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Research Report

U.S. NAVY EVALUATION OF THE HIGH REYNOLDS' NUMBER THERMAL STABILITY (HiReTS) TEST UNIT

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EXECUTIVE SUMMARY

The High Reynolds' Number Thermal Stability (HiReTS) test unit was developed by Shell Global Solutions, Fuels Business Group as a small-scale unit for evaluating the thermal stability of jet fuel prior to shipment to the consumer. This unit was designed to operate at relatively high fuel flow rates through a heated, stainless steel tube (capillary) representative of turbulent flow conditions in actual engine fuel injectors. At the standard operating conditions (SOC), the fuel flow rate is 35 mL/min, bulk fuel exit temperature (T_{Fo}) of the capillary is 290°C (554°F), and the test duration is two hours. As deposits buildup within the capillary, its surface temperature increases and is monitored in real-time by a non-invasive infrared pyrometer that scans the hottest section of the tube (last 21 mm). At the end of test, the overall temperature increase of the capillary surface that occurs over the test duration at the different scan positions is called the HiReTS Number (HN).

The purpose of this testing and analysis program was to evaluate the HiReTS as a potential tool for measuring the thermal stability properties of Navy fuels (jet and diesel), viz., as both a specification test and a research tool. This program was conducted using the Shell Prototype Model #2 at the U.S. Naval Air Systems Command over the two-year period from February 1999 through March 2001, and had two primary objectives: (1) Evaluate the HiReTS at SOC, and (2) Evaluate alternate HiReTS test conditions, or non-SOC.

To determine the feasibility of using the HiReTS as a new specification test to replace the Jet Fuel Thermal Oxidation Tester (JFTOT), the program evaluated the HiReTS over a large number of jet and diesel fuels (78 total) of various fuel qualities with a wide range of JFTOT Breakpoint Temperatures (BPTs). These fuels were classified into two main categories: (1) *refinery samples*, to denote the fact that they came directly from the refinery and have never come into direct contact with the fuel distribution system, and (2) *field samples*, that came from a wide array of sources, were exposed to a variety of environments and/or contaminants, and/or were transported in the fuel distribution system, and/or stored for extended periods of time. Three additives were also evaluated in this program to determine if the HiReTS could measure their deposit-reducing tendencies: (1) Metal Deactivator Additive, (2) Betz 8Q406, and (3) Betz 8Q462.

For quantification of thermal stability, a LECO Carbon Analyzer was used to measure the post-test weight of carbon (in μg) inside the HiReTS capillary. In addition, a Graphite Furnace Atomic Absorption Spectroscopy was used to measure the soluble copper concentration (in parts per billion (ppb, w/w)) present in the various test fuels.

The summary results at SOC showed that the HN agreed with the JFTOT BPT for 76% of the 78 fuels tested when evaluated on a pass-fail basis. This agreement was better for the *refinery samples* (86%) as compared to the *field samples* (70%). In addition, the capillary carbon deposit correlated poorly with the HN for the 78 fuels tested. However, a strong correlation was observed between carbon deposits versus HN for the *refinery samples*.

Fuels containing >30 ppb of soluble copper caused an unusually high HN, relatively low amount of carbon deposits (compared to HN), and a premature shutdown of the HiReTS at SOC. When normalizing these results by test duration (hrs), the carbon deposition rate (μg/hr) produced from one copper-contaminated JP-5 (Fuel A) showed a strong linear correlation with respect to increasing copper concentration over the range of 50-800 ppb.

The summary results at non-SOC showed that decreasing the fuel flow rate from 35 mL/min (to 25 mL/min and 15 mL/min) will increase the deposition rate and deposit yield (mg/L) while still maintaining good repeatability and turbulent flow conditions. However, the scan length of the capillary (21 mm) is insufficient under certain non-SOC conditions of flow rate and/or T_{Fo} to capture all of the deposits.

For a JP-5 fuel (Fuel A) containing >40-50 ppb soluble copper, premature shutdowns that typically occurred at SOC were eliminated when the HiReTS was operated at T_{Fo} of 230°C (446°F) or less. For concentrations in the range of 40-3400 ppb, both the carbon deposits and HN reached a maximum at 280 ppb, and then rapidly decreased as the copper level was increased to 3400 ppb. A further increase in the T_{Fo} beyond 260°C (500°F) caused a reduction in the deposition rate.

Operating the HiReTS at a lower T_{Fo} (220°C) and allowing the test duration to vary until an abrupt increase in the HN rate is observed (at HN = 300-400) showed better discernment in a fuel's stability. By recording the time of this occurrence (in hours), or failure condition, fuels can be ranked on their ability to increase or decrease this time as compared to a known reference fuel. This modified protocol had also shown to better discern the relative effectiveness of additives.

For research purposes, recommendations are made to modify the HiReTS SOC to operate closer to actual aircraft engine operating conditions: (1) Run at lower fuel flow rates, lower T_{Fos} (180°- 220°C), variable test duration, and terminate the test when at HN = 300-400; (2) Scan a longer length (at least 50%) of the capillary to improve the correlation of μg carbon to HN at SOC and non-SOC; and (3) Conduct an in-depth study to determine the impact of turbulence by operating at variable flow rates while holding T_{Fo} constant. Subsequently, optimize the variables for flow rate, T_{Fo}, and test duration so that results would be produced in a more reasonable test period.

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LIST OF ACRONYMS/ABBREVIATIONS

AST	Average System Temperature
ASTM	American Society for Testing and Materials
BPT	Breakpoint Temperature (JFTOT)
CBO	Carbon Burnoff (LECO)
DFM	Diesel Fuel Marine (F-76)
GFAA	Graphite Furnace Atomic Absorption
HiReTS	High Reynolds' Number Thermal Stability
HN	HiReTS Number
IR	Infrared
JFTOT	Jet Fuel Thermal Oxidation Tester
LECO	Laboratory Equipment Company
NAFTSS	Naval Aviation Fuel Thermal Stability Simulator
NAVAIR	U.S. Naval Air Systems Command
PC	Personal Computer
ppb (w/w)	Part Per Billion (weight per weight basis)
ppm (v/v)	Part Per Million (volume per volume basis)
ppm (w/v)	Part Per Million (weight per volume basis)
QA	Quality Assurance
QC	Quality Control
RDTF	Red-Dye Test Fuel
Re	Reynolds' Number

LIST OF ACRONYMS/ABBREVIATIONS Continued

SOC	Standard Operating Conditions (HiReTS)
STR	Single Tube Reactor
SwRI	Southwest Research Institute
$T_{Fo(s)}$	Bulk Fuel Out Temperature(s), exit of HiReTS capillary
$T_{wo(s)}$	Maximum Capillary Outside Wall (Surface) Temperature(s), Beginning of Test
TSIA(s)	Thermal Stability Improving Additive(s)

U.S. NAVY EVALUATION OF THE HIGH REYNOLDS' NUMBER THERMAL STABILITY (HiReTS) TEST UNIT

1. INTRODUCTION

The HiReTS was developed by Shell Global Solutions, Fuels Business Group as a small-scale unit for evaluating the thermal stability of jet fuel prior to shipment to the consumer. The HiReTS was designed to operate at high fuel flow rates through a heated, stainless steel tube (capillary) representative of turbulent flow conditions in actual engine fuel injectors. At the standard operating conditions (SOC), the HiReTS has a Reynolds' Number (Re) of approximately 13,000, well within the turbulent regime. The presence of high turbulence in the HiReTS also eliminates the sensitivity of mass transport effects that occur in laminar flow test devices such as the Jet Fuel Thermal Oxidation Tester (JFTOT), which operates at a Re of approximately 10.

The HiReTS capillary is electrically heated and controlled by a PC-based data acquisition system that ensures a constant bulk fuel exit temperature (T_{Fo}). As deposits buildup within the capillary, its surface temperature increases and is monitored in real-time by a non-invasive infrared pyrometer that scans the hottest section of the tube (last 21 mm of effective heated length). The more deposits that form inside this section, the more the surface temperature rises. At the end of test, the overall temperature increase of the capillary surface that occurs over the test duration at the different scan positions is called the HiReTS Number (HN). This is considered a quasi-measurement of thermal fouling within the capillary.

For the JFTOT, on the other hand, the deposits that form on the tube surface are measured by comparing the color of this deposit (post-test) to that of the Color Standard established by the American Society for Testing and Materials (ASTM). The measurement is qualitative, thus making an interpretation of results subjective. In addition, current fuel research to improve the thermal stability of fuels has led to an increased interest in the development of thermal stability improving additives (TSIAs). Since many ways exist for evaluating the effectiveness of TSIAs to control deposit formation, the use of the JFTOT Breakpoint Temperature (BPT) may not the best approach.

The purpose of this test evaluation program is to evaluate the HiReTS as a potential tool for measuring the thermal stability properties of Navy fuels (jet and diesel), viz., as both a specification test and a research tool. This program was conducted using the Shell Prototype Model #2 at the U.S. Naval Air Systems Command (NAVAIR) over the two-year period from February 1999 through March 2001.

2. PROGRAM OBJECTIVE

In order to fulfill the program purpose, the study conducted and reported herein had two primary objectives:

(1) Evaluate the HiReTS at SOC.
(2) Evaluate alternate HiReTS test conditions, i.e., non-SOC.

3. EXPERIMENTAL

3.1 Equipment

3.1.1 ***HiReTS.*** A schematic of this device is given in Figure 1. The capillary tube is made of stainless steel with an overall length of 6" (15.24 cm), effective heated length of 5.3125" (13.5 cm), OD of 0.125" (0.3175 cm), and ID of 0.01 (0.0254 cm). At SOC, the HiReTS pumps fuel via a HPLC pump at a flow rate of 35 mL/min through the capillary, which is heated electrically via bus bars clamps to maintain the T_{Fo} at to 290°C (554°F). The system backpressure is maintained constant throughout the test via a pressure regulator at 500 psig to prevent the fuel from boiling. Under these conditions, the fuel residence time is 0.01 sec and the maximum capillary surface temperature (T_{wo}), before deposition occurs, will vary from 380° to 400°C (716° to 752°F) for a typical kerosene jet fuel. Surface temperature is measured via a motor driven pyrometer that scans the capillary surface at nine different positions, 2.5 mm apart, over the last 21-mm of the effective heated length, which is the hottest section of the capillary. At the end of the test, the effective heated length of the capillary is cut into four equal sections, approximately 1.3" (3.3 cm) in length, for subsequent post-test carbon analysis via LECO carbon burnoff (CBO) (see section 3.1.2 for a description of this method).

The test duration for a standard, quality control (QC) test as established by Shell is two hours. Since no pre-heating is used prior to the capillary tube, the HiReTS requires a relatively large amount of heat to raise the bulk fuel temperature across the capillary from ambient to the T_{Fo}. As a result, deposits form inside the tube at the fuel/metal interface that have an insulating effect which prevents the capillary from being sufficiently cooled. In addition, since the capillary exit temperature is maintained constant throughout the test, the heat output from the heater is gradually and continually increased. As a result of these two simultaneous phenomena, the capillary surface temperature increases within the 21-mm scan length as the test proceeds. At the end of test, the summation of the temperature rises at each of these nine scan positions (from the lowest value recorded during the test to the end-of-test value) is called the HN. From earlier studies at Shell during the developmental stage of the HiReTS, a HN in excess of 1000 was chosen to be a fuel failure since it was equated to a Code 3 color code in the JFTOT (reference [1]).

3.1.2 ***LECO Carbon Analyzer.*** This analytical instrument is used for the post-test measurement of thermal deposition that accumulates inside the HiReTS capillary during a test by measuring the weight of carbon present in the deposit. A HiReTS tube section is placed in a quartz sample boat and then inserted inside the LECO heated glass combustion tube. Then, low-pressure oxygen flows over and around the sample and is heated to a temperature that is sufficiently high to convert all of the solid carbon from the deposit into carbon dioxide. The final weight of carbon is calculated from the amount of carbon dioxide measured via infrared (IR) technology that converts this IR signal into mass of carbon.

Due to the sensitivity of the LECO to measure extremely low levels of carbon, rinsing of the capillary with residue-free heptane, both pre-test and post-test, was employed to remove any contamination or fuel residue that would otherwise be detected by the LECO. In addition, since the capillaries are made of stainless steel, LECO analyses were conducted on unused capillary sections at the beginning of the program to determine the (average) amount of carbon that the tube itself contributes to the total carbon deposit. This average carbon weight present in an unused capillary section, or blank as it is referred, was subtracted from the carbon results obtained from all subsequent HiReTS fuel tests conducted throughout this program. This way, the true amount of carbon resulting from thermal stressing could be determined.

3.1.3 ***Graphite Furnace Atomic Absorption Spectroscopy (GFAA).*** This analytical instrument was used throughout this program to measure the copper concentration (ppb, w/w) present in various test fuels following the ASTM D-6732-02 method.

3.2 **Fuels**

Fuels used in this program were classified into two broad categories: refinery samples and field samples.

3.2.1 ***Refinery Samples.*** These fuels are labeled as such to denote the fact that they came directly from the refinery and have never come in contact with the fuel distribution system (i.e., pipelines, trucks, ships, storage tanks, etc.). Nineteen neat (unadditized) samples were provided by Southwest Research Institute (SwRI) and were obtained from various refineries, crude types, and refinery processing techniques. These sample are also referred to as Red-Dye Test Fuels (RDTF), and were previously stored at SwRI as part of the Red-Dye Fuel Program to evaluate the impact of red-dye contamination on the thermal stability of jet fuels. To avoid low temperature oxidation during storage, the fuels were blanketed with argon. These samples were stored for approximately two to three months before being shipped to NAVAIR at Patuxent River, Maryland. The thermal stability of these fuels was determined by the JFTOT BPT method and is documented within this report in Table 1A along with other background fuel information. These fuels are identified consecutively by the SwRI designation of RDTF-1 through RDTF–19.

3.2.2 ***Field Samples.*** These fuels consisted of 59 different samples that had come from a wide array of sources. These fuels had been previously used in other test programs, had been exposed to a variety of environments and/or contaminants, and/or had been transported in the distribution system, and/or had been stored for extended periods.

(1) ***NAVAIR Test Fuels.*** This group of samples consisted of 53 different fuels which included JP-5s, JP-8s, Jet-As, Jet A-1s, Diesel Fuel Marine (F-76), contaminated fuels (viz., copper, high nitrogen, and red dye), and even one high stability JPTS. These fuels had been stored for extended periods of time ranging up to ten years. Specific information on these fuels is summarized in Table 1B. Of the 53 fuels, 19 of these samples were the same RDTF fuels

mentioned in Section 3.2.1, with the only exception that these fuels were doped with approximately 0.5 mg/L of red dye.

(2) *NAVAIR Test Fuels (Copper-Contaminated).* One NAVAIR test fuel, Fuel A, inherently contained 40-60 ppb copper. This fuel was then copper contaminated to higher levels (80-3400 ppb) by the immersion of copper shims into the fuel, and is thus referred to as Fuel B. Before immersion, the shims were sandblasted so that a freshly exposed surface was created to facilitate copper uptake into the fuel. When the desired concentration of soluble copper was achieved, the shims were then removed and the concentration measured by GFAA. This fuel can also be found in Table 1B.

(3) ***ASTM HiReTS Round-Robin Fuels.*** ASTM had conducted a round robin exercise in early 2001 to determine the precision of the HiReTS. Six laboratories had participated - one being NAVAIR at Patuxent River, MD - and were all supplied the same test fuels. Six of these fuels were supplied by Shell Global Solutions and were approximately one to ten years old at the time of this test program. These fuels were manufactured at two European refineries that consisted of various hydrotreated and Merox-treated Jet A-1s. Specific information for these fuels can be found in Table 1C.

3.3 Additives

Three additives were evaluated in this program to determine if the HiReTS could measure their deposit-reducing tendencies when doped in various fuels tested. These additives are as follows:

3.3.1 ***Metal Deactivator Additive (MDA).*** N, N-disalicylidene 1,2-propane diamine. This is a chelate type of compound approved for use in jet fuel that is used to suppress the catalytic activity of soluble copper. The allowable dosage is 2 mg/L at the refinery and 5.8 mg/L maximum. For this test program, 5.8 mg/L was used.

3.3.2 ***Betz 8Q406.*** A proprietary formulation consisting of a detergent/dispersant and a butylated hydroxyltoluene antioxidant contained in a hydrocarbon carrier. The recommended dosage is 125 ppm (v/v) which was use throughout this study.

3.3.3 ***Betz 8Q462.*** This additive comprises Betz 8Q406 plus 2 mg/L MDA, and is diluted with a 50:50 mixture of naptha solvent to improve its low-temperature flow properties. It is used at a concentration of 256 ppm (v/v) in practice as well as throughout this test program.

4. DISCUSSION OF RESULTS

4.1 Evaluation of HiReTS at SOC

4.1.1 ***Correlation Between HiReTS and JFTOT.*** The JFTOT BPT is an empirical, qualitative measure of the level of a fuel's thermal stability. A fuel is considered to have acceptable stability if its BPT ≥ 260°C (500°F). On the other hand, the HN (generated from the HiReTS test at SOC) has been reported to provide a more quantitative measure of fuel thermal stability, but has not yet been firmly established as a reliable method (reference [1]). Early attempts to establish a correlation between the HN and BPT have been hampered due to the lack of availability of a sufficient number of fuels with a wide range in thermal stability. Furthermore, it has been suggested (in the same reference) that the HiReTS may not have the ability to discern between very good fuels, i.e., fuels with BPTs $\geq$ 290°C.

To determine the feasibility of using the HiReTS as a new specification test to replace the JFTOT, the program reported herein evaluated the HiReTS over a large variety of fuel qualities with a wide range of BPTs.

4.1.1.1 **Refinery Samples**

(1) ***Red-Dye Program Test Fuels***. Initially, this set of fuels was tested at SOC and then compared to the JFTOT BPT results. These results are summarized in Table 2. Data that show contrary pass-fail results between the HN and the JFTOT BPT are in ***bold italics***. These fuels show conflicting results in that they show a passing result in one unit, yet a failure in the other. This point can be demonstrated more clearly in Figure 2A for the 19 RDTF fuels. When plotting HN versus BPT, a great deal of scatter exists in the data, thus indicating no direct, statistical relationship between the two parameters. However, when comparing the results of each unit on their ability to discern fuels on a pass-fail basis, an improved qualitative correlation is achieved. In these two figures, the data points labeled as blue diamonds indicate agreement between units on a pass-fail basis, i.e., fuels that show a pass (fail) in the HN also show a pass (fail) with respect to BPT. On the other hand, data points labeled as red squares indicate a disagreement in pass-fail results between the two units.

For the 19 RDTF fuels, 86% of the fuels showed agreement between the HN and the BPT on a pass-fail basis. Three of these fuels (and four HiReTS runs), RDTF-5, -8, and –12, produced contrary results when comparing data between the two units. For RDTF-5 & RDTF-8, both fuels had failed the HN (1212 & 1405, respectively) but passed the BPT (290° & 295°C, respectively). For RDTF-12, the opposite result was obtained, i.e., this fuel passed the HN (value of 5) but failed the BPT (255°C). As a result, repeat runs were made to see if these results could be duplicated. For RDTF-5, two repeat runs were made and both tests produced a pass in the HiReTS (454 & 352), contrary to the first run. For RDTF-8, one repeat run was performed and again a failure in HN (value of 1806) was achieved. No repeat runs were made for RDTF-12.

4.1.1.2 **Field Samples**

(1) ***NAVAIR Test Fuels.*** A broad range of fuels from NAVAIR was also tested in the HiReTS and the same type of analysis performed as was done for the RDTF fuels. A total of 53 different fuels were tested multiple times for a total of 144 runs, which also included the copper-contaminated runs with Fuel A. Summarizing and comparing the overall results revealed that 70% of the fuels (37 out of 53) tested showed agreement between the HN and the JFTOT BPT on a pass-fail basis (see Figure 2B). Furthermore, as with the *refinery samples*, a large amount of scatter exists which indicates no mathematical correlation between the HN and the JFTOT BPT. Due to the large amount of data, a summary table was not constructed.

(2) ***ASTM HiReTS Round-Robin Fuels.*** The same approach was used to evaluate the six fuels from the ASTM HiReTS Round-Robin Program. Each fuel was run in duplicate to check for repeatability, for a total of 12 HiReTS tests. As shown in Table 3 and Figure 2C, good agreement is demonstrated for the HN for the repeat runs. However, the HN for sample S3 produced a failure for both runs (1721 & 1769), whereas the JFTOT BPT yielded a pass (275°C). In addition, the same type of scatter can be demonstrated between the two units, again showing no real statistical correlation. However, a good qualitative correlation resulted, with 5 of the 6 fuels (10 of 12 tests, or 83%) showing agreement when the HN was compared to the BPT on a pass-fail basis.

4.1.1.3 **All Fuels**

When all of the fuels tested in this program were included, a slightly better qualitative correlation between HN and BPT is achieved as compared to the *field samples* alone. These results are shown in Figure 2D. For this summary, 78 total fuels and 169 tests were tested at SOC in the HiReTS. These results showed a 76% agreement (59 of 78 fuels) between the HN and the BPT when compared on a pass-fail basis.

This lack of mathematical correlation and degree of disagreement between the two methods on a pass-fail basis is most likely attributed to the two very different ways in which each unit assesses fuel stability. The HiReTS, at SOC, has a turbulent flow through a very narrow passage made of stainless steel that is heated to a very high bulk fuel temperature (290°C). The resulting deposits that form at the end of the HiReTS capillary are measured indirectly via temperature rise along the tube surface of the last 21 mm of axial length. As these deposits accumulate, they cause an insulating effect that impedes heat transfer from the capillary surface into the bulk fuel stream, thus causing the tube surface to rise. The JFTOT, on the other hand, flows fuel very slowly (in the laminar regime) over the outside surface of the aluminum test tube whereby the hottest surface of the tube is controlled, thus yielding different and most likely lower bulk fuel exit temperatures as compared to the HiReTS. At the end of the JFTOT test, the colored stain on this tube is compared to a color chart to determine the fuel's stability.

4.1.2 ***Correlation of HN to Carbon Deposition.*** One of the important features of the HiReTS is the claim that a correlation exists between the HN and the amount of carbon deposits that form in the capillary at the end of the test. To determine the validity of this claim, all capillaries from the tests in Section 4.1.1 (above) were subjected to a LECO CBO (post-test) to determine the weight of carbon deposit (in μg), and subsequently plotted graphically versus the HN to determine the extent of the correlation.

4.1.2.1 **Refinery Samples**

(1) ***Red-Dye Program Test Fuels.*** A summary of the results for the 19 RDTF fuels (28 tests) are summarized in Table 2 and plotted graphically in Figure 3A. As shown in this figure, these fuels demonstrated a strong correlation ($R^2 = 0.95$) between carbon deposits versus HN over the entire range of the data set. Upon closer examination, approximately half of the points

(15 total) are tightly grouped in the range of 0-20 μg and 0-50 HN, which can be viewed more clearly in Figure 3B. As shown in this figure, a poor correlation exists between carbon deposits and HN as evidenced by the scatter in this data set ($R^2 = 0.43$), demonstrating that the HiReTS does not correlate with LECO CBO in this range. This is most likely due to the uncertainty in the LECO CBO measurement of the HiReTS unused (blank) capillary, which has an average value of 23.2 μg and a standard deviation of 3.1 μg.

4.1.2.2 **Field Samples**

(1) ***NAVAIR Test Fuels.*** The same plot was generated for the 53 different fuels (144 total tests) and is shown in Figure 3C. As shown on the graph, these fuels demonstrated a very poor correlation ($R^2 = 0.27$) between carbon deposits versus HN over the entire range of the data set. This lack of correlation can be further demonstrated upon review of Table 4 and Figure 3D for 7 of these 53 fuels in which multiple runs were made on each fuel (see Section 4.1.3 for a more comprehensive analysis). As shown in the figure, no significant correlation exists for this data set. For example, if a horizontal line is passed through 80 μg of carbon (y-axis), it will bisect four or possibly five fuels each having different HNs, ranging from 100 to 1500.

