GENERAL DECLASSIFICATION SCHEDULE

IN ACCORDANCE WITH
DOD 5200.1-R & EXECUTIVE ORDER 11652

THIS DOCUMENT IS:

Subject to General Declassification Schedule of Executive Order 11652-Automatically Downgraded at 2 Years Intervals- DECLASSIFIED ON DECEMBER 31, 1972

BY

Defense Documentation Center
Defense Supply Agency
Cameron Station
Alexandria, Virginia 22314

SECURITY
MARKING

The classified or limited status of this report applies to each page, unless otherwise marked.
Separate page printouts MUST be marked accordingly.

CONFIDENTIAL

AFRPL-TR-283

(Unclassified)

HEAT TRANSFER STUDY OF PREPACKAGED PROPELLANTS

Roger E Anderson
Donald C Rousar
Norman E Van Huff
Aerojet-General Corporation

TECHNICAL REPORT AFRPL-TR-66-283

October 1966

Downgraded at 3 Year Intervals
Declassified after 12 Years
DOD DIR 5200.10

In addition to security requirements which must be met, this document is subject to special export controls, and each transmittal to foreign governments or foreign nationals may be made only with prior approval of AFRPL (RPPR/STINFO), Edwards California, 93523

This document contains information affecting the National defense of the United States within the meaning of the Espionage Laws. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

prepared for

AIR FORCE ROCKET PROPULSION LABORATORY

Edwards Air Force Base California

1068

CONFIDENTIAL

NOTICES

AFRPL-TR-283

(Unclassified)

HEAT TRANSFER STUDY OF PREPACKAGED PROPELLANTS

Roger E Anderson
Donald C Rousar
Norman E Van Huff

"This document contains information affecting the National Defense of the United States within the meaning of the Espionage Laws, Title 18, U. S. C., Section 793 and 794. Its transmission or the revelation of its contents in any manner to an unauthorzied person is prohibited by law."

Downgraded at 3 Year Intervals
Declassified after 12 Years
DOD DIR 5200.10

In addition to security requirements which must be met, this document is subject to special export controls, and each transmittal to foreign governments or foreign nationals may be made only with prior approval of AFRPL (RPPR/STINFO), Edwards California, 93523

This document contains information affecting the National defense of the United States within the meaning of the Espionage Laws. Its transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

FOREWORD

This is the first quarterly technical report submitted in partial fulfillment of Contract AF 04(611)-11607, Heat Transfer Study of Prepackaged Propellants. The report period is 1 July through 30 September 1966. The Air Force Project Engineer is 1st/Lt. William H. Summers, RPCL.

The Heat Transfer Study of Prepackaged Propellants is being conducted by the Engineering Division of Liquid Rocket Operations, Aerojet-General Corporation, Sacramento, California.

Classified information has been extracted from the asterisked documents listed under References in Appendix A.

Contributors to this report, in addition to those noted on the title page, include the following Aerojet personnel:

N. B. Davidson

A. Fink

Y. W. Louie

R. J. Wondra

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

UNCLASSIFIED ABSTRACT

This report summarizes the work performed during the first three months of an experimental program in which the forced-convection and burnout heat flux characteristics of MHF-5 and MMH are to be investigated. The results of 20 tests conducted with MHF-5 at pressures from 500 to 3000 psia, velocities from 19.5 to 189 ft/sec, bulk temperatures from 70 to 278°F, and at heat fluxes up to 49.6 Btu/in^2 sec are presented and discussed, correlations for the burnout heat flux of MHF-5 at subcritical and supercritical pressures are presented. The physical properties that were extrapolated from available data and estimated are presented in an appendix, along with discussions on the extrapolation and estimation techniques that were used. The results of chemical analyses performed on MHF-5 samples taken from the heat transfer test system before and after testing are also presented.

TABLE OF CONTENTS

TABLE LIST

FIGURE LIST

I. INTRODUCTION

The objective of this program is to experimentally determine the forced-convection heat transfer and burnout heat flux characteristics of MHF-5 and monomethyl hydrazine (MMH) at subcritical and supercritical pressures. The work is to be accomplished in three phases. Phase I consists of a literature survey for the available MHF-5 and MMH physical properties, analytical determination of the physical properties of MHF-5 and MMH not available from the literature, and the equipment buildup work necessary to prepare Aerojet's high pressure heat transfer loop for MHF-5 testing. Phase II consists of testing with MHF-5, and Phase III consists of testing with MMH.

II. SUMMARY

Preparation of the heat transfer loop for testing and the literature survey for MHF-5 and MMH physical properties have been completed. The available MHF-5 properties data have been extrapolated to a pressure of 400 atmospheres and 685°F and a complete compilation of the available and estimated MHF-5 physical properties is given as an appendix to this report. A similar compilation of MMH physical properties will be completed during the next reporting period.

Approximately 100 gallons of MHF-5 have been mixed and chemical analyses of the propellant have been obtained using a gas chromatograph and a nitron precipitation test.

Twenty MHF-5 heat transfer tests have been conducted at pressures of from 500 to 3000 psia, velocities of from 19.5 to 189 ft/sec, and bulk temperatures of from 70 to 278°F. Heat fluxes up to 49.6 Btu/in.^{2} sec have been achieved. In these tests, the forced convection and burnout heat flux characteristics of MHF-5 were evaluated in Inconel 718 and 347 stainless steel test sections. Extended duration behavior has also been investigated.

III. LITERATURE SURVEY AND PHYSICAL PROPERTIES

To properly determine and evaluate the forced-convection heat transfer characteristics of MHF-5 and MMH, certain physical and transport properties of these fuels must be known over a wide range of temperatures and pressures. The most significant properties from a heat transfer standpoint include density, viscosity, heat capacity, thermal conductivity, and vapor pressure. In general, these properties are neither available in the literature nor readily measurable over the required range of temperatures (-65°F to the critical temperature) and pressures (saturation to approximately 5000 psia); therefore, estimation techniques must be employed to either extend experimental data or totally generate properties information in the absence of experimental data. The most desirable estimation techniques vary considerably from one fluid to another and often vary with the property. The accuracy of such estimations is always open to question, but fortunately only a modest level of accuracy (perhaps ±10 to 20% is necessary to properly conduct a test program and to evaluate and correlate the test data. Certainly, the best set of property data that can be developed within the scope of the program is desired. In this program the approach to developing a "best set" of properties data involves: (1) a careful literature search to retrieve all available data and thereby minimize reliance upon estimation techniques, and (2) the use of the most proven estimation techniques (generally those based on the theory of corresponding states).

A. LITERATURE SURVEY

A search of the literature for information relative to the physical and transport properties of MHF-5 and MMH has been completed. This survey utilized both computer and hand search techniques. Computer searches covered the holdings of NASA, Defense Documentation Center (DDC), and Aerojet-General libraries. Hand searches were made on the Aerojet libraries holdings, CPIA Abstracts, and Chemical Abstracts. In addition, the contents of Aerojet's propellant files and of the standard liquid propellant manuals and handbooks (CPIA and Battelle Memorial Institute) were reviewed.

On the basis of literature searches, originals of documents that appeared pertinent were secured and screened for content and further references. Those documents which contained pertinent properties data were then abstracted in-depth in the areas of interest. The abstracts, thus, concisely provided the available literature data and the starting points from which extrapolation and estimation techniques were employed to extend the data.

B. PHYSICAL PROPERTIES

1. MHF-5

As expected, the literature data on MHF-5 were relatively scanty on most of the properties of interest and entirely missing in the cases of critical properties and thermal conductivity. Data were found on the density of MHF-5 from -65.2 to 194°F, on viscosity from -67 to 160°F, on heat capacity from 40 to 155°F, and on vapor pressure from 32 to 203°F. No properties data were found covering temperature greater than 203°F or pressures greater than one atmosphere.

Since properties data are required from approximately -65°F to the critical temperature and from saturation pressure to approximately 5000 psia, extensive estimation and extrapolation was necessary to generate the required data. These estimations and extrapolations have been completed and a complete set of MHF-5 physical properties is given in an appendix to this report. The experimental data retrieved and the methods employed in generating or extending the data are also fully documented in the appendix. Because reduced state correlations were extensively utilized to extend the data on density, viscosity, and heat capacity, and to generate thermal conductivity data; significant effort was devoted to estimating a set of critical properties. The methods used to estimate the critical properties are also documented in the appendix.

No experimental work was done to define properties except for the measurement of surface tension and index of refraction. These measurements were made because of their usefulness in estimating critical volume and because they are easily obtained.

III, B, Physical Properties (cont.)

Significant properties values (or references to appropriate discussions, tables, and figures in the appendix) are summarized below:

Property	Value	Citation in Appendix Section	Table	Figure
Critical Pressure	1470 lb/in.^{2}	I	-	-
Critical Temperature	1145°R	II	-	-
Critical Density	0.316 g/cm^3	III	-	-
Density	-	IV	-	3 and 4
Viscosity	-	V	1	5 and 7
Heat Capacity	-	VI	2	9
Thermal Conductivity	-	VII	-	11
Vapor Pressure	-	I,B and VIII	4	1 and 12

2. MMH

The properties of liquid MMH are much better known than those for MHF-5. The critical properties are known, the density is known over a wide range of temperatures (~-60 to 518°F) and at pressures to 92.9 atm, the viscosity is known from -60 to 176°F, heat capacity from -62 to 77°F, thermal conductivity from 0 to 305°F, and vapor pressure from ~35°F to the critical temperature. With this relatively large amount of data available, the extension of the data to the critical temperature and to pressures of approximately 5000 psia will present far less a problem than in the case of MHF-5. The estimations and extrapolations of density, viscosity, heat capacity and thermal conductivity remain to be completed.

IV. EQUIPMENT BUILDUP

Preparation of Aerojet's high pressure heat transfer loop for testing with MHF-5 was completed during this report period. The following tasks were accomplished:

1. The loop was cleaned. The loop cleaning procedure was initiated by flushing methanol through the system with gaseous nitrogen pressurization. The methanol was then dumped and the system blown dry with gaseous nitrogen. The flushing with methanol and drying with gaseous nitrogen were then repeated. Methanol and nitrogen were discharged through all of the loop outlets in this second operation.

   Examination of the loop fittings then revealed significant "gumming" of the fittings in the dump tank system which was apparently caused by a reaction between AeroZINE 50 (a test program on this propellant was conducted before this program started) and the sealant which had been applied to the threads of these fittings. The dump tank system was then completely disassembled, cleaned, and reassembled using a thread sealant which is compatible with hydrazine fuels.

   The entire loop was then flushed with methanol, blown dry with gaseous nitrogen, evacuated with a vacuum pump for a period of ten hours, and placed under a 10 psi nitrogen blanket. Special passivation of the loop for MHF-5 service was not performed as the long exposure to AeroZINE 50 (about 2-1/2 months) provided sufficient passivation.

2. Pressure transducers, bulk temperature thermocouples, and flowmeters were checked out and installed.

3. The instrumentation recording system was checked out from the sensing element to the recording device.

4. Electrical insulators in the region of the test section were cleaned, checked for integrity, and reinstalled.

5. Water injection systems for the drain and vent lines were installed and pressure checked to 350 psi. These systems provide thorough flushing of the drain and vent lines and prevent the formation of shock-sensitive hydrazine nitrate crystals.

6. A precooler that will be used to obtain low MHF-5 bulk temperatures was fabricated. The cooler consists of an 80 ft coil, through which the MHF-5 will flow, installed in a liquid nitrogen container. During a low bulk temperature test this coil will be immersed in liquid nitorgen. The coil was fabricated from stainless steel tubing having an OD of 1/2 in. and a wall thickness of 0.035 in. Electrodes were attached to the precooler coil so that it can be preheated prior to initiating MHF-5 flow. Preheating of the coil is necessary to prevent freezing of the MHF-5 during the starting transient.

V. PROPELLANT MIXING AND CHEMICAL ANALYSIS

(c) Five 20-gallon batches of MHF-5 were mixed prior to the start of testing. Each batch of propellant was prepared by mixing 92.9 lb of MMH, 54.7 lb of N_2H_4, and 27.01 lb of NH_4NO_3. Ammonia was removed from the propellant by pumping off the vapor generated when the propellant was heated to a temperature of 85 to 100°F. Density measurements of these five batches ranged from 1.008 to 1.011 gm/cc at a temperature of 77°F, which compares well with the value of 1.010 given in Figure 4 of the appendix.

(u) No further propellant mixing is contemplated. Propellant loss resulting from physical burnout of the test section has reduced the volume of MHF-5 in the heat transfer system to about 80 gallons; however, this is considered a sufficient quantity to conduct the remaining MHF-5 test program.

(u) Some difficulties were encountered in obtaining chemical analyses of the MHF-5. The results obtained with a gas chromatograph (the only available device for analyzing MHF-5) tended to be inconsistent due to retention of hydrazine nitrate in the components of the chromatograph system. Several chromatograph column materials were tried with varying degrees of success. The best results were obtained with 5% Carbowax 600 (polyethylene glycol) on Teflon. This is the material used to obtain AeroZINE 50 chemical analyses.

(u) The results listed below were obtained for MHF-5 samples taken from the heat transfer loop and for an MHF-5 laboratory sample. The concentrations of all constituents except the hydrazine nitrate were determined from gas chromatograph readings. The nitrate concentration was determined gravimetrically in a nitron precipitation test. These results are considered adequate for this heat transfer program, but not entirely satisfactory as a precise analysis because the estimated accuracy for the MMH and N_2H_4 constituents is ±1 to 2 wt%. Further investigation into improved MHF-5 chemical analysis techniques is recommended; however, this effort is considered beyond the scope of this program. Future analyses will be carried out using the AeroZINE 50 column material along with the nitron precipitation test.

V, Propellant Mixing and Chemical Analysis (cont.)

(c)

	Sample	MMH Wt%	N_2H_4 Wt%	$N_2H_5NO_3$ Wt%	H_2O Wt%	NH_3 Wt%	Date
1.	Lab Standard	54.0	23.9	19.8	0.2	2.1	8-31-66
		53.5	24.3	19.8	0.5	1.9	
2.	From Run Tank Prior to Testing	55.7	25.6	17.7	0.8	0.2	8-31-66
		56.3	24.6	17.7	1.2	0.2	
3.	Before Test -110	54.2	26.2	18.4	0.9	0.3	9-16-66
4.	From Run Tank Prior to Testing	53.8	26.5	18.4	1.0	0.3	9-16-66
5.	Before Test -114 (Extended Duration Test)	53.5	26.9	18.3	1.0	0.3	9-23-66
6.	After Test -114	53.0	27.3	18.4	1.0	0.3	9-23-66
7.	From Run Tank Prior to Testing	52.7	27.5	18.35	1.0	0.3	9-23-66
	Nominal Values	55.0	26.0	19.0	---	---	

(u) These results indicate: (1) the composition of the propellant that was prepared is sufficiently close to the nominal composition of MHF-5, and (2) there was no significant decomposition of the MHF-5 during the course of testing.

VI. MHF-5 TESTING

A. ACCOMPLISHMENTS

Twenty MHF-5 heat transfer tests have been conducted. The range of conditions encountered in these tests are as follows:

Pressure:	500 to 3000 psia
Velocity:	19.5 to 189 ft/sec
Bulk Temperature:	70 to 278°F
Heat Flux:	up to 49.6 Btu/in.^{2} sec

Eighteen of these tests were burnout tests in which the burnout or ultimate heat flux and the forced-convection heat transfer characteristics of MHF-5 were evaluated. In two tests, extended duration heat transfer with MHF-5 at heat fluxes up to 80% of the burnout heat flux were investigated.

During this reporting period, testing at nominal subcritical pressure levels of 500 and 1000 psia has been emphasized and 16 tests (14 burnout tests and 2 extended duration tests) were conducted at these pressures. Four burnout tests were conducted at a supercritical pressure level of 3000 psia.

Test sections were uniformly heated Inconel 718 and 347 stainless steel tubes with 3/16 in. and 1/4 in. OD and 0.012 to 0.024 in. wall thickness. The test sections are shown in post-test condition in Figures 1, 2, and 3.

Preliminary analysis of the data obtained in these tests has been accomplished using the liquid densities and specific heats given in Ref 1, and the results obtained are presented in the following sections of this report. Final analysis and correlation of these data will be accomplished during the next quarterly report period using the physical properties given in the appendix.

B. RESULTS OF SUBCRITICAL PRESSURE TESTS

1. Burnout Test Results

Fourteen burnout tests have been conducted with MHF-5 at subcritical pressures; the results are summarized in Table 1. In 12 of these tests, the heat flux was increased incrementally until physical failure, or burnout, of the test section occurred. Physical burnout did not occur during Tests HT-8-101 and -120. Test -101 was terminated before burnout due to a power supply problem; however, forced convection data were obtained at three heat flux levels prior to shutdown. Test -120 was terminated at a heat flux of 49.6 Btu/in.^{2} sec when the fluid level in the run tank became precariously low. Steady-state heat transfer was achieved at five lower heat flux levels. It is believed that burnout was imminent at the 49.6 Btu/in.^{2} sec heat flux because the test section was observed (via closed-circuit television) to suddenly "glow" just as the test section power was shut off. In previous tests with MHF-5, this "glowing" has been observed to immediately precede physical burnout of the test section. Posttest photographs of the test sections are shown in Figures 1, 2, and 3.

The data obtained to date indicate that in stainless steel test sections the heat transfer characteristics of MHF-5 at subcritical pressures are similar to those observed for many other fluids at subcritical pressures. Two distinct heat transfer mechanisms are apparent, as demonstrated in Figures 4 through 7, which show test section heat flux as a function of inside tube wall temperature (calculated from outer wall temperature and electrical power measurements) for velocities of 20, 50, 100, and 150 ft/sec.

At wall temperatures below the saturation temperature, a normal forced-convection heat transfer mechanism is evident as the heat flux is proportional to the wall-to-bulk fluid temperature difference and the slope of the heat flux - wall temperature curve increases with increasing velocity. Nucleate boiling is generally evidenced at wall temperatures higher than the saturation temperature by a sharp

VI, B, Results of Subcritical Pressure Tests (cont.)

increase in the slope of the heat flux - wall temperature curve. The wall temperature data obtained at 1000 psia pressure and 150 ft/sec velocity (Figure 7, Tests -103 and -106) indicate nucleate boiling behavior at wall temperatures somewhat below the saturation temperature. These data should be considered preliminary and are currently being reviewed.

Burnout occurs when the test section wall temperature increases suddenly at a fixed heat flux. This excursion in wall temperature is attributed to the occurrence of a transition from nucleate boiling to film boiling at the tube wall. High frequency whistling has been heard in each of the subcritical pressure tests conducted at 20 to 50 ft/sec velocity. This whistling generally begins at 50 to 75% of the burnout heat flux and continues until burnout. No relation between the occurrence of whistling and the magnitude of the burnout heat flux is apparent.

Somewhat different heat transfer characteristics have been observed with subcritical MHF-5 in Inconel 718 test sections. The data obtained in two tests with Inconel 718 test sections, Tests HT-8-104 and -105, at nominal conditions of 150 ft/sec velocity, 1000 psia pressure, and 150°F bulk temperature, are shown in Figure 8. These data indicate a rather gradual increase in heat transfer coefficient as burnout is approached instead of the sharp transition from forced convection heat transfer to nucleate boiling heat transfer indicated by the stainless steel test section data. Furthermore, as shown in Table 1, the burnout heat fluxes observed in these Inconel 718 tests are about 30% lower than the values observed in two tests with 347 stainless steel test sections at the same nominal test conditions (Tests HT-8-103 and -106). This apparent difference in heat transfer characteristics suggests a basic incompatibility between Inconel 718 and MHF-5 at subcritical pressures. Such an incompatibility has previously been indicated by the results reported in Ref 2.

Correlations for the burnout heat flux of MHF-5 at subcritical pressures are shown in Figures 9 and 10. In figure 9, the burnout heat flux is shown as a function of the velocity - subcooling product. As discussed in Ref 2, this velocity - subcooling product has been found to correlate the burnout heat flux of many fluids. The MHF-5 data also correlate with this parameter; however, a pronounced effect of pressure is also evident. This pressure effect is not generally observed with other fluids.

The burnout heat fluxes observed with MHF-5 at 1000 psia nominal pressure show fairly good agreement with the correlation developed for N_2H_4 (Ref 2):

$$\phi_{Bo} = 5.0 + 0.000\,445\, V\Delta T_{sub}$$

where:

ϕ_{Bo} = burnout heat flux, Btu/in.^{2} sec

V = velocity, ft/sec

ΔT_{sub} = subcooling = $T_{sat} - T_B$, °F

T_{sat} = saturation temperature, °F

T_B = bulk temperature, °F

The 500 psia burnout heat fluxes are higher than the 1000 psia values. For a given value of $V\Delta T_{sub}$ this difference is about 40%.

The effect of pressure is not as significant in the correlation presented in Figure 10, which shows burnout heat flux as a function of velocity. This velocity correlation does not show the pronounced effect of pressure evidenced in the $V\Delta T_{sub}$ correlation; however, the correlation of data at a given pressure is not as precise.

VI, B, Results of Subcritical Pressure Tests (cont.)

The forced-convection data will be correlated in terms of the dimensionless Nusselt, Reynolds, and Prandtl numbers during the next reporting period, using the MHF-5 physical properties tabulated in the appendix.

2. Extended Duration Test Results

The operating conditions of the two extended duration tests, Tests HT-8-113 and -114, are summarized in Figures 11 and 12. In each of these, normal steady-state operation was maintained for a total duration of eight minutes and no unusual occurrences were observed. Some degradation of the tube wall thermocouple integrity with time was observed, particularly in Test -114, as evidenced by a slowly decreasing wall temperature.

