	% Cohesive	Low Temp Flex	Volume Change (%)
Control	38	100	Passed	
7 Days @ 140F in JP-4	35	100	Passed	1
7 Days @ 140F in HD	40	100	Passed	3
6 Months @ 140F in JP-4	31	100	Passed	-1
6 Months @ 140F in HD	37	100	Passed	-2
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	36	100	Passed	0
12 Months @ 140F in JP-4	31	100	Passed	-3
12 Months @ 140F in HD	35	100	Passed	-6
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	31	100	Passed	-4
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	32	100	Passed	1

TABLE 8

PS 890 B-2 FUEL TANK SEALANT - CURING TYPE

Conditioning	Peel Strength (lbs)	% Cohesive	Low Temp Flex	Volume Change (%)
Control	26	100	Passed	
7 Days @ 140F in JP-4	35	100	Passed	-1
7 Days @ 140F in HD	40	100	Passed	0
6 Months @ 140F in JP-4	18	100	Passed	-2
6 Months @ 140F in HD	15	100	Passed	-3
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	19	100	Passed	-4
12 Months @ 140F in JP-4	15	100	Passed	-2
12 Months @ 140F in HD	13	100	Passed	-4
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	16	100	Passed	-6
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	45	100	Passed	0

TABLE 9

PR 1750 B-2 FUEL TANK SEALANT - CURING TYPE

Conditioning	Peel Strength (lbs)	% Cohesive	Low Temp Flex	Volume Change (%)
Control	55	100	Passed	
7 Days @ 140F in JP-4	48	100	Passed	-1
7 Days @ 140F in HD	43	100	Passed	0
6 Months @ 140F in JP-4	32	100	Passed	-3
6 Months @ 140F in HD	35	100	Passed	-4
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	36	100	Passed	-3
12 Months @ 140F in JP-4	32	100	Passed	-5
12 Months @ 140F in HD	36	100	Passed	-4
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	35	100	Passed	-4
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	43	100	Passed	0

TABLE 10

PR 1221 B-2 FUEL TANK SEALANT - CURING TYPE

Conditioning	Peel Strength (lbs)	% Cohesive	Low Temp Flex	Volume Change (%)
Control	70	100	Passed	
7 Days @ 140F in JP-4	60	100	Passed	-10
7 Days @ 140F in HD	52	100	Passed	-8
6 Months @ 140F in JP-4	39	100	Passed	-41
6 Months @ 140F in HD	43	100	Passed	-46
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	42	100	Passed	-41
12 Months @ 140F in JP-4	30	100	Passed	-50
12 Months @ 140F in HD	28	100	Failed	-52
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	26	100	Passed	-47
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	75	100	Passed	-6

TABLE 11

Q4-2817 FUEL TANK SEALANT - CURING TYPE

Conditioning	Peel Strength (lbs)	% Cohesive	Low Temp Flex	Volume Change (%)
Control	22	70	Passed	
7 Days @ 140F in JP-4	9	100	Passed	5
7 Days @ 140F in HD	21	100	Passed	2
6 Months @ 140F in JP-4	17	100	Passed	5
6 Months @ 140F in HD	13	23	Passed	1
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	14	100	Passed	1
12 Months @ 140F in JP-4	7	100	Passed	5
12 Months @ 140F in HD	15	44	Passed	-1
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	15	100	Passed	1
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	17	100	Passed	1

TABLE 12

PR 703 FUEL TANK SEALANT - NON-CURING

Conditioning	Pressure Rupture (In. Merc.)	Volume Swell (%)
Control	48	
7 Days @ 140F in JP-4	38	5
7 Days @ 140F in H.D.	44	6
6 Months @ 140F in JP-4	>61	3
6 Months @ 140F in H.D.	>61	0
6 Months @ 140F in JP-4/H.D. alt. every month	>61	2
12 Months @ 140F in JP-4	>61	-3
12 Months @ 140F in H.D.	6	-22
12 Months @ 140F in JP-4/H.D. alt every month	34	-8
7 Days @ 77F in JP-4 + 7 Days @ 77F in H.D.	38	4 6

TABLE 13

94-031 FUEL TANK SEALANT - NON-CURING

Conditioning	Pressure Rupture (In. Merc.)	Volume Swell (%)
Control	26	
7 Days @ 140F in JP-4	17	10
7 Days @ 140F in H.D.	24	7
6 Months @ 140F in JP-4	15	17
6 Months @ 140F in H.D.	23	11
6 Months @ 140F in JP-4/H.D. alt. every month	25	11
12 Months @ 140F in JP-4	14	14
12 Months @ 140F in H.D.	25	12
12 Months @ 140F in JP-4/H.d. alt every month	14	10
7 Days @ 77F in JP-4 + 7 Days @ 77F in H.D.	29	11