There are two possible explanations for the spread of HN values occurring for a single carbon deposit amount. First, the density of the deposit, and hence its thermal conductivity, will vary from fuel to fuel depending upon the diameter of the deposit sphere and its chemical structure. That is, some deposits have a spongy or flaky consistency while others are comprised of smaller, highly granular material that is more tightly packed. The type and structure of the deposit will ultimately affect the heat transfer from the wetted-wall of the capillary to the bulk fuel stream, thus resulting in a different HN for a given mass of deposit. Second, the capillary deposits are measured as μg carbon, whereas the entire deposit within the tube is comprised of different heteroatoms such as oxygen, sulfur, and hydrogen in addition to carbon. Each fuel, depending upon its individual chemistry, will produce deposits that are unique, and thus the percentage of carbon will most likely be different for each fuel. Analysis of deposits from a previous test program has shown carbon levels to range from 57% to 80% of the total deposit (reference [1]). Thus, the relationship between the μg of carbon and HN is only an approximation of the deposit level in the test specimen.

(2) ***ASTM HiReTS Round-Robin Fuels.*** A summary of the results for the six ASTM fuels is shown in Table 3 and plotted graphically in Figure 3E. As shown in this figure, these fuels demonstrated a poor correlation ($R^2 = 0.22$), which is similar to the correlation for the NAVAIR Test Fuels.

(3) ***All Fuels.*** When the 19 refinery (RDTF) samples were added to the graph, a slight improvement in the correlation (μg carbon versus HN) was observed as compared to the 59 *field samples* alone. However, this graph was not constructed for all 78 fuels since this slightly improved correlation was still very weak.

4.1.3 ***Repeatability Studies.*** As mentioned previously in Section 4.1.2 above, seven NAVAIR test fuels were evaluated under multiple runs at SOC to better determine the repeatability of the

HiReTS as measured by the carbon content and HN. Table 4 summarizes all the data, whereas Figures 3D and 3F show the results graphically. Where test durations of less than two hours are reported, this was due to excessive deposition within the capillary scan length, thus causing a premature shutdown of the HiReTS due to an over-temperature condition. A statistical analysis of the results for each fuel (i.e., mean and standard deviation) shows the HN to be more repeatable than the carbon content. The latter data, however, have several outliers for some of the fuels that affect the degree of repeatability. When the data are plotted, it becomes more apparent that the carbon data have a wider range between the minimum and maximum values as compared to the range of HNs. This point can be further supported when the fuel with the most HiReTS runs (16 total), Fuel H, is plotted by itself (see Figure 3F). A more detailed statistical analysis using 95% confidence intervals further demonstrates that the HN is more repeatable than the carbon content, with HN varying by +/- 10% (978 +/- 98) versus the carbon deposit varying by +/- 18% (108 μg +/- 20 μg).

Another interesting point with respect to HiReTS repeatability is that five of the seven fuels showed consistent and repeatable passes or fails when run in replicate. In other words, the repeat runs for each of these five fuels all passed the HiReTS ($HN < 1000$), or all failed the HiReTS ($HN \geq 1000$), with no inconsistencies. For the other two fuels, Fuel H and Fuel O however, some of the replicate runs for each fuel had passed the HiReTS while other replicate runs had failed. For example, for Fuel O the HNs showed two failures (1130 & 1190), two passes (410 & 744), and a marginal pass (964). These results demonstrate the need to improve the repeatability for the HiReTS test method.

4.1.4 ***HiReTS Response to Soluble Copper in Fuel.*** Two NAVAIR test fuels from the repeatability studies, Fuel D and Fuel A, had soluble copper levels of 30 ppb and 50 ppb, respectively. Both fuels aborted prematurely due to an over-temperature condition of the capillary (and hence high HN), which may be due to the copper content. Upon closer observation of the data in Table 4, the recorded T_{wos} for Fuel D were higher relative to other tests that did not abort. A comparison of the times to system shutdown for these tests shows that the higher the T_{wo}, the shorter the test duration.

In order to explore the impact of copper contamination at SOC in further detail, additional studies tests were conducted with Fuel A at copper levels varying from 50 ppb to 800 ppb. A summary of this data is shown in Table 5. The HiReTS system behaved similarly as observed with tests run 30 ppb and 50 ppb in that the tests aborted prematurely. However, as the copper concentration was increased, the test duration decreased, and T_{wo} appeared to trend upward with each incremental increase in copper concentration. Plotting the μg carbon content versus the HN produces a lot of scatter with no real correlation as shown in Figure 4A. Alternatively, a fair amount of scatter is also observed when plotting μg carbon content versus copper concentration (in ppb), with an $R^2 = 0.67$, as shown in Figure 4B. However, when the carbon data for each test were normalized to their corresponding test durations, i.e., expressed as a rate (μg/hr), and plotted versus copper concentration (ppb), a very linear relationship ($R^2 = 0.93$) was produced as shown in Figure 4C.

4.1.5 ***Summary of HiReTS Evaluation at SOC.*** When the HiReTS was under development, its intended use was as a quantitative quality-assurance (QA) test that could distinguish between acceptable and non-acceptable fuels. The fact the HiReTS agreed with the JFTOT for three-fourths of the fuels tested must be considered a significant result. These two units use completely different conditions and methods for determining deposits, but still show 75% agreement on a pass-fail basis.

The determination of which laboratory test unit offers the most reliable results should be based upon what is required by the user. The JFTOT is strictly an empirical test and does not simulate turbulent flow regimes typically found in actual engines. However, the JFTOT's utility as a quality control test has been successful for more than 30 years. Evaluating the thermal stability of fuels in this manner has resulted in very few reports of engine problems due to a fuel's poor thermal stability. The HiReTS, on the other hand, simulates the turbulent fuel flow regime in the engine and measures the deposit semi-quantitatively. The choice of which method to use is therefore dependent on the user's requirements.

4.2 Evaluation of HiReTS at Non-SOC

4.2.1 ***Variation of Fuel Flow Rate.*** The high fuel flow rate used in the HiReTS at SOC (35 mL/min) produces a Re of approximately 13,000, which simulates the turbulent flow regime and fluid mechanics in aircraft engine fuel nozzles. Most researchers over the years have always believed using test units that simulate this flow regime produce results that better simulate aircraft hardware and provide a more absolute measure of thermal stability than laminar units such as the JFTOT. In addition, the HiReTS uses a relatively low fuel flow when compared to larger simulators, which make its use as a research tool fairly attractive. However, 35 mL/min is still a relatively high flow when considering its use in the laboratory as a tool to study fuel chemistry effects on deposition tendencies. Therefore, lower HiReTS flow rates of 25 mL/min and 15 mL/min were also investigated at the standard capillary exit temperature of 290°C (554°F) to determine the impact on thermal deposition.

The results for of these experiments are summarized in Table 6 for two different JP-5 fuels (NAVAIR Fuel I and Fuel A). Decreasing the flow rate from 35 mL/min did not significantly alter the T_{wos} for either fuel. Also, the test time was increased for the lower flows to ensure that the same quantity of fuel would be passed through the capillary for all tests. For the first fuel, Fuel I, an increase in the total carbon deposit (μg) and HN were observed each time the flow was decreased. For example, reducing the flow rate from 35 mL/min to 25 mL/min (or 29%) showed an average increase in deposit of 539% (from 26 to 163 μg carbon), and an average increase in HN of 138% (from 406 to 966). As the flow rate was decreased further, i.e., from 25 mL/min to 15 mL/min, these incremental increases in deposit weight and HN became more substantial.

For the second fuel, Fuel A, all runs aborted. Even for these aborted runs, the deposit weight increased as the flow was reduced. From 35 mL/min to 25 mL/min, the carbon deposit increased an average of 125% (from 36 to 81 μg), whereas from 25 mL/min to 15 mL/min, the average increase in carbon was 127% (from 81 to 184 μg). On the other hand, a slight decreasing trend was observed for the HN, with an average decrease in HN of 8% (from 1881 to 1728) from 35 mL/min to 25 mL/min, a small increase of 3.5% from 25 mL/min to 15 mL/min (from 1728 to 1788), and an overall decrease of 5% from 35 mL/min to 15 mL/min (from 1881 to 1788). Two possible reasons that the HNs trend behaved differently than the deposit weight may be due to the following: (1) all tests aborted due to high ΔTs, and hence HNs, which may have been caused by the level of soluble copper present, and (2) the decreasing flow rates caused the maximum capillary surface temperatures to move up the axial length of the tube, and hence outside the 21-mm scan length, causing less deposits to be detected by the pyrometer, which ultimately produced lower ΔTs and HNs.

When normalizing the deposition data for both fuels as weight of carbon (in mg) to the volume of fuel that passed through the capillary at the end of a test (in liters), expressed as mg/L or ppm (w/v), interesting results are produced. A summary of these results is also shown in Table 6 and graphically in Figure 5A for both fuels, where deposit concentration (ppm, w/v) is plotted versus fuel flow rate (mL/min). For Fuel I, the deposit concentration (or yield) increases significantly each time the flow rate is decreased in 10-mL/min increments. For example, from 35 mL/min to 25 mL/min, the average yield increases by more than 6 times (from 0.0061 to 0.0384 ppm), whereas from 25 mL/min to 15 mL/min, it increases more than 8 times (from 0.0384 to 0.314 ppm). Similar results are observed for Fuel A as well. Furthermore, as seen on the graph, Fuel I at 15 mL/min showed higher deposit yields than Tank 20/22, but less yields at the two higher flow rates.

According to a study by Chin and Lefebvre (reference [3]), the deposition rate (mg/cm^2-hr) or yield (mg/L) increased as the Re increased in the range of 2000-6000. In the HiReTS, for Re in the range of 5,000-13,000, the exact opposite results are observed. Apparently, the increased fuel residence time (at the lower flow rates) in the heated zone of the capillary has a greater influence on increasing the deposit yield than the degree of turbulence.

Upon further analysis, the μg carbon versus HN relationship is vastly different for each of the two fuels. Using the ratio of HN to μg carbon deposits, or the inverse slope, emphasizes this difference. As shown in Figure 5B, the ratio decreases as the flow decreases, or conversely, the slope of the μg to HN relationship increases as the flow decreases. The differences in these two curves, in general, show a lack of correlation between the μg carbon deposit and HN. This agrees with the conclusions as that were drawn in Section 4.1.2 above, i.e., the HN can only be used to track changes in the heat transfer to the bulk fuel stream due to deposit buildup, and not as an accurate predictor of μg carbon.

Deposit weight and yield are greatly magnified when reducing the flow rate from 35 mL/min to 15 mL/min (for Re from 13,000 to 5,000, respectively). This should allow the HiReTS researcher to decrease test duration and fuel consumption while still remaining in the turbulent regime.

4.2.2 ***Variation of Capillary Exit Temperature.*** Although the fuel flow in the HiReTS simulates the turbulent flow regime that exists in an actual engine fuel nozzle, the T_{Fo} of 290°C (554°F) is much hotter than that experienced in current fuel nozzles. This temperature was chosen because it could produce measurable carbon formation in two hours, a desirable target for a QC/QA test.

Another problem with operating the HiReTS at T_{Fo} of 290°C is that tests were shutting down prematurely due to an over-temperature condition of the capillary surface with 30-50 ppb soluble copper in fuel. Therefore, to prevent aborted runs from occurring, T_{Fo} was decreased incrementally to temperatures that were closer to actual operating conditions. Using a copper-contaminated JP-5, Fuel B (Fuel A + 280 ppb Cu), T_{Fo} was decreased in steps from 290°C (554°F) to 210°C (410°F), while holding the flow rate and test duration constant at 35 mL/min and two hours, respectively. This fuel was selected for two reasons: (1) it showed the lowest thermal stability in the HiReTS among all other copper concentrations tested (in the range of 40-3400 ppb), and (2) the level of copper was the average concentration measured during a previous Navy shipboard JP-5 survey. The results of these experiments are summarized in Table 7 and Figures 6A, 6B, and 6C.

In Figure 6A, the correlation of µg carbon versus HN shows no correlation at all ($R^2 = 0.15$). However, when the deposition rate (µg/hr) is plotted versus T_{Fo} in Figure 6B, a much better correlation (R2 = 0.78) is demonstrated even though scatter still exists. In addition, the HiReTS test did not abort at $T_{Fos} \leq 230$°C (446°F).

In Figure 6C, the data was viewed in an alternative way, i.e., by plotting carbon deposition rate (µg/hr) versus the Average System Temperature (AST). AST is the arithmetic mean of the maximum outside surface temperature at the beginning of the test (T_{wo}) and bulk fuel exit temperature (T_{Fo}) of the capillary, calculated by $AST = (T_{wo} + T_{Fo}) / 2$. AST compensates for the variations in T_{wo}, for a given T_{Fo}, that typically occur due to slight variations in the manufacture of the capillaries. An example of this variation occurs for Test# H4-2C, which is one of three tests run at the T_{Fo} of 230°C (446°F). For this test, T_{wo} is the lowest among the three data points (313°C versus 329°C for H4-2B and 334°C for H4-2D), which may explain the scatter in Figure 6B. When re-plotting the deposition rate data versus AST, the correlation improves significantly (from $R^2 = 0.78$ to $R^2 = 0.89$), as shown in Figure 6C. This plot also shows that linearity is achieved at T_{Fo} of 230°C and below, for an AST ≤ 278°C (532°F). The reason for the horizontal portion of the curve and subsequent reduction in deposition rate at higher ASTs is currently unknown, but is commonly found in similar data produced from other thermal stability test rigs.

Since the HiReTS did not abort at T_{Fo} of 230°C for Fuel A + 280 ppb Cu, this temperature was selected to evaluate the impact of copper concentrations from 40 ppb to 3400 ppb in the same base fuel. This temperature was also selected to prevent premature shutdowns that may occur as a result of higher T_{wos} that typically occur when soluble copper levels of 30 ppb or more are present in the fuel. This data is summarized in Table 8, and a plot of carbon deposit versus the HN is plotted in Figure 7A. As shown, a correlation of $R^2 = 0.66$ was obtained. The deposition rate and HN were plotted individually versus copper concentration and are shown in Figures 7B and 7C, respectively. Both plots show an unexpected trend at 280 ppb Cu, whereby the deposits and HN reach a maximum, followed by a rapid decrease in their values as the copper concentration is increased to 3400 ppb. The cause of this behavior is unknown and was not explored further since it was beyond the scope of this study. However, one interpretation could be that by increasing the soluble concentration of copper caused deposits to form within the bulk fuel stream of the capillary, and hence exit the capillary, in preference to adhering to the inside wall. However, this effect was not measured experimentally.

4.2.3 ***Variation of Test Duration.*** Another method of evaluating a fuel's thermal stability is to conduct tests at variable duration to measure the buildup of deposits over time. This method may be more realistic with respect to actual aircraft since fuel nozzles typically fail when a sufficient amount of deposits accumulate over extended periods of aircraft operation. This method is particularly effective when dealing with test pieces of very narrow inside diameter, such as the HiReTS capillary. Due to the small cross-sectional area, a choking effect due to deposit buildup over time will cause a disturbance in the system measurements, viz., a rise in capillary surface temperature. The latter can be done with the HiReTS by monitoring the HN for any abrupt changes over the duration of the test, which indicates that the deposit weight (and hence rate) has changed from a slow linear to a very rapid exponential buildup with respect to test time.

To evaluate thermal stability by this method, the standard HiReTS flow rate of 35 mL/min was selected along with a T_{Fo} of 220°C (428°F). These conditions would enable the HiReTS test to run for at least several hours before any disturbance to the capillary was observed. Two JP-5 fuels were evaluated: Fuel A and Fuel O. Both fuels had copper concentrations of 50 and 25 ppb, respectively, and both had the same BPT (255°C). The data are summarized in Table 9 and plotted in Figures 8A and 8B. Looking at the familiar relationship of µg carbon versus HN in Figure 8A shows an excellent correlation for both fuels ($R^2 = 0.98$ for both). As shown, by lowering the T_{Fo} for both fuels (as compared to 290°C at SOC), the correlation had improved greatly. When normalizing this data to test duration (i.e., µg/hr and HN/hr), the correlation remained strong for both fuels ($R^2 = 0.95$ and 0.94, respectively), as shown in Figure 8B.

The data also is plotted in Figure 8C for µg carbon and Figure 8D for HN versus test duration, respectfully. Both fuels show a very small buildup of deposits for the shorter durations, and then at some "breakpoint" this buildup increases rapidly, possibly indicating a significant increase in collection efficiency of the capillary. For example, Fuel A shows a bend or break in the curve at approximately 2.5-3 hours, whereas Fuel O shows this break at 10 hours. For both fuels, this breakpoint occurs at a carbon deposit level of approximately 25-35 µg and a HN of approximately 300-400.

The time period prior to this break (or increased rate in deposition) has been often referred to as the *pre-induction period.* This is indicative of a very slow, linear deposition rate early in the test. The time at which the break occurs is referred to as the *induction period,* where a noticeable increase in this rate is observed, then followed by very rapid rise in the rate until a plugging condition occurs, referred to as the *post-induction period* (reference [4]). This method gives a clear distinction between the stability of each fuel, i.e., the tendency of each fuel to foul the capillary. During these experiments, Fuel A caused fouling in the capillary from 3.5 to 4 times earlier than Fuel O. This is in contrast to the JFTOT BPTs for these fuels which both gave BPTs of 255°C.

Though this method shows promise, the main concern with using this approach is the time factor involved in acquiring the data. That is, if high stability fuels or TSIAs were evaluated, estimated test duration could be as high as 100 hours before a sufficient fouling condition would occur. If a lower flow rate were used to increase the deposition rate (such as 15 mL/min), then the test period could be shortened even at a lower T_{Fo}.

4.2.4 ***Addition of Additives under Modified Operating Conditions.*** The use of the laminar flowing JFTOT to evaluate TSIAs has usually been met with considerable opposition from the aviation fuel community, since the effectiveness of the additives would be measured via an elevation of the BPT. Engine designers have had problems using the BPT as a guide for designing advanced aircraft engines. This is due to the fact that this parameter is qualitative and cannot be directly related to carbon deposition rates. This becomes increasingly difficult for designers and users to accurately assess the potential effectiveness of TSIAs in an actual aircraft fuel system (viz., fuel nozzles).

Since the HiReTS was designed to be quantitative and operate at a high Re representative of actual fuel nozzles, it is believed to produce more correlatable data as compared to the JFTOT (and other laminar test units). Using the test time as the principle variable, the standard test protocol (SOC) was modified by allowing the test duration to vary beyond the normal two hours until a HN of 1000 was reached. As previously mentioned in Section 3.1.1 of this report, Shell had estimated this number to be equivalent to a Code 3 deposit in the JFTOT. Therefore, in the study of TSIAs, it was assumed that when a HN of 1000 is reached, the capillary tube had collected a significant amount of deposits, and the test would then be terminated.

At the end of the test, two measurements were made to evaluate the fuel's stability: (1) the test time (in hrs) that it takes a given fuel/additive combination to reach failure, and (2) the amount of deposit accumulated during this time period, expressed as a rate (μg/hr).

It was originally intended to study additives at a lower T_{Fo} (e.g., 230°C), but as mentioned previously, this would have taken an unreasonably long time to reach a HN of 1000. Therefore, a T_{Fo} of 290°C was selected. Alternatively, the end-of-test HN could have been lowered to decrease the overall test duration. However, this would have required several additional experiments and time constraints existed that prevented a more in-depth study.

Table 10 summarizes the results of these experiments for three NAVAIR test fuels (Fuel N, Fuel O, and Fuel A), each run unadditized and then each individually doped with the effective concentrations of each additive. The relative effectiveness of each additive (as compared to the unadditized fuel) is shown in Figure 9A as μg/hr. In most cases the three additives did reduce the rate of deposition for the fuels tested, with the only exception of Betz 8Q406 in Fuel N, which showed no improvement at all (34 μg/hr for the neat versus 35 μg/hr for additized fuel). No definitive explanation for this behavior can be given at this time. However, even though the Betz 8Q406 did not reduce the deposition rate in this fuel, it did cause an extension in test duration (8 hrs for the neat versus 2.3 hours for the additized fuel).

Evaluating the relative effectiveness of each additive as time to failure, i.e., test time hours to reach HN of 1000, shows slightly different results as shown in Table 10 and Figure 9B. All additives showed an increase (or extension) in failure time when compared to the unadditized fuels, with only one exception. When MDA was doped in Fuel N, it showed no improvement or a slight decrease in failure time (8 hrs for the neat versus 7.2 hours for MDA). Overall, Betz

8Q462 showed superior performance to the other additives in its ability to reduce the deposition rate and extend the "life" of the capillary before it reached the failure condition of HN of 1000.

5. CONCLUSIONS

5.1 HiReTS at SOC:

5.1.1 The HN agreed with the JFTOT BPT for 76% of the 78 fuels tested when evaluated on a pass-fail basis. This agreement was better for the *refinery samples* (86%) as compared to the *field samples* (70%).

5.1.2 The µg carbon deposit measured in the HiReTS capillary at the end of the test does not correlate with the HN. Each fuel appears to produce unique deposits that have a different µg/HN relationship. This may be due to the fact that each fuel produces a slightly different deposit structure that contains different percentage of heteroatoms of carbon, oxygen, sulfur, and hydrogen. This unique deposit structure ultimately affects the overall density and thermal conductivity of the deposit.

5.1.3 The HN showed better repeatability than the µg carbon deposit.

5.1.4 Fuels containing soluble copper (>30 ppb) tend to cause an unusually high HN, relatively low amount of carbon deposits (compared to HN), and a premature shutdown of the HiReTS at SOC.

5.1.5 The carbon deposition rate (µg/hr) produced from one copper-contaminated JP-5 (NAVAIR Fuel A) showed a strong linear correlation with respect to increasing copper concentration in the range of 50-800 ppb.

5.1.6 The HiReTS correlation of µg capillary carbon deposits versus HN has shown to be useful predictor of fuel thermal stability for *refinery samples*, whereas it shows less predictable results for the *field samples*.

5.2 HiReTS at Non-SOC:

5.2.1 Decreasing the fuel flow rate in the HiReTS (by 30%-60%), and hence increasing the residence time, will increase the deposition rate (µg/hr) and yield (mg/L) while still maintaining data repeatability and turbulent flow conditions (Re = 5,000-10,000) at T_{Fo} of 290°C (554°F).

5.2.2 The scan length of the capillary (21 mm) is insufficient under certain non-SOC conditions of flow rate and/or T_{Fo} to capture all of the deposits.

5.2.3 Premature shutdowns of the HiReTS with JP-5 fuel containing copper contamination were eliminated at $T_{Fo} \leq 230$°C (446°F).

5.2.4 The rate of deposit formation (in µg/hr) shows a linear relationship from T_{Fos} in the range of 210°-250°C (410°-482°F) for Fuel B (Fuel A + 280 ppb copper). A further increase in the T_{Fo} beyond 250°C (482°F) causes a reduction in the rate.

5.2.5 Operating the HiReTS at T_{Fo} of 230°C and varying copper concentration from 40 ppb to 3400 ppb causes both the µg carbon deposits and HN to reach maximums at 280 ppb, and then rapidly decreases as the copper level is increased to 3400 ppb.

5.2.7 Re-plotting carbon deposition rate versus AST (instead of T_{Fo}) produces a statistically improved correlation that compensates for the variations in T_{wo}, for a given T_{Fo}, that typically occur due to slight variations in the manufacture of the capillaries.

5.2.8 Operating the HiReTS at a lower T_{Fo} (220°C) and allowing the test duration to vary until an abrupt increase in the HN rate is observed (at HN = 300-400) shows better discernment in a fuel's stability. By recording the time of this occurrence, or failure condition, fuels can be ranked on their ability to increase or decrease this time as compared to a known reference fuel.

5.2.9 The HN is a good indicator of capillary fouling at T_{Fo} of 220°C (428°F).

5.2.10 Capillary carbon deposits (µg) and HN correlate better at lower T_{Fos} (220°C) than at SOC (T_{Fo} = 290oC).

5.2.11 The measurement of the relative effectiveness of additives is improved by a modification of the HiReTS test protocol that allows the unit to run until a HN of 1000, instead of constant test duration.

6. RECOMMENDATIONS

6.1 Modify the standard HiReTS test protocol (SOC) for research purposes so that it operates closer to actual aircraft engine operating conditions. Run the HiReTS at a lower flow rate, lower T_{Fo} (180°- 220°C), and variable test duration. Terminate the test when a disturbance to the capillary occurs (HN = 300-400).