Test -113 was conducted at nominal conditions of 50 ft/sec velocity, 500 psia pressure, and 150°F bulk temperature, and at heat fluxes of 8.5 and 9.5 Btu/in.^{2} sec. These heat flux levels correspond to about 50 and 60% of the burnout heat flux indicated by the 500 psia $V\Delta T_{sub}$ correlation shown in Figure 9. Whistling was heard at both heat flux levels during this test.

The nominal conditions of Test -114 were: 150 ft/sec velocity, 1000 psia pressure, and 150°F bulk temperature. Heat flux levels of 25.5 and 29.5 Btu/in.^{2} sec, which correspond to 70 and 80% of the burnout heat flux, were employed.

C. SUPERCRITICAL PRESSURE TEST RESULTS

Testing with MHF-5 at the 3000 psia level consisted of four burnout tests at 150°F bulk temperature and at velocities of 20, 50, and 100 ft/sec. Physical burnout of the test section occurred in each of these tests and the test results are summarized in Table 2.

VI, C, Supercritical Pressure Test Results (cont.)

The wall temperature and heat flux data obtained in three of the 3000 psia tests (50 and 100 ft/sec velocity) are shown in Figure 13. These data indicate that MHF-5 exhibits a normal forced-convection heat transfer mechanism until the temperature of the wall adjacent to the fluid approaches the MHF-5 critical temperature (estimated as 685°F). At this point, an apparent degradation in heat transfer coefficient occurs. This degradation is more apparent in the 100 ft/sec tests (Tests HT-8-107 and -108) than in the 50 ft/sec test (Test -109). In all three tests, burnout occurred when the wall temperature achieved or exceeded the critical temperature. At supercritical pressures, the occurrence of burnout at wall temperatures near the critical temperature is not unexpected since at this temperature fluids generally become gas-like in nature rather than liquid-like, and a [illegible] in heat transfer coefficient would be expected. This type of burnout has previously been observed with ClF_3 at a supercritical pressure.

A significant characteristic of the burnouts observed at 300 psia is that increasingly large negative test section energy balances are indicated as the burnout heat flux is approached. A negative energy balance indicates that the MHF-5 bulk temperature rise is higher than the electrical power measurements would indicate. Energy balances within ± 10% have been consistently observed in the subcritical pressure testing, but excess energies from -17% to -57% occur at burnout in the 3000 psia tests. This implies that some exothermic decomposition of the MHF-5 is occurring as the burnout heat flux is approached; this exothermic decomposition may contribute to the degradation of heat transfer coefficient which causes burnout. As noted previously in this report, no significant amounts of MHF-5 decomposition have been measured during the course of testing. The amount of MHF-5 decomposition required to yield the observed excess energies has been estimated as about 0.5 wt%. This relatively small amount of decomposition is difficult to detect since it occurs only near the burnout point and thus will not affect the bulk of the MHF-5 propellant.

VI, C, Supercritical Pressure Test Results (cont.)

The burnout heat flux data obtained to date correlate quite well with velocity as demonstrated in Figure 10. The relative effects of pressure and bulk temperature are unknown at this time, and will be investigated during the next reporting period. The effect of test section material on burnout heat flux at 3000 psia pressure does not appear as significant as in the subcritical tests. This is indicated by the results of Tests HT-8-107 and -108 (shown in Figure 13 and Table 2), which were conducted with Inconel 718 and 347 stainless steel test sections at the same nominal test conditions. The burnout heat flux observed with the stainless steel test section is about 10% higher than the value obtained with Inconel 718, whereas differences on the order of 30% were observed at subcritical pressures. Further testing to evaluate the material effect at 3000 psia pressure is planned.

VII. FUTURE TESTING

The remaining tests for the MHF-5 test program are shown in Table 3. The majority of these will be conducted at supercritical pressure levels of 2000, 3000, and 4000 psia. In the remaining subcritical pressure tests, the effect of high bulk temperatures, very low bulk temperatures, and pressures near the critical pressure on the burnout heat flux will be evaluated. It is currently anticipated that a total of 35 MHF-5 heat transfer tests will be conducted.

The MHF-5 testing will be followed by the MMH testing.

REFERENCES

1. "Advanced Propellant Investigation for Prepackaged Liquid Engines," Reaction Motors Report RMD 5046 - Q2 (Confidential).

2. "Correlation of Burnout Heat Flux for Fluids at High Velocity and High Subcooling Conditions," D. C. Rousar, M.S. Thesis, University of California, Davis, June 1966.

TABLE 1

BURNOUT TEST RESULTS FOR MHF-5 AT SUBCRITICAL PRESSURES

Parameters Given are for the Maximum Heat Flux
Condition at the Burnout Site
(or Test Section Outlet)

Test No.	ϕ, $\frac{\text{Btu}}{\text{in.}^2\text{sec}}$	V*, $\frac{\text{ft}}{\text{sec}}$	P, psia	T_B, °F	Heat Balance* tr %	Test Section	Remarks
HT-8-101	3.25	46.4	522	86.3	+ 6.2	347 Stainless 1/4x0.016x6.0	No Burnout. Outlet conditions given.
-102	14.48	51.3	531	204.9	-10.3	347 Stainless 1/4x0.016x6.0	Burnout, $X_{Bo}^{(**)} = 0.1$ Whistling at $\phi = 7$ to burnout
-103	33.25	156.0	1075	178.5	-10.6	347 Stainless 3/16x0.016x4.0	Burnout, $X_{Bo} = 0.4$
-104	22.0	141.6	1067	135.1	- 7.0	Inconel 718 3/16x0.015x3.5	Burnout, $X_{Bo} = 1.0$
-105	24.84	148.6	1055	150.0	- 3.1	Inconel 718 3/16x0.015x3.5	Burnout, $X_{Bo} = 0.9$
-106	33.43	155.7	1074	167.8	- 9.4	347 Stainless 3/16x0.016x4.0	Burnout, $X_{Bo} = 1.0$
-110	7.49	19.5	512	217.4	- 3.5	347 Stainless 1/4x0.016x5.5	Burnout, $X_{Bo} = 0.1$ Whistling at $\phi = 4$ to burnout
-111	11.64	53.1	1024	215.1	- 9.3	347 Stainless 1/4x0.016x5.0	Burnout, $X_{Bo} = 0.1$ Whistling at $\phi = 9$ to burnout
-112	22.96	97.1	1031	141.0	- 5.3	347 Stainless 3/16x0.0.6x4.0	Burnout, $X_{Bo} = 0.6$

(*) Preliminary Data, Heat Balance = $(Q_{in} - Q_{out})/Q_{in}$: Q_{in} = input electrical energy = 0.948×10^{-3} EI, Btu/sec

Q_{out} = output sensible energy = $w\, C_p \Delta T_B$, Btu/sec

(**) X_{Bo} = Distance between burnout site and downstream end of heated test section length, in.

TABLE 1 (cont.)

BURNOUT TEST RESULTS FOR MHF-5 AT SUBCRITICAL PRESSURES

Parameters Given are for the Maximum Heat Flux
Condition at the Burnout Site
(or Test Section Outlet)

Test No.	ϕ, $\frac{\text{Btu}}{\text{in.}^2\text{sec}}$	V*, $\frac{\text{ft}}{\text{sec}}$	P psia	T_B °F	Heat Balance*, tr %	Test Section	Remarks
-115	39.7	156.1	652	178.1	+ 0.1	347 Stainless 3/16x0.02x4.0	Burnout, $X_{Bo} = 0.1$
-116	22.8	108.7	552	276.8	- 1.2	347 Stainless 3/16x0.024x6.0	Burnout, $X_{Bo} = 0.1$
-117	19.5	97.2	1071	264.6	-11.0	347 Stainless 3/16x0.024x6.0	Burnout, $X_{Bo} = 0.1$
-119	12.77	50.5	536	264.4	+ 1.2	347 Stainless 1/4x0.016x4.5	Burnout, $X_{Bo} = 0.1$ Whistling at $\phi = 7$ to burnout
-120	49.6	189.0	1071	108.7	- 0.1	347 Stainless 3/16x0.012x1.5	No Physical Burnout Burnout "imminent"

(*) Preliminary Data, Heat Balance = $(Q_{in} - Q_{out})/Q_{in}$: Q_{in} = input electrical energy = 0.948×10^{-3} EI, Btu/sec

Q_{out} = output sensible energy = $w\, C_p\, \Delta\, T_B$, Btu/sec

TABLE 2

BURNOUT RESULTS FOR MHF-5 AT SUPERCRITICAL PRESSURE

Parameters Given are for the Maximum Heat Flux
Condition at the Burnout Site

Test No.	ϕ, $\frac{\text{Btu}}{\text{in.}^2\text{sec}}$	V*, $\frac{\text{ft}}{\text{sec}}$	P, psia	T_B, °F	Heat Balance* tr %	Test Section	Remarks
HT-8-107	11.15	104.1	3036	162.9	-24	Inconel 718 3/16x0.024x5.0	Burnout, X_{Bo} = 0.7 Ht. Bal. = 4.5 to -24%
-108	12.22	104.0	2987	157.2	-17.2	347 Stainless 3/16x0.024x5.0	Burnout, X_{Bo} = 1.3 Ht. Bal. = -0.7 to -17.2%
-109	5.74	50.5	2990	156.2	-57	Inconel 718 3/16x0.015x5.5	Burnout, X_{Bo} = 1.3 Ht. Bal. = -1.1 to -57%
-118	3.07	19.1	2962	148.7	-53	Inconel 718 1/4x0.015x5.5	Burnout, X_{Bo} = 0.5 Ht. Bal. = -3.8 to -53%

(*) Preliminary Data, Heat Balance = $(Q_{in} - Q_{out})/Q_{in}$

Q_{in} = input electrical energy = 0.948×10^{-3} E I, Btu/sec

Q_{out} = output sensible energy = W C_p T_B, Btu/sec

(**) X_{Bo} = Distance between burnout site and downstream end of heated test section length, in.

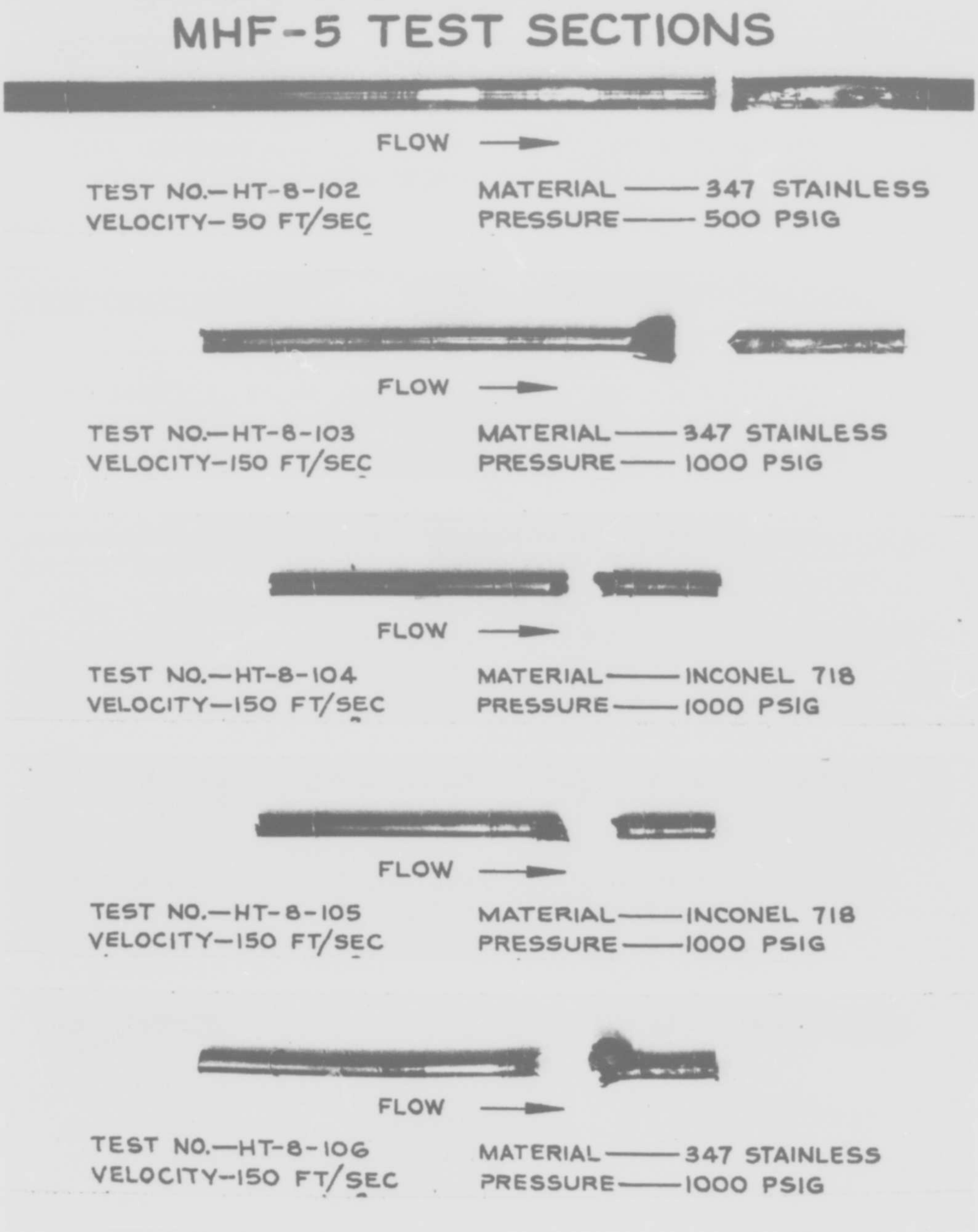
TABLE 3

REMAINING MHF-5 TESTS

Test No.	Objective	P, psia	V, ft/sec	T_B, °F (1)
21	High Bulk Temperature (Repeat of Test HT-8-119)	500	50	300
22	Low Bulk Temperature	500	50	-5
23		1000		10
24		3000	100	0
25	Material Effects at High Pressure (Repeat of Test HT-8-109 conditions)	3000	50	150
*26	Critical Pressure Effect	1400	50	200
27	Velocity Effects	3000	150	150
28		3000	200	150
29	Duration Effects	3000	50	150
30		3000	150	150
*31	Pressure Effects	2000	50	150
*32		4000	50	150
33	High Bulk Temperature	3000	50	300
34	Pressure Effects	2000	150	150
35		4000	150	150

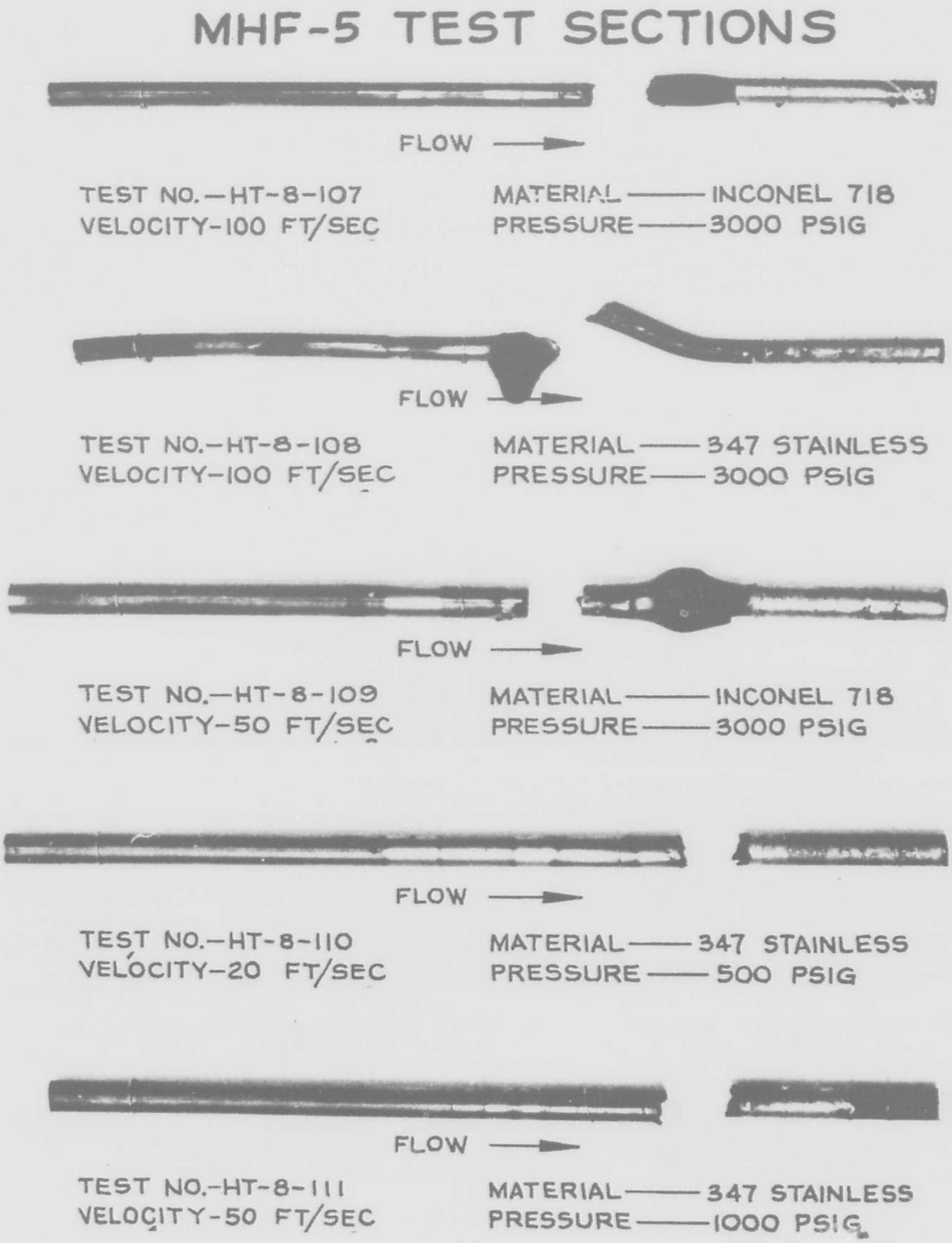
(1) Bulk Temperature at test section outlet

* Velocity reduced from 100 ft/sec to 50 ft/sec so that the effect of pressure can be evaluated with the minimum number of tests from 500 to 4000 psia at constant velocity and essentially constant bulk temperature conditions (by comparing the results to the burnout data obtained in tests -102, -111, and -109)



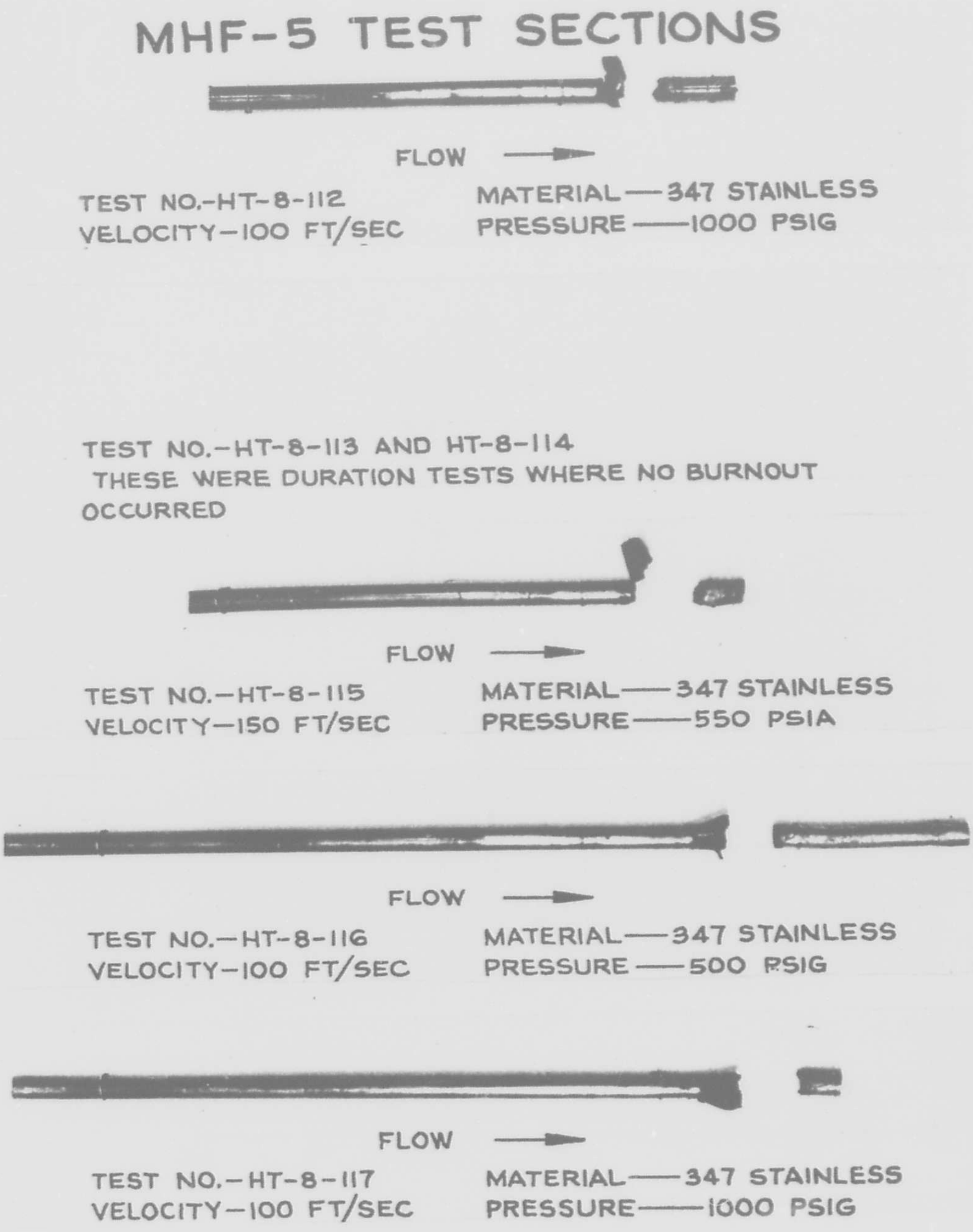
MHF-5 Test Section after Tests HT-8-102 through -106