8

TABLE 14

G651 FUEL TANK SEALANT - NON-CURING

Conditioning	Pressure Rupture (In. Merc.)	Volume Swell (%)
Control	22	
7 Days @ 140F in JP-4	19	2
7 Days @ 140F in H.D.	30	11
6 Months @ 140F in JP-4	32	0
6 Months @ 140F in H.D.	25	-3
6 Months @ 140F in JP-4/H.D. alt. every month	38	1
12 Months @ 140F in JP-4	23	-2
12 Months @ 140F in H.D.	21	-2
12 Months @ 140F IN jP-4/H.D. alt every month	19	1
7 Days @ 77F in JP-4 + 7 Days @ 77F in H.D.	18	8
		11

TABLE 15

PERMEABILITY OF FUEL CELL BLADDER MATERIALS

Material	Permeability
51956	0.0185
in JP-8X	0.0186
H.D. Fuel	0.0133
Avg.	0.0168
51956	0.0290
in JP-4	0.0237
Avg.	0.0263
80C29	0.0945
in JP-8X	0.0811
H.D. Fuel	0.0856
Avg.	0.0871
80C29	0.1283
in JP-4	0.1110
Avg.	0.1196
82C39	0.1060
in JP-8X	0.1095
H.D. Fuel	0.1048
Avg.	0.1068
82C39	0.1894
in JP-4	0.1840
Avg.	0.1867

TABLE 16

51956 BLADDER MATERIAL - BUNA-N

Conditioning	Tensile Strength (psi)	Elongation (%)	Volume Change (%)
Control	2013	450	
7 Days @ 140F in JP-4	1858	394	1
7 Days @ 140F in HD	1715	471	7
6 Months @ 140F in JP-4	1035	150	0
6 Months @ 140F in HD	973	193	7
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1157	200	7
12 Months @ 140F in JP-4	713	50	-1
12 Months @ 140F in HD	835	134	6
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1048	101	6
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	1708	462	3
			6

TABLE 17

80C29 BLADDER MATERIAL - URETHANE

Conditioning	Tensile Strength (psi)	Elongation (%)	Volume Change (%)
Control	5352	310	
7 Days @ 140F in JP-4	4316	302	11
7 Days @ 140F in HD	4434	318	13
6 Months @ 140F in JP-4	6561	400	9
6 Months @ 140F in HD	6528	410	12
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	7027	396	12
12 Months @ 140F in JP-4	6885	388	10
12 Months @ 140F in HD	6933	438	13
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	7060	374	14
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	4173	324	10
			11

TABLE 18

82C39 BLADDER MATERIAL - URETHANE

Conditioning	Tensile Strength (psi)	Elongation (%)	Volume Change (%)
Control	4770	370	
7 Days @ 140F in JP-4	3448	377	13
7 Days @ 140F in HD	3452	406	18
6 Months @ 140F in JP-4	3336	442	16
6 Months @ 140F in HD	4044	480	25
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	4196	478	22
12 Months @ 140F in JP-4	3030	413	14
12 Months @ 140F in HD	3332	431	23
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	3756	415	24
7 Days @ 77F in JP-4 + 7 Days @ 77F in HD	3168	396	11
			17

TABLE 19

26950 SELF-SEALING BLADDER MATERIAL

Conditioning	Volume Change (%)
7 Days @ 77F in JP-4	0.5
	1.0
	0.6
	0.2
	0.4
Avg.	0.5
7 Days @ 77F in HD	4.9
	6.1
	4.6
	5.2
	6.1
Avg.	5.4

TABLE 20

BLADDER ADHESIVES - 1895C AND 80C29

Conditioning	1895C T-Peel Load(lbs)	% Cohesive	80C29 T-Peel Load(lbs)	% Cohesive
Control	26	100	31	100
7 Days @ 140F in JP-4	24	72	20	0
7 Days @ 140F in H.D.	32	80	24	0
6 Months @ 140F in JP-4	32	94	19	23
6 Months @ 140F in H.D.	36	90	15	20
6 Months @ 140F in JP-4/H.D. alt.every month	25	76	16	15
12 Months @ 140F in JP-4	24	88	23	10
12 Months @ 140F in H.D.	32	88	17	10
12 Months @ 140F in JP-4/H.D. alt.every month	24	72	14	25