6.2 Scan a longer length (at least 50%) of the HiReTS capillary to determine to what extent it would improve the correlation of µg to HN at SOC and non-SOC (viz., lower T_{Fos} and lower flow rates).

6.3 Conduct a more in-depth study to determine the impact of turbulence on thermal deposition by operating the HiReTS at different fuel flow rates, and hence velocities, while holding T_{Fo} constant.

6.4 Upgrade the current HiReTS test equipment for use as a research tool by adding pre-heater(s) upstream of the capillary. Install hot and cold filters downstream of the capillary to collect bulk fuel stream deposits. Also include pre-filters upstream of all heaters and operate in recycle/recirculation mode.

6.5 Conduct tests with this upgraded HiReTS and optimize the combination of variables for flow rate, T_{Fo}, and test duration that will produce results in a more reasonable test period. Conduct tests in the Naval Aviation Fuel Thermal Stability Simulator (NAFTSS) on the same fuels and determine the extent of correlation between the two units.

6.6 Conduct further repeatability studies with this upgraded HiReTS, at this non-SOC protocol, to determine if the HiReTS gives better repeatability, reproducibility, and ranking of thermal stability as compared to the JFTOT.

7. REFERENCES

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TABLE 1A: FUEL DESCRIPTIONS (REFINERY SAMPLES [RED DYE PROGRAM])

Nineteen RDTF Fuels from SwRI Red-Dye Program
(Obtained from Various Crude Sources, Crude Types, and Refineries)

Fuel Designation	Fuel Type	Crude Type(s)	Fuel Refinery Processing	Copper Level (ppb)	JFTOT BPT (°C)
RDTF-1	Jet A	Heavy, Sour + Canadian Syncrude	Straight Run; Hydrotreated	0	270
RDTF-2	"	Light, Sour	Straight Run; Hydrotreated	0	280
RDTF-3	"	Mixed Light & Heavy, Sour	Straight Run; Hydrotreated	0	290
RDTF-4	"	Heavy, Sour	Straight Run; Hydrotreated	0	305
RDTF-5	"	Light, Sweet	Straight Run; No Treatment	1	290
RDTF-6	"	Light, Sweet	Straight Run; Clay Treated	9	280
RDTF-7	"	Light, Sweet	Straight Run; Merox Treated	1	280
RDTF-8	"	Light, Sweet	Straight Run; Doctor Sweetened	0	295
RDTF-9	"	Light, Sweet	Straight Run; Hydrotreated	0	295
RDTF-10	"	Mixed Heavy	Approx. 40% Hydrocracked	0	280/270/260$^{(3)}$
RDTF-11	"	Mixed Heavy	Approx. 30% Thermal Cracked	4	285
RDTF-12	"	Mixed Heavy	Approx. 40% Hydrocracked	4	255
RDTF-13	"	Mixed Heavy, Sour	Approx. 30% Hydrocracked	2	315
RDTF-14	"	Light, Sweet	Straight Run; Merox Treated	2	340
RDTF-15	"	Light, Sweet	Straight Run, Bender Sweetened	1	335
RDTF-16	"	Light, Sweet	Straight Run; Merox Treated	Not Run	285
RDTF-17	"	Light, Sour	Straight Run; Hydrotreated	4	290
RDTF-18	"	Heavy, Sour	Hydrotreated	0	345 to >370
RDTF-19	"	Heavy, Sour	Hydrotreated	1	300

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. = 290°C, Duration = 2 hours.
(3) JFTOT BPT decreased during SwRI Red-Dye Program.
(4) RDFP = Red-Dye Fuel Program; AHRRP = ASTM HiReTS Round Robin Program; NTSP = Navy Thermal Stability Program

TABLE 1B: FUEL DESCRIPTIONS (NAVAIR FIELD SAMPLES)

Fifty-Three Fuels Obtained from Previous Test Programs

Item #	Fuel Designation	Fuel Type	Fuel Description	Fuel Refinery Processing	Previous Test *	Copper Level (ppb)	JFTOT BPT (°C)
1	RDTF-1 + RD	Jet A	RDTF-1 + 0.549 mg/L Red Dye	Straight Run; Hydrotreated	RDFP	2	255
2	RDTF-2 + RD	"	RDTF-2 + 0.540 mg/L Red Dye	Straight Run; Hydrotreated	RDFP	2	285
3	RDTF-3 + RD	"	RDTF-3 + 0.557 mg/L Red Dye	Straight Run; Hydrotreated	RDFP	2	290
4	RDTF-4 + RD	"	RDTF-4 + 0.543 mg/L Red Dye	Straight Run; Hydrotreated	RDFP	1	305
5	RDTF-5 + RD	"	RDTF-5 + 0.55 mg/L Red Dye	Straight Run; No Treatment	RDFP	2	285
6	RDTF-6 + RD	"	RDTF-6 + 0.544 mg/L Red Dye	Straight Run; Clay Treated	RDFP	1	285
7	RDTF-7 + RD	"	RDTF-7 + 0.555 mg/L Red Dye	Straight Run; Merox Treated	RDFP	2	280
8	RDTF-8 + RD	"	RDTF-8 + 0.540 mg/L Red Dye	Straight Run; Doctor Sweetened	RDFP	1	290
9	RDTF-9 + RD	"	RDTF-9 + 0.553 mg/L Red Dye	Straight Run; Hydrotreated	RDFP	1	295
10	RDTF-10 + RD	"	RDTF-10 + 0.555 mg/L Red Dye	Approx. 40% Hydrocracked	RDFP	2	275/265/260(3)
11	RDTF-11 + RD	"	RDTF-11 + 0.56 mg/L Red Dye	Approx. 30% Thermal Cracked	RDFP	4	285
12	RDTF-12 + RD	"	RDTF-12 + 0.554 mg/L Red Dye	Approx. 40% Hydrocracked	RDFP	2	260
13	RDTF-13 + RD	"	RDTF-13 + 0.550 mg/L Red Dye	Approx. 30% Hydrocracked	RDFP	2	315
14	RDTF-14 + RD	"	RDTF-14 + 0.552 mg/L Red Dye	Straight Run; Merox Treated	RDFP	2	330
15	RDTF-15 + RD	"	RDTF-15 + 0.556 mg/L Red Dye	Straight Run, Bender Sweetened	RDFP	2	340
16	RDTF-16 + RD	"	RDTF-16 + 0.550 mg/L Red Dye	Straight Run; Merox Treated	RDFP	4	285
17	RDTF-17 + RD	"	RDTF-17 + 0.550 mg/L Red Dye	Straight Run; Hydrotreated	RDFP	4	290
18	RDTF-18 + RD	"	RDTF-18 + 0.553 mg/L Red Dye	Hydrotreated	RDFP	0	335
19	RDTF-19 + RD	"	RDTF-19 + 0.548 mg/L Red Dye	Hydrotreated	RDFP	1	290

TABLE 1B: FUEL DESCRIPTIONS (NAVAIR FIELD SAMPLES Continued)

Fifty-Three Fuels Obtained from Previous Test Programs

Item #	Fuel Designation	Fuel Type	Fuel Description	Fuel Refinery Processing	Previous Test *	Copper Level (ppb)	JFTOT BPT (°C)
20	N1	JP-5	JP-5 from U.S. Naval Storage Depot	Unknown	AHRRP	26	265
21	N2	"	"	"	AHRRP	30	260
22	N3	"	JP-5 from U.S. Naval Storage Depot (60 ppm nitrogen)	"	AHRRP	6	245
23	N4	"	JP-5 from NAS Patuxent River Fuel Farm (3 February 2000)	"	AHRRP	13	260
24	N5	"	JP-5 from U.S. Naval Storage Depot	"	AHRRP	4	255
25	N6	DFM/HHO Blend	50% Blend Diesel Fuel Marine (DFM): 50% Blend of Home Heating Oil (HHO)	"	AHRRP	46	220

TABLE 1B: FUEL DESCRIPTIONS (NAVAIR FIELD SAMPLES Continued)

Fifty-Three Fuels Obtained from Previous Test Programs

Item #	Fuel Designation	Fuel Type	Fuel Description	Fuel Refinery Processing	Previous Test *	Copper Level (ppb)	JFTOT BPT (°C)
26	Fuel A	JP-5	JP-5 from U.S. Naval Storage Depot	Unknown	NTSP	40-50	255
27	Fuel B	"	Fuel A + Various Cu Levels	"	NTSP	80-3400	< 210
28	Fuel C	Special	JPTS	"	NTSP	2	>345
29	Fuel D	JP-8	Field JP-8	"	NTSP	30	240
30	Fuel E	JP-5	JP-5 from U.S. Naval Storage Depot	"	NTSP	15	280
31	Fuel F	"	"	"	NTSP	8	260
32	Fuel G	"	"	"	NTSP	7	260
33	Fuel H	"	"	"	NTSP	8	265
34	Fuel I	"	"	"	NTSP	6	275
35	Fuel J	"	JP-5 from Patuxent River Fuel Farm (Cu Doped)	"	NTSP	259	200
36	Fuel K	"	JP-5 from NAS Patuxent River Fuel Farm	"	NTSP	13	260
37	Fuel L	JP-5	Fuel I + Various Cu Levels	Unknown	NTSP	60-1800	< 205
38	Fuel M	"	JP-5 from U.S. Naval Storage Depot	"	NTSP	17	240
39	Fuel N	"	"	"	NTSP	8	250
40	Fuel O	"	"	"	NTSP	15	255
41	Fuel P	HHO/DFM	Home Heating Oil and Diesel Fuel Marine Blends	"	NTSP	68	215
42	Fuel Q	JP-5	JP-5 from NAS Patuxent River Fuel Farm	"	NTSP	40	265
43	Fuel R	Diesel	F-76	"	NTSP	10	220

TABLE 1B: FUEL DESCRIPTIONS (NAVAIR FIELD SAMPLES Continued)

Fifty-Three Fuels Obtained from Previous Test Programs

Item #	Fuel Designation	Fuel Type	Fuel Description	Fuel Refinery Processing	Previous Test *	Copper Level (ppb)	JFTOT BPT (°C)
44	Fuel S	JP-5	JP-5 from NAS Patuxent River Fuel Farm	"	NTSP	6	275
45	Fuel T	"	"	"	NTSP	13	275
46	Fuel U	JP-5	JP-5 from U.S. Naval Storage Depot	Unknown	NTSP	25	240
47	Fuel V	"	"	"	NTSP	26	240
48	Fuel W	"	"	"	NTSP	20	265
49	Fuel X	"	"	"	NTSP	40	260
50	Fuel Y	"	"	"	NTSP	131	240
51	Fuel Z	"	"	"	NTSP	0	270
52	Fuel AA	"	"	"	NTSP	0	260
53	Fuel AB	"	"	"	NTSP	33	265

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. = 290°C, Duration = 2 hours.
(3) JFTOT BPT decreased during SwRI Red-Dye Program.
(4) RDFP = Red-Dye Fuel Program; AHRRP = ASTM HiReTS Round Robin Program; NTSP = Navy Thermal Stability Program

TABLE 1C: FUEL DESCRIPTIONS (ASTM ROUND ROBIN FIELD SAMPLES)

Six Fuels from ASTM HiReTS Roung-Robin Program
(Provided by Shell Global Solutions, UK)

Fuel Designation	Fuel Type	Fuel Description	Fuel Refinery Processing	Copper Level by GFAA (ppb)	JFTOT BPT (°C)
S1	Jet A-1	ASTM HiReTS Round-Robin Program	Merox Treated	6	280
S2	"	"	Hydrotreated	8	275
S3	"	"	75% Hydrotreated : 25% Merox Treated	6	275
S4	"	"	Hydrotreated	2	265
S5	"	"	Hydrotreated	1	275
S6	"	"	Merox Treated	2	290

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. = 290°C, Duration = 2 hours.
(3) JFTOT BPT decreased during SwRI Red-Dye Program.
(4) RDFP = Red-Dye Fuel Program; AHRRP = ASTM HiReTS Round Robin Program; NTSP = Navy Thermal Stability Program

TABLE 2: HiReTS DATA SUMMARY (REFINERY SAMPLES)

Nineteen RDTF Fuels Obtained from SwRI Red-Dye Program
(28 HiReTS Tests at SOC)

Test No.	Fuel Designation	JFTOT BPT	Test Duration (hrs)	T_{Wo} ⁽³⁾	HiReTS No.	Capillary Carbon Deposits
		(°C)	(hrs)	(°C)	(Δ°C)	(µg)
SW-2A	RDTF-1	270	2	397	779	70
-2B	"	270	2	392	111	27
-2C	"	270	2	393	200	25
SW-3A	RDTF-2	280	2	371	92	34
SW-4A	RDTF-3	290	1.5	393	8	0
-4B	"	290	2	388	15	1
SW-5A	RDTF-4	305	2	395	27	5
SW-6A	RDTF-5	***290***	2	407	***1212***	174
-6B	"	290	2	394	454	66
-6C	"	290	2	387	352	56

TABLE 2: HiReTS DATA SUMMARY (REFINERY SAMPLES Continued)

Nineteen RDTF Fuels Obtained from SwRI Red-Dye Program
(28 HiReTS Tests at SOC)

Test No.	Fuel Designation	JFTOT BPT	Test Duration (hrs)	$T_{wo}^{(3)}$	HiReTS No.	Capillary Carbon Deposits
		(°C)	(hrs)	(°C)	(Δ°C)	(μg)
SW-7A	RDTF-6	280	2	385	18	4
SW-8A	RDTF-7	280	2	398	30	0
SW-11A	RDTF-8	***295***	2	401	***1405***	160
SW-11B	"	***295***	2	399	***1806***	253
SW-9A	RDTF-9	295	2	386	11	7
SW-9B	"	295	2	410	236	14
SW-9C	"	295	2	404	35	19
SW-10A	RDTF-10	270	2	381	11	0
SW-12A	RDTF-11	285	2	385	23	7
-12B	"	285	2	406	13	9

TABLE 2: HiReTS DATA SUMMARY (REFINERY SAMPLES Continued)

Nineteen RDTF Fuels Obtained from SwRI Red-Dye Program
(28 HiReTS Tests at SOC)

Test No.	Fuel Designation	JFTOT BPT	Test Duration (hrs)	T_{wo} (3)	HiReTS No.	Capillary Carbon Deposits
		(°C)	(hrs)	(°C)	(Δ°C)	(µg)
SW-23A	RDTF-12	***255***	2	386	***5***	31
SW-27A	RDTF-13	315	2	387	23	2
SW-28A	RDTF-14	340	2	379	108	4
SW-29A	RDTF-15	335	2	377	72	25
SW-24A	RDTF-16	285	2	386	7	1
SW-21A	RDTF-17	290	2	382	12	3
SW-30A	RDTF-18	345	2	400	19	11
SW-25A	RDTF-19	300	2	387	44	19

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. =290°C, Duration = 2 hours.
(3) T_{wo} - Maximum outside wall temperature, beginning of test

TABLE 3: HiReTS DATA SUMMARY (REFINERY SAMPLES)

Six Jet Fuels Obtained from ASTM HiReTS Round-Robin Program
(12 HiReTS Tests at SOC)

Test No.	Fuel Designation	Fuel Type	Fuel Refinery Processing	Copper Level by GFAA (ppb)	JFTOT BPT	Test Duration	T_{wo} [(3)]	HiReTS No.	Capillary Carbon Deposits
					(°C)	(hrs)	(°C)	(Δ°C)	(µg)
S1-A	S1	Jet A-1	Merox Treated	6	280	2	380	14	10
S1-B	"	"	"	"	280	2	383	26	4
S2-A	S2	"	Hydrotreated	8	275	2	386	215	12
S2-B	"	"	"	"	275	2	386	232	0
S3-A	S3	"	75% Hydrotreated : 25% Merox Treated	6	*275*	2	403	*1721*	16
S3-B	"	"	"	"	*275*	2	408	*1769*	23
S4-A	S4	"	Hydrotreated	2	265	2	379	17	14
S4-B	"	"		"	265	2	378	26	3
S5-A	S5	"	Hydrotreated	1	275	2	385	11	14
S5-B	"	"	"	"	275	2	379	11	0
S6-A	S6	"	Merox Treated	2	290	2	387	382	30
S6-B	"	"	"	"	290	2	394	448	27

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. =290°C, Duration = 2 hours.
(3) T_{wo} - Maximum outside wall temperature, beginning of test

TABLE 4: HiReTS REPEATABILITY STUDIES (NAVAIR FIELD SAMPLES)

Seven NAVAIR Test Fuels
(45 Tests at SOC)

Test No.	Fuel Designation	Fuel Type	Cu Conc	JFTOT BPT	Test Duration	T_{wo}	HiReTS No.	Capillary Carbon Deposits	HiReTS No. Rate	Capillary Carbon Dep. Rate
			(ppb)	(°C)	(hrs)	(°C)	(Δ°C)	(µg)	(Δ°C/hr)	(µg/hr)
H1-1A	Fuel M	JP-5	17	240	2	400	360	86	180	43
H1-1B	"	"	"	"	2	405	410	96	205	48
H1-1C	"	"	"	"	2	398	345	141	173	70.5
H1-1D	"	"	"	"	2	387	204	46	102	23
H1-1E	"	"	"	"	2	396	212	98	106	49
H1-1F	"	"	"	"	2	395	328	56	164	28
						mean:	*310*	*87*		
						standard deviation:	*84*	*34*		
H1-2A	Fuel N	JP-5	8	250	2	404	124	54	62	27
H1-2B	"	"	"	"	2	401	90	46	45	23
H1-2C	"	"	"	"	2	396	108	96	54	48
H1-2D	"	"	"	"	2	389	96	44	48	22
H1-2E	"	"	"	"	2	398	150	148	75	74
						mean:	*114*	*78*		
						standard deviation:	*24*	*45*		
H1-3A	Fuel A	JP-5	50-60	255	0.75	412	2058	60	2744	80
H1-3B	"	"	"	"	0.75	411	2018	45	2691	60
H1-3C	"	"	"	"	0.67	411	1993	40	2975	60
H1-3D	"	"	"	"	0.6	422	1780	35	2967	58
						mean:	*1962*	*45*		
						standard deviation:	*124*	*11*		

TABLE 4: HiReTS REPEATABILITY STUDIES (NAVAIR FIELD SAMPLES Continued)

Seven NAVAIR Test Fuels
(45 Tests at SOC)

Test No.	Fuel Designation	Fuel Type	Cu Conc	JFTOT BPT	Test Duration	T_{wo}	HiReTS No.	Capillary Carbon Deposits	HiReTS No. Rate	Capillary Carbon Dep. Rate
			(ppb)	(°C)	(hrs)	(°C)	(D°C)	(mg)	(D°C/hr)	(mg/hr)
HI-6B	Fuel O	JP-5	15	255	2	389	964	154	482	77
HI-6I	"	"	"	"	2	382	410	18	205	9
HI-6J	"	"	"	"	2	397	1130	126	565	63
HI-6R	"	"	"	"	2	393	1190	136	595	68
HI-6L	"	"	"	"	2	391	744	62	372	31
						mean:	*888*	*99*		
						standard deviation:	*318*	*57*		
HI-8A	Fuel D	JP-8	30	240	0.42	446	1739	199	4140	474
HI-8B	"	"	"	"	0.33	421	1653	141	5009	427
HI-8C	"	"	"	"	0.25	455	1652	86	6608	344
						mean:	*1681*	*142*		
						standard deviation:	*50*	*57*		
HI-10A	Fuel F	JP-5	8	260	2	384	9	0	5	0
HI-10B	"	"	"	"	2	393	52	54	26	27
HI-10C	"	"	"	"	2	398	62	4	31	2
HI-10D	"	"	"	"	2	385	6	2	3	1
HI-10E	"	"	"	"	2	393	86	14	43	7
HI-10F	"	"	"	"	2	389	52	16	26	8
						mean:	*45*	*15*		
						standard deviation:	*31*	*20*		

TABLE 4: HiReTS REPEATABILITY STUDIES (NAVAIR FIELD SAMPLES Continued)

Seven NAVAIR Test Fuels
(45 Tests at SOC)

Test No.	Fuel Designation	Fuel Type	Cu Conc	JFTOT BPT	Test Duration	T_{wo}	HiReTS No.	Capillary Carbon Deposits	HiReTS No. Rate	Capillary Carbon Dep. Rate
			(ppb)	(°C)	(hrs)	(°C)	(D°C)	(mg)	(D°C/hr)	(mg/hr)
H1-10A	Fuel F	JP-5	8	260	2	384	9	0	5	0
H1-10B	"	"	"	"	2	393	52	54	26	27
H1-10C	"	"	"	"	2	398	62	4	31	2
H1-10D	"	"	"	"	2	385	6	2	3	1
H1-10E	"	"	"	"	2	393	86	14	43	7
H1-10F	"	"	"	"	2	389	52	16	26	8
						mean:	*45*	*15*		
						standard deviation:	*31*	*20*		
H1-13U	Fuel H	JP-5	8	265	2	424	836	87	418	43.5
H1-13V	"	"	"	"	2	411	610	62	305	31
H1-13W	"	"	"	"	2	417	818	84	409	42
H1-13X	"	"	"	"	2	411	1154	176	577	88
H1-13Y	"	"	"	"	2	417	1028	166	514	83
H1-13Z	"	"	"	"	2	415	1022	150	511	75
H1-13AA	"	"	"	"	2	404	964	124	482	62
H1-13AB	"	"	"	"	2	400	880	78	440	39
H1-13AC	"	"	"	"	2	409	922	92	461	46
H1-13AD	"	"	"	"	2	400	914	84	457	42
H1-13AE	"	"	"	"	2	406	1060	124	530	62
H1-13AF	"	"	"	"	2	389	1204	140	602	70
H1-13AG	"	"	"	"	2	391	1374	122	687	61
H1-13AH	"	"	"	"	2	387	1140	94	570	47
H1-13AI	"	"	"	"	2	404	800	54	400	27
H1-13AJ	"	"	"	"	2	402	922	84	461	42
						mean:	*978*	*108*		
						standard deviation:	*184*	*37*		

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. =290°C, Duration = 2 hours.
(3) T_{wo} - Maximum outside wall temperature, beginning of test

TABLE 5: HiReTS RESPONSE TO COPPER-CONTAMINATED JP-5 USING SOC

All Tests at SOC

						Deposition Data			
Test No.	Fuel Designation	Fuel Type	Cu Conc.	Test Duration	T_{wo}	HiReTS No.	HiReTS No. Rate	Capillary Carbon Deposits	Capillary Carbon Dep. Rate
			(ppb)	(hrs)	(°C)	(Δ°C)	(Δ°C/hr)	(μg)	(μg/hr)
H1-3A	Fuel A	JP-5	50	0.75	412	2058	2744	60	80
H1-3B	"	"	50	0.75	411	2018	2691	45	60
H1-3C	"	"	50	0.67	411	1993	2975	40	60
H1-3D	"	"	50	0.6	422	1780	2967	35	58
H1-4C	"	"	80	0.67	414	2293	3422	32	48
H1-4D	"	"	80	0.58	409	2138	3686	20	34
H1-4A	"	"	280	0.33	556	912	2764	49	148
H1-4B	"	"	280	0.52	478	612	1177	87	167
H1-4G	"	"	700	0.33	534	1076	3261	92	279
H1-4E	"	"	800	0.33	510	1509	4573	85	258
H1-4F	"	"	800	0.33	526	1422	4309	84	255

NOTES:

(1) All test run at Standard Operating Conditions (SOC)
(2) SOC: Flow = 35 mL/min, Capillary Exit Temp. =290°C, Duration = 2 hours.
(3) T_{wo} - Maximum outside wall temperature, beginning of test

TABLE 6: HiReTS RESPONSE TO COPPER-CONTAMINATED JP-5 AT T_{Fo} = 290°C

All Tests at T_{Fo} = 290°C

Test No.	Fuel Designation	Fuel Type	Cu Conc.	Fuel Flowrate	Fuel Volume Consumed	Test Duration	T_{wo}	HiReTS No.	Capillary Carbon Deposits	Capillary Carbon Dep. Rate	Slope^{-1}
			(ppb)	(mL/min)	(Liters)	(hrs)	(°C)	(Δ°C)	(µg)	(ppm, w/v)	(HN/µg)
H1-14A	Fuel I	JP-5	6	35	4.2	2	382	346	23	0.0055	15.0
H1-14B	"	"	6	35	4.2	2	393	466	28	0.0067	16.6
H2-6A	"	"	6	25	4.25	2.83	380	806	139	0.0327	5.8
H2-6B	"	"	6	25	4.25	2.83	390	1125	187	0.0440	6.0
H2-7A	"	"	6	15	4.2	4.67	396	2044	1336	0.3181	1.5
H2-7B	"	"	6	15	4.2	4.67	405	1983	1303	0.3102	1.5
H1-3C	Fuel A	JP-5	55	35	1.41	0.67	411	1983	37	0.0262	53.6
H1-3D	"	"	55	35	1.26	0.6	422	1779	35	0.0278	50.8
H2-1A	"	"	55	25	1.02	0.68	433	1689	100	0.0980	16.9
H2-1B	"	"	55	25	1.02	0.68	419	1768	62	0.0608	28.5
H2-2A	"	"	55	15	0.83	0.92	421	1732	167	0.2012	10.4
H2-2B	"	"	55	15	0.83	0.92	418	1844	200	0.2410	9.2

NOTES:

(1) All test run at Capillary Exit Temperature of 290°C (554°F)
(2) Flow Rates = 35, 25, & 15 mL/min, Durations = 2,2.83, & 4.67 hrs, respectively, in order to fuel volume constant through capillary.
(3) T_{wo} - Maximum outside wall (surface) temperature on the HiReTS capillary, beginning of test

TABLE 7: EFFECT OF LOWER CAPILLARY EXIT TEMPERATURE

Fuel A (Tank 20/22) + 280 ppb Cu
Fuel Flow Rate = 35 mL/min for All Tests

Test No.	Fuel Designation	Fuel Type	Cu Conc.	Test Duration	T_{wo}	T_{Fo}	AST	HiReTS No.	HiReTS No. Rate	Capillary Carbon Deposits	Capillary Carbon Dep. Rate
			(ppb)	(hrs)	(°C)	(°C)	(°C)	(Δ°C)	(Δ°C/hr)	(µg)	(µg/hr)
H1-4A	Fuel A	JP-5	280	0.33	556	290	423	921	2792	39	118
H1-4B	"	"	"	0.52	478	290	384	608	1170	87	168
H4-1B	"	"	"	0.75	372	250	311	2121	2828	133	178
H4-1C	"	"	"	0.75	362	250	306	2179	2905	136	182
H4-2B	"	"	"	2	329	230	279	1700	850	259	129
H4-2C	"	"	"	2	313	230	271	502	251	117	58
H4-2D	"	"	"	2	334	230	282	1783	892	288	144
H4-4B	"	"	"	2	316	220	268	724	362	110	55
H4-4C	"	"	"	2	314	220	267	1124	562	197	98
H4-5A	"	"	"	2	312	215	263	685	342	148	74
H4-3B	"	"	"	2	304	210	257	355	178	82	41
H4-3C	"	"	"	2	298	210	254	177	88	45	22

NOTES:

(1) T_{wo} - Maximum outside wall (surface) temperature on the HiReTS capillary, beginning of test
(2) AST - Average System Temperature, the arithmetic mean of T_{wo} and T_{FO}.