Figure 1



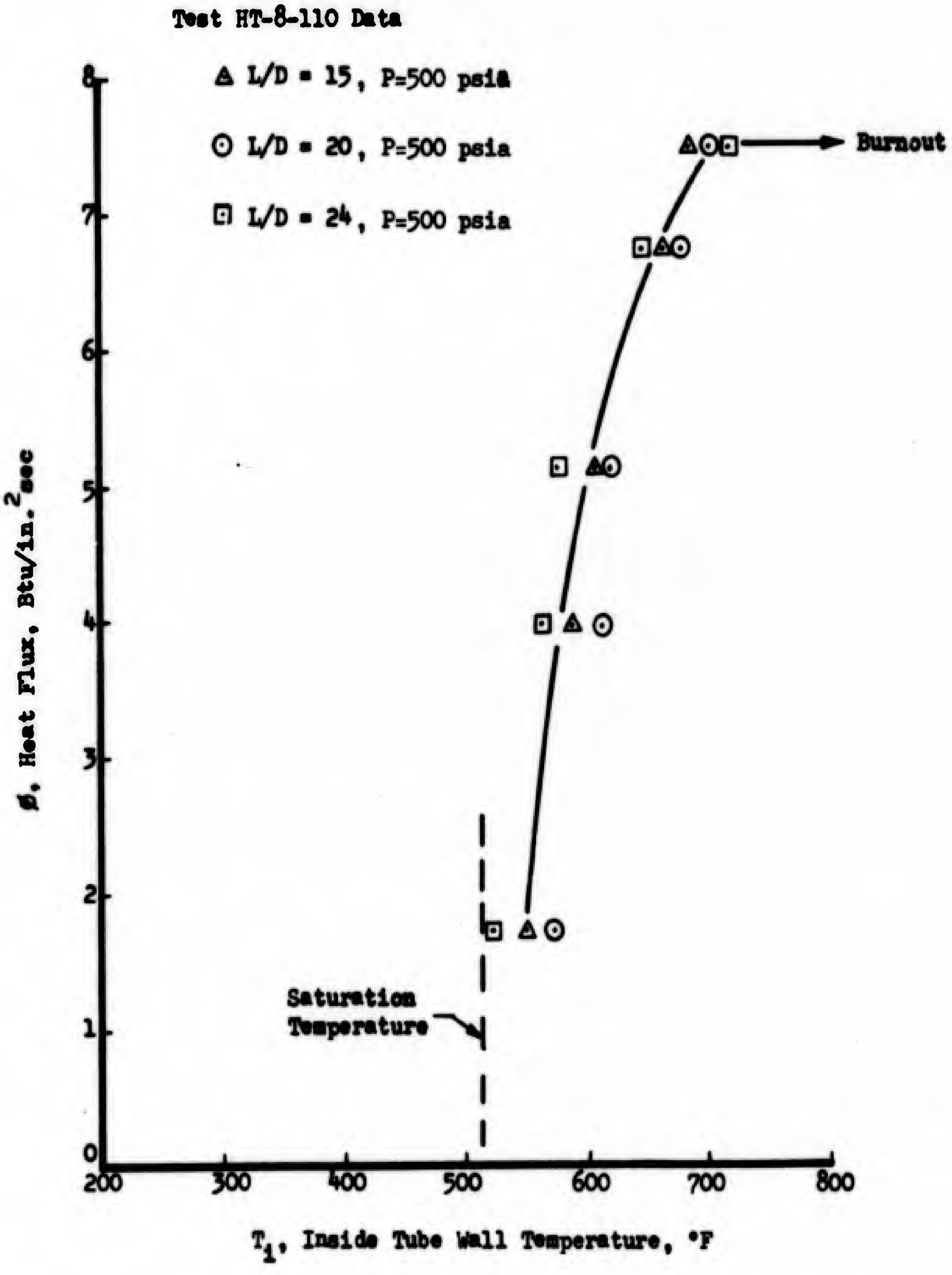
MHF-5 Test Section after Tests HT-8-107 through -111

Figure 2



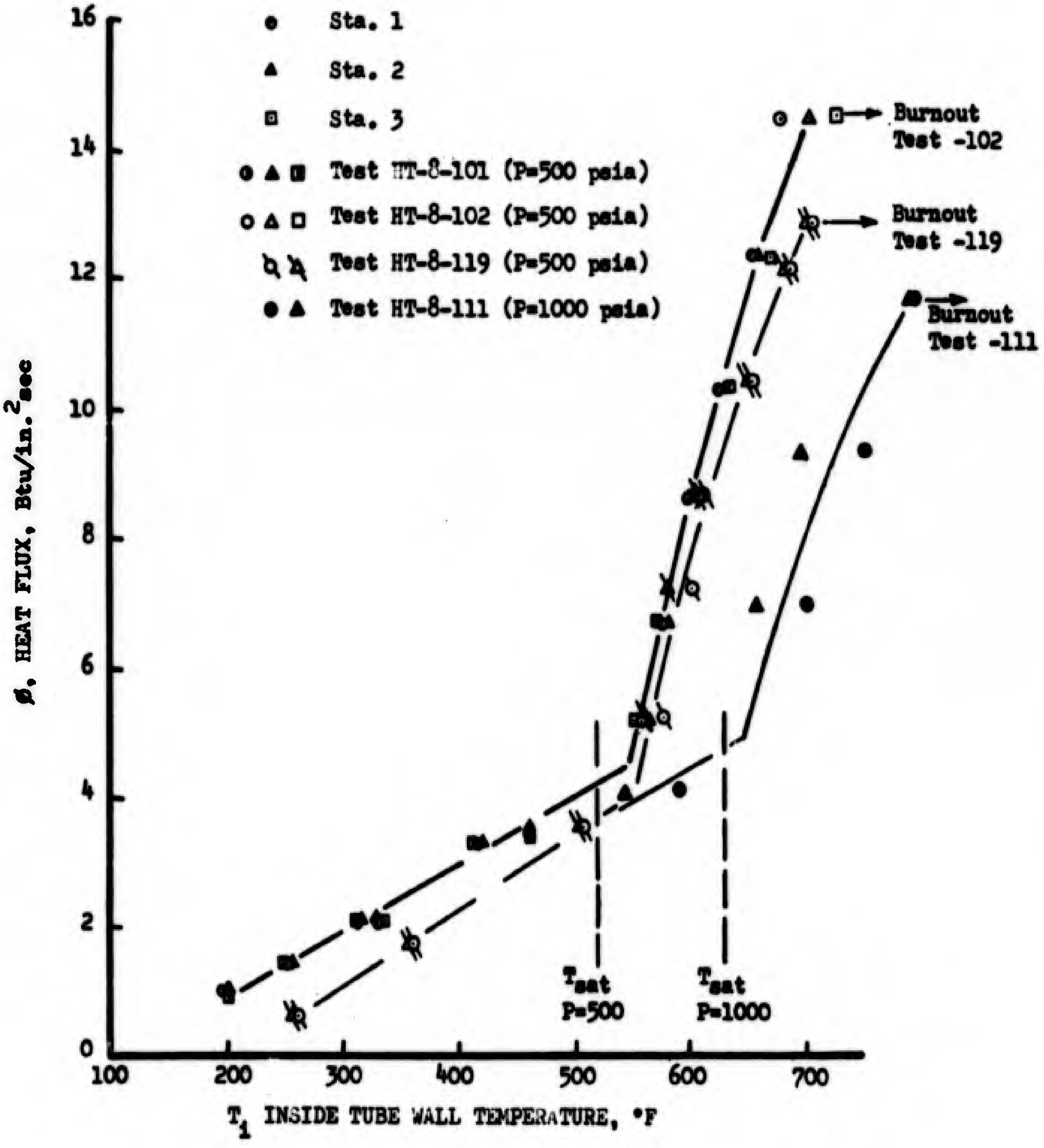
MHF-5 Test Section after Tests HT-8-112 through 117

Figure 3



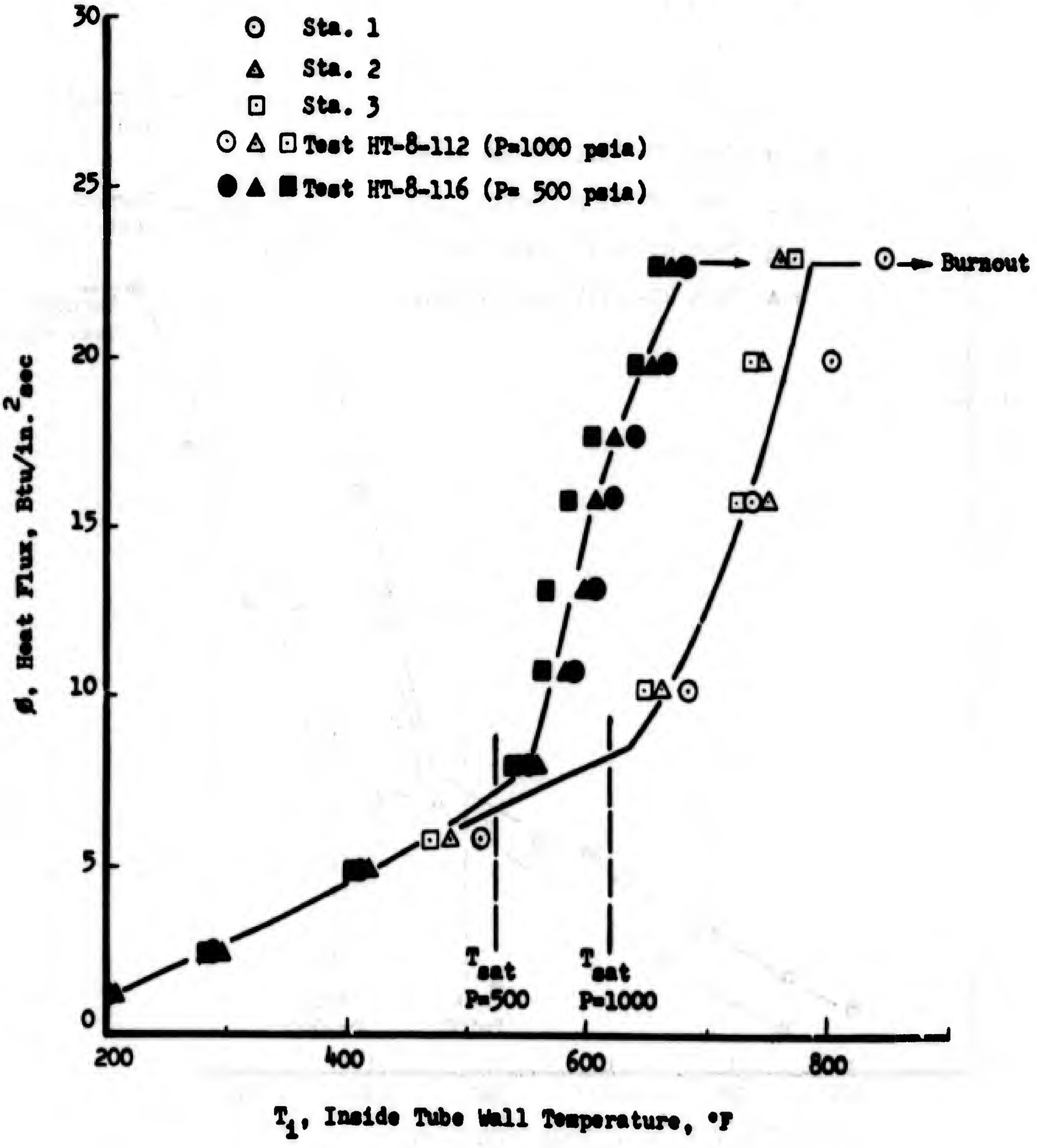
MHF-5 Heat Transfer at 20 ft/sec Velocity and 500 psia Pressure

Figure 4



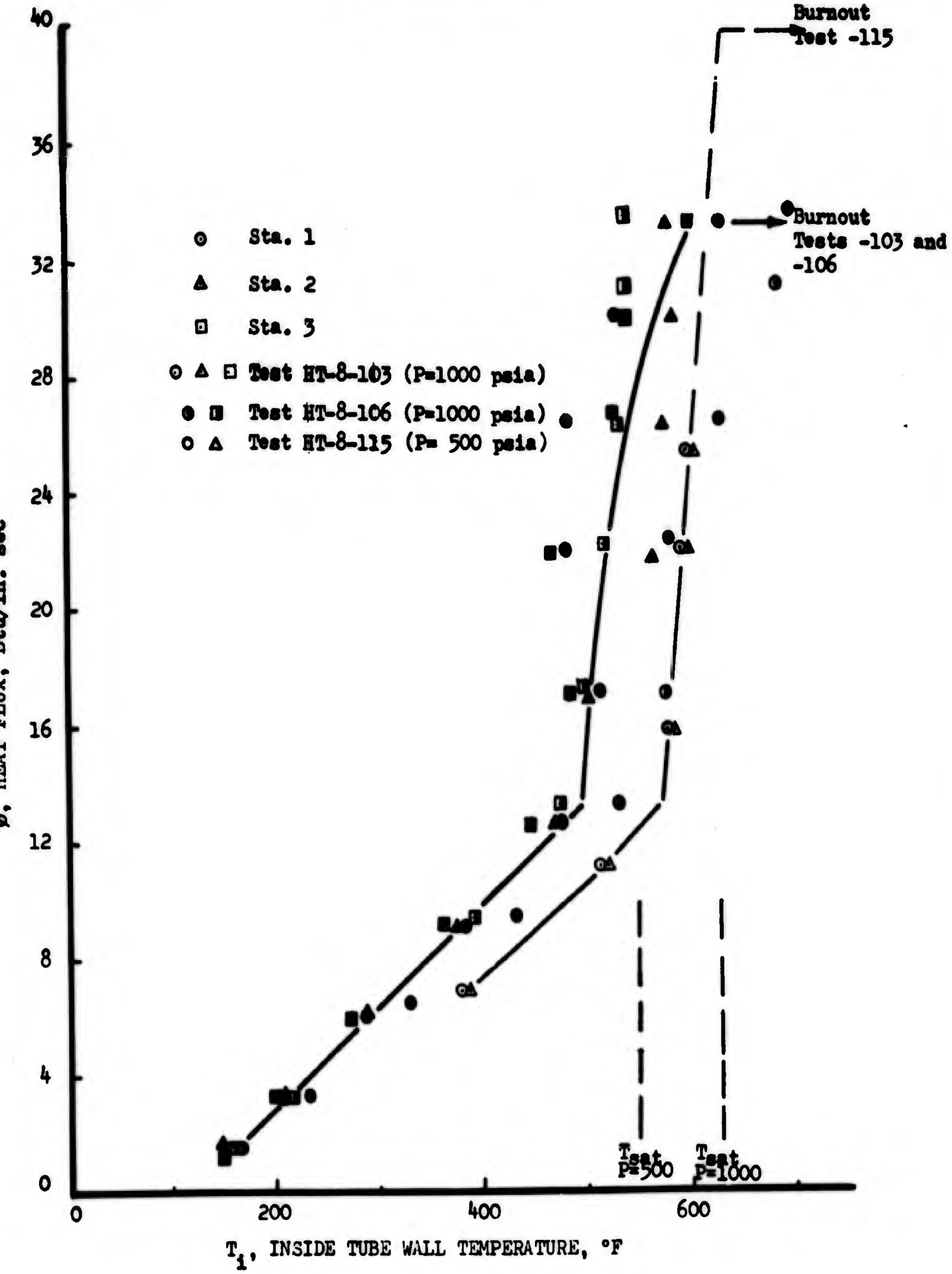
MHF-5 Heat Transfer at 50 ft/sec Velocity

Figure 5



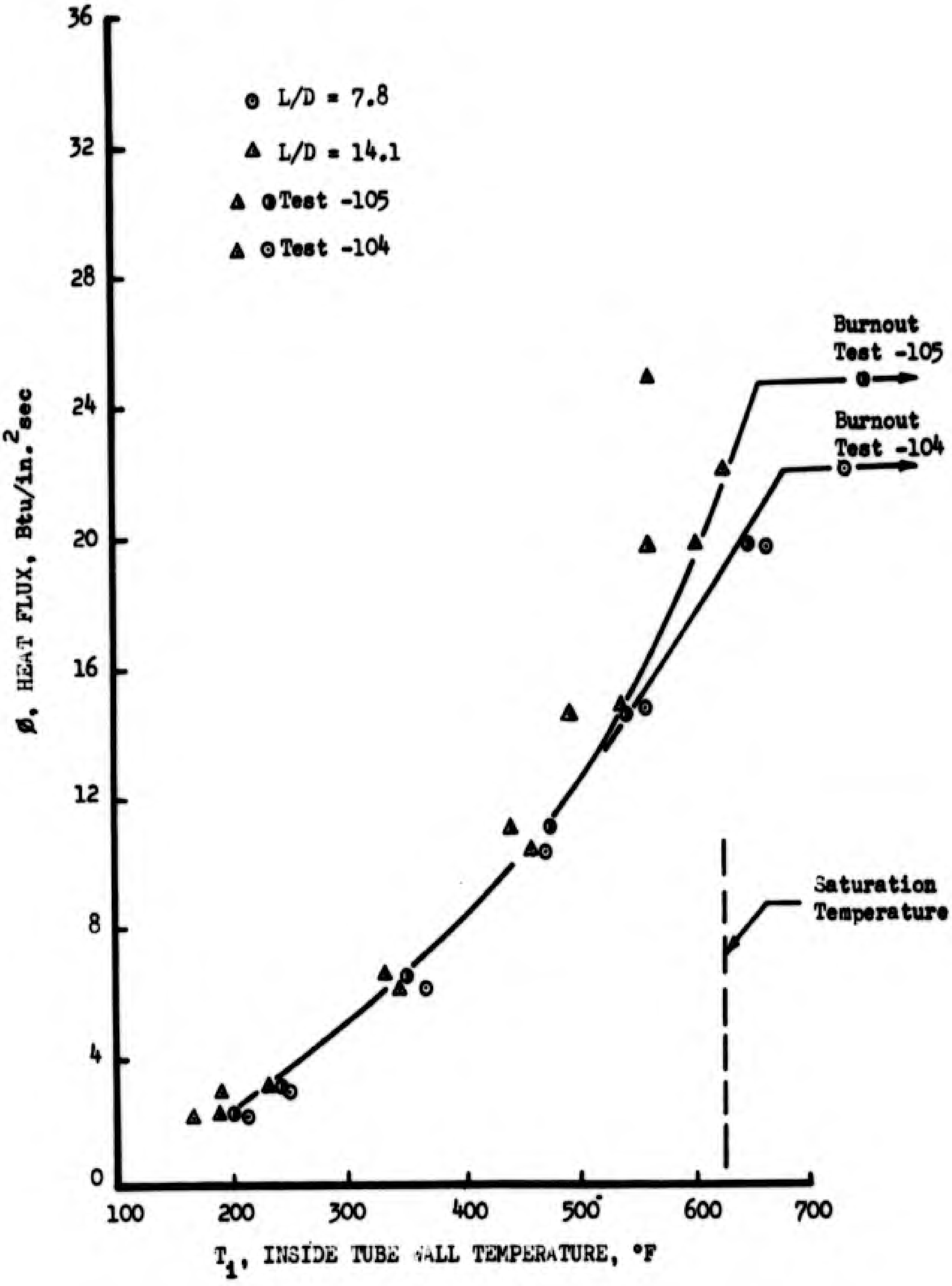
MHF-5 Heat Transfer at 100 ft/sec Velocity