TABLE 21

MIL-B-83054, TYPE III FUEL TANK FOAM

Conditioning	Tensile Strength (psi)	Elongation (%)	Volume Change (%)
Control	25	292	
7 Days @ 140F in JP-4	29	283	-11
7 Days @ 140F in HD	28	304	-12
6 Months @ 140F in JP-4	26	310	-1
6 Months @ 140F in HD	25	310	-2
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	25	300	1
12 Months @ 140F in JP-4	21	264	0
12 Months @ 140F in HD	22	270	-3
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	20	280	-3

TABLE 22

MIL-B-83054, TYPE V FUEL TANK FOAM

Conditioning	Tensile Strength (psi)	Elongation (%)	Volume Change (%)
Control	16	186	
7 Days @ 140F in JP-4	12	157	6
7 Days @ 140F in HD	13	173	8
6 Months @ 140F in JP-4	16	160	15
6 Months @ 140F in HD	25	210	14
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	16	170	15
12 Months @ 140F in JP-4	10	151	18
12 Months @ 140F in HD	14	174	24
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	11	136	22

TABLE 23

VOLUME RESISTIVITIES OF FUEL TANK FOAMS

Conditioning	Type III	Type V
Control	6.74E+12	1.35E+14
7 Days @ 140F/JP-4	9.19E+12	1.04E+14
7 Days @ 140F/H.D.	7.35E+12	1.22E+14
6 Months @ 140F/JP-4	6.74E+12	5.51E+12
6 Months @ 140F/H.D.	7.35E+12	4.59E+13
6 Months @ 140F/JP-4/H.D.	7.96E+12	5.51E+13
12 Months @ 140F/JP-4	3.61E+12	1.78E+13
12 Months @ 140F/H.D.	2.76E+12	1.59E+13
12 Months @ 140F/JP-4/H.D.	3.37E+12	2.33E+13

TABLE 24

STRUCTURAL ADHESIVES - EC3569, FM-47
AND AF126-2

Conditioning	EC-3569 Lap Shear Load(lbs)	% Coh.	FM-47 Lap Shear Load(lbs)	% Coh.	AF-126-2 Lap Shear Load(lbs)	% Coh.
Control	3304	100	3224	100	4957	100
7 Days @ 140F in JP-4	4024	100	2992	100	5252	100
7 Days @ 140F in H.D.	4130	100	2996	100	5318	100
6 Months @ 140F in JP-4	4094	100	3202	100	4968	100
6 Months @ 140F in H.D.	3707	100	3144	100	4924	100
6 Months @ 140F in JP-4/H.D. alt.every month	3775	100	3200	100	5291	100
12 Months @ 140 in JP-4	3846	100	3264	100	5143	100
12 Months @ 140 in H.D.	3932	100	3395	100	5279	100
12 Months @ 140 in JP-4/H.D. alt.every month	3534	100	3207	100	5464	100

TABLE 25

STRUCTURAL ADHESIVES - AF143-2, EPON 828/DTA, AND FM73/BR-127

Conditioning	AF 143-2 Lap Shear Load(lbs)	% Coh.	EPON 828/DTA Lap Shear Load(lbs)	% Coh.	FM-73/BR 127 Lap Shear Load(lbs)	% Coh.
Control	4628	100	1775	0	6192	100
7 Days @ 140F in JP-4	4340	100	2016	0	6020	100
7 Days @ 140F in H.D.	4330	100	2214	0	5780	100
6 Months @ 140F in JP-4	4290	100	1910	0	5444	100
6 Months @ 140F in H.D.	3988	100	1661	0	6156	100
6 Months @ 140F in JP-4/H.D. alt.every month	4270	100	2540	0	5962	100
12 Months @ 140F in JP-4	3864	100	2050	0	6390	100
12 Months @ 140F in H.D.	4325	100	2081	0	6438	100
12 Months @ 140F in JP-4/H.D. alt.every month	4026	100	2153	0	5223	100

TABLE 26

STRUCTURAL ADHESIVES - AF-10/EC1290 AND AF-10/EC3960

Conditioning	AF 10/EC1290 Lap Shear Load(lbs)	% Coh.	AF 10/EC3960 Lap Shear Load(lbs)	% Coh.
Control	2988	91	2700	87
7 Days @ 140F in JP-4	3652	93	3190	92
7 Days @ 140F in H.D.	3520	95	3200	85
6 Months @ 140F in JP-4	3192	92	2112	98
6 Months @ 140F in H.D.	3352	94	2297	90
6 Months @ 140F in JP-4/H.D. alt.every month	3296	95	2976	97
12 Months @ 140F in JP-4	2575	94	2570	83
12 Months @ 140F in H.D.	2737	95	2118	58
12 Months @ 140F in JP-4/H.D. alt.every month	2861	99	3034	82