TABLE 8: HiReTS RESPONSE TO COPPER-CONTAMINATED JP-5 AT NON-SOC

Fuel A (Tank 20/22) + Copper
All Test at Flow Rate = 35 mL/min and T_{Fo} = 230°C

						Deposition Data			
Test No.	**Fuel Designation**	**Fuel Type**	**Cu Conc.**	**Test Duration**	**T_{wo}**	**HiReTS No.**	**HiReTS No. Rate**	**Capillary Carbon Deposits**	**Capillary Carbon Dep. Rate**
			(ppb)	**(hrs)**	**(°C)**	**(Δ°C)**	**(Δ°C/hr)**	**(µg)**	**(µg/hr)**
H4-2A	Fuel A	JP-5	40	2	316	1596	798	142	71
H4-2N	"	"	50	2	322	784	392	32	16
H4-2O	"	"	50	2	311	354	177	8	4
H4-2M	"	"	50	2	328	1010	505	54	27
H4-2C	"	"	280	2	313	302	151	118	59
H4-2D	"	"	280	2	334	1784	892	288	144
H4-2B	"	"	280	2	327	1700	850	260	130
H4-2F	"	"	320	2	321	796	398	126	63
H4-2G	"	"	600	2	322	602	301	128	64
H4-2H	"	"	600	2	317	396	198	90	45
H4-2K	"	"	870	2	319	240	120	66	33
H4-2L	"	"	870	2	315	254	127	54	27
H4-2P	"	"	1030	2	316	288	144	92	46
H4-2Q	"	"	1120	2	317	288	144	76	38
H4-2I	"	"	1140	2	308	7	4	0	0
H4-2J	"	"	1280	2	309	15	8	6	3
H4-2R	"	"	1340	2	318	210	105	58	29
H4-2S	"	"	2000	2	321	138	69	28	14
H4-2E	"	"	3400	2	321	82	41	6	3

NOTES:

(1) T_{WO} Maximum outside wall (surface) temperature on the HiReTS capillary, beginning of test.

TABLE 9: EFFECT OF TEST DURATION

All Tests at Flow Rate = 35 mL/min and T_{Fo} = 220°C

Test No.	Fuel Designation	Fuel Type	Cu Conc.	JFTOT BPT	Test Duration	T_{wo}	HiReTS No.	Capillary Carbon Deposits	HiReTS No. Rate	Capillary Carbon Dep. Rate
			(ppb)	(°C)	(hrs)	(°C)	(Δ°C)	(µg)	(Δ°C/hr)	(µg/hr)
H14a-1A	Fuel A	JP-5	50	255	2	305	287	16	144	8
H14a-1B	"	"	"	"	4	305	1777	234	444	59
H14a-1C	"	"	"	"	3	305	406	25	135	8
H14a-1D	"	"	"	"	1	309	54	9	54	9
H14a-1E	"	"	"	"	3	306	380	22	127	7
H14a-1F	"	"	"	"	2	307	164	11	82	5
H14a-1G	"	"	"	"	3.6	308	1515	211	421	59
H14a-1H	"	"	"	"	4	311	2459	364	615	91
H14a-3A	Fuel O	JP-5	15	255	2.0	306	53	1	26	1
H14a-3B	"	"	"	"	4.0	304	137	6	34	1
H14a-3C	"	"	"	"	11.7	309	1784	333	153	29
H14a-3D	"	"	"	"	5.7	294	19	10	3	2
H14a-3E	"	"	"	"	7.7	300	199	10	26	1
H14a-3F	"	"	"	"	9.7	311	1139	193	118	20
H14a-3G	"	"	"	"	9.0	298	48	8	5	1
H14a-3H	"	"	"	"	5.8	295	21	9	4	2
H14a-3I	"	"	"	"	10.7	297	19	22	2	2

NOTES:

(1) T_{WO} Maximum outside wall (surface) temperature on the HiReTS capillary, beginning of test.

TABLE 10: EFFECT OF ADDITIVES AT NON-SOC

All Tests at Modified SOC (Flow Rate = 35 mL/min, T_{Fo} = 290°C, Test Duration = Variable)
(Test Terminated when HN = 1000)

Test No.	Fuel Designation	Fuel Type	Additive Type	Additive Conc.	Test Duration	T_{wo}	HiReTS No.	Capillary Carbon Deposits	HiReTS No. Rate	Capillary Carbon Dep. Rate
				ppm	(hrs)	(°C)	(Δ°C)	(μg)	(Δ°C/hr)	(μg/hr)
H14a-9A	Fuel N	JP-5	None	None	8	395	1000	271	125	34
H1-6K	Fuel O	"	"	"	1.9	393	1000	137	526	72
H1-3B	Fuel A	"	"	"	0.45	411	1000	45	2222	100
H14b-9A	Fuel N	"	MDA	5.8	7.2	391	1000	151	139	21
H14b-10A	Fuel O	"	"	"	25.5	501	1000	202	39	8
H14b-11(B,C,D)	Fuel A	"	"	"	1.1	402	1000	75	909	68
H14c-9A-1	Fuel N	"	Betz 8Q406	125	12.3	502	1000	432	81	35
H14-C-10A	Fuel O	"	"	"	8.7	517	1000	200	115	23
H8-4C	Fuel A	"	"	"	0.7	390	1000	34	1429	49
H14d-9A1	Fuel N	"	Betz 8Q462	256	21	507	1000	200	48	10
H14d-10A1	Fuel O	"	"	"	19	501	1000	301	53	16
H14d-11A1	Fuel A	"	"	"	7.2	419	1000	319	139	44

NOTES:

(1) Capillary Failure reached when HN = 1000.
(2) Test duration indicates time to reach HN = 1000.
(3) These values are not included in the averages. Also, the negative value shown in the column "% Reduction in Surface Deposits" actually indicates a percent increase in deposition.

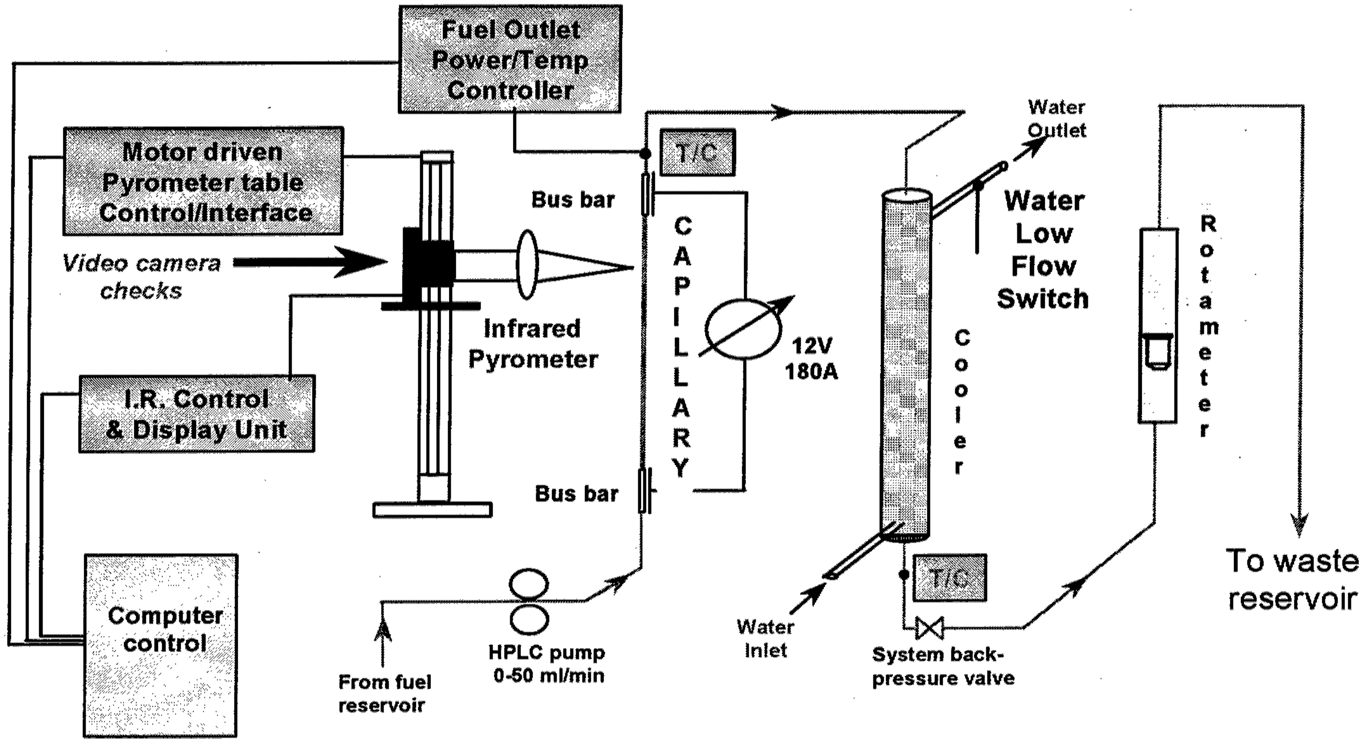

FIGURE 1: SCHEMATIC OF THE HiReTS TEST UNIT

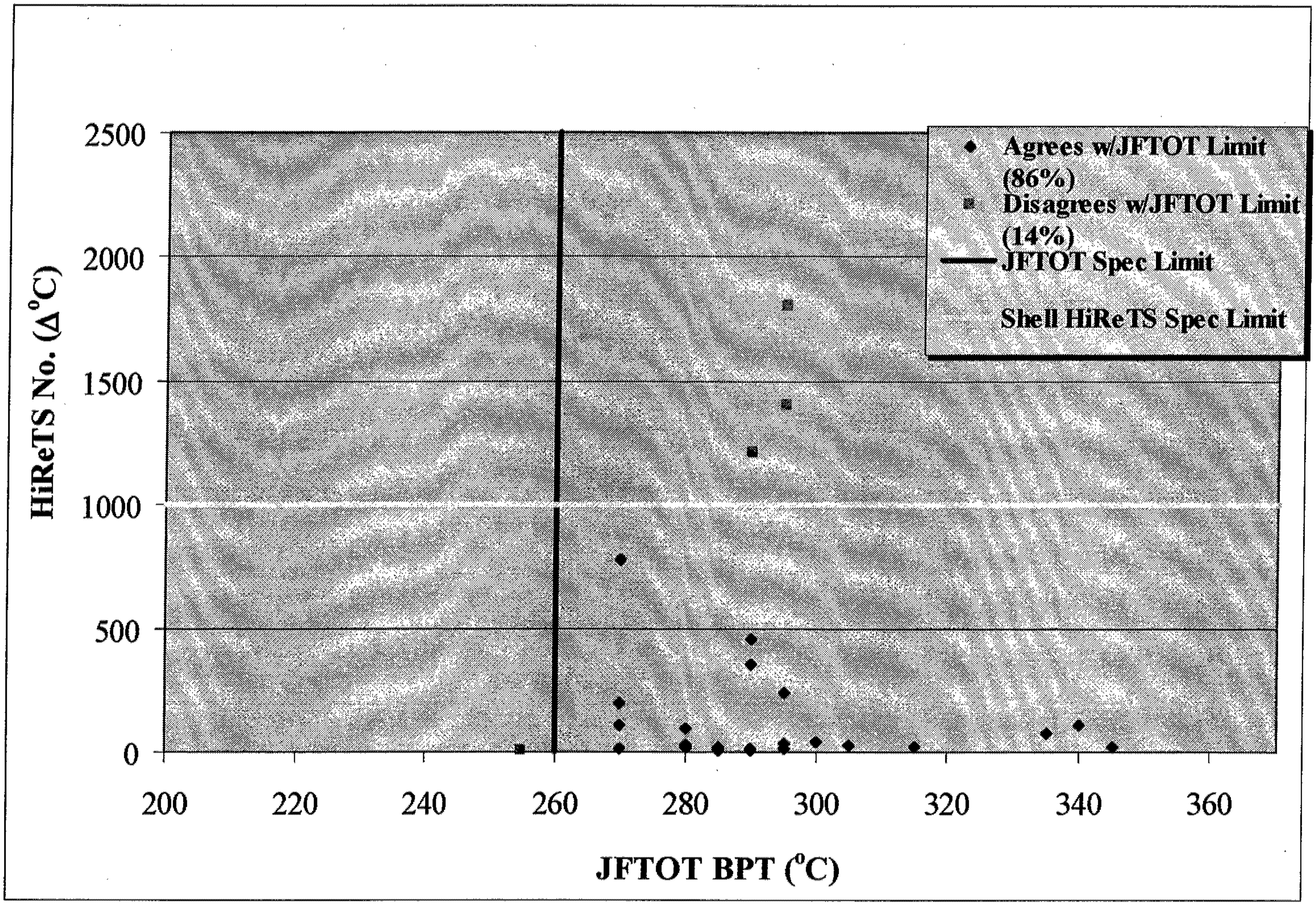

FIGURE 2A: CORRELATION OF HN VS. JFTOT BPT
Red Dye Test Program Fuel Samples
Nineteen RDTF Fuels (Refinery Samples)
(28 HiReTS Tests at SOC)

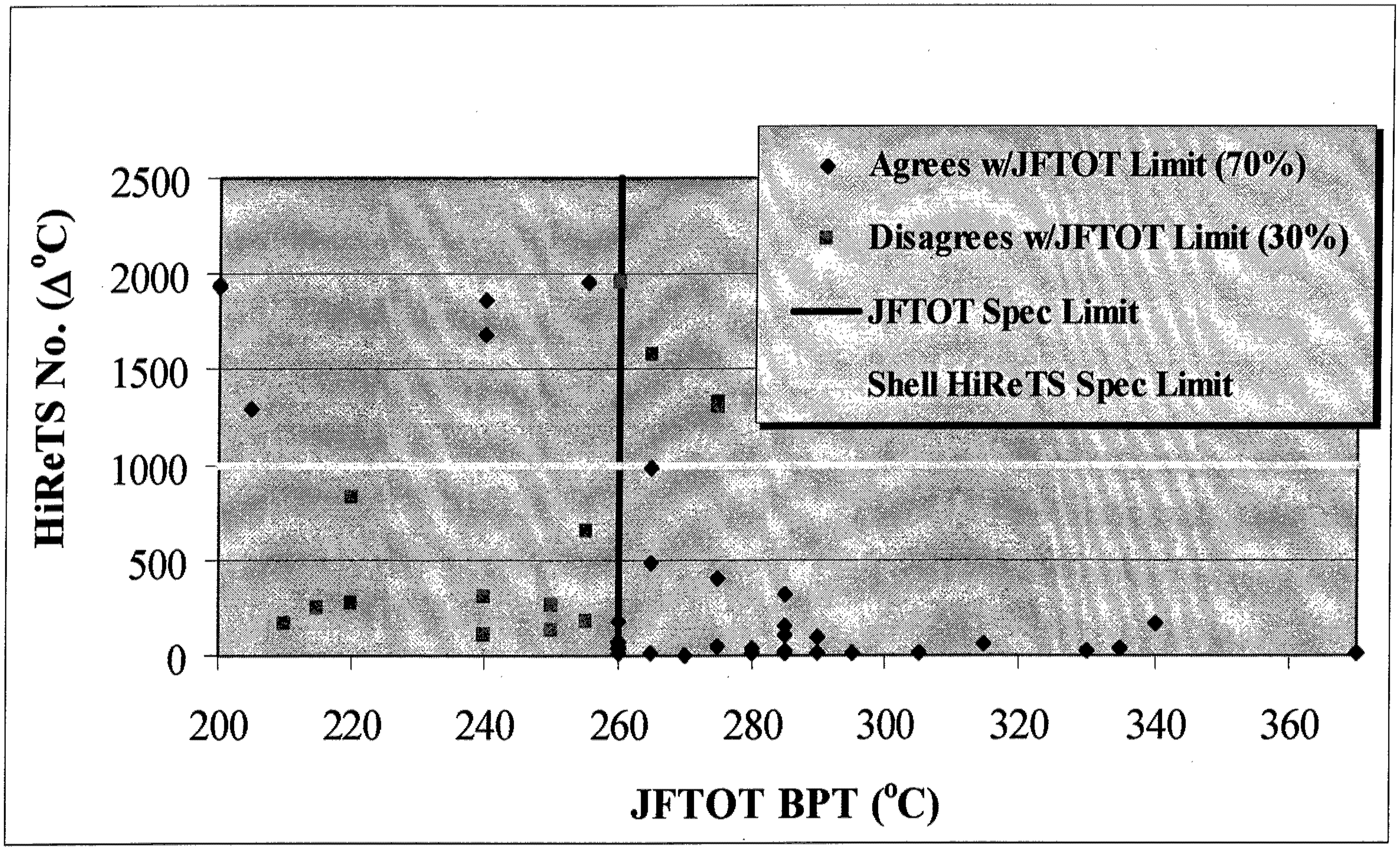

FIGURE 2B: CORRELATION OF HN VS. JFTOT BPT
NAVAIR Test Fuels (Field Samples)
Fifty-Three NAVAIR Test Fuels (Field Samples)
(144 HiReTS Tests at SOC)

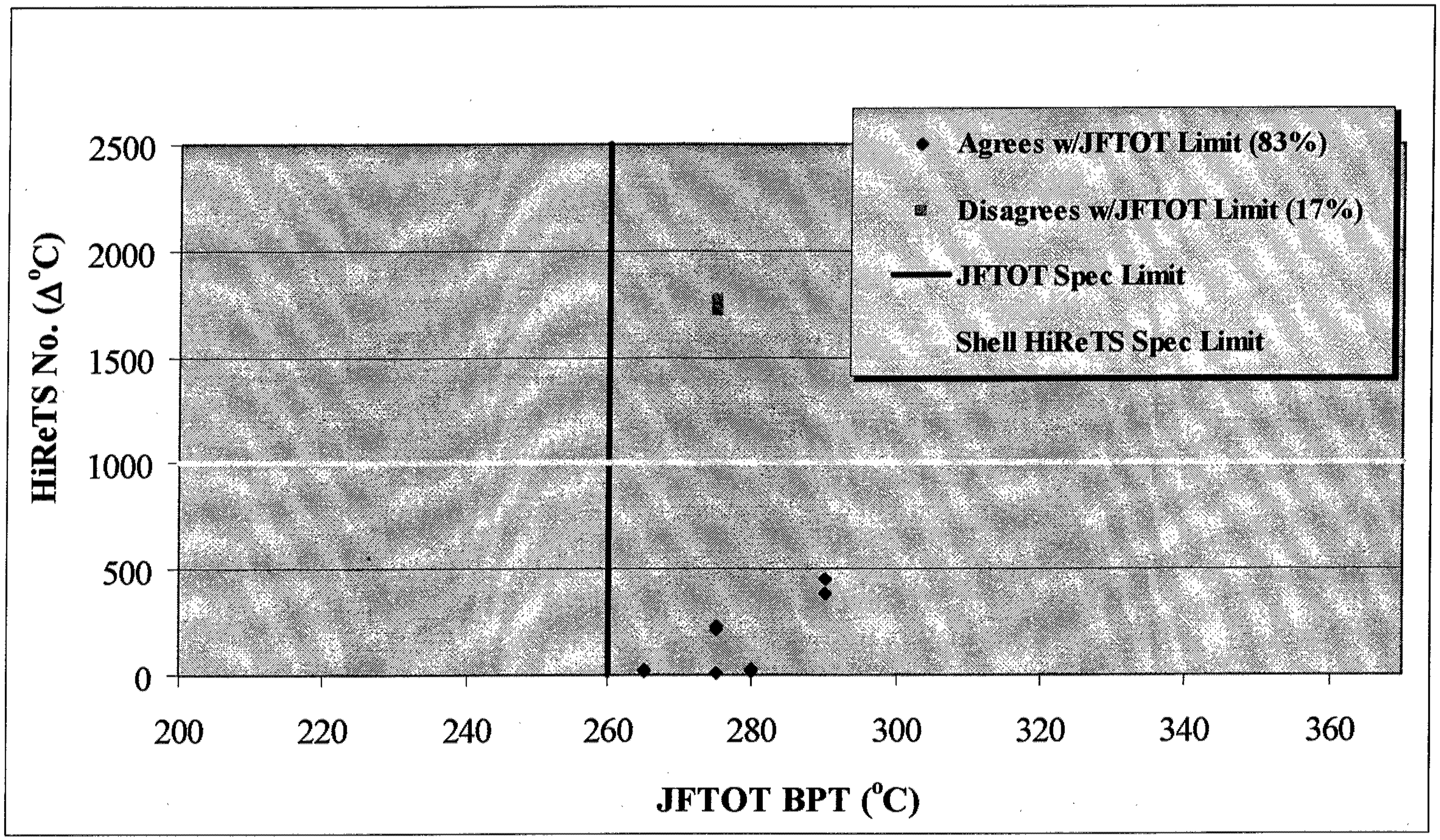

FIGURE 2C: CORRELATION OF HN VS. JFTOT BPT
ASTM HiReTS Round Robin Test Fuels (Field Samples)
Six ASTM HiReTS Round Robin (Field Samples)
(12 HiReTS Tests at SOC)