Figure 6



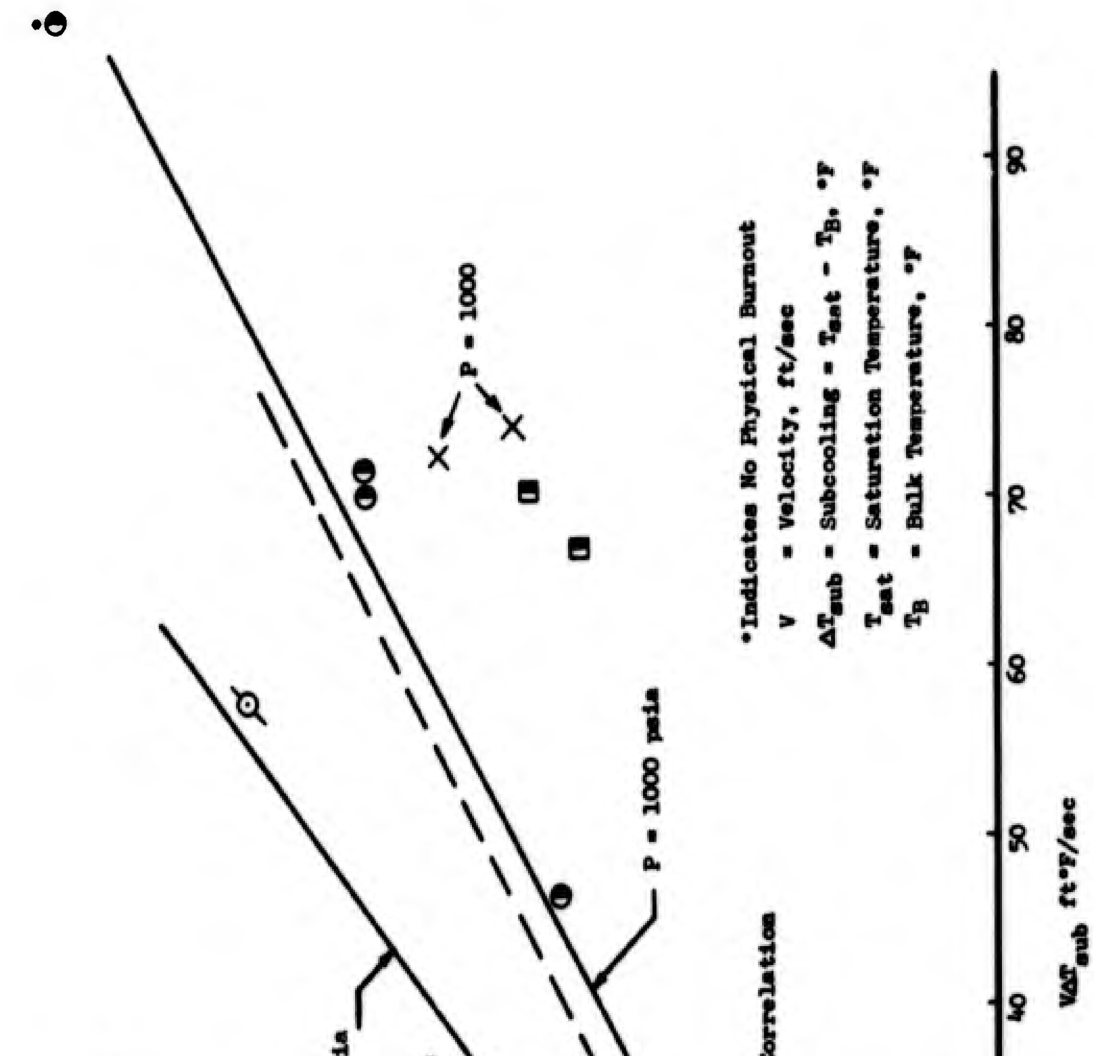
MHF-5 Heat Transfer at 150 ft/sec Velocity

Figure 7



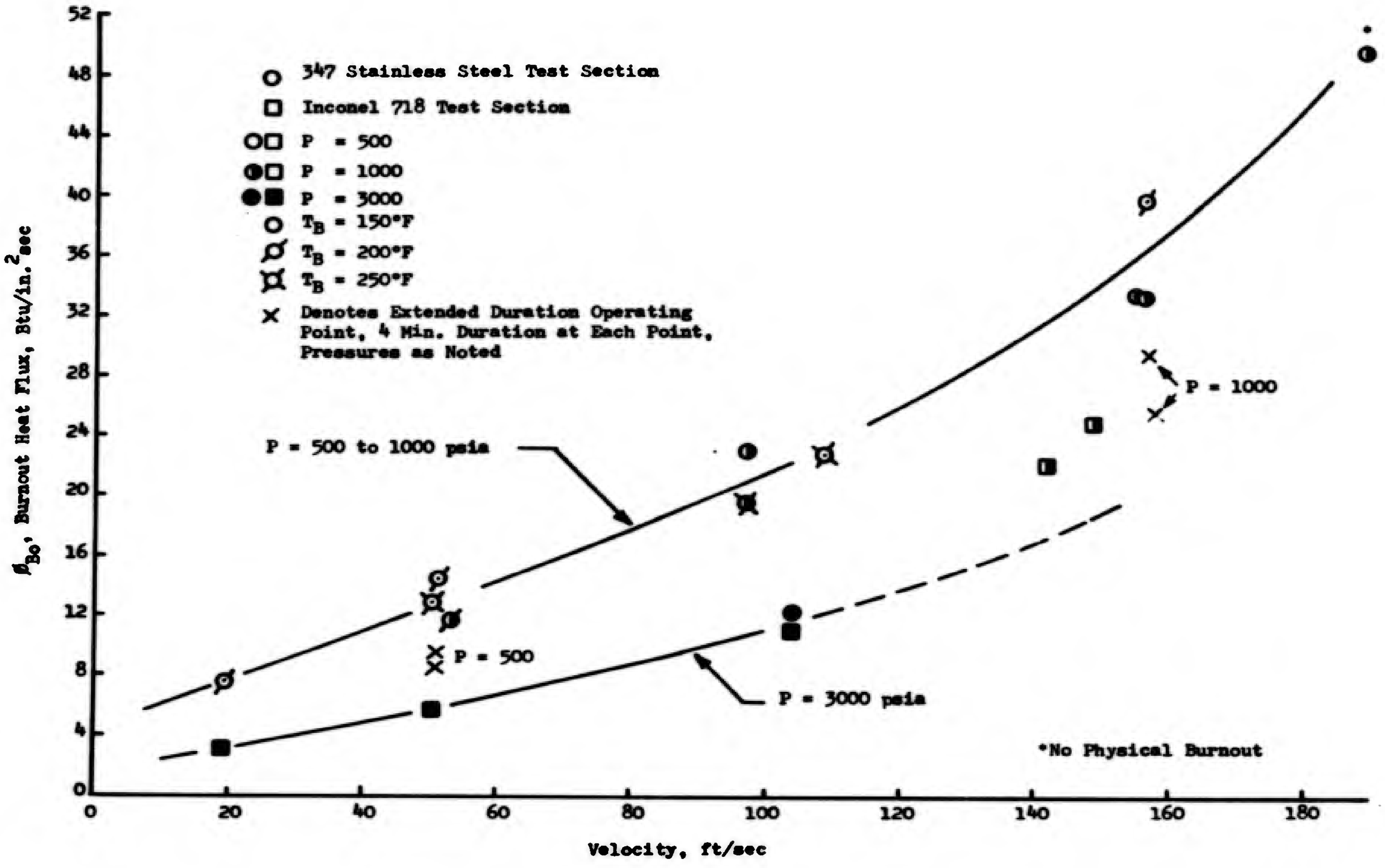
MHF-5 Heat Transfer at 150 ft/sec Velocity and 1000 psia Pressure in Inconel 718 Test Sections

Figure 8



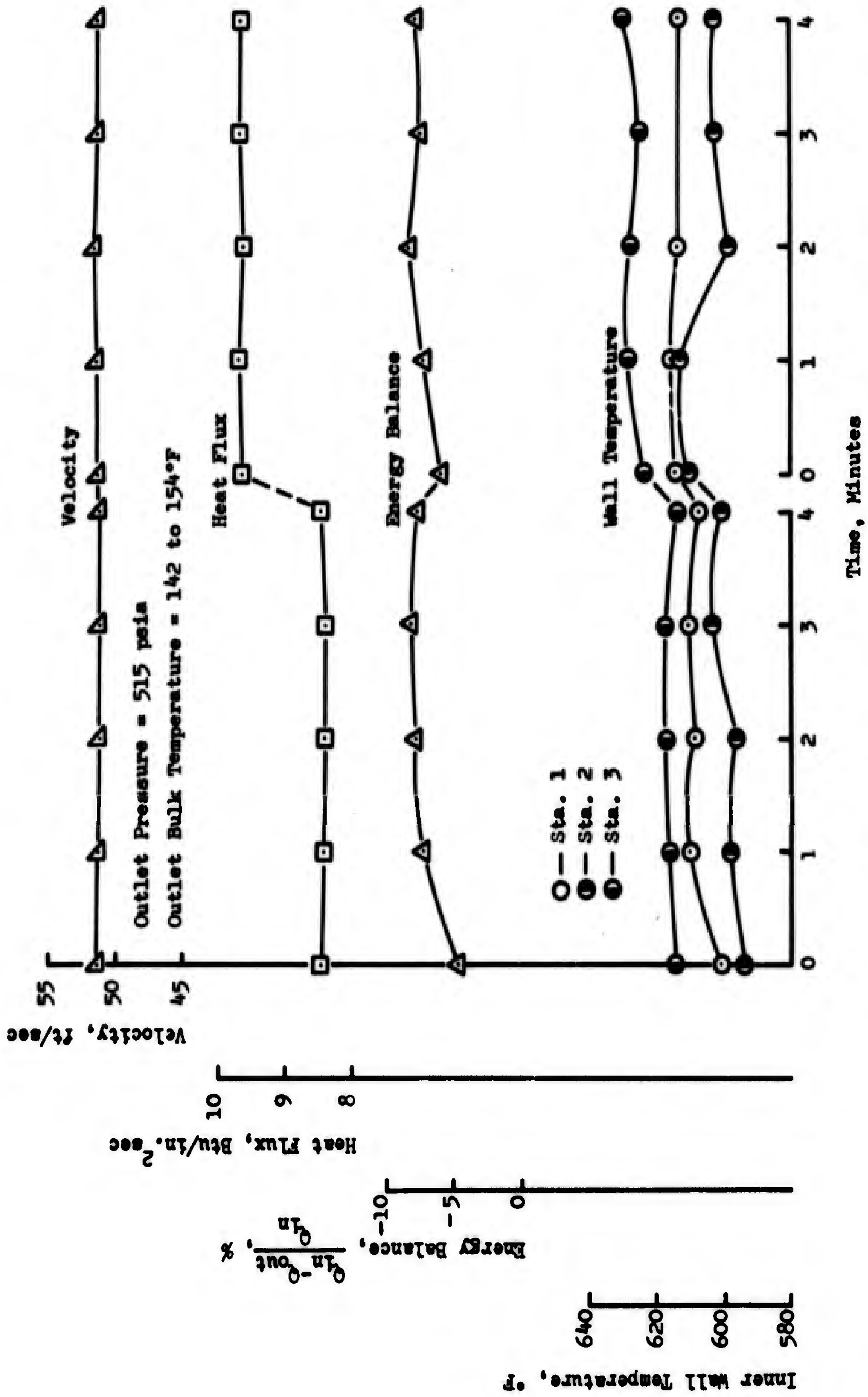
Subcritical MHF-5 Burnout Heat Flux Correlation

Figure 9



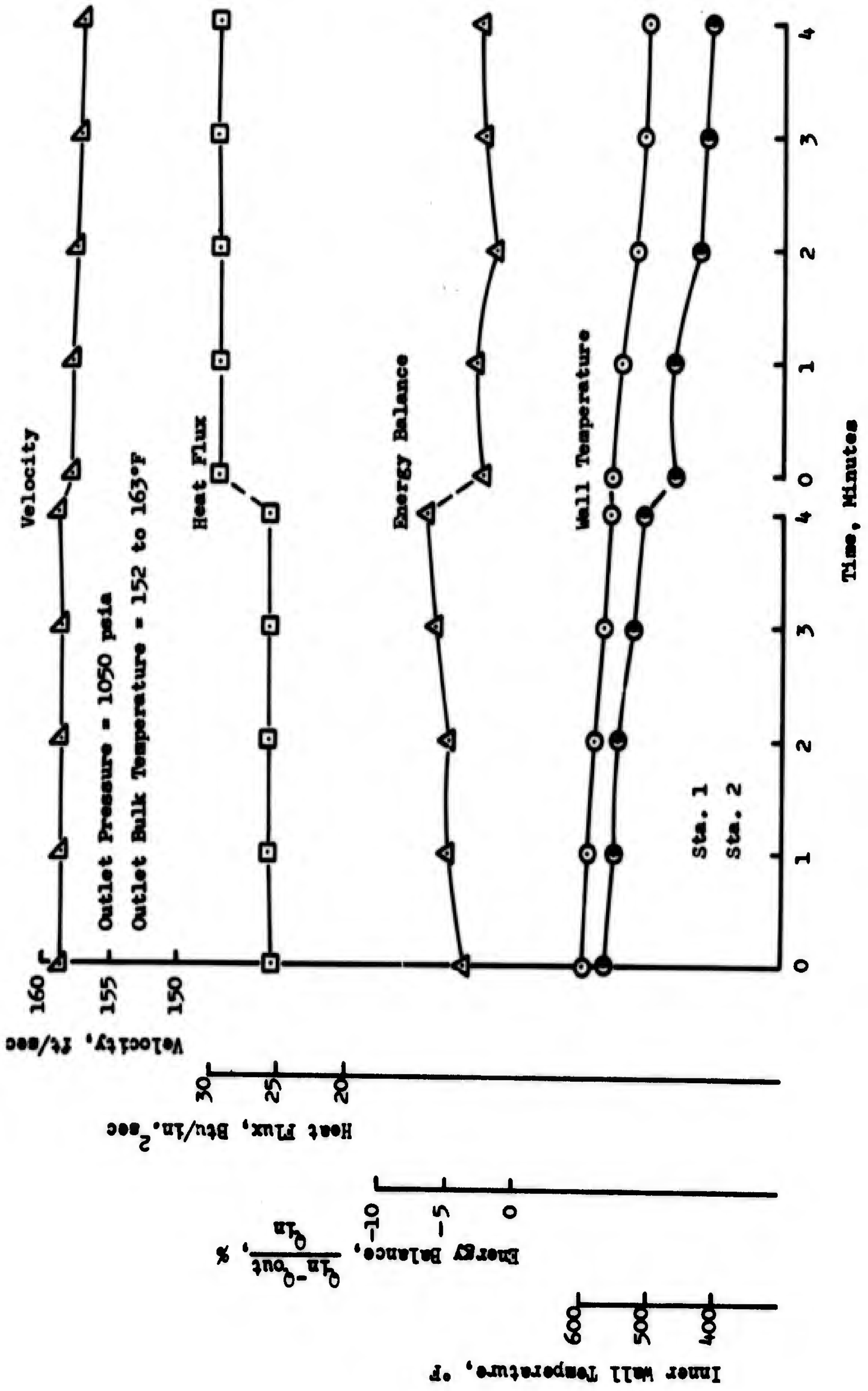
Correlation of MHF-5 Burnout Heat Flux with Velocity

Figure 10



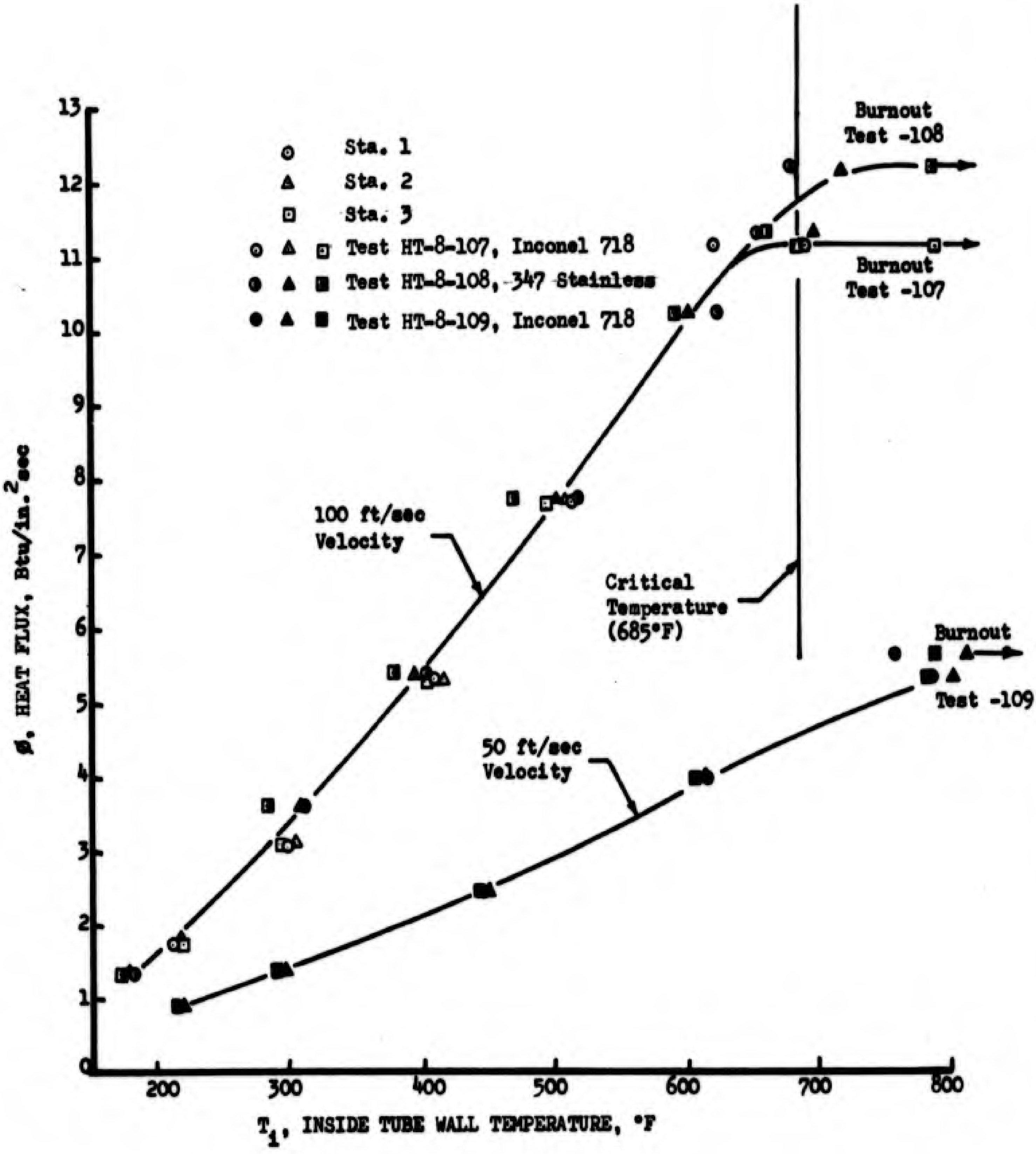
Extended Duration Test Parameters, Test HT-8-113

Figure 11



Extended Duration Test Parameters, Test HT-8-114

Figure 12



MHF-5 Heat Transfer at 3000 psia Pressure

Figure 13

APPENDIX A

PHYSICAL PROPERTIES OF MHF-5

TABLE OF CONTENTS

TABLE LIST

FIGURE LIST

I. ESTIMATED PSEUDOCRITICAL PRESSURE OF MHF-5

A. KAY'S METHOD

(u) The pseudocritical pressure of MHF-5 can be estimated by Kay's method (Ref 1) from the composition of MHF-5 and the critical pressures of its components by the following formula:

$$P_{c}, _{mix} = y_A P_{c,A} + y_B P_{c,B} + y_C P_{c,C}$$

where y_A, y_B, y_C are the mole fraction of the components A, B, and C

$P_{c,A}$, $P_{c,B}$, and $P_{c,C}$ are the critical pressures of components A, B, and C.

(c) MHF-5 is composed of 55 wt% monomethylhydrazine (MMH), 26% wt hydrazine (N_2H_4), and 19 wt% hydrazine nitrate (HN). This corresponds to the following composition in terms of mole fractions:

Component	Mole Fraction
MMH	0.54140
N_2H_4	0.36795
HN	0.09065

The critical pressure of MMH is 1195 psia (Ref 2) and of N_2H_4 is 2131 psia (Ref 3). No experimental value is available for HN but one can be estimated by various methods.

(u) From Riedel's method (Ref 4) the critical pressure of HN is estimated to be 894 psia, from Lydersen's method (Ref 5) 1134 psia, from Vowles' method (Ref 6) 655 to 734 psia, and from Herzog's method (Ref 7) 682 to 749 psia. Based on the data in Section I,C, Vowles' methods appears most applicable.

I, A, Kay's Method (cont.)

Using an average value from Vowles' method of 695 psia as the critical pressure of HN, the pseudocritical pressure of MHF-5 is evaluated by Kay's method:

$$P_c = (.54150)(1195)+(.36795)(2131)+(.09065)(695) = 1494 \text{ psia}$$

Note that a significant error in the critical pressure of HN has a relatively small effect on the estimated pseudocritical pressure of MHF-5.

B. EXTRAPOLATION OF VAPOR PRESSURE DATA

The pseudocritical pressure of MHF-5 has also been estimated by extrapolation of experimentally determined vapor pressure data to the estimated pseudocritical temperature.

Vapor pressures of MHF-5 over the temperature range 32 to 203°F have been reported by Reaction Motors Division of Thiokol Chemical Corporation in References 8 and 9. These data and those for monomethylhydrazine (MMH) from References 2 and 10 have been plotted on log p versus reciprocal absolute temperature coordinates to yield the smooth curves shown in Figure 1. The vapor pressure curve of MHF-5 has been extrapolated by first developing a Duhring-type plot (Figure 2, a plot of the temperatures at which MHF-5 exerts a given pressure versus the temperature at which some reference material exerts the same vapor pressures) utilizing monomethylhydrazine as the reference material. The Duhring plot (Figure 2) and the experimentally defined vapor pressure curve of MMH (Figure 1) permits extrapolation of the MHF-5 curve to the critical pressure of MMH. Finally, the MHF-5 vapor pressure curve is graphically extrapolated from the critical pressure of MMH to the estimated pseudocritical temperature of MHF-5 (1100 to 1180°R). This later extrapolation yields a value in the range of 1150 to 1750 psia as the pseudocritical pressure of MHF-5.

I, B, Extrapolation of Vapor Pressure Data (cont.)

Assuming the pseudocritical pressure estimated in the preceding paragraph (1494 psia) is correct, the vapor pressure curve (Figure 1) would indicate the pseudocritical temperature should be approximately 1150°R.