TABLE 27

FUEL TANK COATINGS -
MIL-S-4383, MIL-C-27725 AND BMS 10-20

Conditioning	MIL-S-4383	MIL-C-27725	BMS 10-20
Control	HB	>9H	>9H
7 Days @ 140F in JP-4	2H	>9H	>9H
7 Days @ 140F in H.D.	HB	>9H	>9H
6 Months @ 140F in JP-4	HB	>9H	>9H
6 Months @ 140F in H.D.	HB	>9H	>9H
12 Months @ 140F in JP-4	HB	>9H	>9H
12 Months @ 140F in H.D.	HB	>9H	>9H
6 Months @ 140F in JP-4/H.D. alt.every month	3H	>9H	>9H
12 Months @ 140F in JP-4/H.D. alt.every month	HB	>9H	>9H

TABLE 28

TEFLON TFE WIRE INSULATION

Conditioning	Tensile Strength (psi)	Elongation (%)
Control	1868	250
7 Days @ 140F in JP-4	1877	240
7 Days @ 140F in HD	1927	220
6 Months @ 140F in JP-4	1956	276
6 Months @ 140F in HD	1992	192
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1966	226
12 Months @ 140F in JP-4	1689	230
12 Months @ 140F in HD	1675	154
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	1711	200

TABLE 29

NYLON 101 WIRE INSULATION

Conditioning	Tensile Strength (psi)	Elongation (%)
Control	10640	370
7 Days @ 140F in JP-4	10745	162
7 Days @ 140F in HD	10648	407
6 Months @ 140F in JP-4	10557	51
6 Months @ 140F in HD	9551	68
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	9968	81
12 Months @ 140F in JP-4	2664	8
12 Months @ 140F in HD	9938	16
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	8060	15

TABLE 30

POLYETHYLENE WIRE INSULATION

Conditioning	Tensile Strength (psi)	Elongation (%)
Control	3891	82
7 Days @ 140F in JP-4	3345	122
7 Days @ 140F in HD	3404	116
6 Months @ 140F in JP-4	3342	126
6 Months @ 140F in HD	3430	110
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	3383	136
12 Months @ 140F in JP-4	3267	87
12 Months @ 140F in HD	3220	90
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days	3217	102

TABLE 31

AR-184 SELF-SEALING HOSE

Conditioning	Tensile Strength (psi)	Elongation (%)	Volume Change %
Control	1548	568	--
7 Days @ 140F in JP-4	1128	414	21
7 Days @ 140F in HD	965	390	36
6 Months @ 140F in JP-4	889	288	45
6 Months @ 140F in HD	550	268	45
6 Months @ 140F in JP-4 + HD(alt.fuel every 30 days)	644	252	44
12 Months @ 140F in JP-4	227	10	38
12 Months @ 140F in HD	149	102	48
12 Months @ 140F in JP-4 + HD(alt.fuel every 30 days)	171	104	46

TABLE 32

SUMMARY OF MATERIALS/FUELS COMPATIBILITY

Material	Sensitivity to JP-4			Sensitivity to HDF		
	None	Slight	Large	None	Slight	Large
O-Ring Materials						
N602-70		X			X	
L-677-70	X			X		
V 747-75	X			X		
N506-70		X			X	
PNF953	X			X		
KKK-125			X			X
Fuel Tank Sealants						
(curing)						
PR 1422 B-2	X			X		
PS 890 B-2		X			X	
PR 1750 B-2		X			X	
Q4-2817	X				X	
PR 1221 B-2			X			X
(non-curing)						
PR 703		X				X
94-031	X			X		
G657	X			X		
Bladder Materials						
(bladders)						
51956		X			X	
80C29	X			X		
82C39	X			X		
(self-sealing)						
26950	X			X		
(repair adhesives)						
1895C		X			X	
80C29		X			X	
Fire Suppressant Foams						
Type III	X			X		
Type V	X			X		
Structural Adhesives						
EC 3569	X			X		
FM 47	X			X		
AF 126-2	X			X		
AF 143-2	X			X		
EPON 828/DTA	X			X		
FM 73 W/BR-127	X			X		
AF 10 W/EC 1290	X			X		
AF 10 W/EC 3950	X			X		
Fuel Tank Coatings						
MIL-S-8343	X			X		
MIL-C-27725	X			X		
BMS-10-20	X			X		
Wire Insulation						
Teflon TFE		X			X	
Nylon 101			X		X	
Polyethylene	X			X		
Self-Sealing Hose						
AR 184			X		X	

*U.S.Government Printing Office: 1989 —648-056/04393