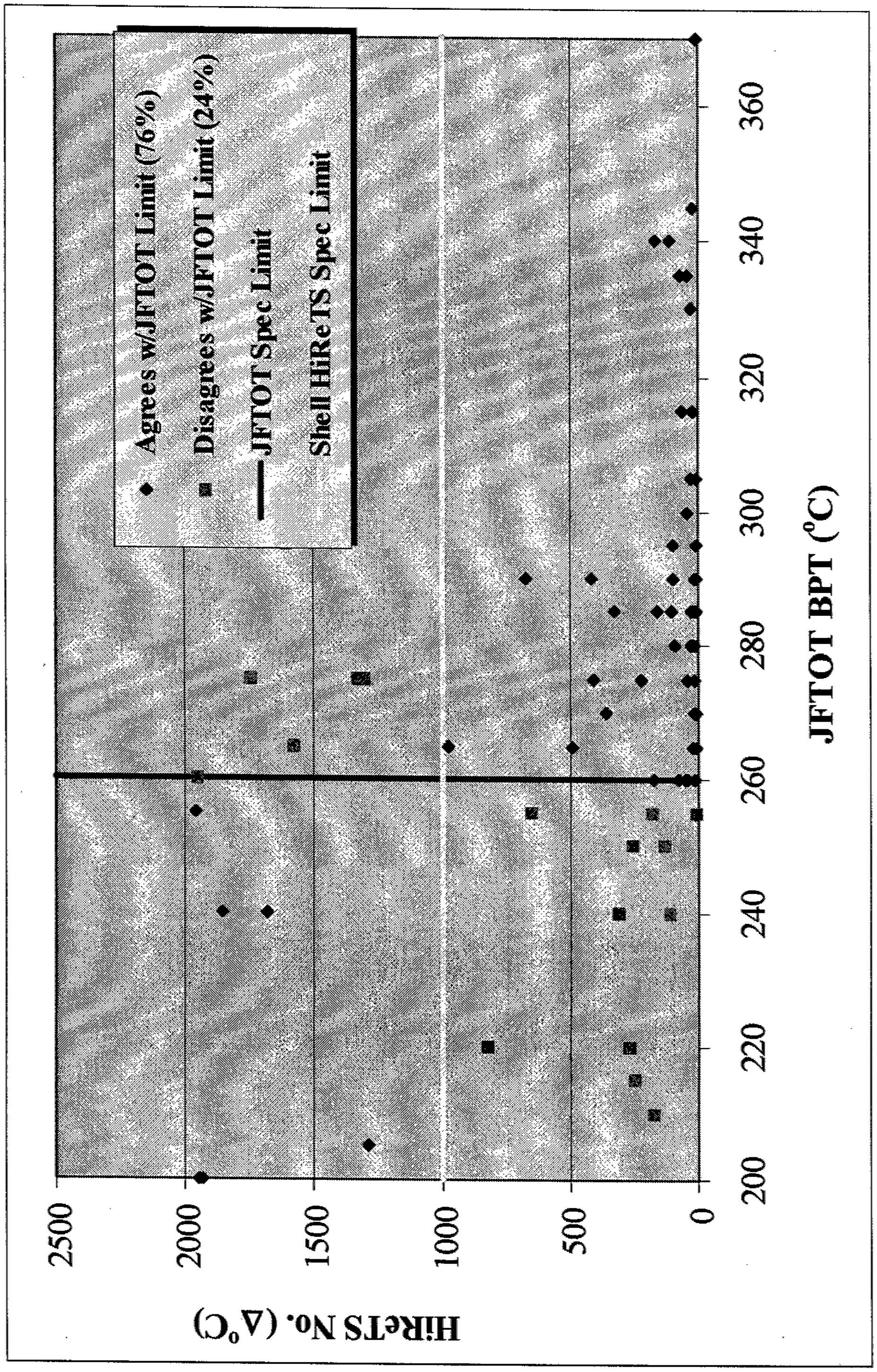

FIGURE 2D: CORRELATION OF HN VS. JFTOT BPT
All 78 Fuels (Refinery & Field Samples)
(169 HiReTS Tests at SOC)

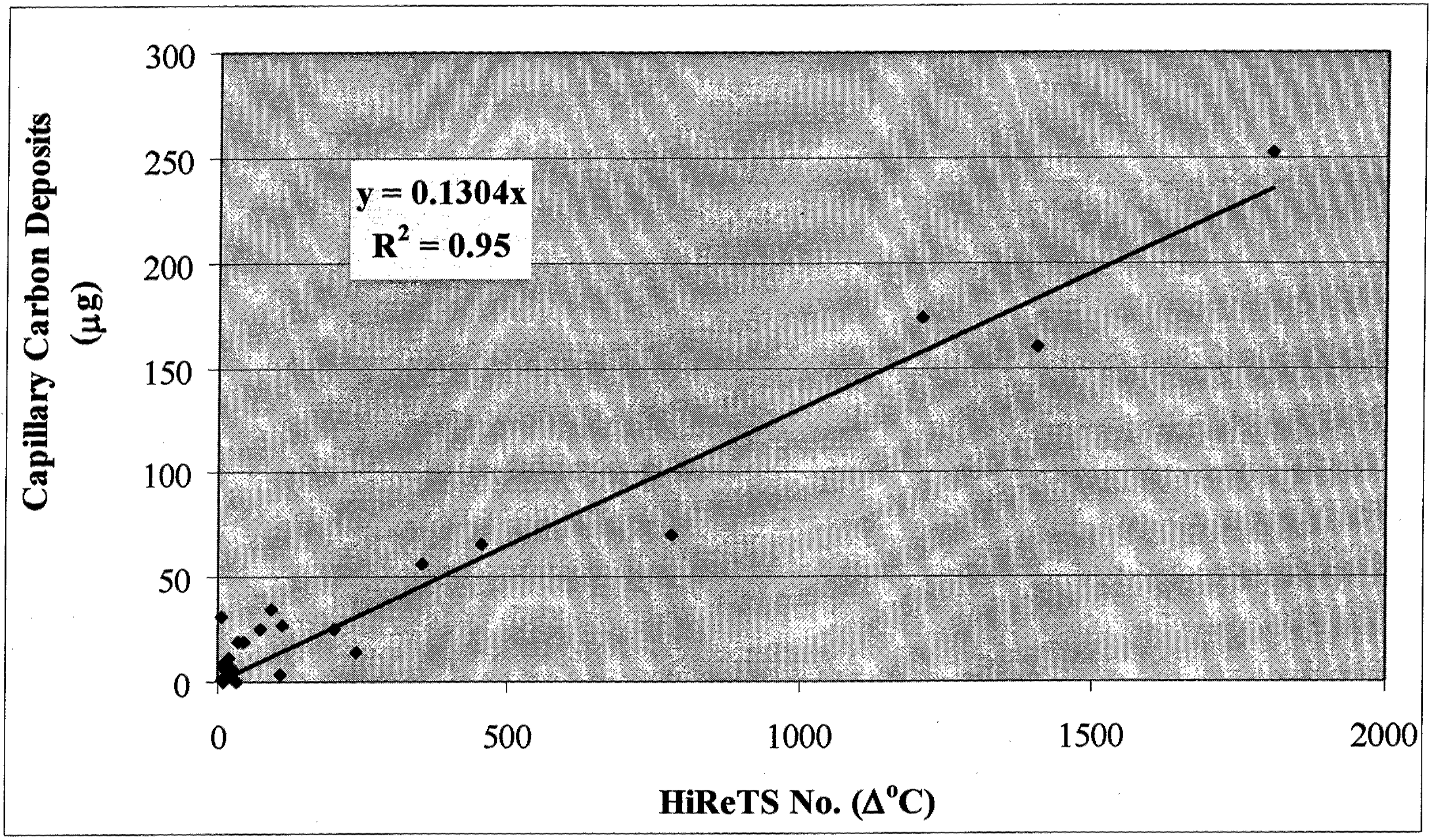

FIGURE 3A: CORRELATION OF CAPILLARY CARBON DEPOSITS TO HN
Red Dye Test Program Fuel Samples
Nineteen RDTF Fuels (Refinery Samples)
(28 Tests at SOC)

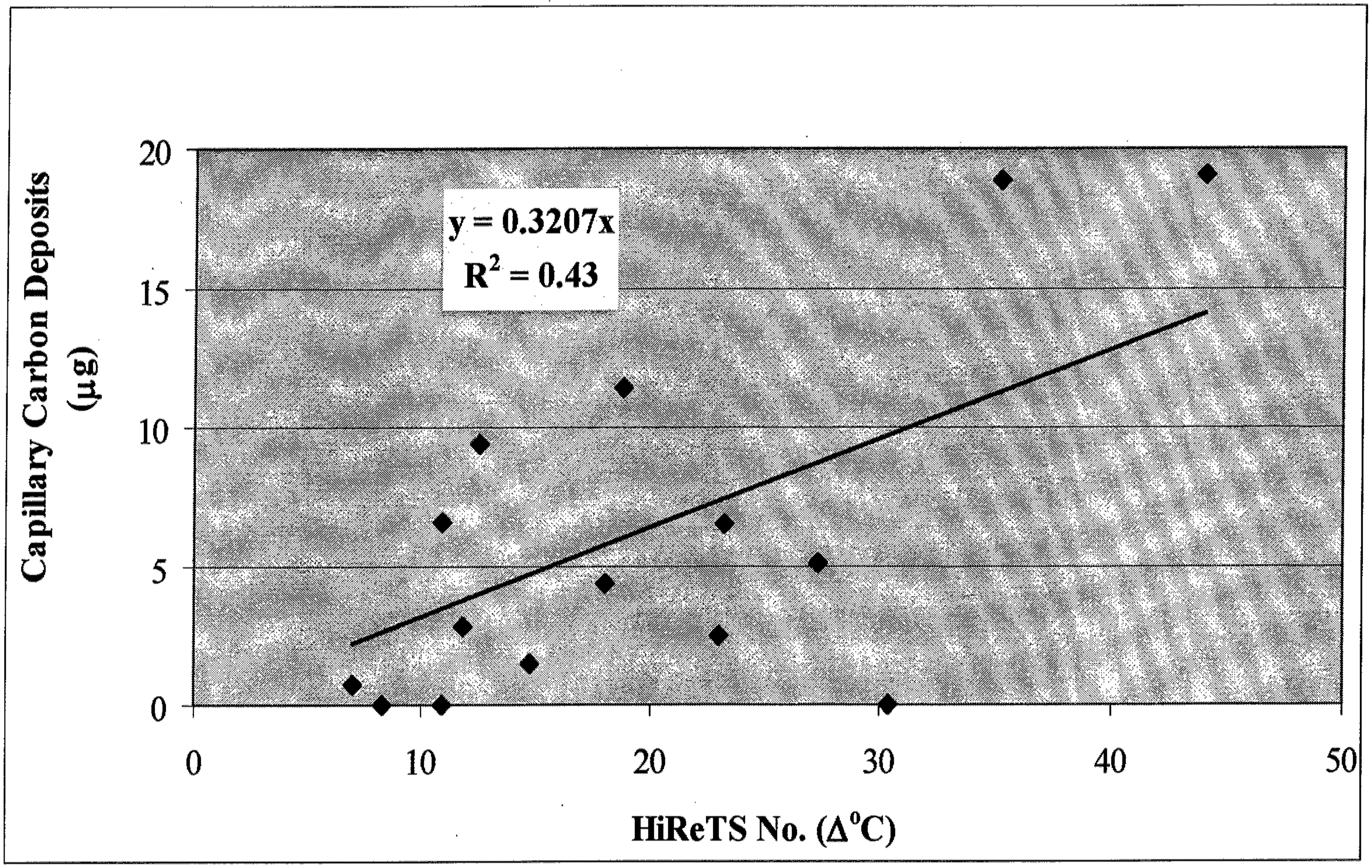

FIGURE 3B: CORRELATION OF CAPILLARY CARBON DEPOSITS TO HN
Red Dye Test Fuels Showing Very High Stability
(15 Tests at SOC: Avg. Carbon = 6 +/- 4 mg, Avg. HN = 20 +/- 6)

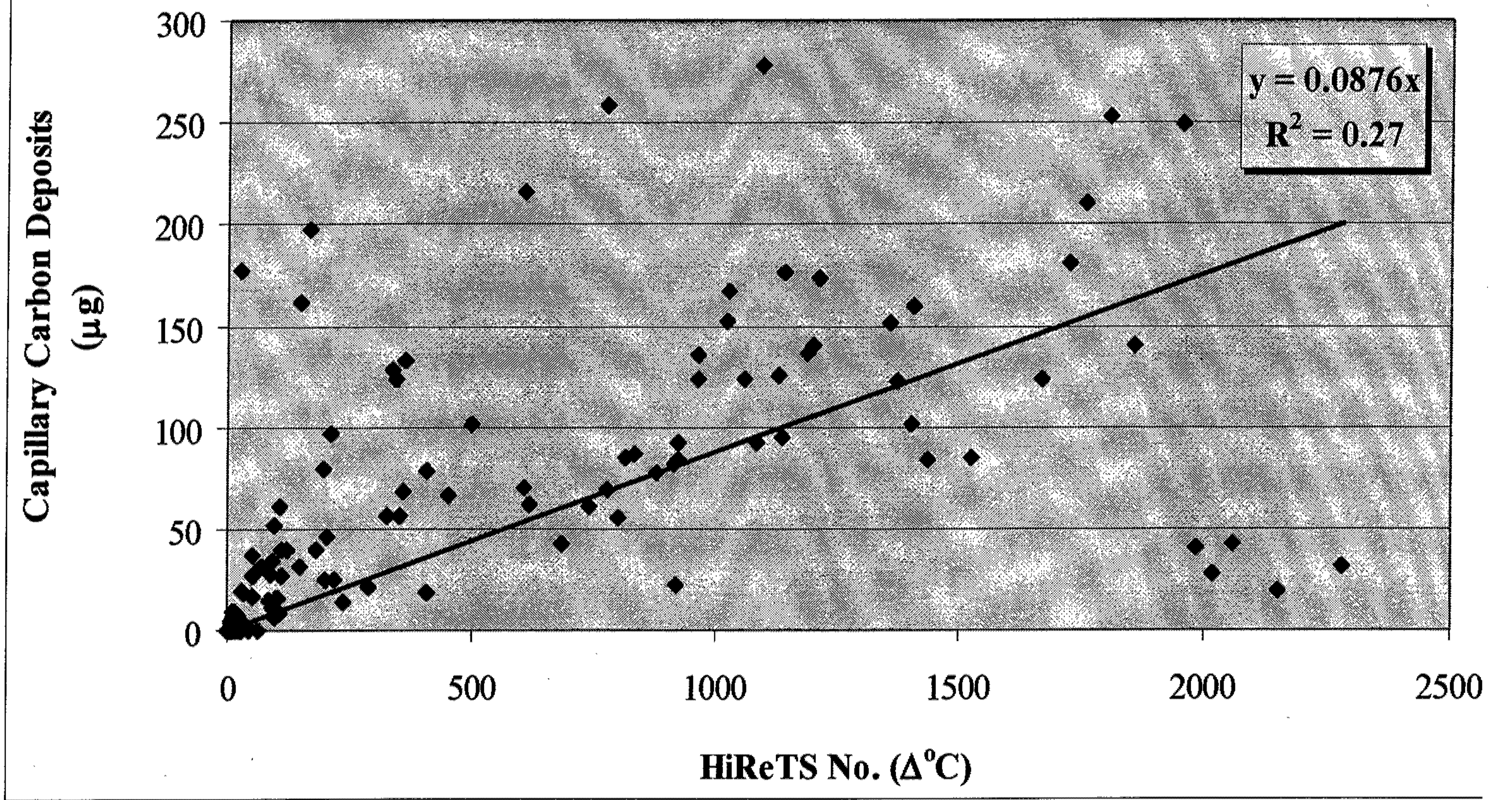

FIGURE 3C: CORRELATION OF CAPILLARY CARBON DEPOSITS TO HN NAVAIR Test Fuels (Field Samples)
(53 Fuels - 144 Tests at SOC)

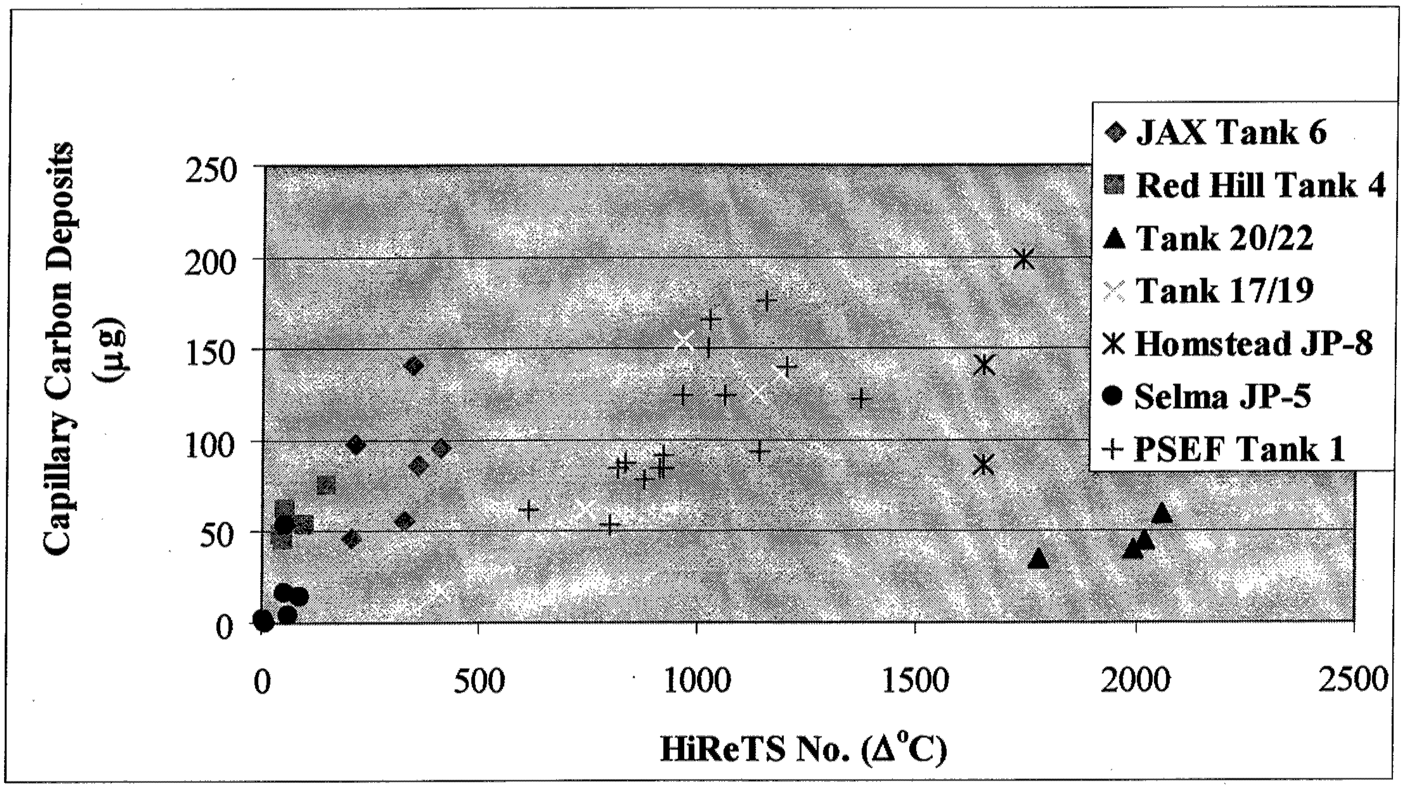

FIGURE 3D: CORRELATION OF CAPILLARY CARBON DEPOSITS TO HN Repeatability Studies on Seven NAVAIR Test Fuels
(45 Tests on 7 NAVAIR Test Fuels)

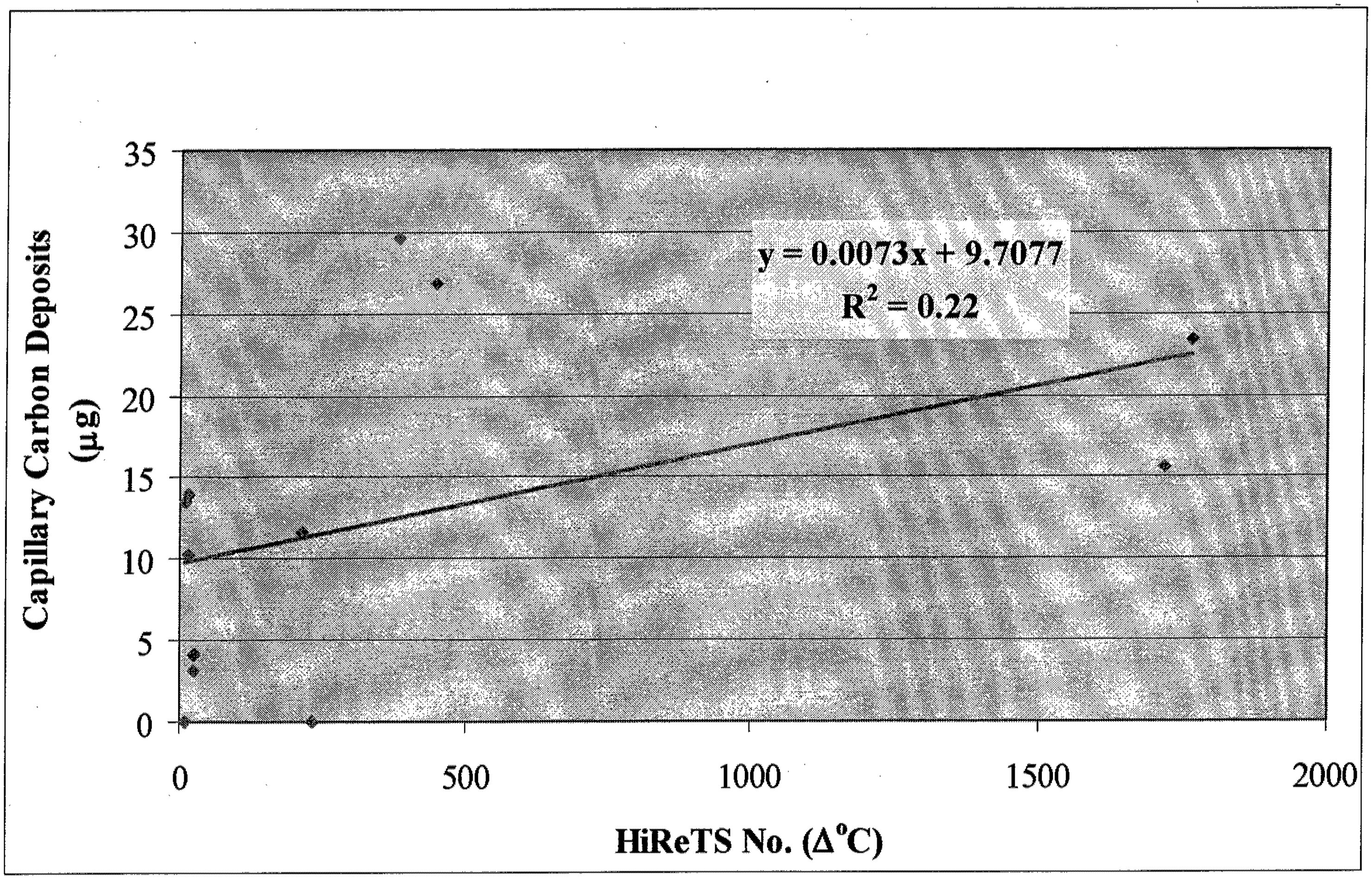

FIGURE 3E: CORRELATION OF CAPILLARY CARBON DEPOSITS TO HN ASTM Round-Robin Fuels (Field Samples)
(Six Fuels Run in Duplicate at SOC)