C. OTHER METHODS

The use of the methods of Reidel (Ref 4), Lyderson (Ref 5) Vowles (Ref 6) and Herzog (Ref 7) have also been briefly examined for applicability to the estimation of the pseudocritical pressure of MHF-5 directly. This has been done by using the methods to estimate the critical pressures of MMH and N_2H_4 (primary components of MHF-5) and comparing the estimated values with the experimental values. The results are shown below:

Method	Error in Predicting P_c, %	
	N_2H_4	MMH
Riedel	-32.0	-11.5
Lydersen	-21.3	-10.8
Vowles	- 2.8	- 1.9
Herzog	-43.1	-26.3

From the above it is readily evident that Vowles' method is most applicable to hydrazine-type structures. Applying Vowles' method to MHF-5 by the following equation:

$$P_c = \frac{T_c}{\Upsilon}^{1.25}$$

where T_c is taken as 638.89°K (1150°R)
and Υ is 16.578 evaluated from Vowles' atomic contribution increments

$$P_c = (38.54)^{1.25} = 96.03 \text{ atm} = 1411 \text{ psia}$$

Assuming the errors involved in predicting N_2H_4 and MMH critical pressures are equivalent in the prediction of the pseudocritical pressure of MHF-5 by Vowles' method, the value above should be adjusted upward by approximately 2.3%. This adjustment yields an estimated pseudocritical pressure of 1443 psia.

D. RECOMMENDED VALUE

From Section I, A the pseudocritical pressure of MHF-5 is estimated to be 1494 psia, from I, B to be in the range of 1150 to 1750 psia, and from paragraph I, C to be 1443 psia. The average of the first and last values is judged to the most reasonable value and is recommended.

$$P_c\text{, avg} = 1470 \text{ psia} = 100 \text{ atm}$$

II. ESTIMATED PSEUDOCRITICAL TEMPERATURE OF MHF-5

A. KAY'S METHOD

(u) The pseudocritical temperature of MHF-5 can be estimated by Kay's method (Ref 1) from the composition of MHF-5 and the critical temperatures of the substances composing MHF-5 by the following formula:

$$T_c, \text{mix} = y_A T_{c,A} + y_B T_{c,B} + y_C T_{c,C}$$

where y_A, y_B, and y_C are the mole fractions of components A, B, and C.

$T_{c,A}$, $T_{c,B}$, and $T_{c,C}$ are the critical temperatures of components A, B, and C.

(c) The critical temperature of MMH is given as 1053.3°R in Ref 2 and N_2H_4 is given as 1175.7°R by Ref 3. The critical temperature of HN is not known and must be estimated before Kay's methods can be applied to MHF-5.

(u) Although the critical temperature of HN probably has no real physical meaning because of its relatively poor thermal stability, values can be estimated on the basis of the following correlation:

$$T_c = \frac{T_b}{\theta}$$

where T_b = normal boiling point, °K
T_c = critical temperature, °K
θ = a constant

The constant, θ, can be calculated by summing atomic and structural contributions given by Vowles (Ref 6) or from a simple equation and atomic and structural contributions given by Lydersen (Ref 5). The boiling point of HN can, perhaps, be reasonably assumed to be its sublimation temperature, 140°C (Ref 11) in view of the fact that HN does not exhibit a normal boiling point. Taking 140°C as equivalent to

II, A, Kay's Method (cont.)

the normal boiling point and evaluating values for Θ by the methods of Vowles and Lydersen, critical temperatures of 1063 and 1084°R, respectively, are estimated for HN. The average of these two values appears to be the most desirable single value to utilize.

(u) Substituting the mole fractions and critical temperatures of MHF-5's components into Kay's equation, the pseudocritical temperature of MHF-5 is:

$$\begin{aligned} T_c &= (.54140)(1053.3) + (.36795)(1175.7) + (.09065)(1073.5) \\ &= 1100^\circ R \end{aligned}$$

B. VOWLES' AND LYDERSEN'S METHODS

(c) The pseudocritical temperature of MHF-5 can be estimated directly by the methods of Vowles and Lydersen in a manner similar to that used to estimate the critical temperature of HN as given above. Using the boiling point of MHF-5 from Tannenbaum (Ref 8), 207°F, and evaluating the constant, Θ, by the methods of Vowles (Ref 6) and Lydersen (Ref 5), the pseudocritical temperature of MHF-5 is estimated to be 1041 and 1048°R by the respective methods.

(u) It is known that each of these methods yield estimated values for hydrazine which are approximately 60°R low (Ref 12). Since MHF-5 is a hydrazine-based fuel, it would appear that an adjustment in the estimated values of MHF-5 would be reasonable. Thus, a value of approximately 1107°R is the most logical value to evolve from these methods.

II, Estimated Pseudocritical Temperature of MHF-5 (cont.)

C. METHOD OF SMITH et al

(u) Smith, Greenbaum, and Rutledge (Ref 13) have proposed the following equation for the estimation of critical temperature, T_c:

$$T_c = \frac{T_2 - T_1}{(\rho_1/\rho_2)^{10/3} - 1} + T_2 + 6$$

where T_c = critical temperature, °K

T_1, T_2 = temperatures, °K, at which liquid densities ρ_1, and ρ_2 are measured

Based on a recommendation by Rutledge (Ref 14), it appears that if possible, the temperature interval should be at least 20°C and that the arithmetic average temperature, $0.5\ (T_2 + T_1)$, should be about 75% of the value of the normal boiling point expressed in degrees absolute.

(c) The normal boiling point of MHF-5 is reported to be 207°F (666.7°R) by Tannenbaum (Ref 8). Thus, the most desirable temperature interval to be considered in evaluating Eq. (1) with respect to MHF-5 is an interval near 500°R (75% of 666.7°R). Density data on MHF-5 are available from 395 to 660°R from References 8, 9, and 15 and therefore, permit the evaluation of Eq. (1) as recommended.

(c) Taking T_1 and T_2 as 394.7 and 604.7°R, respectively ρ_1 and ρ_2 are found to be 1.076 and 0.979 g/ml, respectively, from Figure 3 which was constructed from the density data presented in References 8, 9, and 15. Evaluating Eq. (1):

$$T_c = \frac{(604.7-394.7)/1.8}{(1.076/0.979)^{10/3} - 1} + \frac{604.7}{1.8} + 6$$

$$T_c = 657°K = 1183°R = 723°F$$

II, Estimated Pseudocritical Temperature of MHF-5 (cont.)

D. RECOMMENDED VALUE

The scatter in the estimated values of the pseudocritical temperature of MHF-5 as given in the preceding paragraphs is quite large, nearly 13%, and the applicability of each of the estimation techniques is questionable. It does appear, however, that a value in the range of 1100 ot 1180°R is reasonable and a value of 1145°R is most consistent with the estimated pseudocritical pressure (1470 psia) and extrapolated vapor pressure data (Figure 1).

III. ESTIMATED PSEUDOCRITICAL VOLUME AND DENSITY OF MHF-5

(u) Although no known method for the estimation of pseudocritical volume appears to be applicable to complex systems such as MHF-5, the need for a value forces one to utilize some of the more well known correlations in spite of their apparent inapplicability.

A. HERZOG'S METHOD

(u) Herzog (Ref 7) relates critical volume to the parachor and critical temperature as shown below:

$$V_c = \frac{k(P_{ch})^{1.2}}{(T_c)^{0.3}} \quad \text{cm}^3/\text{g-mole} \tag{2}$$

where k would appear to be 2.92 for substances not containing

-C = O, -C = N, -COOH, -OH and one to three additional nonfunctional carbons

T_c = critical temperature, °K

P_{ch} = the parachor, a measure of the molecular volume of a liquid at a standard surface tension and defined as:

$$P_{ch} = \frac{M\sigma^{0.25}}{\rho_l - \rho_g} \tag{3}$$

where M = molecular weight

σ = surface tension, dynes/cm

ρ_l = density of liquid, g/cm^3

ρ_g = density of gas, g/cm^3

III, A, Herzog's Method (cont.)

(c) Now, considering MHF-5 to be composed of 55 wt% monomethylhydrazine (MMH), 26 wt% hydrazine (N_2H_5), and 19 wt% hydrazine nitrate (HN) and assuming that the HN is totally ionized to hydrazinium ion ($N_2H_5^+$) and nitrate ion (NO_3^-), the mean molecular weight is calculated to be:

$$\bar{M} = 41.58$$

which corresponds to the following empirical formula:

$$\text{MHF-5} = C_{.4964}\, H_{4.7434}\, N_{1.9169}\, O_{.2494}$$

(u) The surface tension of MHF-5 has been determined by Cabeal (Ref 16) at 77°F and found to be:

$$\sigma = 45.7 \text{ dynes/cm}$$

(c) Taking the density of MHF-5 at 77°F from Figure 3 as 1.010 g/cm^3 and assuming the density of the vapor to be negligible, the parachor is calculated from Eq. (3) to be:

$$P_{ch} = \frac{41.58\ (45.7)^{0.25}}{1.010} = 106.8$$

This value is in excellent agreement with the value of 106.7 estimated on the basis of the structural and atomic contributions of Quale (Ref 17).

(u) Taking the estimated pseudocritical temperature of MHF-5 as 636°K (1145°R) and P_{ch} and k from above, the pseudocritical volume, V_c, is defined by evaluation of Eq. (2):

$$V_c = \frac{2.92(106.8)^{1.2}}{636} = 114.5 \text{ cm}^3\text{/g-mole}$$

III, Estimated Pseudocritical Volume and Density of MHF-5 (cont.)

B. MEISSNER'S METHOD

Meissner (Ref 18) relates critical volume to the parachor and molar refraction by the following equation:

$$V_c = 0.55(1.5\ P_{ch} + 9 - 4.34R_D)^{1.155}\ \text{cm}^3/\text{g-mole} \qquad (4)$$

where P_{ch} = parachor

R_D = molar refraction

The molar refraction is related to the index of refraction, density and molecular weight by the following equation:

$$R_D = \frac{n^2 -1}{n^2 +2} \cdot \frac{M}{\rho} \qquad (5)$$

where n = index of refraction

M = molecular weight

ρ = density

The index of refraction of MHF-5 has been determined by Cabeal (Ref 16) to be 1.461 at 77°F. This value and the values of M and ρ from above permit the definition of R_D from Eq. (5):

$$R_D = \frac{1.461^2 -1}{1.461^2 +2} \cdot \frac{41.58}{1.010} = 11.30$$

Substituting the values of R_D and P_{ch} into Eq. (4):

$$V_c = 0.55\left[(1.5)(106.8) + 9-(4.34)(11.30)\right]^{1.155} = 140.6\ \text{cm}^3/\text{g-mole}$$

III, Estimated Pseudocritical Volume and Density of MHF-5 (cont.)

C. VOWLES' AND LYDERSEN'S METHODS

Vowles (Ref 6) and Lydersen (Ref 5) have both proposed methods of estimating critical volume on the basis of summing incremental constants representing various atom or atomic configurations. Applying their incremental contributions to MHF-5, pseudocritical volumes of 123.2 and 131.1 cm^3/g-mole are obtained.

D. RECOMMENDED VALUE

It is, thus, seen that values of 114.5, 140.6, 123.2, and 131.1 are obtained for the pseudocritical volume of MHF-5 by the methods of Herzog, Meissner, Vowles, and Lydersen, respectively. The scatter in these values is rather disheartening but not unexpected. Of these values only the one based on Herzog's method can be justifiably eliminated. That value is eliminated on the basis that Herzog's correlation involves a constant which is not readily defined for MHF-5 and the critical temperature which is, in turn, an estimated value. The three remaining values appear to be nearly equally reliable and, therefore, the average of these three values is recommended. The average value is given below:

$$V_c = 131.6 \text{ cm}^3/\text{g-mole}$$

From the above value the pseudocritical density, ρ_c, can be defined as

$$\rho_c = \frac{M}{V_c} = \frac{41.58}{131.6} = 0.316 \text{ g/cm}^3$$

IV. DENSITY OF MHF-5

A. EXPERIMENTAL DATA

(c) The density of MHF-5 has been measured by RMD over the temperature range -65.2 to 194°F (Ref 8, 9, 15) and in Ref 8 is reported to vary with temperature according to the following equation:

$$d(\text{g/ml}) = 1.045-4.61 \times 10^{-4}T(°\text{F})$$

This equation is claimed to be applicable from -65 to 200°F. The data points retrieved from Ref 9 and 15 are plotted in Figure 3 and do clearly indicate that the density varies with temperature in nearly a linear manner.

(c) AFRPL (Ref 19) prepared MHF-5* for test firing and reports the density to be defined by an equation equivalent to the one below:

$$d(\text{g/ml}) = 1.0461-5.0888 \times 10^{-4}T(°\text{F})$$

No indication is given concerning the range of temperatures for which the equation is valid.

(u) A comparison of the two equations shows the latter to give a density 0.1% higher than the former at 0°F, approximately 0.9% lower at 100°F, and equal values at 23°F.

(c)*Material assayed MMH, 52.8 wt %; N_2H_4, 25.5 wt%; $N_2H_5NO_3$, 17.9 wt%; H_2O, 2.6 wt%; and impurities 1.2 wt%. Note that this material is slightly low in $N_2H_5NO_3$ content.

IV, Density of MHF-5 (cont.)

B. EXTRAPOLATION OF EXPERIMENTAL DATA

The method of Lydersen, Greenkorn, and Hougen (Ref 20) has been used to extrapolate the available density data to the estimated critical temperature and pressures to 400 atm. This method is based on a correlation between specific volume (or density) and reduced temperature, reduced pressure and critical compressibility. Utilizing the estimated critical temperature, pressure, and volume from the preceding sections, the critical compressibility, Z_c, is estimated to be:

$$Z_c = \frac{P_c V_c}{RT_c} = \frac{(100)(131.6)}{(82.06)(636.1)} = 0.252$$

From tables (Ref 20) relating Z_c, reduced temperature ($T_R = T/T_c$), and reduced pressure ($P_R = P/P_c$), values of reduced density were obtained. Taking the experimental density values from Ref 9 and 15 and the reduced densities from Ref 20, values for a critical density were evaluated from:

$$\rho_c = \rho/\rho_R$$

These calculations resulted in a value for ρ_c of $0.3184^{+.0030}_{-.0036}$*. Using the value 0.3184 for ρ_c and taking ρ_R values from tables (Ref 20), the densities at elevated temperatures and pressures were calculated from:

$$\rho = \rho_c \, \rho_R$$

These calculated values and the experimental data (Ref 9 and 15) were graphically smoothed in the temperature region of 100 to 200°F so that primary emphasis was placed on the experimental data at temperatures below 100°F and on the calculated values of temperatures above 200°F. The resulting curves of specific gravity versus temperature are given in Figure 4.

---

*Note the excellent agreement between this value and the value of 0.316 g/cm^3 estimated in Section III, D.

V. VISCOSITY OF MHF-5

A. EXPERIMENTAL DATA

The viscosity of MHF-5 has been measured (presumably at 1 atm) by RMD over the temperature range of -67 to 160°F (Ref 8 and 9) and by Aerojet (Ref 21) at -40 and 77°F. The original RMD data from Ref 9 was presented in units of centistokes and has been converted to centipoise units by multiplying by corresponding densities taken from Figure 3. The density curve (Figure 3) is, in turn, based upon RMD data from Ref 9 and 15. The resulting compilation of viscosity values is presented in Table 1. These values are also presented graphically in Figure 5.

B. EXTRAPOLATION OF EXPERIMENTAL DATA

The viscosity data presented in Table 1 and Figure 5 have been extrapolated to the estimated critical temperature and to high pressures utilizing a reduced state viscosity correlation.

An inspection of available correlations for water (Ref 22), NH_3 (Ref 23), CO_2 (Ref 24), SO_2 (Ref 25), diatomic gases (Ref 26), and inert gases (Ref 27) indicated the correlation for water to be most applicable to MHF-5. Testing of the water correlation of Theiss (Ref 22) showed that it could predict very closely the experimental viscosity data for MHF-5 if a critical viscosity of approximately 0.104 centipoise was assumed. The use of this correlation, the assumed critical viscosity mentioned above, and the experimental data permitted the generation of a viscosity-temperature curve for the saturated liquid up to the critical temperature. The correlation was also utilized for defining similar curves at high pressure and temperatures from the lower limit of the correlation (approximately 180°F) to the critical temperature. Attempts were made to extend these latter curves to lower temperatures (-65°F) by employing a variety of curve-fitting and graphical extrapolation procedures. These attempts failed to yield a consistent set of data. Because of this failure it was decided to attempt to extend Theiss' correlation to

V, B, Extrapolation of Experimental Data (cont.)

lower temperatures (it was considered likely that the viscosity of compressed water should be available in the literature down to its freezing point and thereby permit such an extension).

The search for the necessary supplemental water viscosity data was somewhat limited in scope but did yield two extensive compilations (Ref 28 and 29), data on supercooled water (Ref 30 and 31), and references to recent Russian (Ref 32) and German (Ref 33 and 34) data. Of the data that were immediately available (Ref 28, 29, 31, and 33) those from Ref 29 and 31 were judged to be most useful in extending the available water correlation. Using the data from Ref 29 and 31, and the critical viscosity of 0.043 centipoise for water from Ref 22 the reduced state correlation shown in Figure 6 was developed. This correlation agrees with that of Theiss very closely for the saturated liquid but deviates substantially at elevated pressures. It is interesting to note that the crossing of the curves in Figure 6 at a reduced temperature of approximately 0.47 corresponds to a change in the sign of the pressure coefficient of viscosity whereas no such trend is indicated in Theiss' correlation. The validity of the change in the sign of the pressure coefficient of viscosity cannot be completely proven but an abstract of Weber's recent work (Ref 34) and Moszynski (Ref 35) specifically mention such a change occurring at 32°C ($T_R = 0.471$) and 35°C ($T_R = 0.476$), respectively, and tends to verify the behavior exhibited in Figure 6.

Figure 6 was thus taken as the best correlation that could be derived for generating MHF-5 viscosity data. Using Figure 6 and the graphically smoothed experimental viscosity data for MHF-5 from Figure 5, values for the critical viscosity of MHF-5 were calculated from:

$$\mu_c = \frac{\mu}{\mu_R}$$

V, B, Extrapolation of Experimental Data (cont.)

The values obtained were $0.1043^{+.0018}_{-.0019}$ centipoise. The viscosity of MHF-5 was then calculated from:

$$\mu = \mu_c \mu_R$$

Where μ_c was taken as 0.1043 and values of μ_R were taken from Figure 6. These data and points from Figure 5 (the experimental data) were then utilized to construct the viscosity-temperature-pressure plot given in Figure 7. Rather than allowing the curves for the elevated pressures to intersect the saturated liquid curve (as predicted by Figure 6) they were simply allowed to converge into the saturated liquid curve at a temperature corresponding to $T_R = 0.47$. This was done because the peculiar behavior exhibited by Figure 6 at low temperatures and high pressure is likely to be correct only for water and because it seems reasonable that the viscosity of a liquid such as MHF-5 increases rapidly as its degree of association or packing increases and that this degree of association or packing becomes almost entirely temperature dependent at some relatively low temperature.

The viscosity data were extended to pressures equivalent to a reduced pressure of only two because of the limitation of immediately available water data. However, based on the data from Ref 33 and an abstract of Ref 34 it appears that viscosity increases linearly with pressure (to at least $P_R = 3.5$) in the temperature region of $T_R = 0.5$ to 0.9. Thus, Figure 7 can probably be linearly extrapolated to pressures of at least 350 atm in the temperature range of approximately 110 to 570°F.

VI. HEAT CAPACITY OF MHF-5

A. EXPERIMENTAL DATA

(c) The heat capacity of MHF-5 has been measured by RMD (Ref 8) over the temperature range of 40 to 155°F in a standard adibatic calorimeter. A straight-line fit of the eight data points reported yields the following equation:

$$Cp(Btu/lb\text{-}°F) = 0.6518 + 1.61 \times 10^{-4} T(°F)$$

The experimental data deviate from values calculated from the above equation by a maximum of ± 1%. The experimental and calculated values are presented in Table 2.

B. EXTRAPOLATION OF EXPERIMENTAL DATA

(u) A review of the recommended methods of estimating and correlating liquid heat capacities as presented in Reid and Sherwood's very recent and authoritative book (Ref 36) shows that no truly good method is available for complex mixtures such as MHF-5. Of the available methods, Watson's method (Ref 37) as modified by Sobel (ref 38) appears preferable for non-hydrocarbons. Unfortunately, even this method is limited to pure components, the saturated liquid, temperatures between T_R = 0.7 and 0.95, and requires the separate estimation of the ideal gas heat capacity. It, thus, becomes apparent that some other method has to be devised.

(u) Chow and Bright (Ref 39) suggested that the variation of heat capacity with temperature might be correlated with Watson's expansion factor ω, since heat capacities have been successfully correlated with densities of petroleum liquids. Tests of the correlation they presented failed to yield acceptable results for the polar liquid water when a wide temperature range is considered, and, therefore, is judged to be unacceptable for MHF-5 also.

VI, B, Extrapolation of Experimental Data (cont.)

(u) It is noted, however, that both of the methods cited above basically involved the correlation of heat capacity with reduced temperature, pressure, density, and compressibility. In the case of Chow and Bright's method, the correlation is relatively simple but appears unsuitable for polar liquids and wide temperature range. In the case of Watson's method, the correlation is very complex and virtually impossible to apply to MHF-5. On the basis of these methods it is postulated that, perhaps, a normalized heat capacity of some model substance can be correlated with its reduced density and be applied to MHF-5 and to then use Lydersen's tables (Ref 20) which correlate reduced density to arrive at a reasonable temperature-pressure-heat capacity relationship.

(u) In accordance with the preceding postulate, heat capacity was normalized to the normal boiling point value as follows: C_{p_p}/C_{p_t}. The boiling point was utilized to achieve a semblance to a corresponding state. The fraction form given above was chosen (rather than its inverse form) so that the normalized values would approach zero rather than infinity as the critical point was approached. Water was chosen as the model substance because data are readily available and because of a number of similarities to MHF-5: (1) they are both polar, (2) both exhibit hydrogen bonding, and (3) they have similar boiling points, densities, and critical temperatures.

(c) Heat capacity data for water were taken from Ref 29, interpolated as necessary, and normalized as defined above. The corresponding reduced densities of water were taken from Lydersen (Ref 20). These data, thus, provided the basic correlation between normalized heat capacity, reduced density, and reduced pressure shown in Figure 8. Using Figure 8 and the heat capacity of MHF-5 at its boiling point, the heat capacity of MHF-5 was defined as a function of reduced pressure and density. The normal boiling point of MHF-5 is reported to be 207°F (Ref 8) and the heat capacity at that temperature was estimated to be 0.6851 Btu/lb-°F, assuming the equation presented in the preceding section is valid to the boiling point. Using Lydersen's tables which correlate reduced temperature, pressure, and critical

VI, B, Extrapolation of Experimental Data (cont.)

compressibility with reduced density (Ref 20), the reduced temperatures corresponding to the various heat capacity-reduced density-reduced pressure values were defined where the critical compressibility (Z_c) of MHF-5 was taken as 0.25 (see Section IV, B for the derivation of Z_c). The reduced temperatures were then converted to normal units of temperature employing 1145°R as the critical temperature of MHF-5 (see Section II, D). The resulting values were plotted and are presented in Figure 9. At temperatures below approximately 250°F the curves were smoothed in to coincide with the available experimental data.

VII. THERMAL CONDUCTIVITY OF MHF-5

A. EXPERIMENTAL DATA

(c) No experimental thermal conductivity data for MHF-5 were found; however, substantial data are available for related fuels. Constantine (Ref 40) reports the thermal conductivity of AeroZINE 50 (N_2H_4-UDMH fuel blend) over the nominal temperature range of 50 to 305°F to be represented by the following equation:

$$k(\text{Btu/hr-ft-°F}) = 0.171 - 6.45 \times 10^{-5}T - 1.25 \times 10^{-7}T^2$$

where T is in °F. Similarly, Constantine (Ref 40) reports the thermal conductivity of monomethylhydrazine over the nominal temperature range of 0 to 305°F to be represented by the following equation:

$$k(\text{Btu/lb-ft-°F}) = 0.146 - 1.63 \times 10^{-5}T - 3.39 \times 10^{-7}T^2$$

The thermal conductivity of UDMH is reported in Ref 41 for the temperature range of 0 to 251°F and a single value is available for hydrazine at 77°F (Ref 42). These data are summarized in Table 3.

B. ESTIMATION OF MHF-5 THERMAL CONDUCTIVITY

(u) From the data presented in Table 3 a plot of thermal conductivity versus reduced temperature for each substance was constructed. The composition of MMH was redefined in terms of an equivalent UDMH - N_2H_4 mixture (34.78 N_2H_4 and 65.22% wt UDMH) and the data cross-plotted to yield a graph of thermal conductivity versus composition at various reduced temperatures (Figure 10). The composition of the solvent portion of MHF-5 (N_2H_4 and MMH) was then defined in terms of an equivalent N_2H_4 - UDMH mixture (55.72 N_2H_4 and 44.28% wt UDMH) and located on Figure 10. Thus, the thermal conductivity of the solvent portion of MHF-5 was defined within the reduced temperature interval of 0.4565 to 0.70. Assuming that the thermal

VII, B, Estimation of MHF-5 Thermal Conductivity (cont.)

diffusivities ($k/\rho C_l$) of a given solvent and solvent-solute system are the same (analogous to Krummel's assumption (Ref 43) whereby he estimated the thermal conductivity of sea water from that of pure water), the thermal conductivity of MHF-5 was estimated to be 5% greater than that of its solvent portion.

The estimated thermal conductivities of MHF-5 were then extrapolated into the high temperature (T_R = 0.6 to 1.0) and high pressure (saturation to 400 atm) region using the average of the reduced state thermal conductivity correlations for water and ethylene from Theiss (Ref 22) and Owens (Ref 44), respectively, and assuming a critical thermal conductivity of 0.052 Btu/hr-ft-°F. This value provides the best correlation between the previously estimated thermal conductivities and the reduced state correlation derived from those of water and ethylene. The low temperature ($T_R < 0.6$) and high pressure ($P_R \geq 1.0$) region was defined by applying pressure corrections (established from the previously mentioned reduced state correlations) to the estimated saturated liquid data. The resulting data are presented in Figure 11.

VIII. VAPOR PRESSURE OF MHF-5

A. EXPERIMENTAL DATA

(c) The vapor pressure of MHF-5 has been measured by RMD over the temperature range of 32 to 203°F (Ref 8 and 9) and can be described within these limits by the following equation:

$$\log_{10}P(\text{mmHg}) = 8.2875 - \frac{1996}{T(^\circ K)}$$

The experimentally determined values are presented in Table 4.

B. EXTRAPOLATION OF EXPERIMENTAL DATA

(u) The procedure utilized to extrapolate the experimental data to the estimated critical point is described in Section I,B, and the resulting data are presented in Figure 1 in the form of a log P versus reciprocal absolute temperature plot. The temperature scale in Figure 1 has been converted to a conventional scale to yield the more readable vapor pressure plot given in Figure 12.

LIST OF REFERENCES

1. Kay, W. B., Ind. Eng. Chem., 28, 1014 (1936)

2.* Lawrence, R. W., "Handbook of the Properties of unsym-Dimethylhydrazine and Monomethylhydrazine", Aerojet-General Corp., Azusa, California, Report No. 1292, May 1958, Contract AF 33(616)-3655. CONFIDENTIAL

3. International Critical Tables, Vol. 3, p. 299, McGraw Hill Book Co. (1928)

4. Riedel, L., Z. Electrochem; 53, 222 (1949)

5. Lydersen, A.L., "Estimation of Critical Properties of Organic Compounds", Coll Eng., Univ. Wisconsin, Eng. Expt. Sta. Report 3, Madison, Wisconsin, April 1955.

6. Vowles, C., S.M. Thesis in chemical engineering, Massachusetts Institute of Technology, 1951

7. Herzog, R., Ind. Eng. Chem., 36, 997 (1944)

8.* Tannenbaum, S., "Advanced Propellants Investigation for Prepackaged Liquid Engines", Thiokol Chem. Corp., Reaction Motors Division, Report RMD 5046-F, 11 May 1964-10 June 1965, Contract N600(19)62259. CONFIDENTIAL

9.* Tannerbaum, S., "Packaged Liquid Propellants", Thiokol Chemical Corp., Reaction Motors Division, Report RMD 5005-F, 2 January to 30 September 1962, Contract NOw 62-0785-c. CONFIDENTIAL

10. Aston, J. G., J. L. Fink, G. L. Janz, and K. E. Russel, J. Am. Chem. Soc., 73, 1939-43 (1951)

11. Handbook of Chemistry and Physics, 46th ed., 1965-66, The Chemical Rubber Co.

12. Reid, R.C. and T.K. Sherwood, *The Properties of Gases and Liquids*, McGraw-Hill Book Co., (1958)

13. Smith, W.T., S. Greenbaum, and G.P. Rutledge, J. Phys. Chem., 58, 443 (1954)

14. Rutledge, G. P., "A Study of the Thermal Expansion Coefficients of Organic Liquids", M.S. Thesis, Dept. of Chemistry, Univ. of Tennessee, 1948

15.* Tannenbaum, S., et. al., "Advanced Propellants Investigation for Prepackaged Liquid Engines", Thiokol Chemical Corp., Reaction Motors Division, Report RMD 5046-Q2, 11 August-10 November 1964, Contract N600(19)62259. CONFIDENTIAL

16. Cabeal, J. A., Lab Notebook No. 8, Propellant Chemistry Laboratory, Aerojet-General Corp., Sacramento, California, 4 August 1966

LIST OF REFERENCES (cont.)

17. Quale, O. R., Chem. Revs., 53, 439 (1953)

18. Meissner, H. P., Chem. Eng. Progr., 45, 149 (1949)

19.* "Experimental Evaluation of Compound 'A' with Selected Hydrazine Fuels", AFRPL, Edwards, California, AFRPL-TR-64-162, September 1964. CONFIDENTIAL

20. Lydersen, A. L., R. A. Greenkorn, and O. A. Hougen, "Generalized Thermodynamic Properties of Pure Fluids", Coll. Eng. Univ. Wisconsin, Eng. Expt. Sta. Rept. 4, Madison, Wisconsin, October 1955.

21. Fish, W. R., "Propellant Technology", Aerojet-General Corporation, Sacramento, California, Report 8709-25, 29 November 1965.

22. Theiss, R. V., "The Viscosity and Thermal Conductivity of Water in the Gaseous and Liquid States," M.S. Thesis, Northwestern University, Evanston, Illinois (1960)

23. Groenier, W. S. and George Thodos, "Viscosity and Thermal Conductivity of Ammonia in the Gaseous and Liquid States," J. Chem. and Eng. Data, 6, 240, (1961)

24. Kennedy, J. T. and George Thodos, "The Transport Properties of Carbon Dioxide," A.I. Ch. E. Journal, 7, 625-31 (1961)

25. Meyer, G. R., "The Viscosity and Thermal Conductivity of Sulfur Dioxide - Gaseous and Liquid States," M.S. Thesis, Northwestern University, Evanston, Illinois (1960)

26. Brebach, W. J. and George Thodos, "Viscosity-Reduced State Correlation for Diatomic Gases," Ind. Eng. Chem., 50, 1095 (1958)

27. Shimotake, Hiroshi and George Thodos, "Viscosity: Reduced State Correlation for the Inert Gases," A.I. Ch.E. Journal, 4, 257, (1958)

28. Dorsey, N. Ernest, Properties of Ordinary Water-Substance, Reinhold Publishing Corp., New York, (1940)

29. Wellman, E. J., "A Survey of the Thermodynamic and Physical Properties of Water," M. S. Thesis, Purdue University, January 1950 (as presented in The Reactor Handbook, Volume 2 Engineering, United States Atomic Energy Commission, AECD-3646, May 1955)

30. Taketoshi Ono, Tieon Kagaku, No. 18A, 1-8 (1959)

31. Hallet, J., Proc. Phys. Soc. (London), 82(530), 1046-50, (1963)

LIST OF REFERENCES (cont.)

32. Timrot, D. L. and A. V. Khlopkina, Teploenergetika, 10(7), 64-67 (1963)

33. Mayinger, F., Intern. J. Heat Mass Transfer, 5, 807-24 (1962)

34. Weber, Wolf, Z. Angew. Phys., 15, 342-52 (1963)

35. Moszynski, J. R., J. Heat Transfer, 83, 111-124 (1961)

36. Reid, R. C. and T. K. Sherwood, The Properties of Gases and Liquid: Their Estimation and Correlation, second ed., McGraw-Hill (1966)

37. Watson, K. M., Ind. Eng. Chem., 35, 398 (1943)

38. Sobel, J. E. and R. C. Reid, Ind. Eng. Chem. Fundamentals, 4, 328 (1965)

39. Chow, W. M. and J. A. Bright, Chem. Eng. Progr., 49, 175 (1953)

40.* Constantine, M. T., "Engineering Properties of Rocket Propellant," Final Report, AFRPL-TR-66-122, Contract AF 04(611)-10546, July 1966. CONFIDENTIAL

41. "Engineering Property Data on Rocket Propellants," First Quarterly Report, AFRPL-TR-66-171, Contract AF 04(611)-11407, July 1966. CONFIDENTIAL

42.* Thompson, T. L., and J. W. Parsons, "Data on Properties and Manufacturing Methods for Anydrous Hydrazine," North American Aviation, Inc., Report No. AL-275, September 18, 1947. CONFIDENTIAL

43. Krummel, O., "Handbuch der Ozeanographic," Vol. 1, p. 208, Stuttgart, J. Engelhorn, 1907.

44. Owens, E. J., and George Thodos, "Thermal Conductivity: Reduced State Correlation for Ethylene and its Application to Gaseous Aliphatic Hydrocarbons and Their Derivatives at Moderate Pressures," A.I.Ch. E. Journal, 6, 676 (1960)

TABLE 1

VISCOSITY OF MHF-5

	Viscosity		
Temperature, °F	Centistokes	Centipoise	Ref
-67	111.4	120.0	9
-65		108	8
-65	90.0	96.8	9
-40		9.2*	21
-31.1	19.4	20.6	9
3.4	6.7	7.0	9
64	2.3	2.3	9
77	1.9	1.9	8,9,21
95	1.6	1.6	9
113	1.3	1.3	9
131	1.1	1.1	9
149	1.0	1.0	9
160	0.9	0.9	9

*This value appears to be a typographic error and is rejected from further consideration. The correct value is 29.

TABLE 2

HEAT CAPACITY OF MHF-5 (Ref. 8)

Temperature °F	Heat Capacity, Btu/lb-°F Experimental	Heat Capacity, Btu/lb-°F Calculated(1)	Deviation, %(2)
39.2	0.661	0.658_1	+0.4
41.9	0.652	0.658_5	-1.0
78.8	0.671	0.664_5	+1.0
81.5	0.666	0.664_9	+0.2
82.4	0.663	0.665_1	-0.3
151.7	0.672	0.676_2	-0.6
153.5	0.679	0.676_5	+0.4
154.4	0.674	0.676_7	-0.4

(1) Calculated from the equation:

$$Cp(\text{Btu/lb-°F}) = 0.6518 + 1.61 \times 10^{-4} T \text{ (°F)}$$

(2) (Experimental-Calculated) (100)/Experimental

(3) Subscripted numbers are of questionable significance

TABLE 3

THERMAL CONDUCTIVITY OF AEROZINE 50, MMH, UDMH and N_2H_4

AeroZINE 50$^{(1)}$

Temperature, °F	Thermal Cond, Btu/lb-ft-°F	Ref
50	0.167_5*	40
100	0.163_3	40
150	0.158_5	40
200	0.153_1	40
250	0.147_1	40
300	0.140_4	40
	Monomethylhydrazine$^{(2)}$	
0	0.146	40
50	0.144_3	40
100	0.141_0	40
150	0.135_9	40
200	0.129_2	40
250	0.120_7	40
300	0.110_6	40

*Subscripted number indicates questionable significance.

TABLE 3 (cont.)

unsym-Dimethylhydrazine(3)

Temperature, °F	Thermal Cond, Btu/lb-ft-°F	Ref
0.6	0.104	41
51.05	0.0958	41
100.7	0.0862	41
150.68	0.0822	41
200.88	0.0740	41
251.0	0.0665	41
	Hydrazine	
77	0.29	42

(1) Calculated from: $k = 0.171 - 6.45 \times 10^{-5}\ T - 1.25 \times 10^{-7} T^2$

(2) Calculated from: $k = 0.146 - 1.63 \times 10^{-5}\ T - 3.39 \times 10^{-7} T^2$

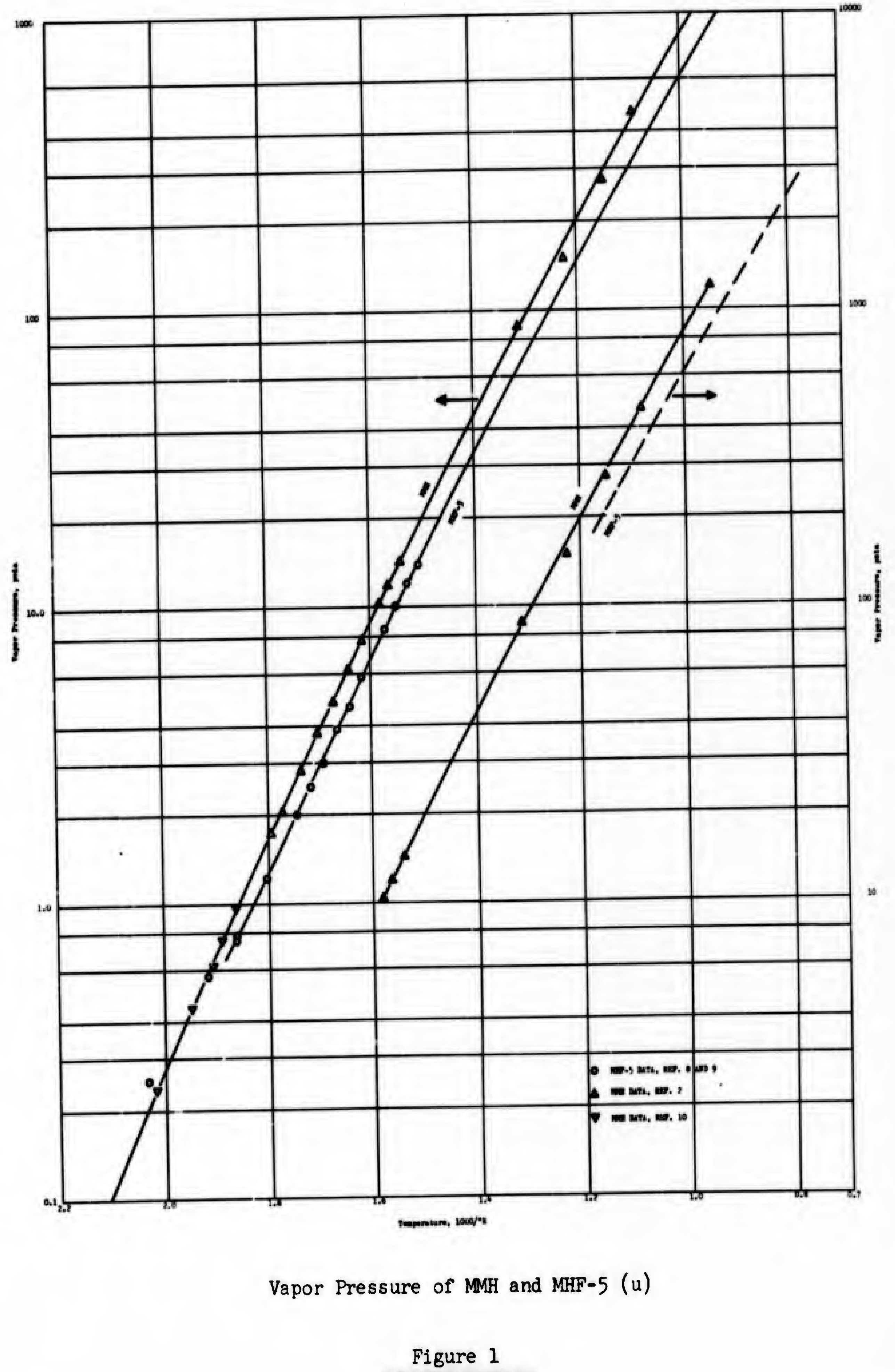
(3) Average values for replicate samples

TABLE 4

VAPOR PRESSURE OF MHF-5

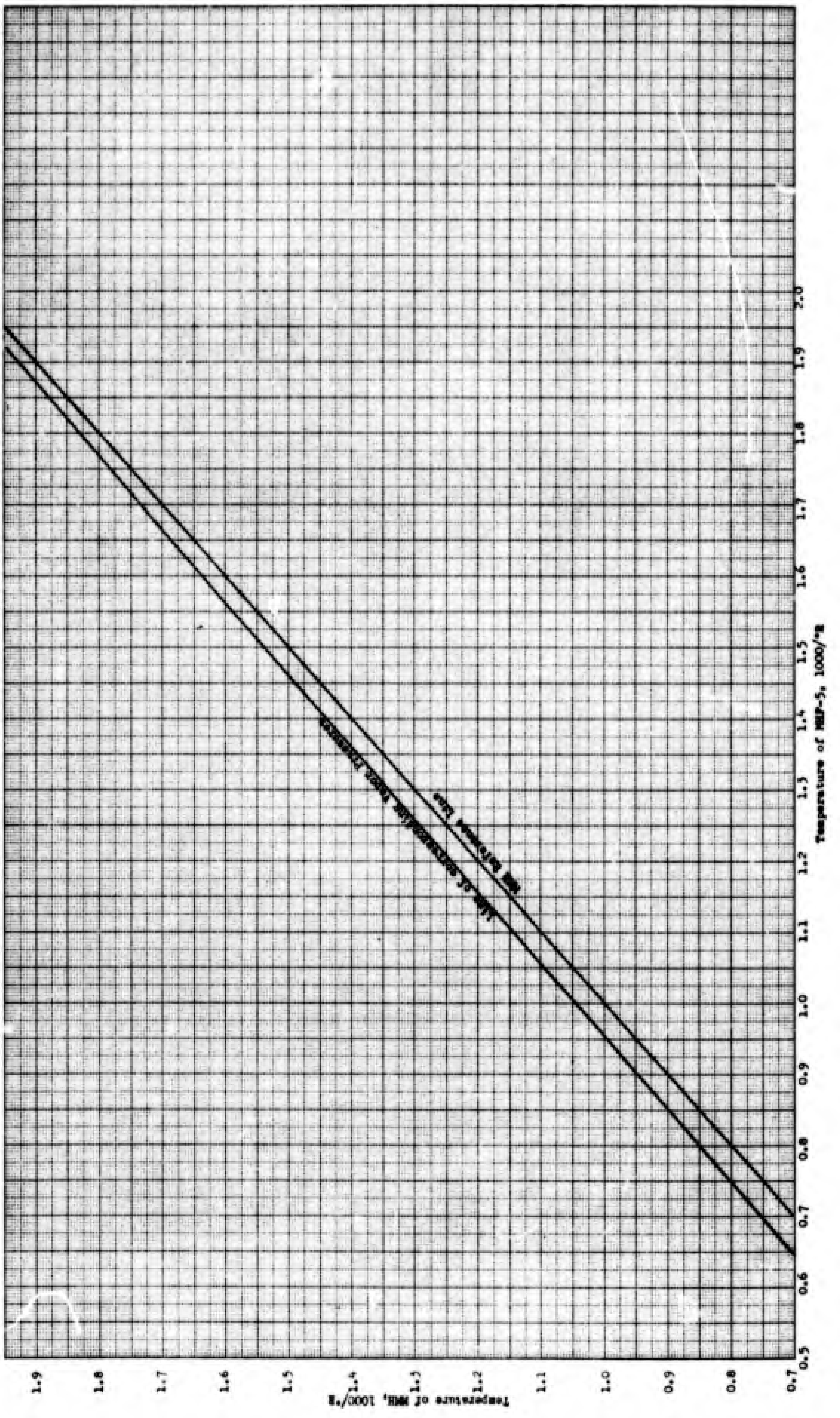
	Vapor Pressure		
Temperature, °F	mm Hg	psia	Ref
32	13.	0.25	8
62	29.4	0.568	9
77	39.	0.75	8
77	39.9	0.771	9
95	63.	1.2	8
95	63.8	1.23	9
113	103.5	2.001	9
122	129.	2.49	8
131	154.8	2.993	9
140	201.0	3.887	9
140	202.	3.91	8
149	239.7	4.635	9
158	300.	5.80	8
176	435.	8.41	8
185	524.	10.1	8
194	621.	12.0	8
203	722.*	13.96	8

*Corrected for residual pressure due to decomposition.