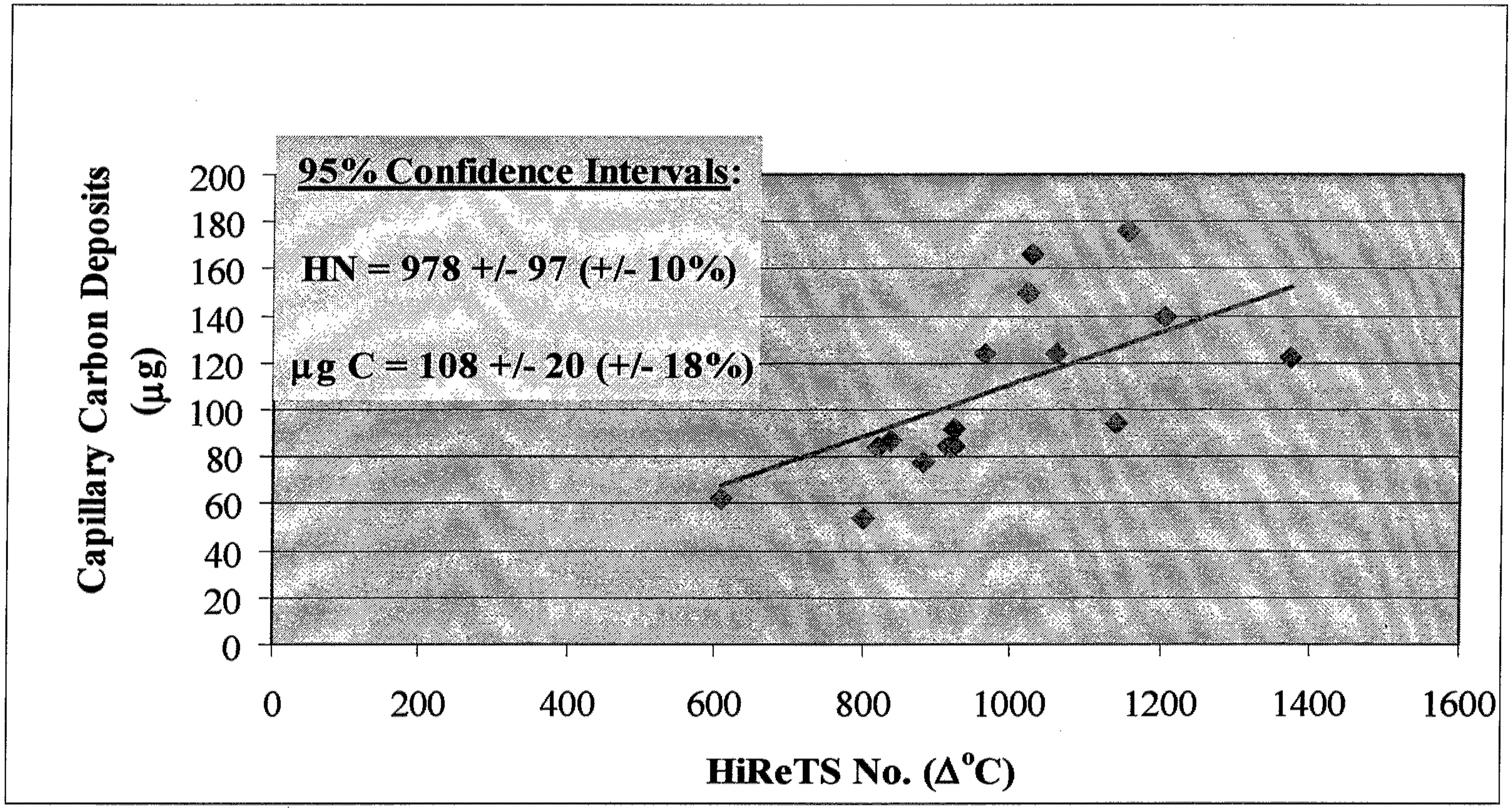

FIGURE 3F: CORRELATION OF CAPILLARY CARBON DEPOSITS TO HN
Repeatability Studies on ASTM Round-Robin Fuels (Field Samples)
(Six Fuels Run in Duplicate at SOC)

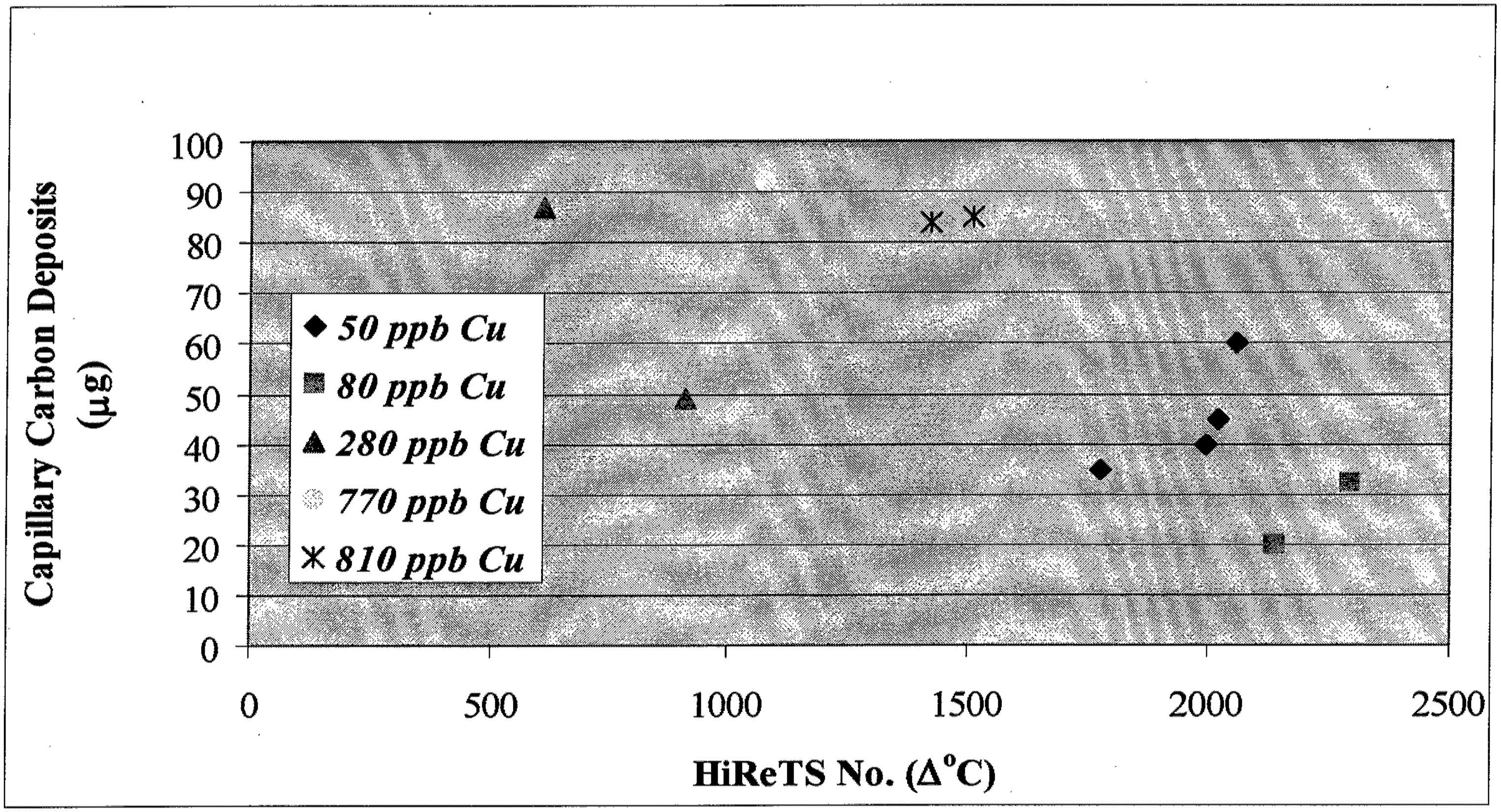

FIGURE 4A: EFFECT OF COPPER CONCENTRATION
Capillary Carbon Deposits versus HiReTS No.
Fuel A (Tank 20/22) + Copper
(All Tests at SOC)

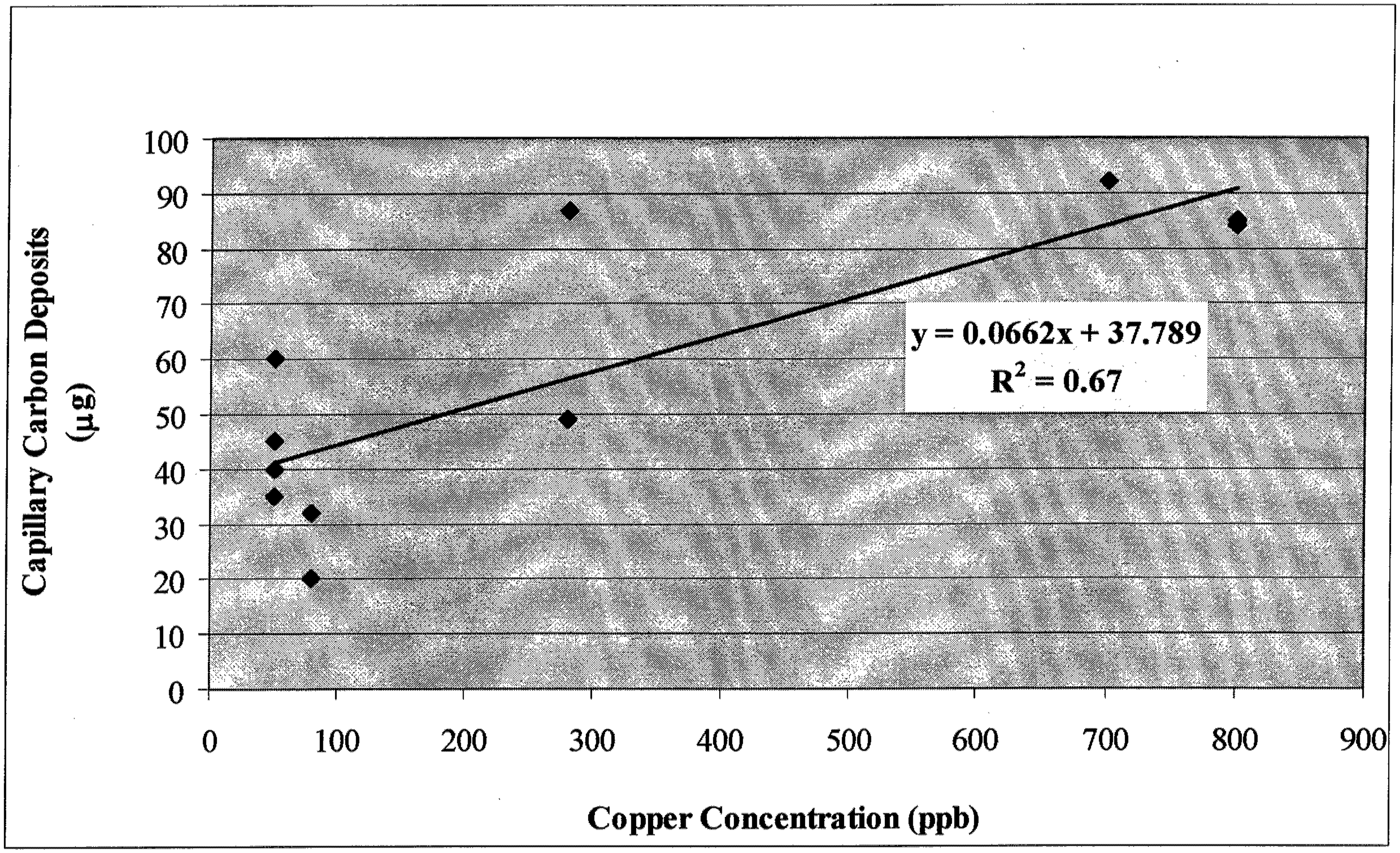

FIGURE 4B: EFFECT OF COPPER CONCENTRATION
Capillary Carbon Deposits versus Fuel Copper Concentration
Fuel A + Copper (50-800 ppb)
(All Tests at SOC)

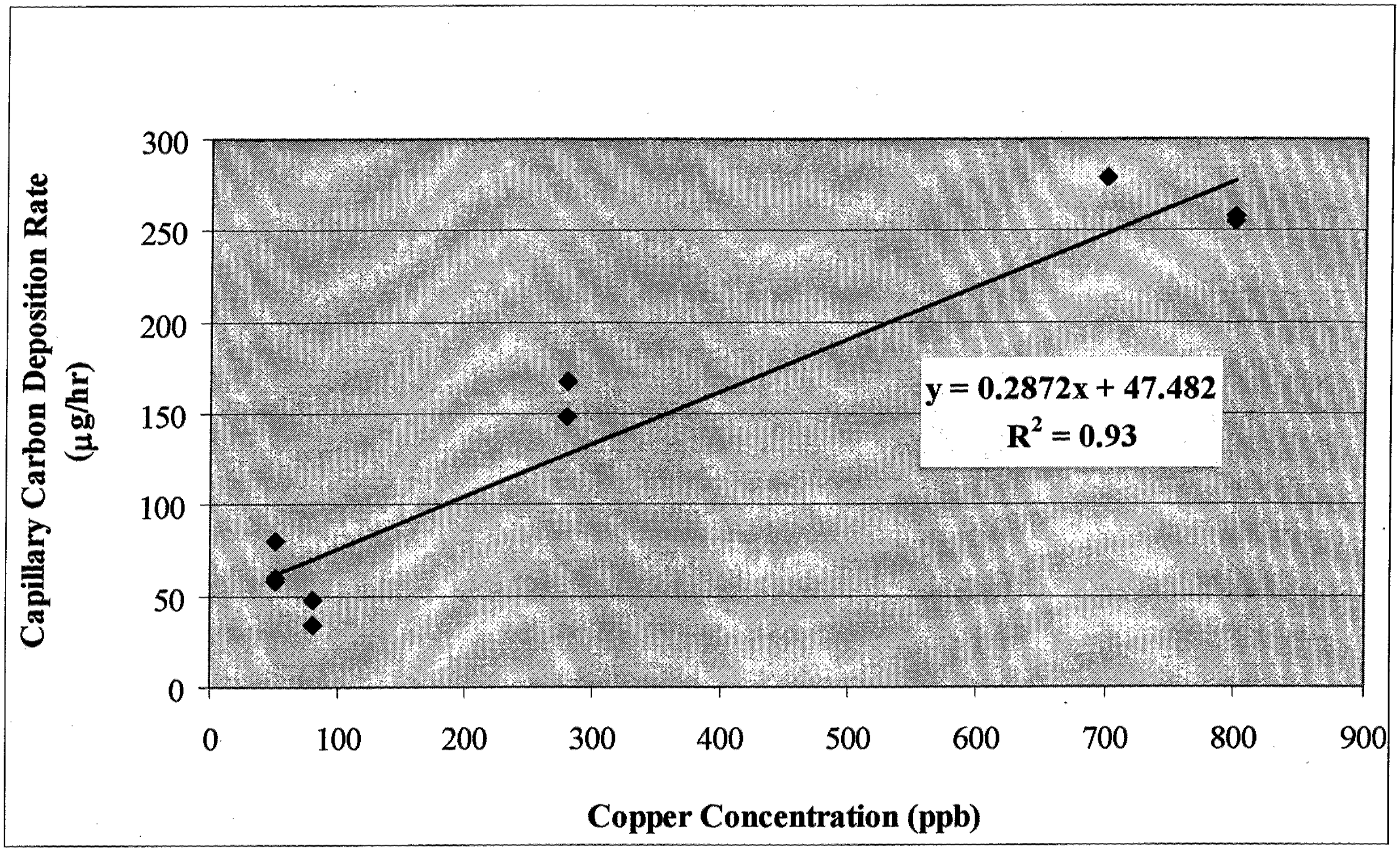

FIGURE 4C: EFFECT OF COPPER CONCENTRATION
Capillary Carbon Deposits Normalized to Test Duration versus Fuel Copper Concentration
Fuel A + Copper (50-800 ppb)
(All Tests at SOC)

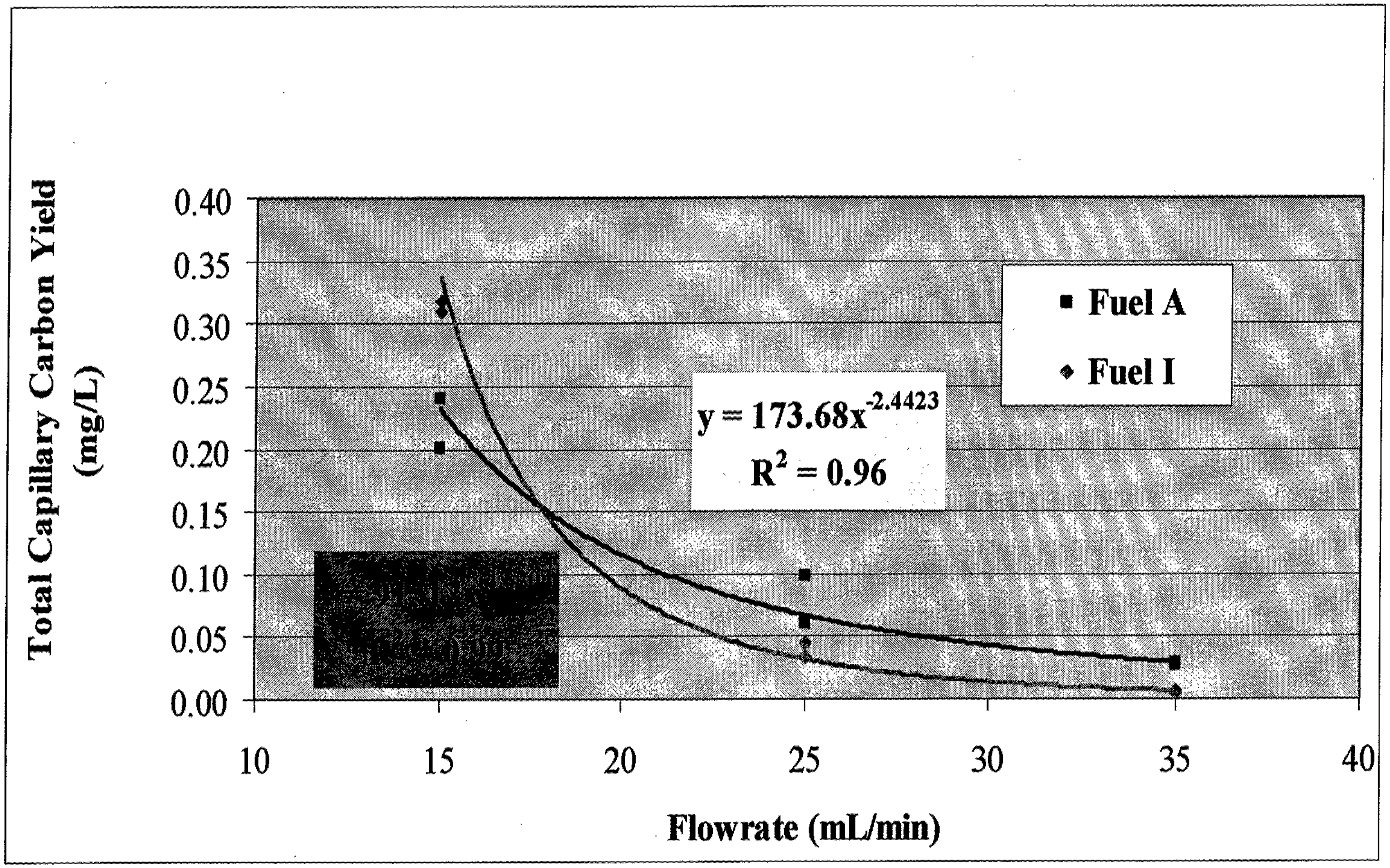

FIGURE 5A: EFFECT OF FUEL FLOW RATE ON DEPOSITION AT TFo = 290°C
Total Capillary Carbon Yield (Deposit Concentration) versus Flowrate
Fuel A (BPT = 255°C)
Fuel I (BPT = 275°C)

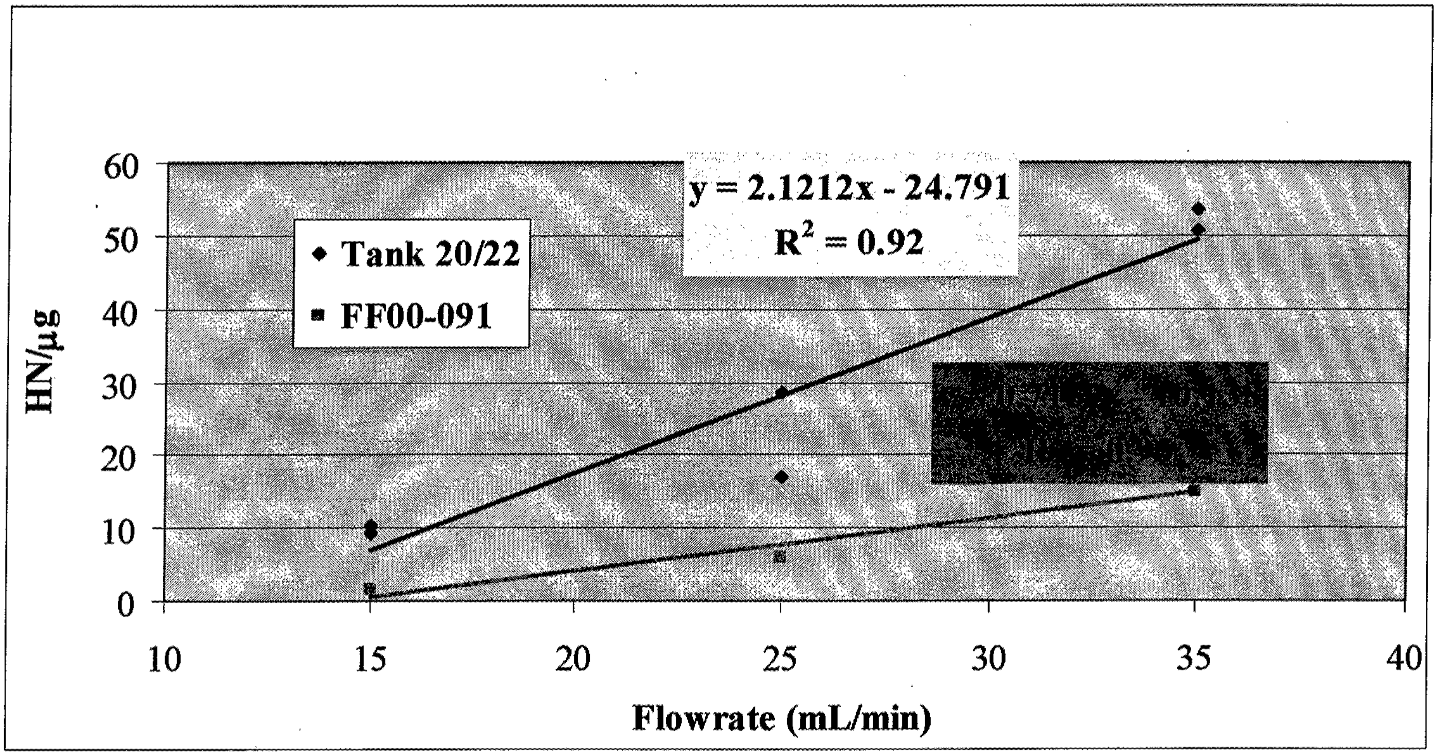

FIGURE 5B: EFFECT OF FUEL FLOW RATE AT TFo = 290°C
Ratio of HiReTS No. to Carbon Deposit versus Flowrate
Fuel A (BPT = 255°C)
Fuel I (BPT = 275°C)

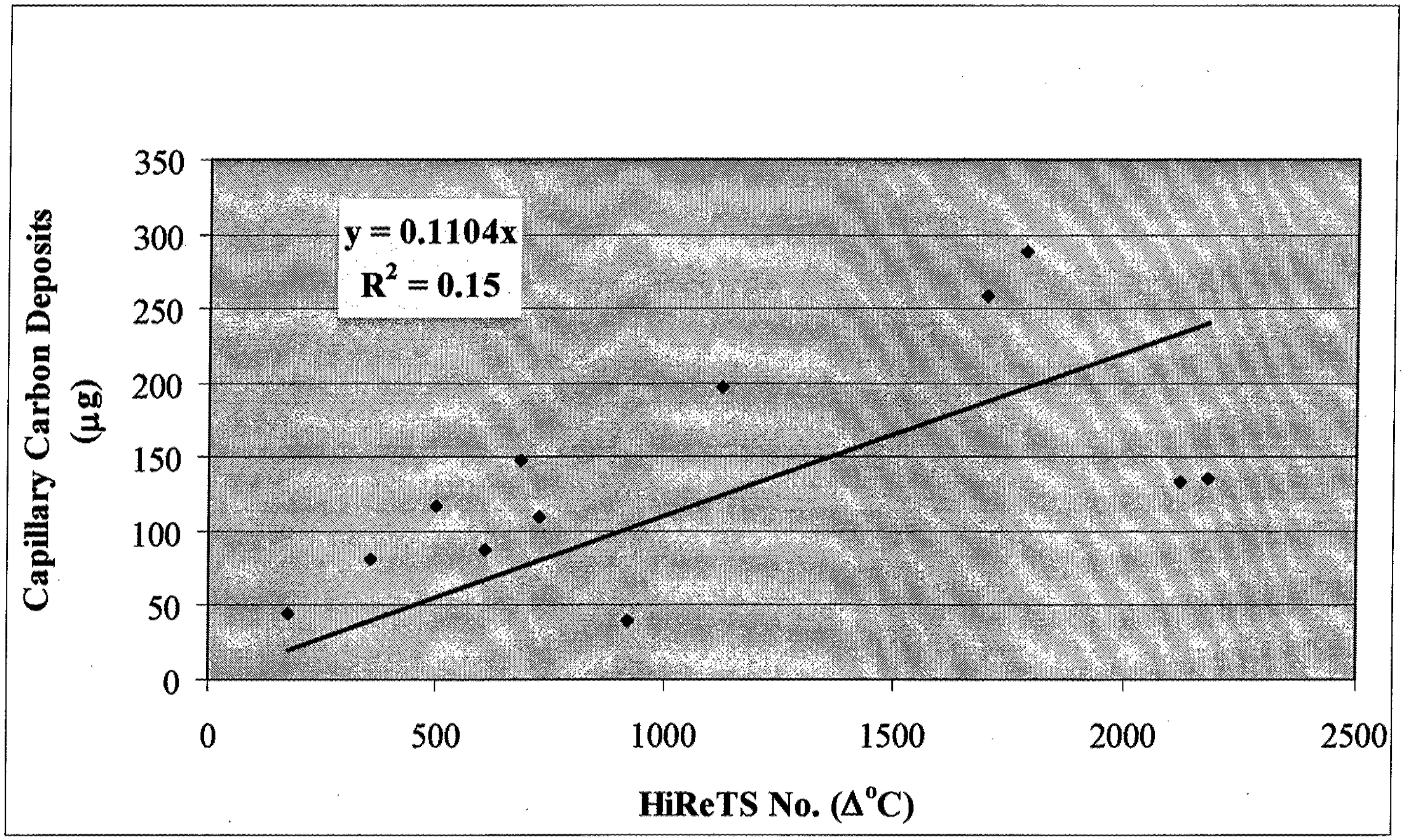

FIGURE 6A: EFFECT OF LOWER CAPILLARY EXIT TEMPERATURE (T_{Fo})
Capillary Carbon Deposits versus HiReTS No.
Fuel B (Fuel A + 280 ppb Cu)
Fuel Flow Rate = 35 mL/min

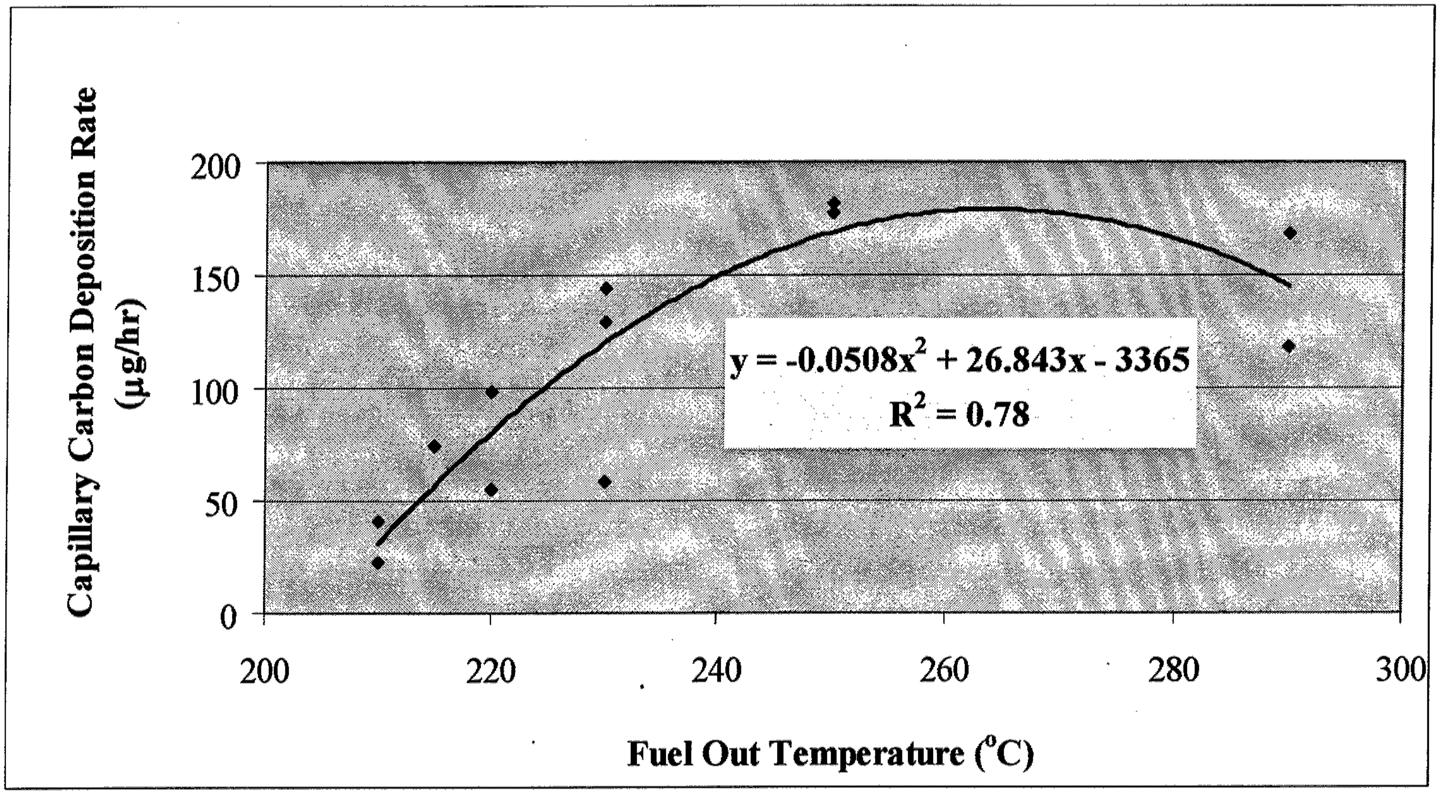

FIGURE 6B: EFEECT OF LOWER CAPILLARY EXIT TEMPERATURE (T_{Fo})
Capillary Carbon Deposition Rate versus Fuel Out Temperature
Fuel B (Fuel A + 280 ppb Cu)
Fuel Flow Rate = 35 mL/min

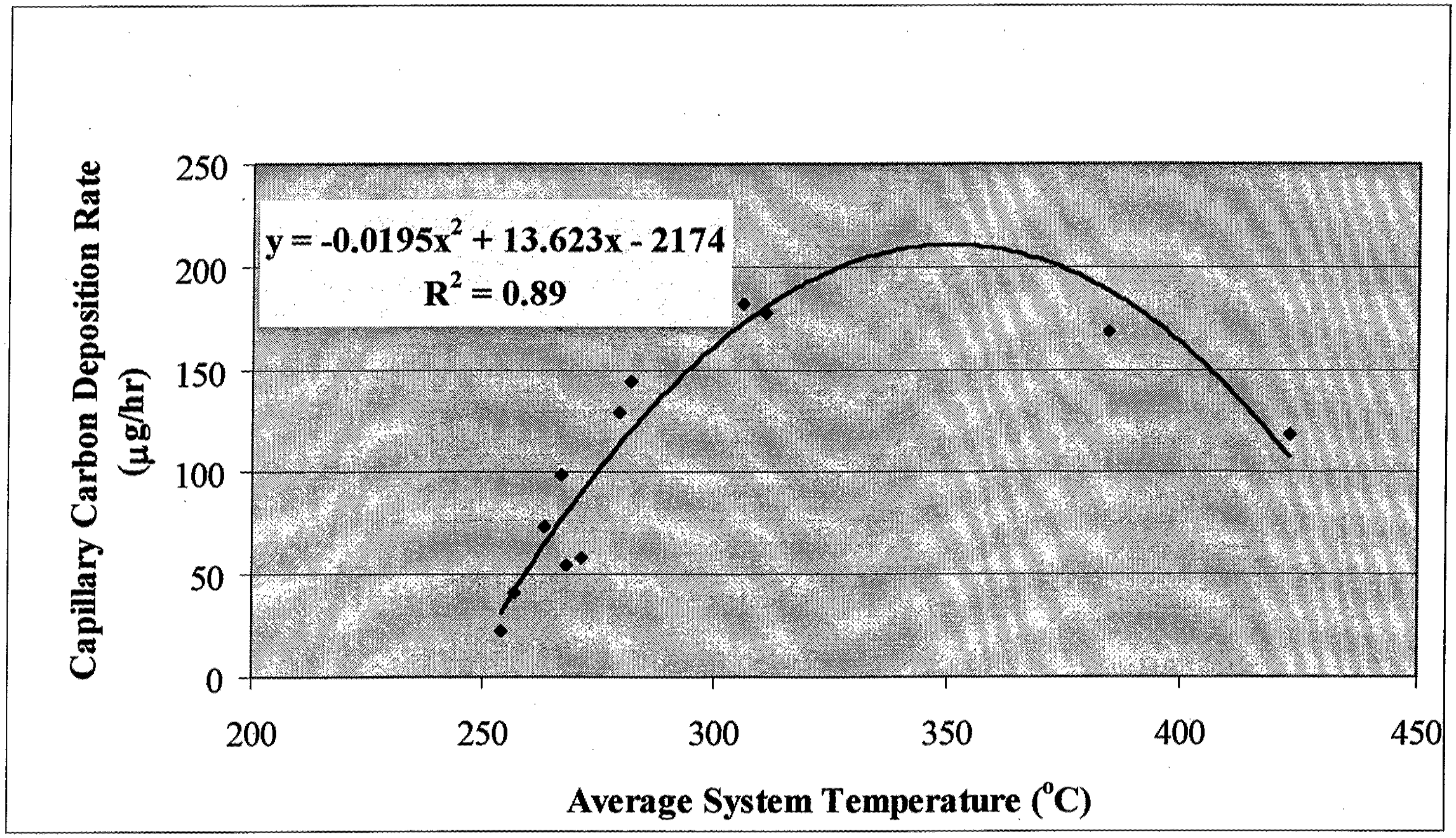

FIGURE 6C: EFFECT OF LOWER CAPILLARY EXIT TEMPERATURE (T_{Fo})
Capillary Carbon Deposition Rate versus Average System Temperature
Fuel B (Fuel A + 280 ppb Cu)
Fuel Flow Rate = 35 mL/min

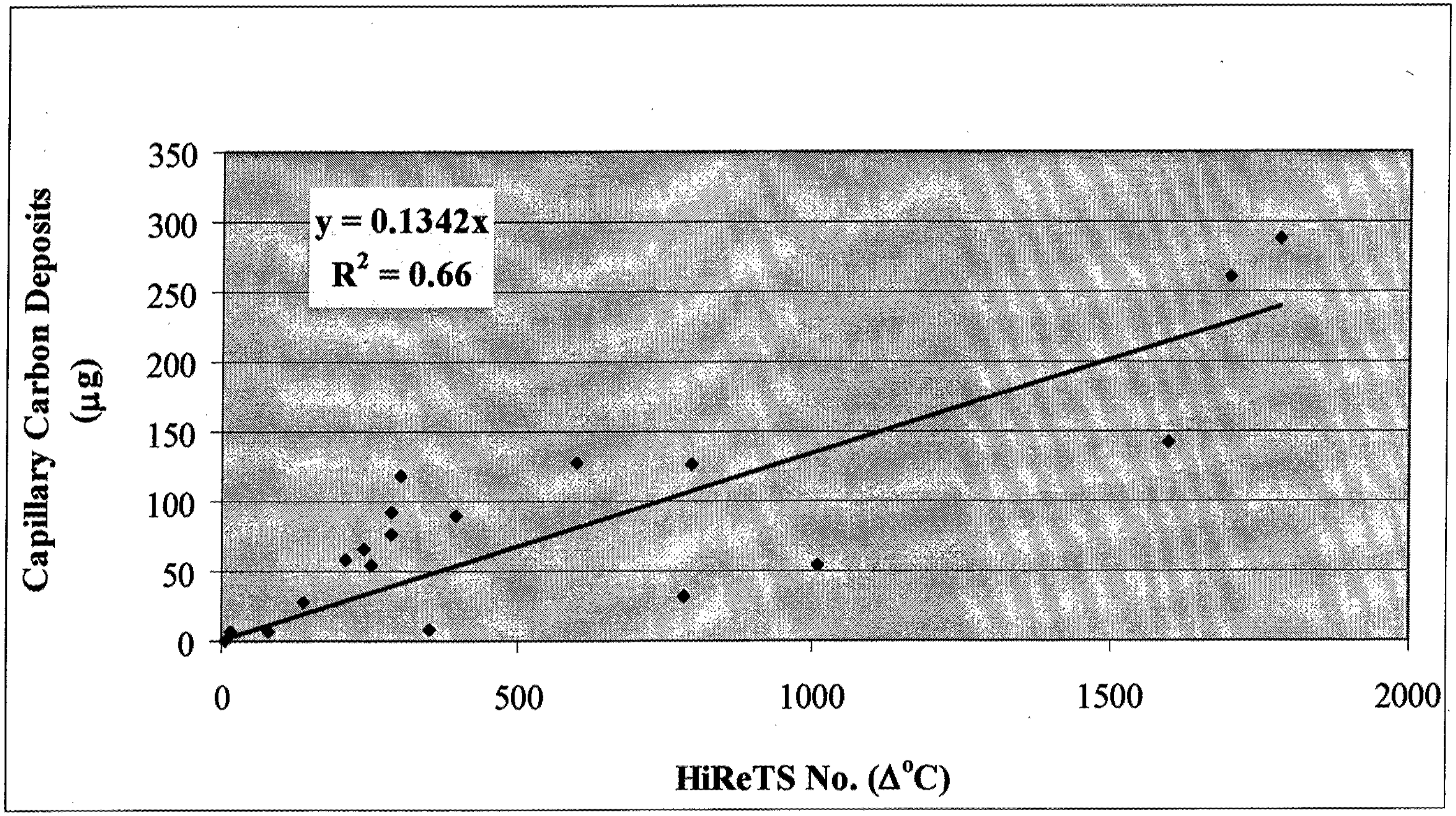

FIGURE 7A: EFFECT OF COPPER CONCENTRTION AT T_{Fo} = 230°C
Capillary Carbon Deposits versus HiReTS No.
Fuel B {Fuel A + Copper (40-3400 ppb)}
(All Tests at Non-SOC)

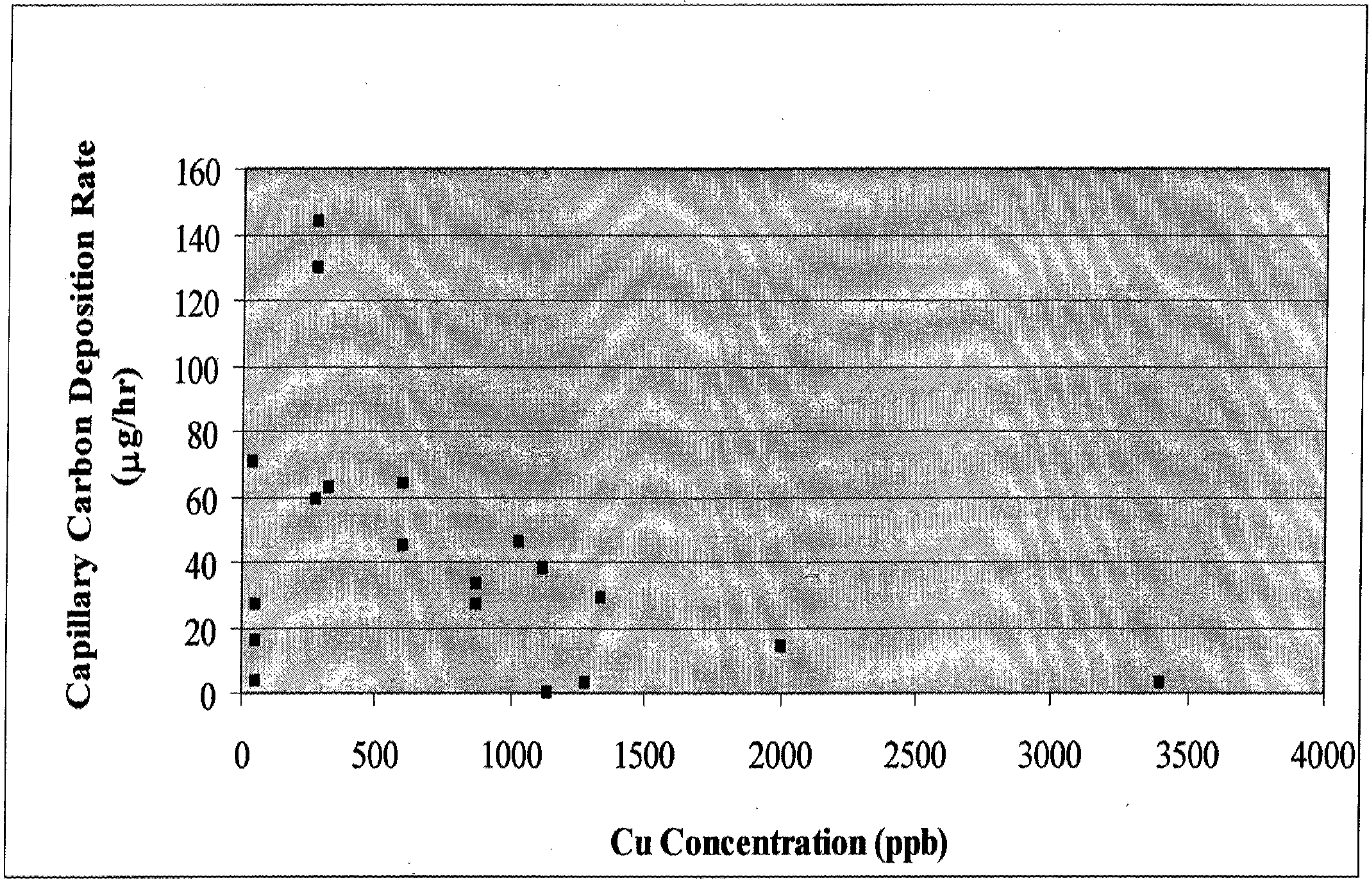

FIGURE 7B: EFFECT OF COPPER CONCENTRATION AT T_{Fo} = 230°C
Capillary Carbon Deposition Rate versus Copper Contamination
Fuel B {Fuel A + Copper (40-3400 ppb)}
Fuel Flow Rate = 35 mL/min

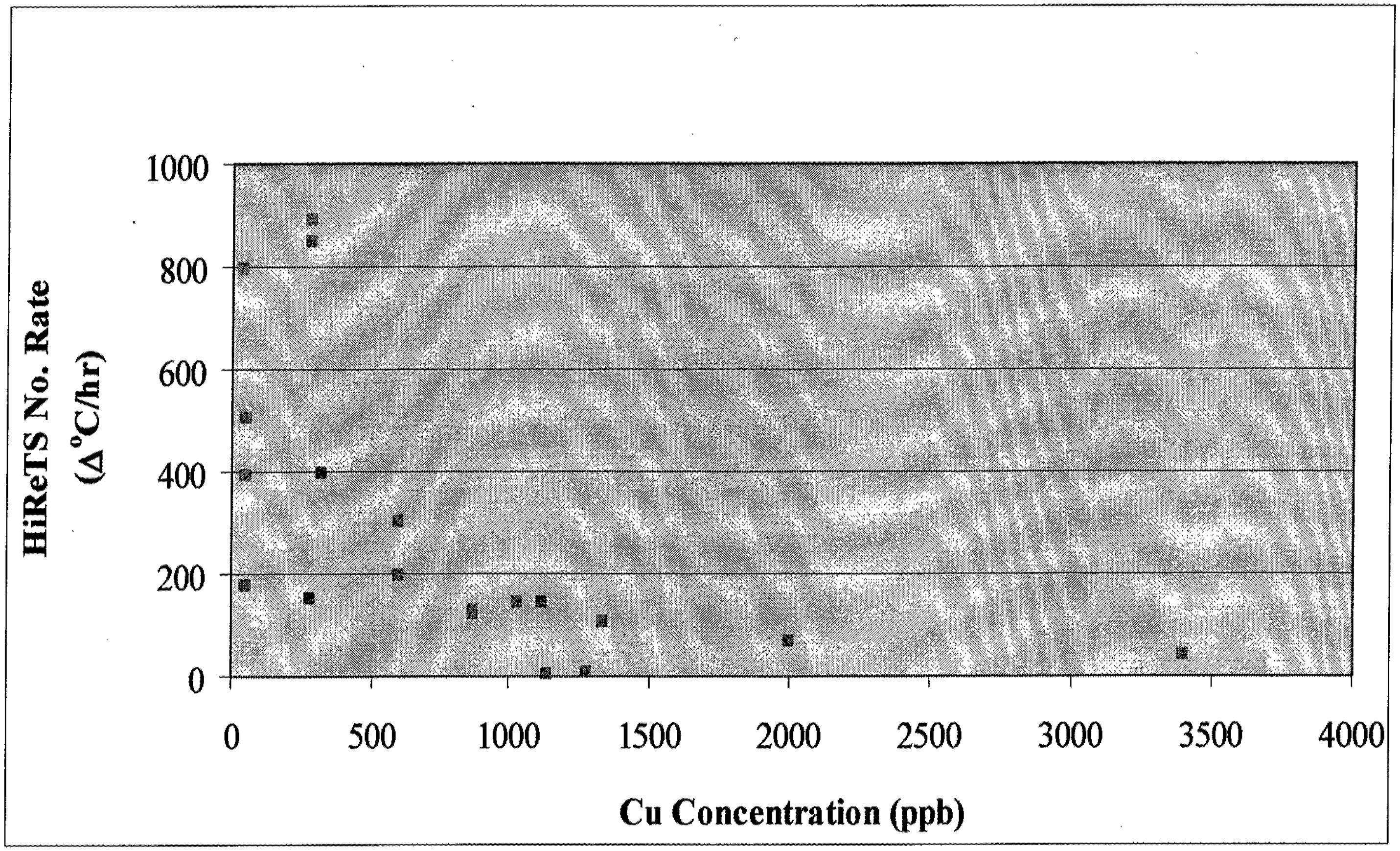

FIGURE 7C: EFFECT OF COPPER CONCENTRATION AT T_{Fo} = 230°C
HiReTS No. Rate versus Copper Concentration
Fuel B {Fuel A + Copper (40-3400 ppb)}
Fuel Flow Rate = 35 mL/min

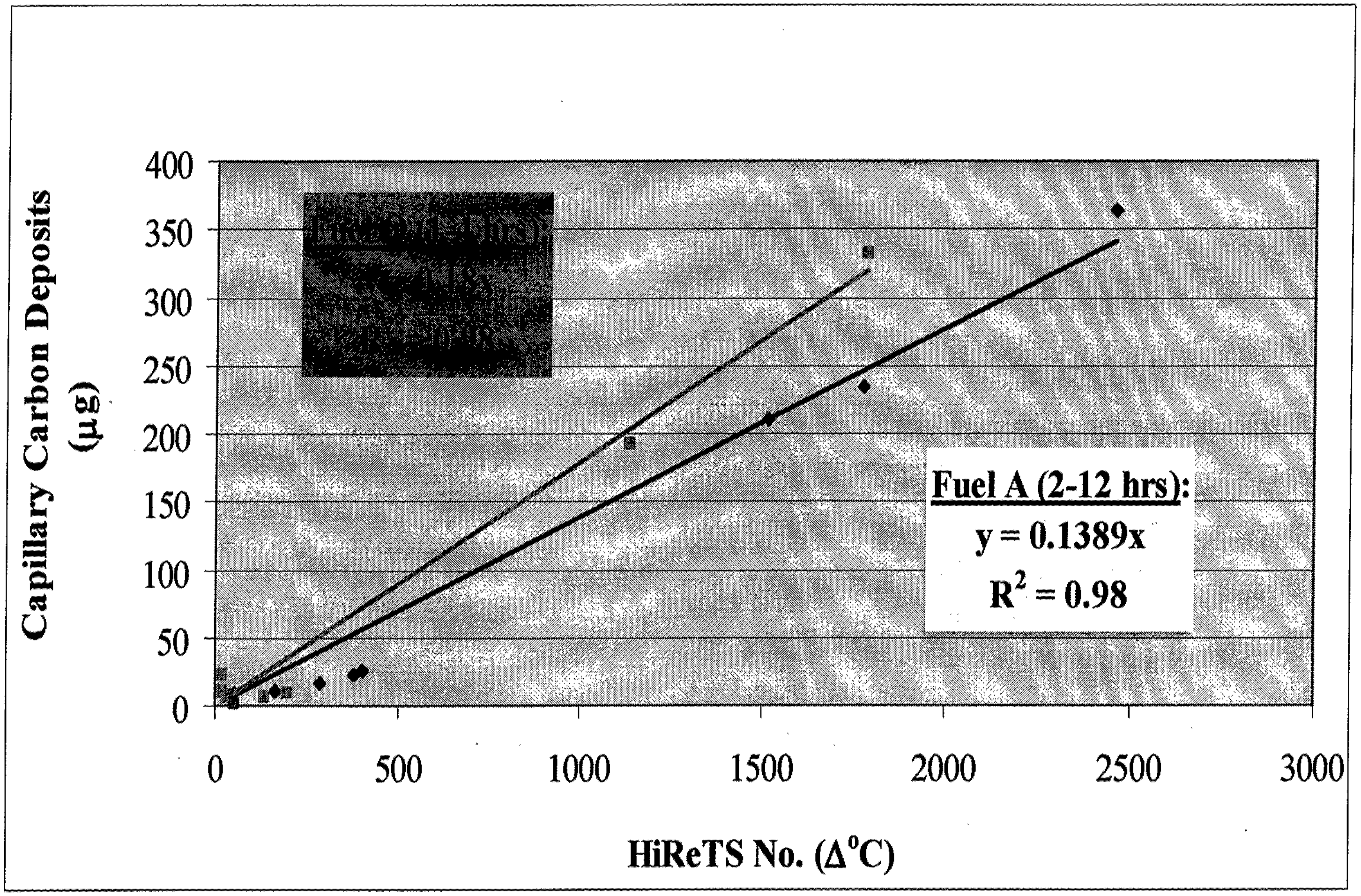

FIGURE 8A: EFFECT OF TEST DURATION
Capillary Carbon Deposits versus HiReTS No.
Fuel Flowrate = 35 mL/min
Fuel Out Temperature (T_{Fo}) = 220°C

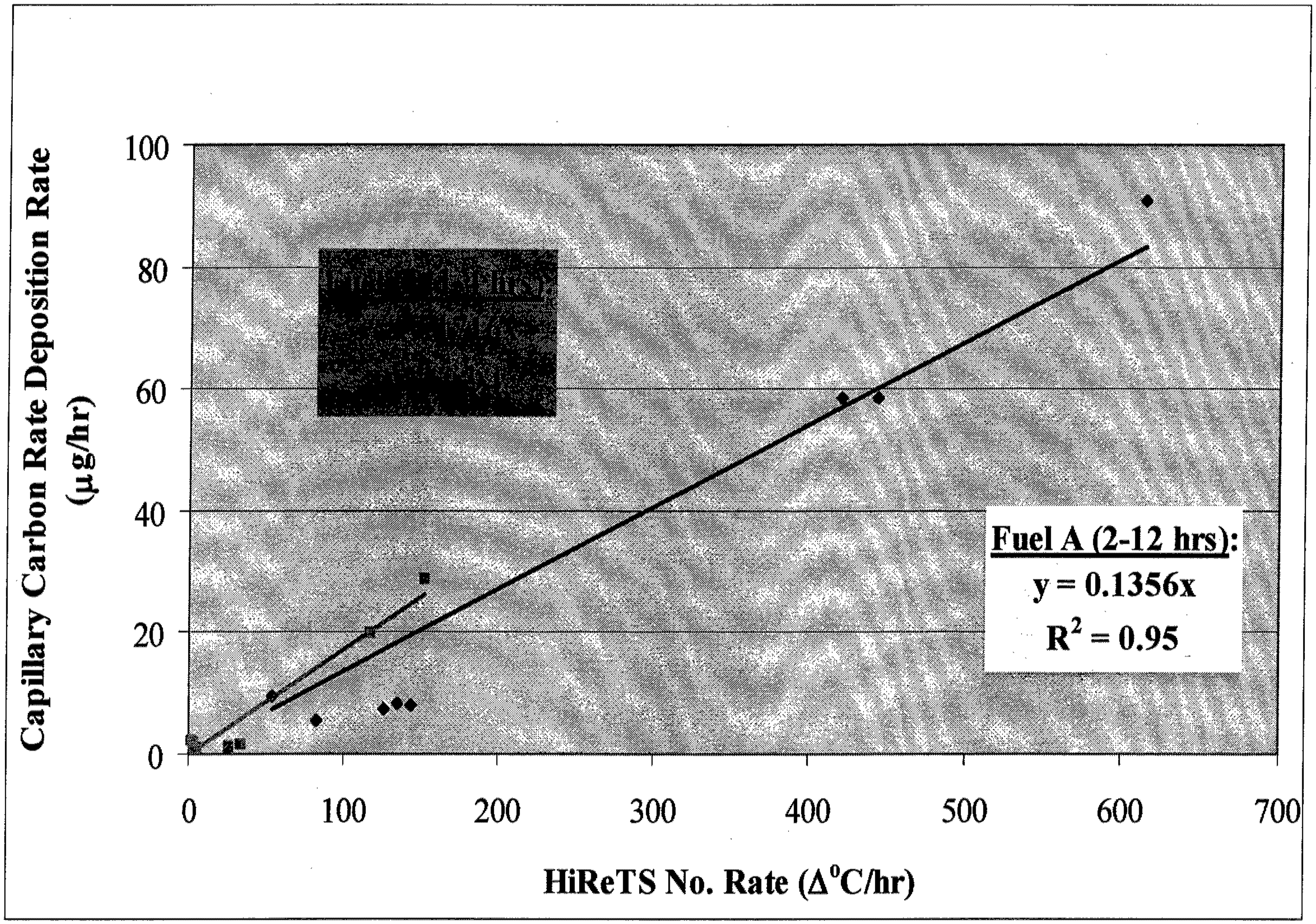

FIGURE 8B: EFFECT OF TEST DURATION
Capillary Carbon Deposition Rate versus HiReTS No. Rate
Fuel Flowrate = 35 mL/min
Fuel Out Temperature (TFo) = 220°C

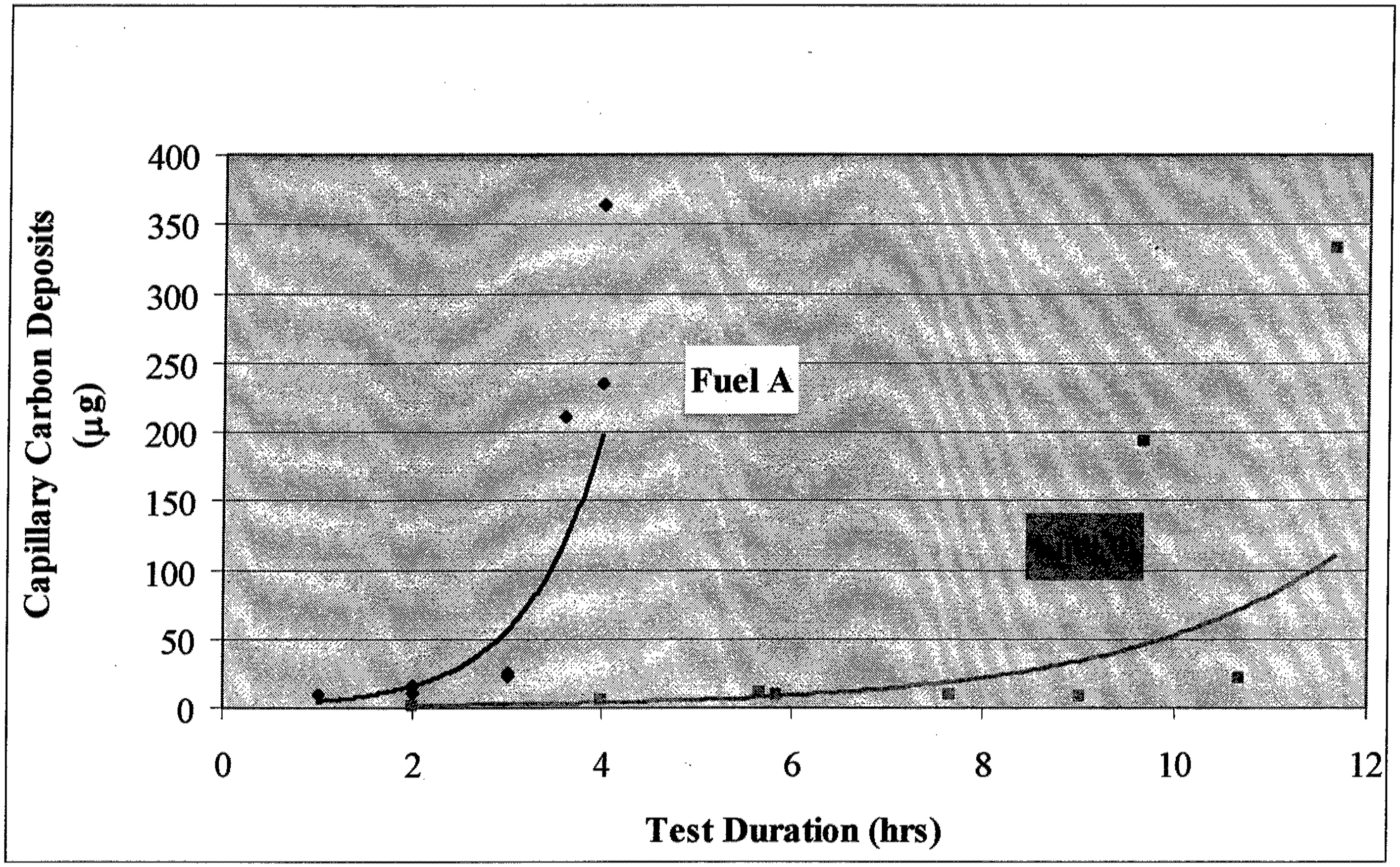

FIGURE 8C: EFFECT OF TEST DURATION
Capillary Carbon Deposits versus Test Duration
Fuel Out Temperature = 220°C
(Critical Deposit Level = 25-35 mg)

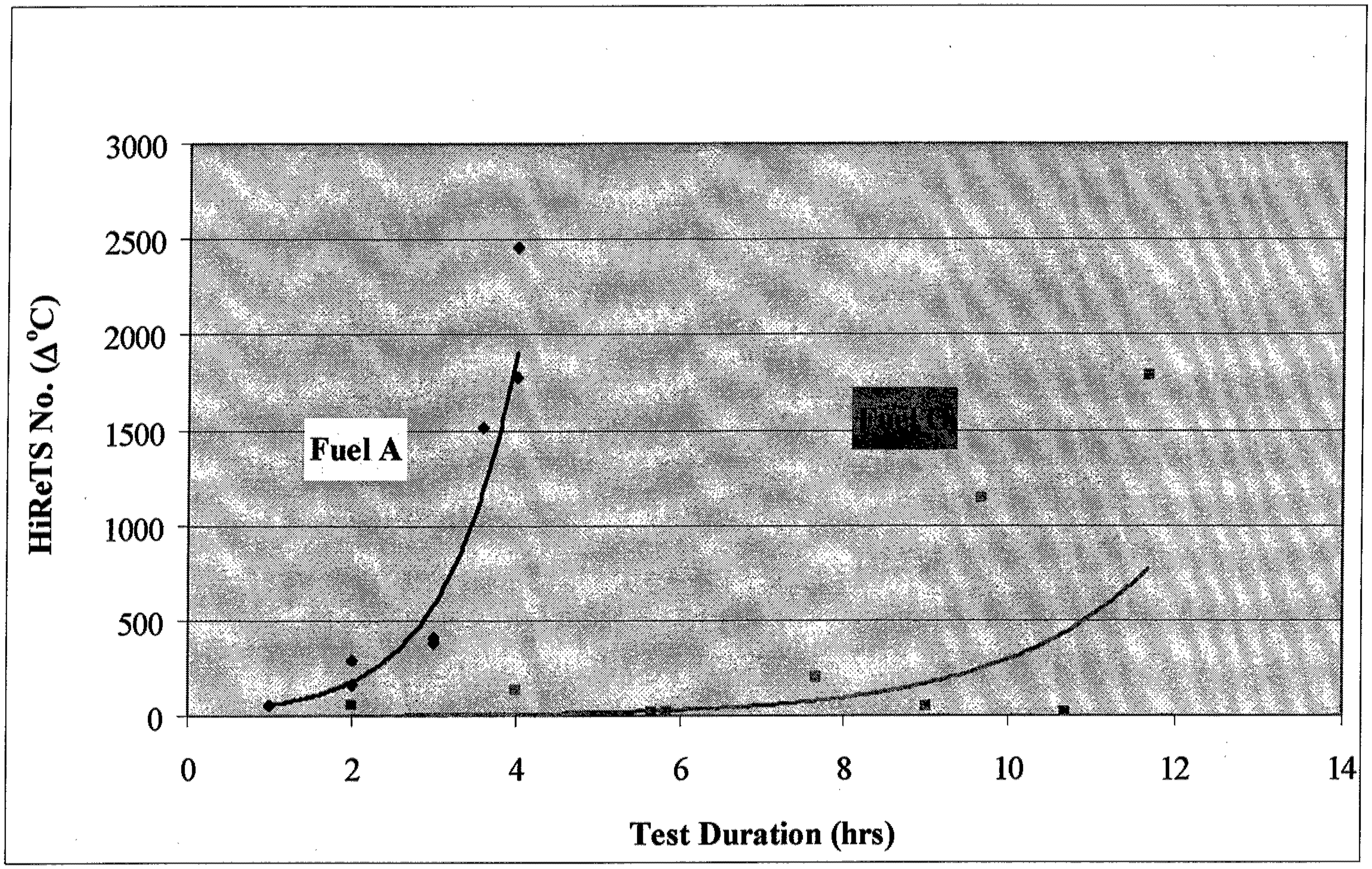

FIGURE 8D: EFFECT OF TEST DURATION
HiReTS No. versus Test Duration
Fuel Out Temperature = 220°C
(Critical HN = 300-400)

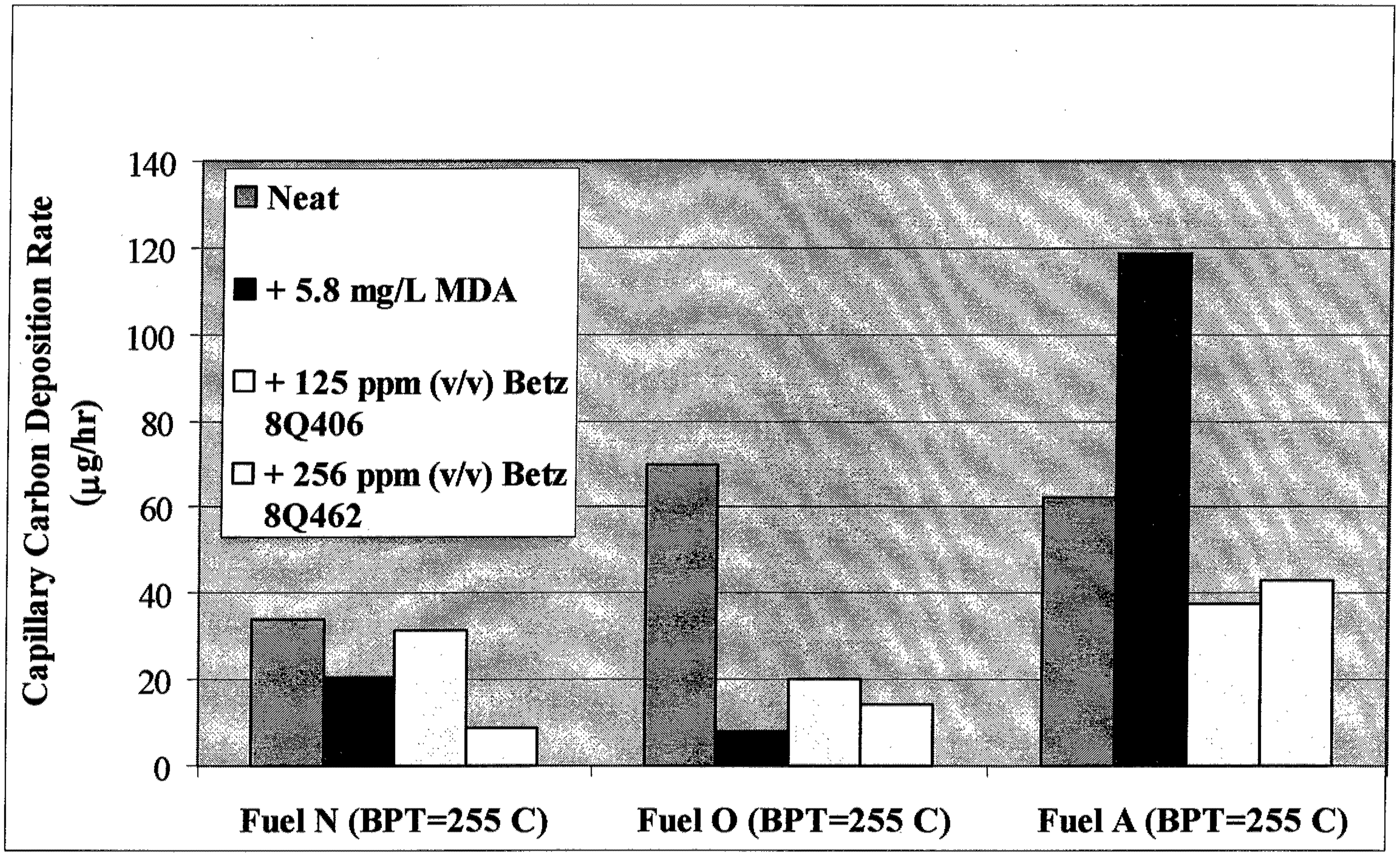

FIGURE 9A: EFFECT OF ADDITIVES IN JP-5
Capillary Carbon Deposition Rates of Neat and Treated Fuels
Modifed SOC: Flow Rate = 35 mL/min, TFo = 290°C, Variable Test Duration
All Tests Terminated at HN=1000

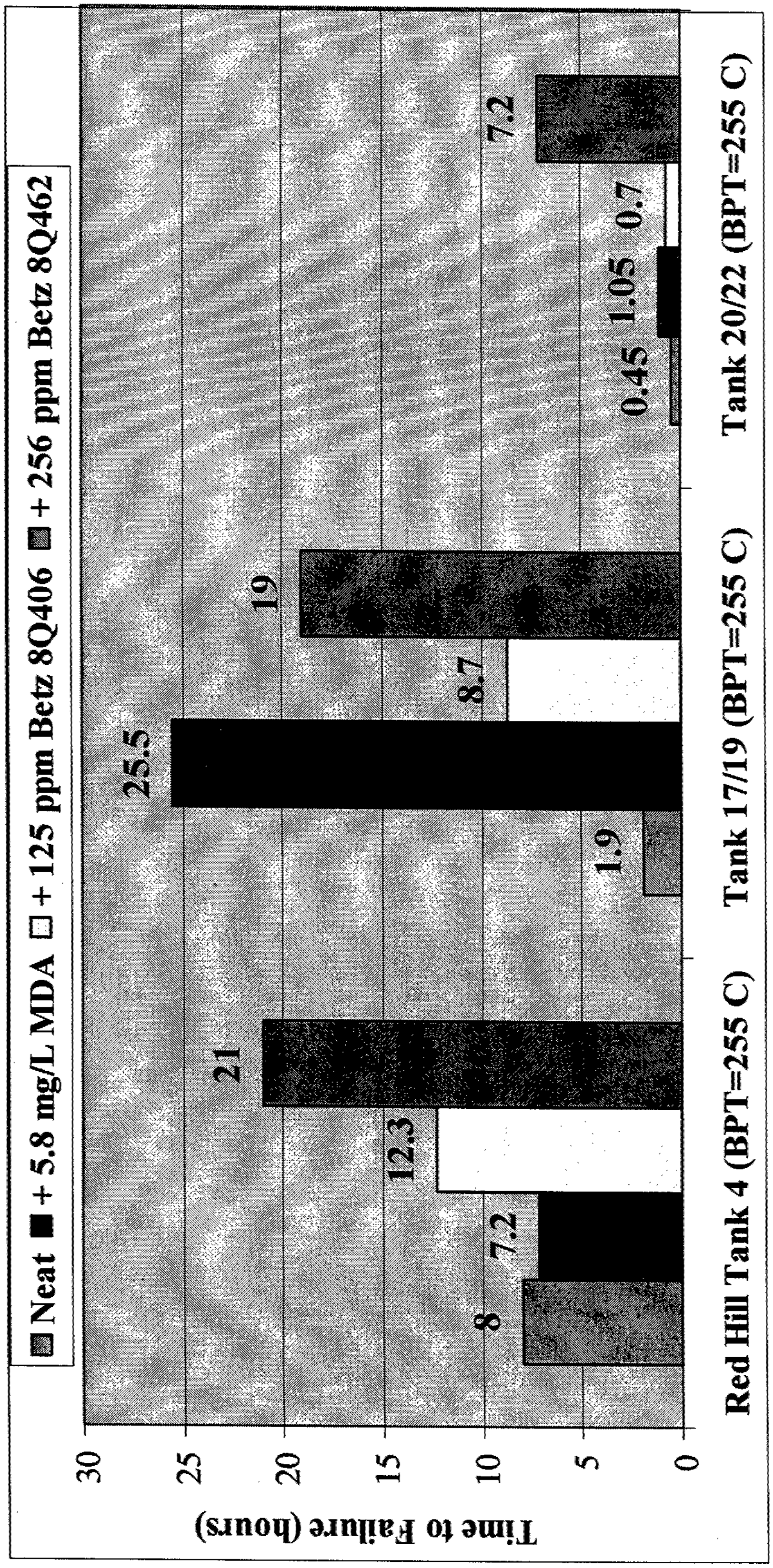

FIGURE 9B: EFFECT OF ADDITIVES IN JP-5
Time to Failure (HiReTS No. ≥1000) of Neat and Treated Fuels

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14. ABSTRACT

The High Reynolds' Number Thermal Stability (HiReTS) test unit was developed by Shell Global Solutions, Fuels Business Group as a small-scale unit for evaluating the thermal stability of jet fuel prior to shipment to the consumer. The purpose of the testing and analysis effort covered by this report was to evaluate the HiReTS as a potential tool for measuring the thermal stability properties of Navy fuels (jet and diesel), viz., as both a specification test and a research tool. The program had two primary objectives: (1) Evaluate the HiReTS at the standard operating conditions (SOC) (fuel flow rate 35 mL/min, bulk fuel exit temperature 290°C (554°F), and test duration two hours; and (2) Evaluate alternate HiReTS test conditions, or non-SOC. A large number of jet and diesel fuels (78 total) of various fuel qualities with a wide range of JFTOT Breakpoint Temperatures (BPTs) were tested. Fuels were also tested with copper contamination and three thermal stability improving additives. At SOC, the HiReTS No. agreed with the JFTOT Breakpoint for 76% of the fuels tested.

15. SUBJECT TERMS
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