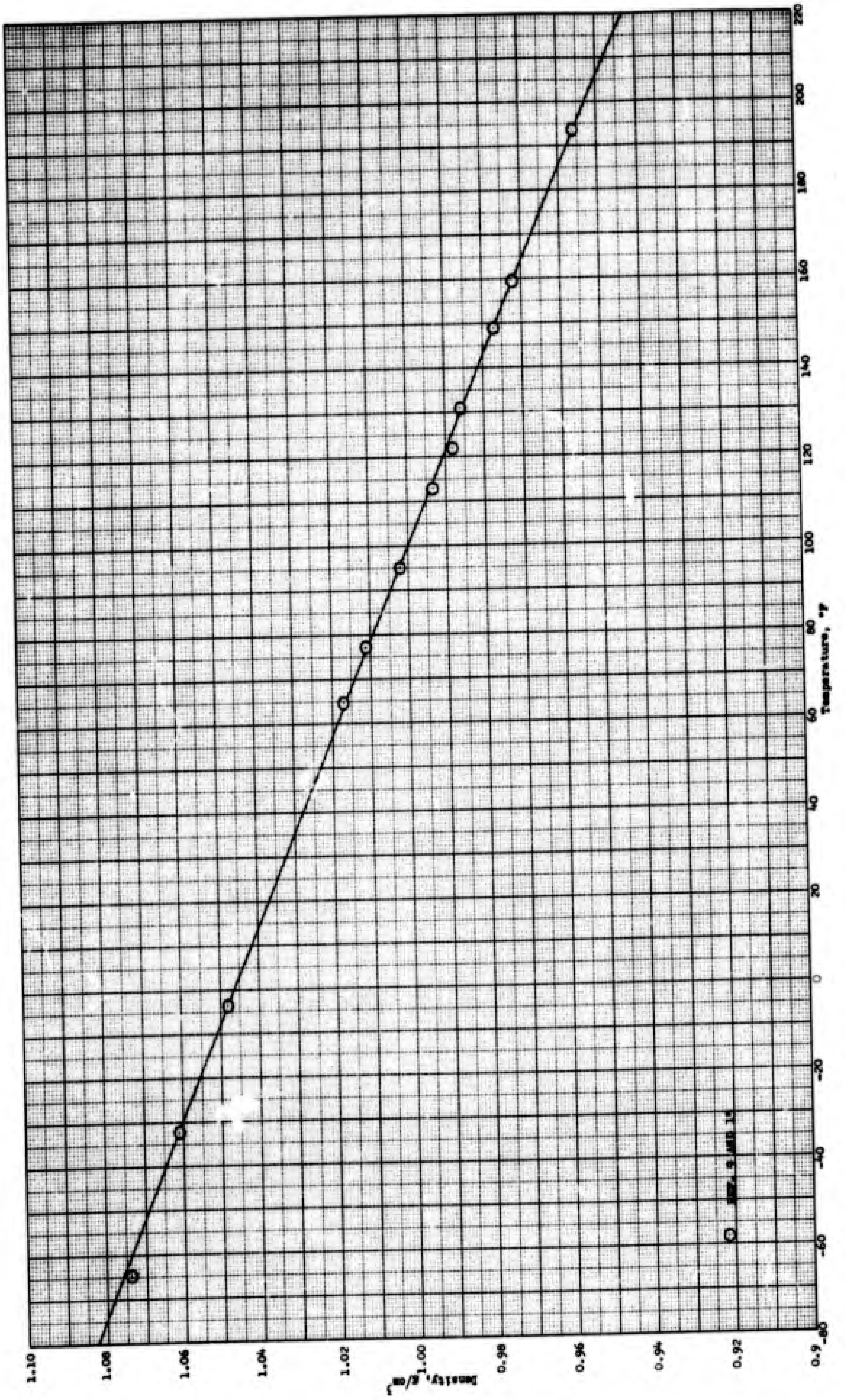
Vapor Pressure of MMH and MHF-5 (u)

Figure 1



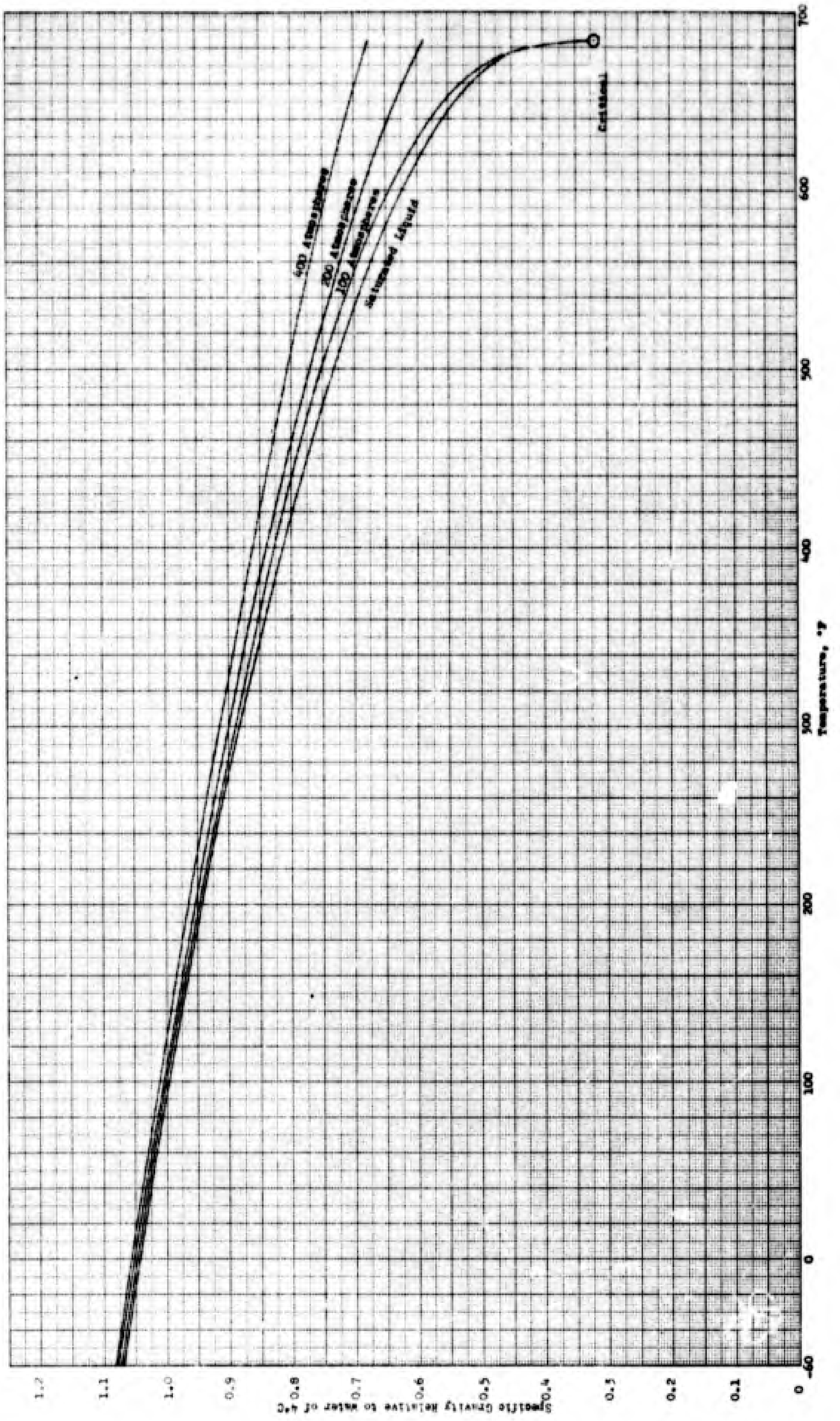
MMH and MHF-5 Vapor Pressure Correlation

Figure 2



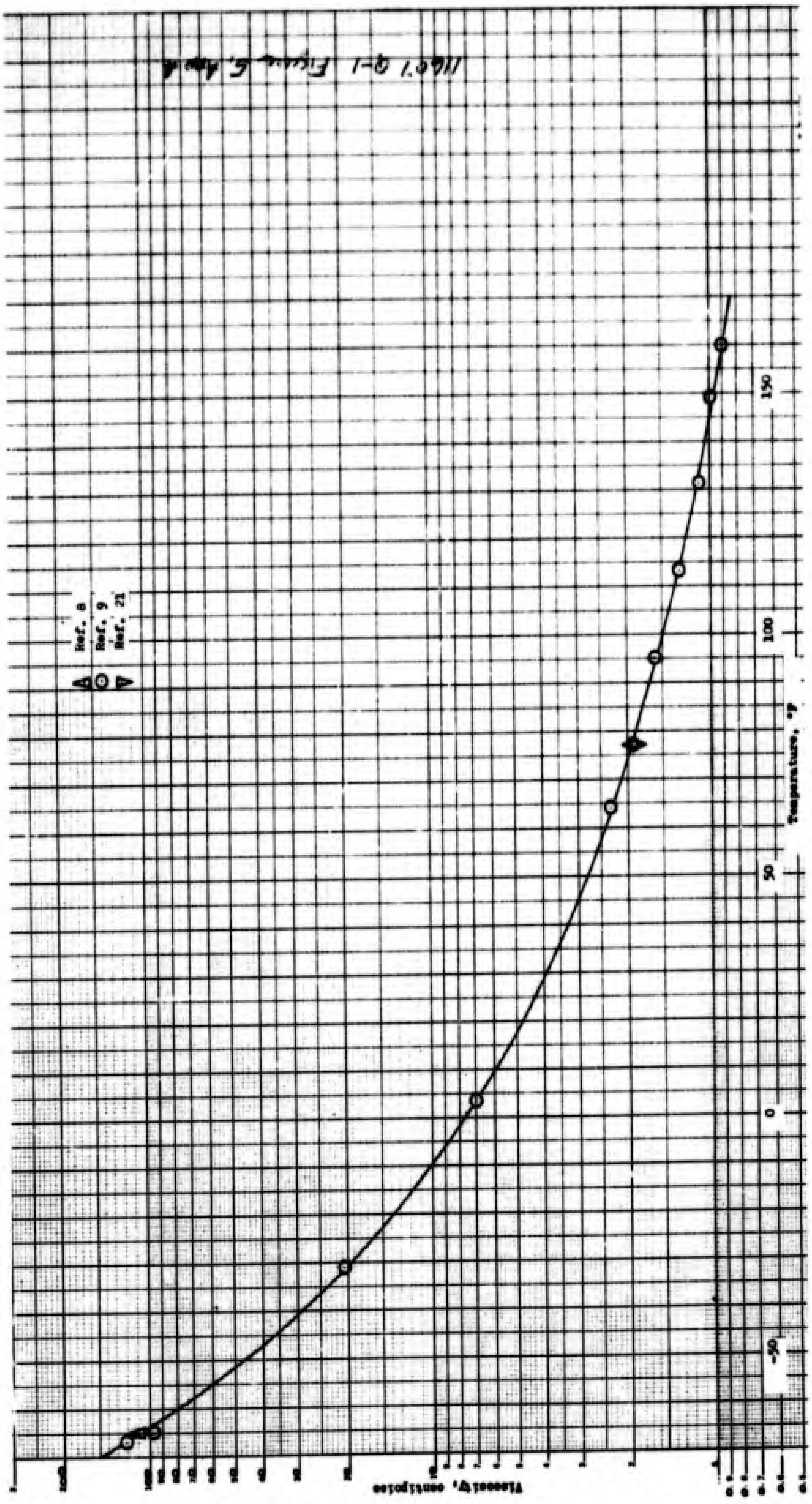
Experimental Density of MHF-5

Figure 3



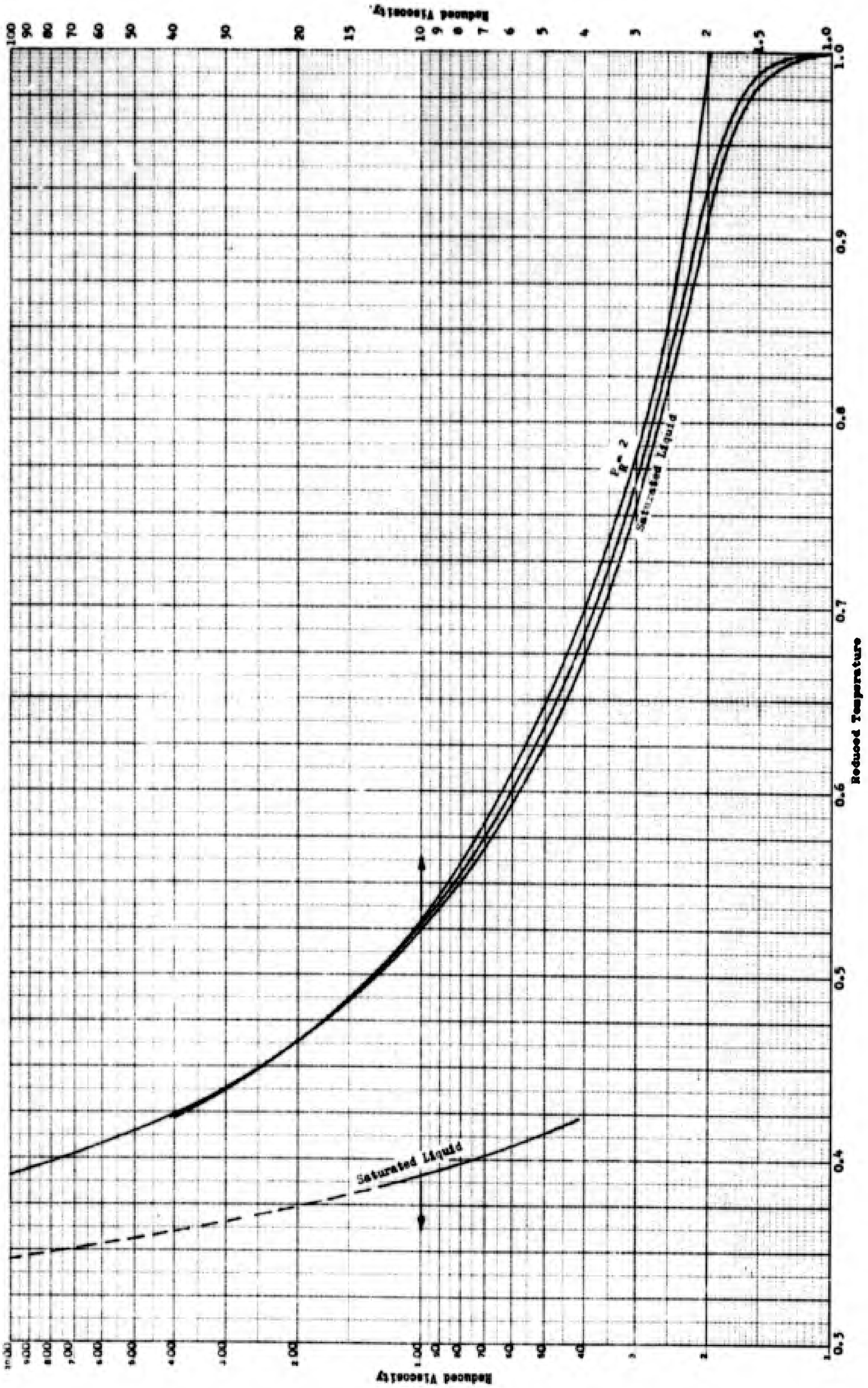
Extrapolated Specific Gravity of MHF-5

Figure 4



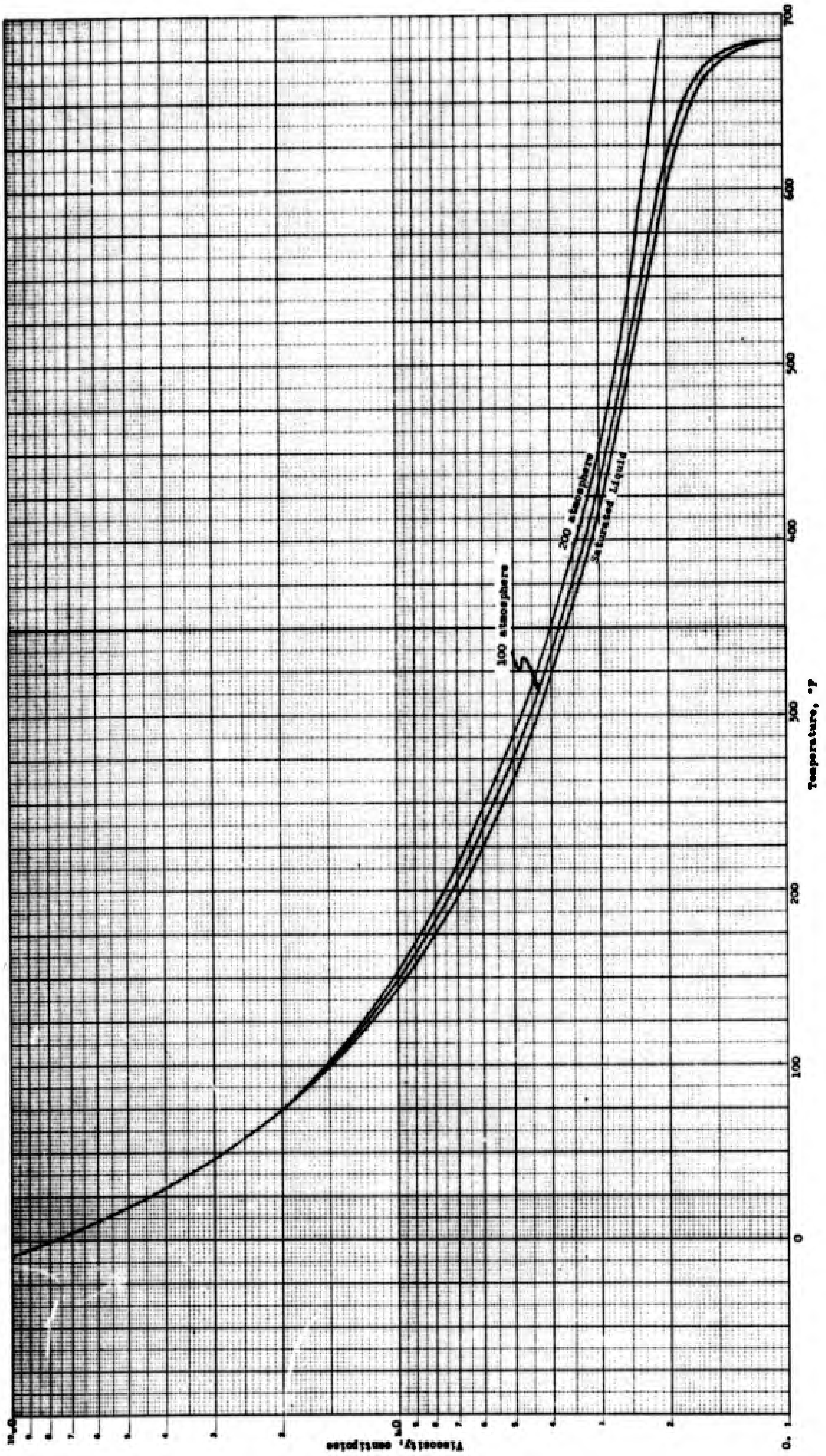
Experimental Viscosity of MHF-5 (u)

Figure 5



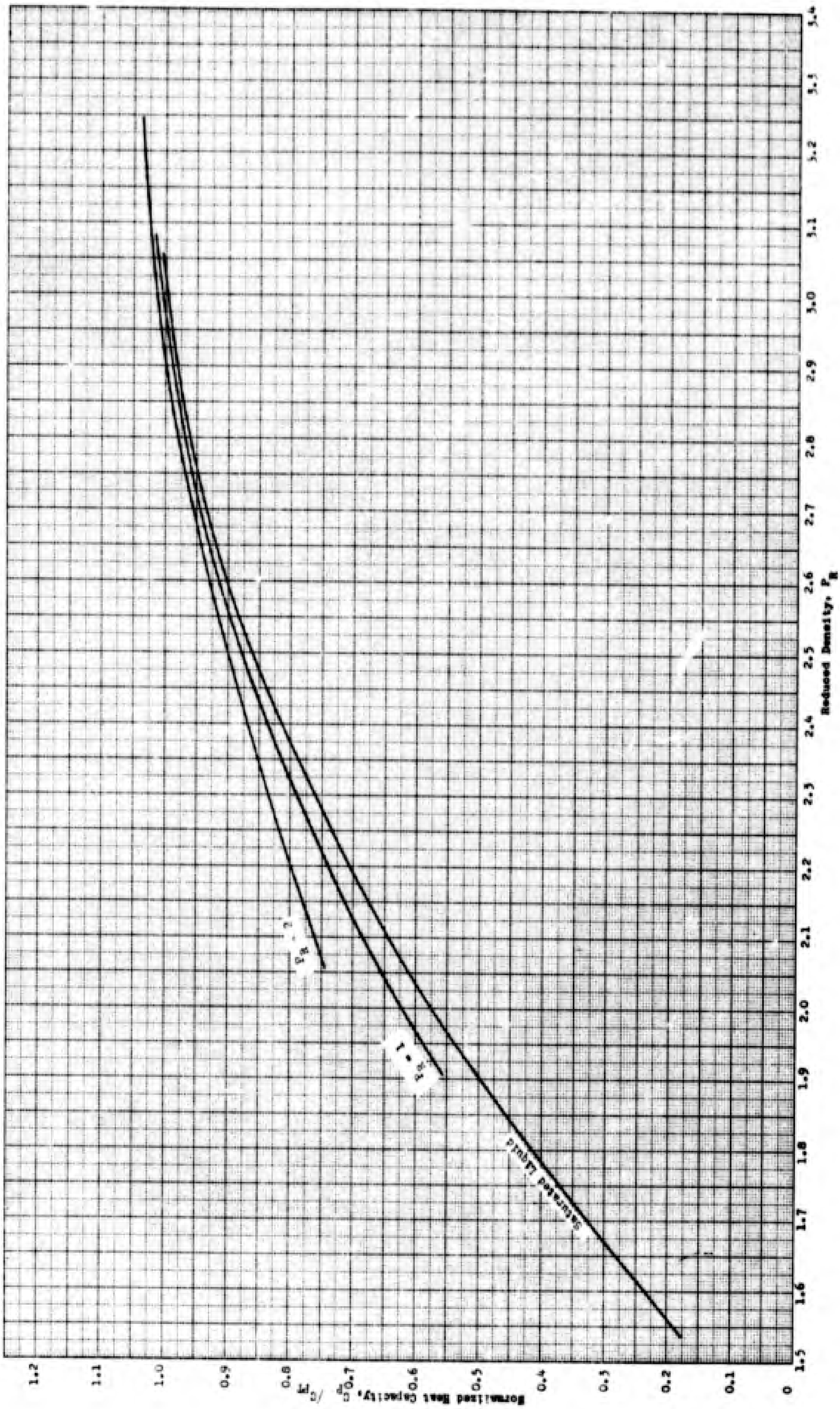
Reduced State Viscosity Correlation for MHF-5

Figure 6



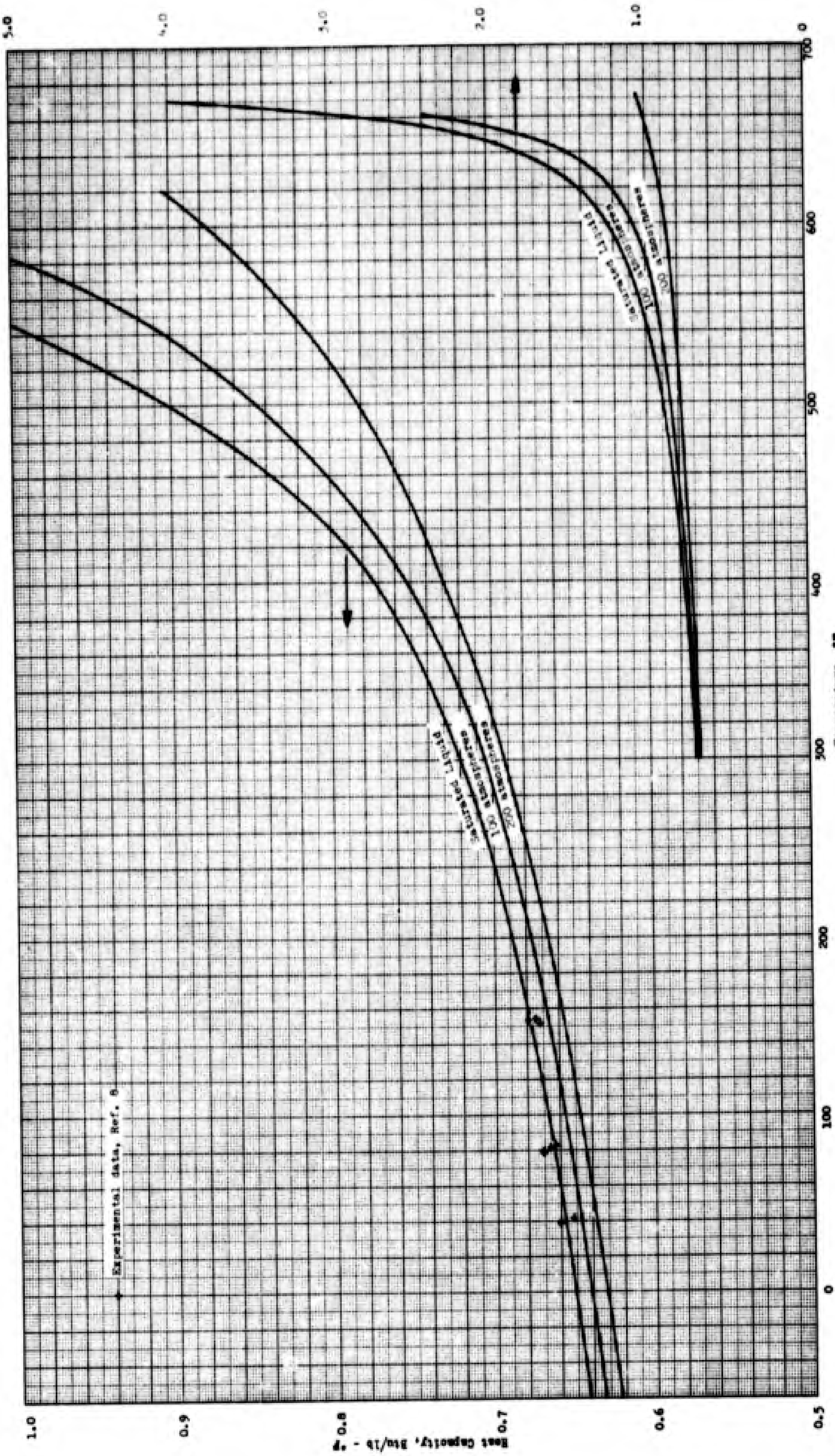
Extrapolated Viscosity of MHF-5 (u)

Figure 7



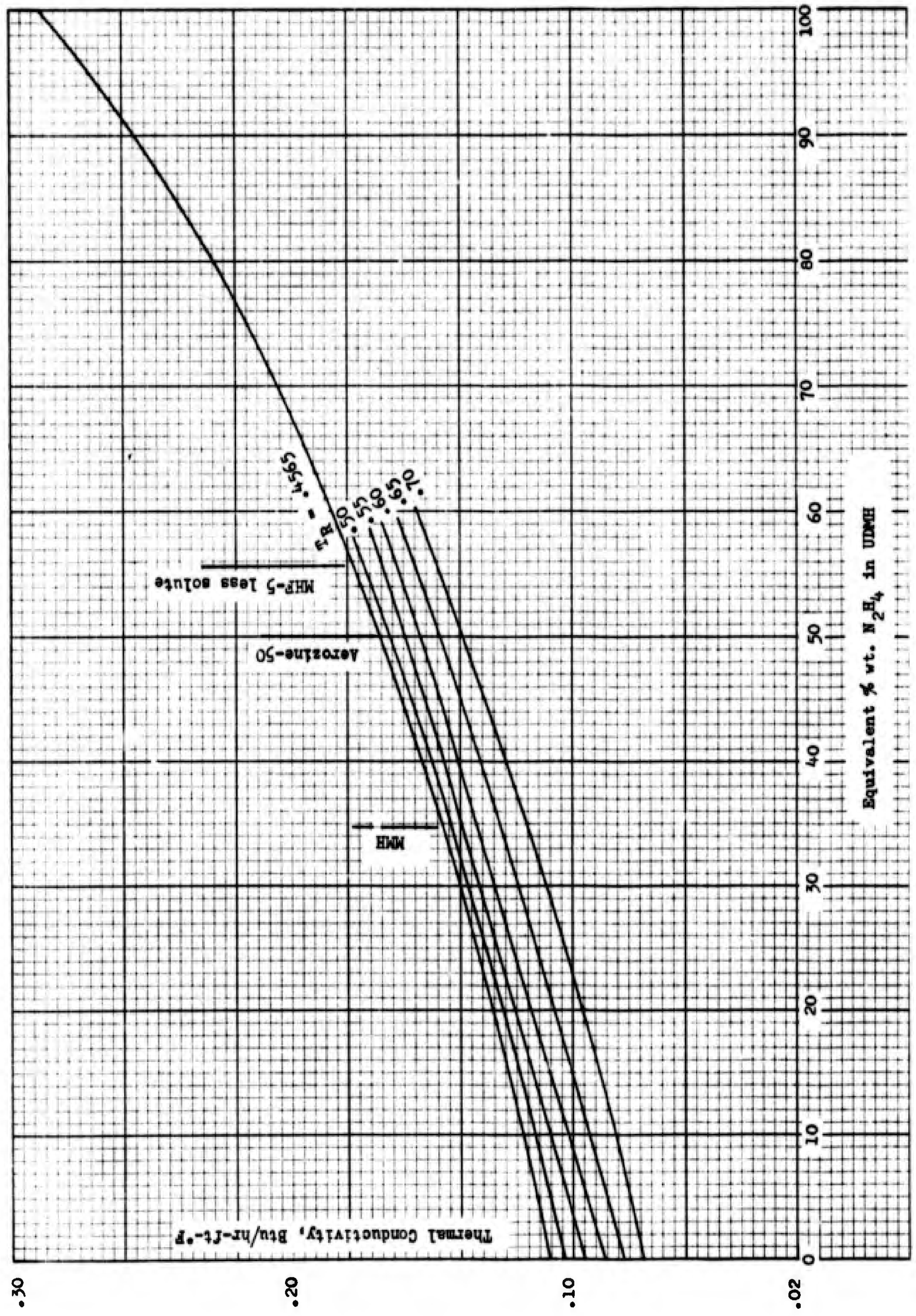
Reduced State Heat Capacity Correlation for MHF-5

Figure 8



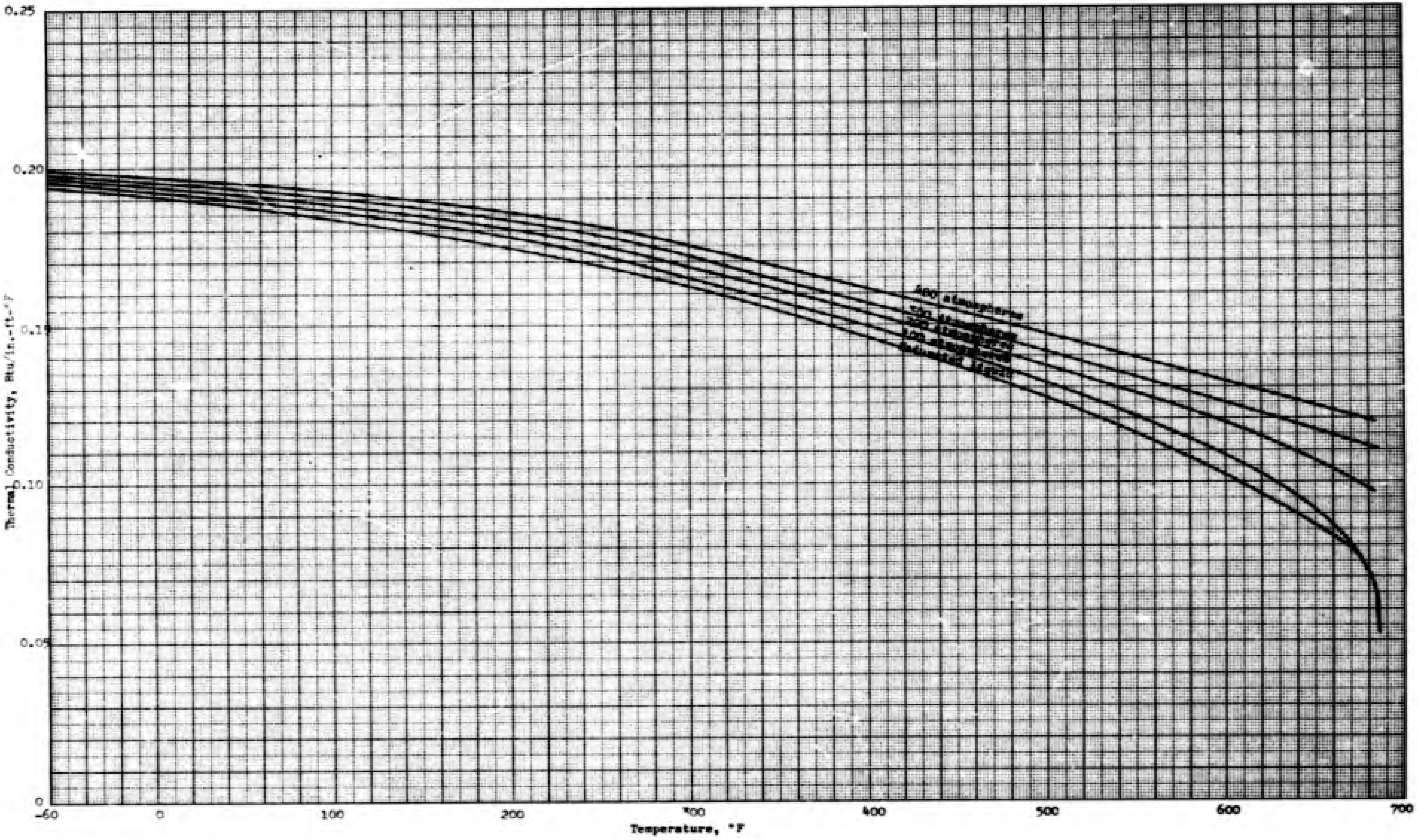
Extrapolated Heat Capacity of MHF-4 (υ)

Figure 9



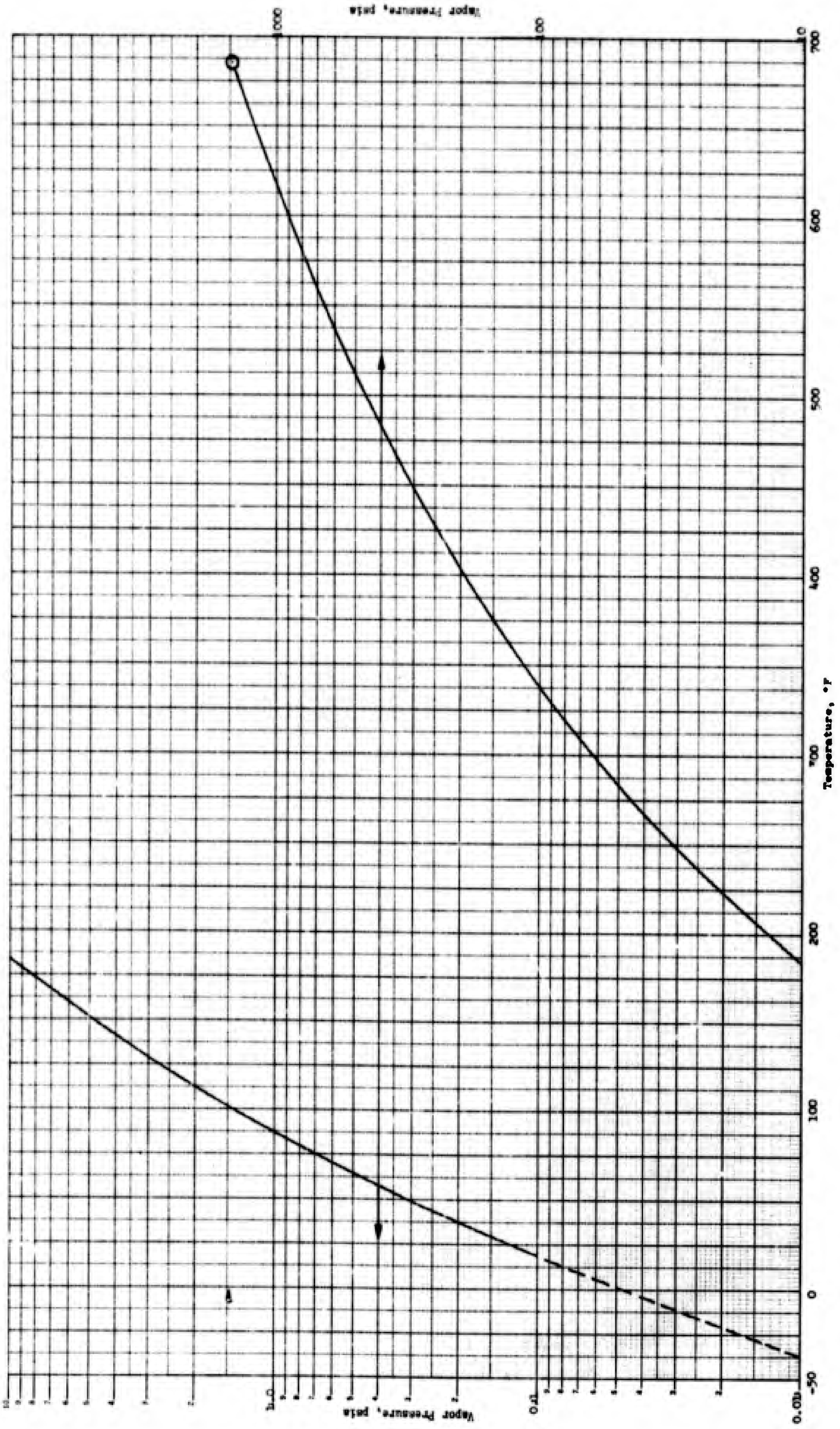
Thermal Conductivity Correlation of Hydrazine-Type Fuels (u)

Figure 10



Extrapolated Thermal Conductivity of MHF-5

Figure 11



Extrapolated Vapor Pressure of MHF-5 (u)

Figure 12

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author)
Aerojet-General Corporation

2a REPORT SECURITY CLASSIFICATION
Confidential

2b GROUP
4

3 REPORT TITLE
Heat Transfer Study of Prepackaged Propellants

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
Quarterly report for the period 1 July to 30 September 1966

5 AUTHOR(S) (Last name, first name, initial)
Anderson, Roger E; Rousar, Donald C; Van Huff, Norman E

6 REPORT DATE
15 October 1966

7a TOTAL NO OF PAGES
[illegible]4 PG, 7 TABLES, [illegible]5 FIG'S

7b NO OF REFS
46

8a CONTRACT OR GRANT NO.
AF 04(611)-11607

b PROJECT NO
3148

c

d

9a ORIGINATOR'S REPORT NUMBER(S)
Report 11607 Q-1

9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10 AVAILABILITY/LIMITATION NOTICES IN ADDITION TO SECURITY REQUIREMENTS WHICH MUST BE MET, THIS DOCUMENT IS SUBJECT TO SPECIAL EXPORT CONTROLS, AND EACH TRANSMITTAL TO FOREIGN NATIONALS MAY BE MADE ONLY WITH PRIOR APPROVAL TO AFRPL (RPPR/STINFO), EDWARDS, CALIFORNIA, 93523

11 SUPPLEMENTARY NOTES

12 SPONSORING MILITARY ACTIVITY
Air Force Rocket
Propulsion Laboratory

13 ABSTRACT

This report summarizes the work performed during the first three months of an experimental program in which the forced-convection and burnout heat flux characteristics of MHF-5 and MMH are to be investigated. The results of 20 tests conducted with MHF-5 at pressures from 500 to 3000 psia, velocities from 19.5 to 189 ft/sec, bulk temperatures from 70 to 278°F, and at heat fluxes up to 49.6 Btu/in.^{2} sec are presented and discussed. Correlations for the burnout heat flux of MHF-5 at subcritical and supercritical pressures are presented. The physical properties that were extrapolated from available data and estimated are presented in an appendix, along with discussions on the extrapolation and estimation techniques that were used. The results of chemical analyses performed on MHF-5 samples taken from the heat transfer test system before and after testing are also presented.

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

INSTRUCTIONS

1. **ORIGINATING ACTIVITY:** Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. **REPORT SECURITY CLASSIFICATION:** Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. **GROUP.** Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. **REPORT TITLE:** Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. **DESCRIPTIVE NOTES:** If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. **AUTHOR(S):** Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. **REPORT DATE:** Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. **TOTAL NUMBER OF PAGES:** The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. **NUMBER OF REFERENCES:** Enter the total number of references cited in the report.

8*a*. **CONTRACT OR GRANT NUMBER:** If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. **PROJECT NUMBER:** Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. **ORIGINATOR'S REPORT NUMBER(S):** Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. **OTHER REPORT NUMBER(S):** If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. **AVAILABILITY/LIMITATION NOTICES:** Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through

____."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through

____."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through

____."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. **SUPPLEMENTARY NOTES:** Use for additional explanatory notes.

12. **SPONSORING MILITARY ACTIVITY:** Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. **ABSTRACT:** Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification