JOURNAL OF PROPULSION AND POWER
Vol. 24, No. 2, March–April 2008

Laboratory-Scale Thermal Stability Experiments on RP-1 and RP-2

Sarah P. Brown* and Robert A. Frederick, Jr.†
UAH Propulsion Research Center, Huntsville, Alabama 35899

DOI: 10.2514/1.27724

The thermal stability of kerosene-based rocket propellants enables successful regenerative cooling of liquid rocket engines. This work experimentally investigates the effect of sulfur level and red dye concentrations on the thermal stability of RP-1 and RP-2 rocket fuels. A high Reynolds number thermal stability test unit evaluated various compositions of the fuels. The experiment consisted of an electrically heated, stainless steel capillary tube with controlled fuel outlet temperature. As deposits built up inside the capillary tube, an optical pyrometer monitored external temperature profiles. Multiple runs at individual test sites provided results on measurement repeatability. Testing at two facilities provided results on measurement reproducibility. The technique is able to distinguish between RP-1 and RP-2 rocket fuels which mainly differ in their sulfur concentrations. Red dye is shown to have a measurable negative impact on thermal stability. Carbon burn-off analysis of residue in the capillary tubes correlates with the external temperature results.

Nomenclature

N = number of repeated experiments
n = measurement station number
R = predicted reproducibility
r = predicted repeatability
T_{final} = final external temperature of capillary tube at one station
$T_{\min}$ = minimum external temperature of capillary tube at one station
T_{out} = bulk outlet temperature of heated fuel
x = average of highest and lowest HiReTS number

I. Introduction

LIQUID rocket engines using kerosene-based fuels have relied on regenerative cooling to keep chamber materials at safe operating temperatures. Precombustion fuel is circulated through wall channels to carry heat away. Engine performance is increased by operating at higher chamber pressures, which results in proportionally higher heat fluxes to the chamber walls [1]. For example, the F-1 engine on the Saturn V operated at 6.7 MPa and experienced a throat heat flux of 1.6 $\mathrm{kW/cm^2}$. The chamber pressure in newer engine designs can reach 25 MPa and have a heat flux of 11 $\mathrm{kW/cm^2}$ at the throat [2]. With higher heat fluxes, the fuel in the cooling passages must operate at higher temperatures to properly cool the engine.

At elevated temperatures, hydrocarbon fuels can decompose and leave behind solid deposits on the wetted surfaces of the passages in a process called coking. A more thermally stable fuel can operate at higher temperatures before the decomposition process starts [3]. Thus, characterizing the thermal stability of the fuel is important to achieving a successful design. The deposits that form during the decomposition process act as a thermal barrier. This increases the wall temperature of the combustion chamber and can eventually cause material failure. A hydrocarbon fuel can also be susceptible to reactions with copper [4], a commonly used cooling channel material. This can result in the formation of copper sulfide (Cu_2S). Operating conditions such as wall temperature, Reynolds number, and fuel velocity have been shown to affect deposition rates inside cooling channels.

Thermal stability is affected by many factors including wall temperature, fuel composition, pressure, and Reynolds number (Re) [5–7]. Temperature effects are evident and directly affect thermal instability. As a fuel approaches 100°C, deposition begins and progressively worsens as temperature increases [8]. At higher temperatures, in the range of 325–400°C, the deposition decreases drastically [8]. This is illustrated in Fig. 1. This deposition continues as the fuel is heated until all oxygen is consumed, at which the deposition ceases. If the temperature of the fuel continues to increase, pyrolytic reactions occur forming more deposits.

Impurities in the fuel such as atomic nitrogen, oxygen, and sulfur are determined by the specific type of hydrocarbon fuel and its refining process. These impurities can bond with thermally generated free radicals to form stable solids. These stable solids form the precursors to deposits. Studies have shown that removing the impurities can help improve the fuel's thermal stability. Pressure effects are more difficult to generalize. It has been found that pressure effects are negligible above a certain minimum pressure. Chin and Lefebvre [9] found that pressure to be 0.8 MPa (115 psia) for diesel fuel 2 (DF 2), but that it could be higher or lower for other unspecified fuels that they tested. In general, the minimum pressure decreases when fuel temperature and/or volatility are increased.

RP-1 is a kerosene-based, liquid hydrocarbon fuel that has been studied in the laboratory and used extensively in rocket engines. Previous studies have examined the effects of temperature, wall material, and sulfur content on coking in RP-1. A study in the 1980s [6,10] used electric resistance heating of a test section operating at 13.8 MPa. The carbon deposit rate was found to be a maximum at wall temperatures between 330 to 430°C. Tests also showed a 20% drop in the deposition rate when a nickel-plated tube was substituted for copper. In the early 1990s, studies [4] showed that increasing the sulfur content of the fuel caused an increase in coking deposits in heated copper tubes having a wall temperature around 300°C. More recent heated tube experiments showed that copper tubes had higher deposition rates than stainless steel tubes [5,11]. Also, changes in wall temperatures had greater effects on deposition than changes in flow rates for the condition studied. Most of the historical tests produced quantitative values for heat transfer coefficients. However, the thermal stability itself was only discussed in terms of trends and

---

Presented as Paper 3850 at the 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, Arizona, 10–13 July 2005; received 20 October 2006; revision received 1 August 2007; accepted for publication 6 November 2007.

*Graduate Research Assistant, Mechanical and Aerospace Engineering, 5000 Technology Drive, TH S231; currently Engineer, Lockheed Martin, 4800 Bradford Drive, Huntsville, AL. Student Member AIAA.

†Associate Professor, Mechanical and Aerospace Engineering, 5000 Technology Drive, TH S231. Associate Fellow AIAA.

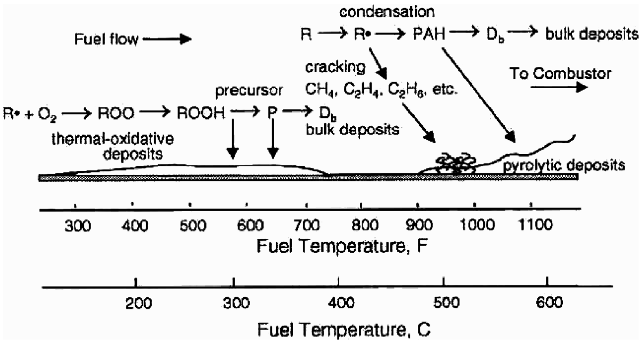


Fig. 1 Fuel deposition regimes [19].

relative comparisons. Larger-scale experiments often make it impractical to perform replicate tests. Although historical testing has sought to match conditions of operational engines, it has not always produced repeatable and systematic information on thermal stability.

Table 1 summarizes chemical and physical properties for the previous (MIL-P-25576C) and the latest (MIL-P-25576D) RP specifications. The previous specification for RP-1 allowed up to 500 mg/kg of sulfur. It also allowed manufacturers to add in a methyl derivative of azobenzene-4-azo-2-naphthol (red dye) in an amount less than or equal to half an ounce by weight per 1000 U.S. gallons of fuel. A committee updated the RP fuel specification [12] in 2005 to create a revised RP-1 and a new RP-2. The specification limits the total sulfur level to 30 mg/kg for RP-1 and 0.1 mg/kg for RP-2. The revised RP-1 contains red dye at the same concentration levels as before. The results of the work presented herein contributed to the decision to leave red dye out of the RP-2 specification. The new RP fuel standard adds the requirement of reporting the results of a jet fuel thermal oxidation test (JFTOT). Although the JFTOT, which was designed for use with aviation fuel, can judge a fuel independently on a pass/fail basis, it operates in a laminar flow regime often inconsistent with turbine and rocket operating conditions. Recent work has also postulated that thermal stability may be more dependent on fuel temperature and residence time rather than Reynolds number for jet fuels [13].

This work evaluates thermal stability differences between RP-1 and RP-2 using a laboratory-scale, high Reynolds number thermal stability (HiReTS) test method [14]. The HiReTS test unit was developed for aviation fuels, but had never been used for rocket propellants. The results of the study contribute new, quantitative thermal stability data on the effect of sulfur content and red dye in RP-type fuels. The results show the location and mass of carbon deposits in a heated tube at high Reynolds numbers. The study also verifies augmented fuel outlet temperatures and test durations necessary to distinguish thermal stability changes in RP fuels.

II. Approach

This experimental research program examined four rocket fuel formulations. The HiReTS method was augmented to find conditions where the results might be able to distinguish among the different formulations. The testing was also performed on two different machines at two different facilities, which will be referred to as facility 1 (FAC1) and facility 2 (FAC2) to establish reproducibility of the results. Carbon burn-off analysis for the heated tubes was also correlated to the HiReTS results.

A. Propellant Formulations

Table 2 shows the designation of each fuel tested, its sulfur content, and its red dye content. "RP-1" contains 30 mg/kg sulfur which is significantly below the previous RP-1 specification of <500 mg/kg. It is a blended fuel and represents the current propellant supplied for operation and testing of full-scale engines. "TS-5" contains less than 5 mg/kg of sulfur and was blended without red dye. RP-2 (or ultralow) contains less than 0.10 mg/kg of sulfur and was blended without red dye. A blend of RP-2 with red dye (RP-2R) at an amount equal to half an ounce by weight per 1000 U.S. gallons of fuel was formulated to examine the effect of the dye on thermal stability (same concentration of red dye in RP-1). Each propellant was blended by one vendor and taken from the same batch of material.

B. HiReTS Test Unit

The HiReTS test method works by pumping fuel through an electrically heated stainless steel capillary tube at a constant flow rate. A feedback circuit increases the power to the heated tube to

Table 2 Propellant properties

Designation	Sulfur, mg/kg	Red dye
RP-1	30	Yes
TS-5	5	No
RP-2	<0.1[a]	No
RP-2R	<0.1[a]	Yes

[a] Below detection limit.

Table 1 Summary of chemical and physical requirements for RP-1 and RP-2 [12]

Property	RP-1 limits MIL-DTL 25576C (1967)	RP-1 limits MIL-DTL 25576D (2005)	RP-2 limits MIL-DTL 25576D (2005)
Distillation			
Fuel cvaporated, 10%, °F	365–410	365–410	365–410
Endpoint, °F (max)	525	525	525
Residue, vol % (max)	1.5	1.5	1.5
Distillation loss vol % (max)	1.5	1.5	1.5
Specific gravity 60/60°F	0.801–0.815	0.799–0.815	0.799–0.815
Existent gum, mg/100 ml (max)	7	1	1
Sulfur, total, mg/kg (max)	500	30	0.1
Mercaptan-sulfur, mg/kg (max)	50	3	NA
Freezing point, °F (max)	−36	−60	−60
Thermal value: net heat of combustion, Btu/lb (min)	18,500	18,500	18,500
Viscosity at −30°F, cSt (max)	16.6	16.5	16.5
Aromatics, vol % (max)	5.0	5.0	5.0
Olefins, vol % (max)	1.0	2.0	1.0
Hydrogen content, % mass (min)	NA	13.8	13.8
Flash point, °F (min)	110	140	140
Particulate mg/gal (max)	5.7	1.0	1.0
Red dye	Yes	Yes	No

maintain a constant bulk fuel outlet temperature during an experiment. The degree of internal coking is then indicated by measuring changes in the external temperature profile of the heated tube. The device is capable of pumping the fuel from 20 to 50 ml per minute (0.005–0.013 gal/ min) from the inlet vessel, through a manometric module, and into the capillary tube. The exit temperature can be set between 250 and 400°C (482–662°F) and is measured by a platinum resistance thermometer (PRT). After the fuel exits the capillary tube, it enters a counter flow heat exchanger where it is cooled to 50°C (122°F), and it is then deposited in the waste container. A backpressure valve maintains the system pressure at 2 MPa (290 psi) or higher to prevent the fuel from boiling. A safety feature in the form of a bypass valve is also in the system to prevent a pressure buildup in the event of a blockage in the tube.

The capillary tube assembly is shown in Fig. 2. The capillary tube is electrically heated by two copper bus bars located at each end of the tube. The capillary tube is made of 316 stainless steel with an inner diameter of 0.28 ± 0.02 mm (0.011 ± 0.0008 in.) and an outer diameter of 1.613 ± 0.025 mm (0.064 ± 0.001 in.). It has a length of 152.5 ± 0.2 mm (6 ± 0.008 in.). The capillary diameter was chosen to ensure turbulent flow. As deposits form inside the tube, they cause a decrease in the thermal conductivity between the fuel and the heated tube wall due to the insulating effects of the deposits. To maintain a constant outlet temperature, the control system adjusts the electrical heating to increase the external wall temperature.

The temperature on the outside of the tube is scanned by an optical pyrometer. Black paint on the outside of the tube [except for 20 mm (0.787 in.) on each end] controls the emissivity of the tube for accurate temperature readings. The pyrometer takes readings starting 1 mm (0.04 in.) below the datum position, which is where the capillary tube meets the bus bar at the fuel outlet. The pyrometer then moves down a step distance of 2.5 mm (0.98 in.) and takes another measurement. It repeats this process and takes 12 measurements scanning a total of 28.5 mm (1.1 in.) of the capillary tube. It was verified during the design of the HiReTS test unit that the vast majority of the deposit would accumulate near the capillary tube outlet for aviation fuels. All 12 measurements taken at the outlet end of the tube make up one scan, and a test can be composed of between 2 and 39 scans. The time between scans can be set as high as 999 s and thus the time of a test can vary anywhere from around 10 min to close to 11 h.

The quantitative result of the HiReTS test unit is the HiReTS number HN. This value is calculated by

$$\mathrm{HN} = \sum_{n=1}^{12} (T_{\mathrm{final}} - T_{\mathrm{min}})$$

The minimum external tube temperature T_{min} is subtracted from the final temperature T_{final} at each of the 12 axial measurement points. Those values are then summed over all 12 points to yield the overall HN for the test. A higher temperature differential, and thus a higher HN, means more deposits and thus more thermal instability in the fuel. Fuels that have a HN higher than 1000 are not considered thermally stable enough to be reliably used in jet engine applications, but this has not been standardized [14].

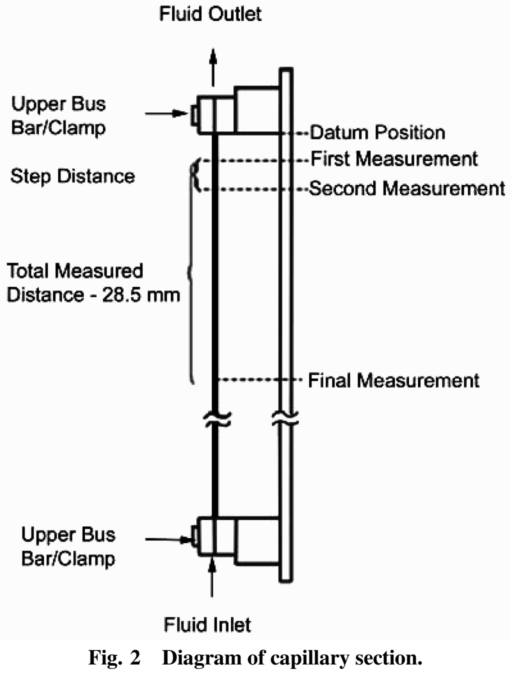


Fig. 2 Diagram of capillary section.

Table 3 HiReTS test conditions

Parameter	ASTM standard	New test conditions
Exit temperature, °C (°F)	290 (554)	290 and 345 (554 and 653)
Flow rate, ml/ min (gal/ min)	35 (0.0090)	35 (0.0090)
No. of scans	13 or 25	25 or 39
Scanning time, s	300	300
Step distance, mm (in.)	2.5 (0.10)	2.5 (0.10)
Measurements per scan	12	

Table 3 shows the test conditions for an American Society for Testing and Materials (ASTM)-compliant HiReTS test compared with the augmented conditions chosen for testing of the RP fuels in this study. The standard operating conditions, as defined by ASTM standard D 6811, are shown in the first column. Because the RP-based fuels were likely to be more stable than the aviation fuels on which the ASTM standard was developed, the test duration (number of scans) and the outlet bulk fuel temperature were both increased to augment the responsiveness of the method. By running 39 scans, the HN for the standard number of scans (25) can also be calculated from the data by looking at the difference between the minimum temperatures and the temperature profile from the 25th scan.

C. Carbon Burn-Off Analysis

Another method used in conjunction with the HiReTS test unit was carbon burn-off (CBO) testing. The carbon burn-off testing used a LECO, RC-412 model carbon determinator. The emissive coating (paint) was first removed before the CBO process. The tested capillary tubes were cut into four 28-mm (1-in.) sections. The entire portion of the tube measured by the pyrometer during a test was encompassed in roughly one of the four sections. The prepared tubes were individually placed inside the LECO carbon analyzer where they were combusted in an oxygen rich environment. The machine measures the amount of carbon dioxide produced, and from that measures the amount of carbon in the sample. This test only measures the amount of carbon in the deposits and thus any portion of the deposit made up of an element other than carbon would not be measured by this method. This procedure was also performed on several untested or blank tubes to provide a baseline. To determine the amount of carbon due to deposition within a tested tube, the amount of carbon determined from a blank tube was subtracted from the amount found from the tested tube.

III. Results and Discussion

Table 4 summarizes the quantitative results for the tests listing fuel description, test facility, fuel bulk outlet temperature, number of tests (N), and results for both 25 scan (HN 25) and 39 scan (HN 39) tests. Maximum and minimum values of the HiReTS number are also show at each condition. Some tests were performed at FAC1 and repeated at FAC2. However, some tests were performed exclusively at FAC1. Baseline tests evaluated RP-1 at the ASTM standard conditions at FAC1. The bulk of the testing employed a 39 scan, 345°C outlet condition to enhance the formation of deposits.

Table 4 Overall HiReTS test results

Description	Test facility	Fuel outlet temp., °C	N	Avg. HN25, °C	Min. HN25, °C	Max. HN25, °C	Avg. HN39, °C	Min. HN39, °C	Max. HN39, °C
RP-1	FAC1	290	2	73	52	93	192	146	239
RP-1	FAC1	345	6	770	605	866	1270	968	1434
RP-1	FAC2	345	3	436	355	581	694	617	844
TS-5	FAC1	345	2	9	4	13	11	11	12
RP-2	FAC1	345	2	3	3	3	4	4	4
RP-2	FAC2	345	4	17	1	59	25	1	75
RP-2R	FAC1	345	4	48	20	87	94	68	103

A. Average HiReTS Number

Figure 3 shows the effect of sulfur content on the average HiReTS number based on the results from FAC1. The results shown are for the augmented test conditions. The error bars represent the range of measurements that should be expected based on the ASTM standard for the repeatability of the method. The results show that there is a difference in the mean value of the RP-2 (<0.1 mg/kg sulfur) and the TS-5 (5 mg/kg sulfur). However, the repeatability bars have a small overlap indicating that if only one test was run, the results may not be able to distinguish between the two fuel types. The RP-1 fuel, with 30 mg/kg of sulfur, has a marked increase in the HiReTS number that is clearly distinct from all the other tests. Thus, the technique can make a clear distinction between RP-1 and RP-2 using the augmented test conditions. The results are consistent with other work that shows that increasing sulfur content decreases the thermal stability of kerosene-based fuels. In this case, going from total sulfur from 0.1–5.0 mg/kg to 30 mg/kg gave a 100-fold increase in the measure of thermal stability for the propellants tested. These results are in an environment of a stainless steel tube where reactions of the sulfur with the walls have not been noted as important in past studies.

The RP-2R formulation also shows a clear and distinct difference from the other formulations. In particular, it is noticeably different from the basic RP-2. This indicates that the addition of red dye makes a discernible degradation to the thermal stability of the propellant, and the HiReTS method is capable of detecting the difference. Studies have suggested that red dyes like this can cause thermal stability problems in some fuels [15]. The HiReTS results in Fig. 2 indicate that red dye is a factor in the kerosene-based fuels as well.

B. Repeatability

The ASTM standard D 6811 [16] provides a formula for determining the repeatability and reproducibility of a test series. These formulas yield a number that should be taken to be the maximum difference between any two tests run within a series and is expected to be exceeded in no more than one out of 20 tests. These formulas are only known to be valid for the operating conditions of the machine as defined in ASTM standard D 6811 which is a test exit temperature of 290°C (554°F) and 25 scans in length. The results of this study, run at augmented test conditions, are now examined to see how they compare with the ASTM guidelines.

The repeatability of the machine is defined as the ability to repeat a result given the same operator, apparatus, operating conditions, and fuel. Equation (1)

$$r = 1.322x^{0.9} \tag{1}$$

describes the limit for aviation fuels. The average of the highest and lowest HN test results for the series being analyzed is x. The repeatability is given by r and denotes the maximum difference one should find between any two tests conducted.

The repeatability range in HN values for all the RP tests conducted as compared to the maximum ASTM value for the range given by the ASTM repeatability guidelines is shown in Fig. 4. The x axis represents the average of the highest and lowest values of the HiReTS number for a particular test condition. The y axis represents the maximum difference in the readings for a particular test condition. The solid curve is a plot of the ASTM function. The solid square represents the data for HN 25 and the hollow square represents the data for HN 39. The graph indicates repeatability well below the ASTM function in the higher HN values, and slightly above it in the lower HN values. This generally indicates that the repeatability of the RP fuels test falls within the ASTM guidelines for the standard test condition and the augmented test condition.

C. Reproducibility

Reproducibility is defined as the ability to reproduce a result given the same fuel but *different* operators at *different* laboratories with *different* test machines. As with repeatability, a function given in Eq. (2) is provided in ASTM standard D 6811. Again, x is the average of the highest and lowest test results for the series being analyzed. The reproducibility is given by

$$R = 1.667x^{0.9} \tag{2}$$

and denotes the maximum difference one should find between any two tests conducted.

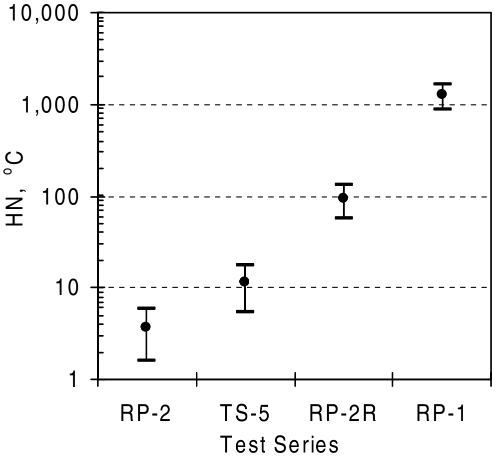


Fig. 3 HiReTS number of different RP fuels for $T_{\text{out}} = 345°\text{C}$, and 39 scans for facility 1 (range based on ASTM repeatability).

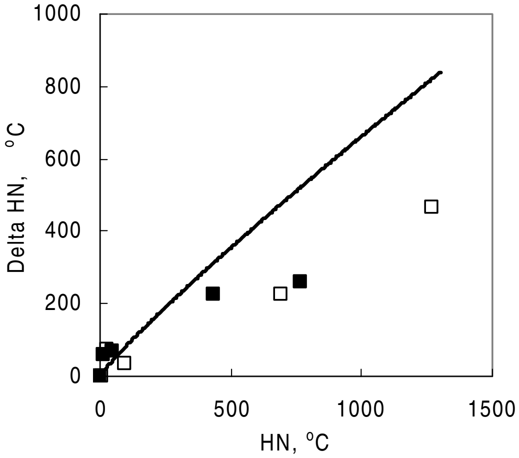


Fig. 4 Repeatability results for RP fuels; (■) is HN 25, (□) is HN 39.

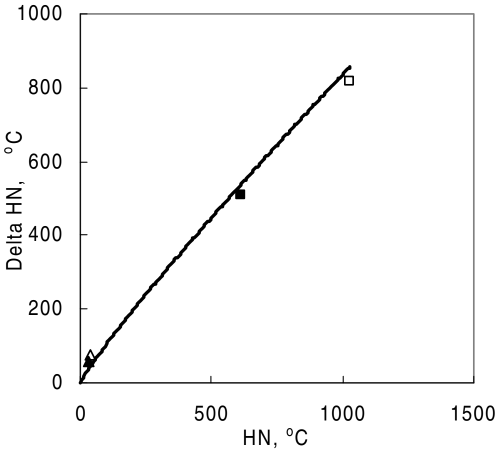


Fig. 5 Reproducibility results for RP fuels; (■) is RP-1, HN 25; (□) is RP-1, HN 39; (▲) is RP-2, HN 25; (△) is RP-2, HN 39.

Figure 5 shows the reproducibility for all tests done at FAC1 and FAC2. The results for RP-1 fall just below the line of the ASTM reproducibility function. Thus, the results from this test series are within the expected reproducibility. The results for the RP-2, which includes all RP-2 tests run at both facilities, fall just above the ASTM boundary. The level that these tests exceed the curve is minor and similar to the data actually used to produce the ASTM standard [17,18]. Examining the graph does show that the results allow for a significant repeatability range. Thus, when using this method, the facility-to-facility variations are significant when considering the highest and lowest value measured for the same test conditions. This suggests the need for multiple runs at each facility.

One possible explanation for the facility-to-facility variation was that the capillary tubes were from different manufacturing lots. However, an exchange of tubes did not produce significantly different results. Another possible explanation is differences in fuel handling between the two facilities that might introduce contamination into the fuel that changed the composition, but time and fuel constraints prevented further analysis of that hypothesis.

It is also possible that differences in the HiReTS test units themselves could be a factor. The manufacturing date of the two machines is different. In analyzing the test results, it was noted that the HiReTS test unit records the temperature of the top bus bar at the beginning of each test. At FAC2, that temperature averaged 360°C (680°F) while it averaged only 270°C (518°F) at FAC1. The range in exit temperature recorded for each test was also slightly larger at FAC2 ranging from 340°C (644°F) to 346°C (655°F) while at FAC1 it ranged from 343°C (649°F) to 346°C (655°F). It is possible that these differences could have played a role in the reproducibility.

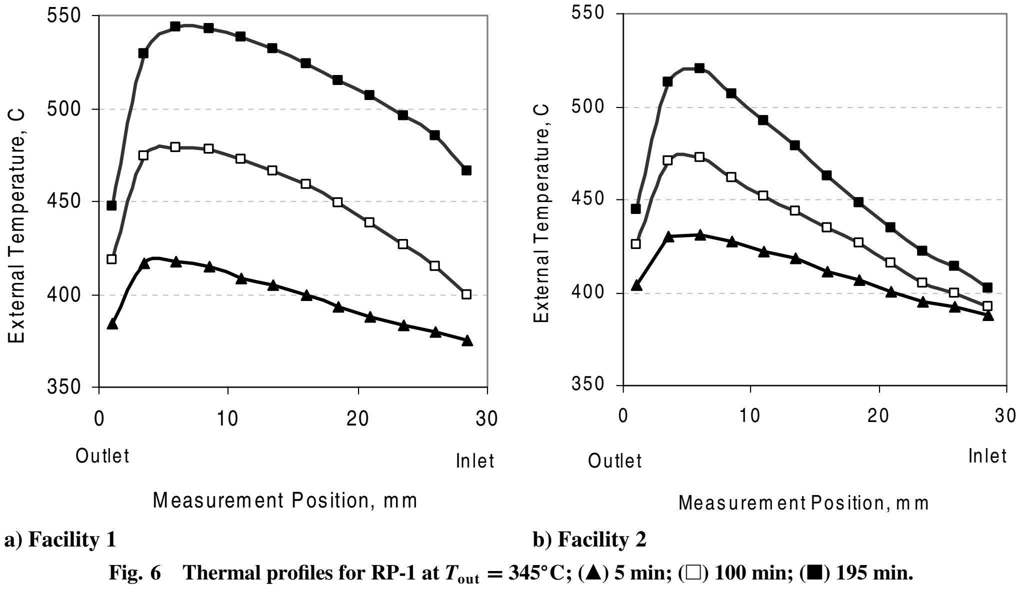
One can also note the difference in the results in the way the temperature profiles progress. Figures 6a and 6b show temperature profiles at three time steps for RP-1 tested at facilities 1 and 2, respectively. The tests were both run at the same test conditions of a 345°C (653°F) exit temperature and 39 scans. The five-minute scan for each test shows a difference in the temperature levels before any appreciable deposits form. The more significant difference that affects the HiReTS number is the difference in the shape of the final (195 min) curves. At FAC1, the temperature profiles remained equally spread out from each other across the entire length of the tube. At FAC2, this separation distance was greatest at the outlet end of the tube, shown on the left side of the graph, and it converged toward the inlet side of the tube. This indicates that at FAC1, more deposition occurred farther upstream in the tube than it did at FAC2. This is supported by the carbon burn-off data available in the following section. The initial temperature profiles from FAC2 are also higher than the ones from FAC1, so there is less room for temperature to increase. Thus, the difference in temperature is less and the HN results are lower. It was expected that the initial conditions would be very similar.

D. Time Dependence

Looking at a graph of HN versus time is another way to compare the different performances of the different grades of fuel. Figure 7 shows the HN versus time plot for representative RP-1, RP-2, and RP-2R tests. On the RP-1 test, the HN curve approaches a steady slope of 8°C per min after the first 30 min of the test. On the RP-2, there is no significant rise in HN over the course of the test. However, even this graph does not accurately reflect the fact that the temperature is going down. By definition the HN can go no lower than zero, so for the RP-2 test shown, the zero values indicate that the temperature profile is actually decreasing with time. The RP-2R test shows a similar trend to the RP-1. The warm-up time to reach a steady slope is longer, at about 135 min, and the end slope is lower at 0.9°C per min. Like the RP-2 test, there is an indication that the temperature profile is dropping during the initial time of the test.

E. Exit Temperature Dependence

The RP fuels are more highly refined than jet fuels and thus are less likely to show a tendency to coke in the HiReTS environment. To "encourage" coking, this study investigated increasing the exit bulk temperature set point of the fuel. It was hoped that this might make



a) Facility 1

b) Facility 2

Fig. 6 Thermal profiles for RP-1 at $T_{\text{out}} = 345°\text{C}$; (▲) 5 min; (□) 100 min; (■) 195 min.

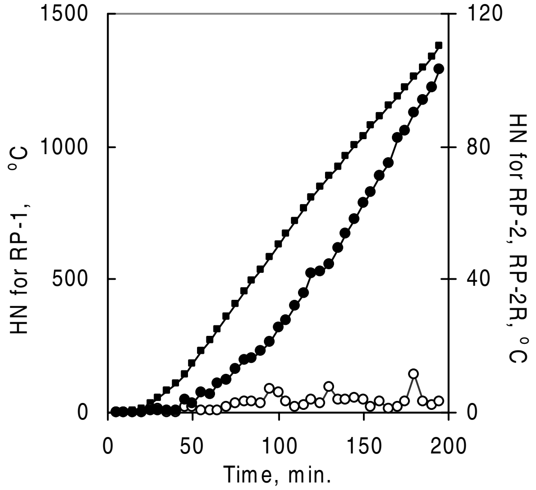


Fig. 7 Time progression of the HiReTS number for representative fuels; (■) RP-1; (●) RP-2R; (○) RP-2.

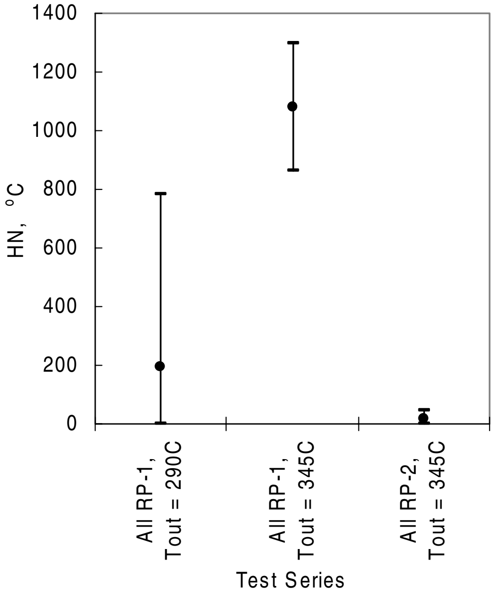


Fig. 8 Temperature comparison of HN 39 results. Range based on confidence intervals.

the method more responsive and allow distinctions to be made among the various grades of fuels.

Figure 8 shows that there is a clear difference between the range of values for RP-1 and RP-2 at the 345°C (653°F) exit temperature. However, at an exit temperature of 290°C (554°F), the test results for RP-1 overlap with those for RP-2. The RP-2 was not tested at 290°C (554°F), but it was assumed that the results would only be lower than those at 345°C (653°F) and thus none of the conclusions based on this chart would change. It is possible if more tests were run on the RP-1 at 290°C (554°F) that the uncertainty bars could be made smaller, and not overlap with those of the RP-2. Based on current information, it appears necessary to run at an elevated exit temperature of 345°C (653°F) to insure a discernible separation in results.

Test length was also varied to encourage coking and hopefully increase the responsiveness of the test. This was done by running a long test and then calculating the HN at earlier stages as part of the post-test analysis. Figure 9 shows a comparison of the results for both HN 25 and HN 39 for the standard grade RP-1, the RP-2, and RP-2R. The numbers presented include the results of all tests conducted on those fuels. The uncertainty bars are based on statistical confidence intervals and the HN values below zero were represented as zero.

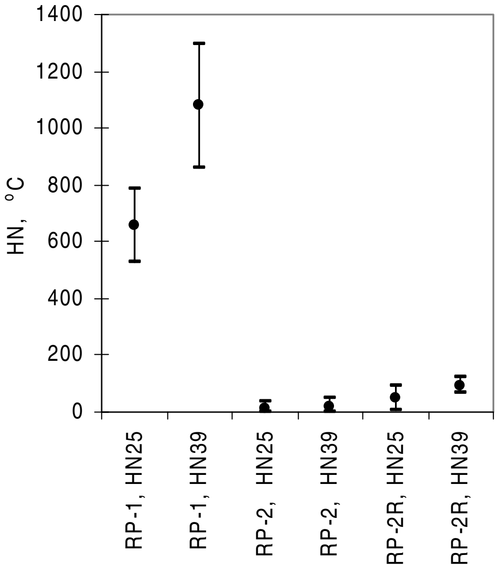


Fig. 9 Test length comparison.

Figure 9 shows that RP-1 and RP-2 can be distinguished using either the HN 25 or HN 39 results. However, there is an overlap between the results for the RP-2R and the regular RP-2 for the HN 25 results. That overlap is not present in the HN 39 results. Thus, the HN 39 results can differentiate between the thermal stability of the RP-2 with and without dye. If testing is being done on fuels with subtle differences, such as the RP-2 with and without dye, then the HN 39 results from the longer test are needed to make an adequate differentiation.

F. Carbon Burn-Off Analysis

Figure 10 shows the correlation between the carbon deposition reported by the CBO analysis and the HN's. The results are normalized for test duration by dividing the mass of carbon by the amount of fuel tested. The *x* axis is the HiReTS number. The *y* axis is the total mass from the carbon burn-off analysis divided by the quantity of fuel tested. The upper line is from FAC1. It shows a generally linear correlation. It is also much higher than the curve from FAC2. The results for the sectioned tubes (not graphed) [17] confirmed that the majority of the deposits occurred in the last 25% of the tube length—the region where the pyrometer scans.

Correlating the carbon burn-off results with the levels of sulfur in the respective fuels shows that the HiReTS test unit will produce about 1 μg/l/mg/kg of sulfur for the conditions and formulations in this study.

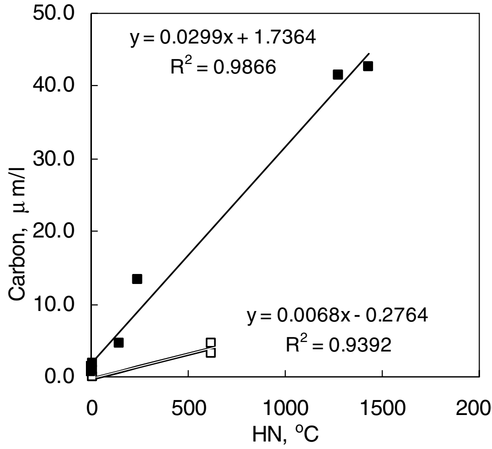


Fig. 10 Carbon burn-off correlation for RP fuels; (■) is facility 1; (□) is facility 2.

IV. Conclusions

The results obtained in this research show that the HiReTS test unit is capable of clearly distinguishing between RP-1 and RP-2 thermal stability characteristics. The ASTM operating conditions must be augmented to allow this distinction to be made. The bulk outlet temperature of the fuel must be increased from 290 to 345°C and the test duration increased from 125 to 195 min. Under the augmented conditions, the reproducibility and the repeatability of the measurements fell within ASTM standards for HiReTS numbers over 100. The external thermal profiles and the carbon burn-off analysis showed that most of the coking deposits formed in the last 25% of the capillary tube. Carbon burn-off analysis of the capillary tube sections showed a linear correlation with HiReTS number. The deposition rate was 1 $(\mu g/l)/[mg/kg\ (sulfur)]$ for the conditions and sulfur levels investigated in this work. Under these augmented conditions, the tester also revealed that the addition of red dye to RP-2 caused a measurable decrease in the thermal stability of the fuel. Even with significant variability between testing facilities, the resulting confidence intervals show that the HiReTS test unit is a viable candidate for conducting further research and distinguishing thermal stability differences between RP-1 and RP-2.

Acknowledgments

This work was supported by NASA Grant NCC8-200 with NASA Marshall Space Flight Center (MSFC) with Mary Trawek as the Contracting Officer for NASA and Clark W. Hawk as Principal Investigator at the UAH Propulsion Research Center. The authors acknowledge the contributions of George R. Wilson III and Cliff Moses at Southwest Research Institute for HiReTS support and technical advice on thermal stability associated with red dyes. Hugh W. Coleman and D. Brian Landrum of UAH and James Urquhart of Pratt and Whitney provided essential technical advice. A. John Wood of Stanhope-Seta provided unprecedented technical assistance on HiReTS operations. Tim Edwards at Wright–Patterson Air Force Base, Ron Bates at Edwards Air Force Base, and Kendal Brown at Marshall Space Flight Center were instrumental in providing fuel for testing. Steve Zabarnick at the University of Dayton Research Institute performed the carbon burn-off analysis. The authors also received substantial support from Propulsion Research Center personnel at the University of Alabama in Huntsville. Tony Hall, Jordan Farina, and Seth Thompson were helpful in preparing for and performing tests as well as solving technical problems.

References

[1] Wagoner, W. R., and Shoji, J. M., "Advanced Regenerative Cooling Techniques for Future Space Transportation Systems," AIAA Paper 75-1247, Sept. 1975.

[2] Bates, R. W., Edwards, T., and Meyer, M. L., "Heat Transfer and Deposition Behavior of Hydrocarbon Rocket Fuels," AIAA Paper 2003-0123, Jan. 2003.

[3] Kendall, D. R., Clark, R. H., and Wolveridge, P. E., "Fuels for Jet Engines: The Importance of Thermal Stability," *Aircraft Engineering*, Vol. 59, No. 12, Dec. 1987, pp. 2–7.

[4] Irvine, S. A., Schoettmer, A. K., Bates, R. W., and Meyer, M. L., "History of Sulfur Content Effects on the Thermal Stability of RP-1 Under Heated Conditions," AIAA Paper 2004-3879, July 2004.

[5] Stiegemeier, B., Meyer, M. L., and Taghavi, R., "A Thermal Stability and Heat Transfer Investigation of Five Hydrocarbon Fuels: JP-7, JP-8, JP-8 + 100, JP-10, and RP-1," AIAA Paper 2002-3873, July 2002.

[6] Roback, R., Szetela, E. J., and Spadaccini, L. J., "Deposit Formation in Hydrocarbon Rocket Fuels—Executive Summary Report," NASA CR-165492, Sept. 1981.

[7] Linne, D. L., Meyer, M. L., Edwards, T., and Eitman, D. A., "Evaluation of Heat Transfer and Thermal Stability of Supercritical JP-7 Fuel," AIAA Paper 1997-3041, July 1997.

[8] Hazlett, R., *Thermal Oxidation Stability of Aviation Turbine Fuels*, ASTM Monograph 1, American Society for Testing and Materials, Philadelphia, PA, 1991.

[9] Chin, J. S., and Lefebvre, A. H., "Influence of Flow Conditions on Deposits from Heated Hydrocarbon Fuels," *Journal of Engineering for Gas Turbines and Power*, Vol. 115, July 1993, pp. 433–438.

[10] Giovanetti, A. J., Spadaccini, L. J., and Szetela, E. J., "Deposit Formation and Heat Transfer in Hydrocarbon Rocket Fuels," NASA CR-168277, Oct. 1983.

[11] Meyer, M. L., and Stiegemeier, B. R., "A Materials Compatibility and Thermal Stability Analysis of Common Hydrocarbon Fuels," NASA Glenn Research Center Contract NCC3-1022, 2005.

[12] "Detail Specification, Propellant Rocket Grade Kerosene," MIL-DTL 25576D, 20 May 2005.

[13] Pande, S. G., Hardy, D. R., Kamin, R. A., Nowak, C. J., Colbert, J. E., Morris, R. E., and Salvucci, L., "Quest for a Reliable Method for Determining Aviation Fuel Thermal Stability: Comparison of Turbulent and Laminar Flow Test Devices," *Energy and Fuels*, Vol. 15, No. 1, 2001, pp. 224–235.

[14] Bauldreay, J. M., Heins, R. J., Houlbrook, G., and Smith, J., "High Reynolds Number Thermal Stability (HiReTS) Rig for Realistic, Rapid Evaluation of Distillate Fuel Thermal Oxidative Stability," *6th International Conference on Stability and Handling of Liquid Fuels*, DOE, Vancouver, BC, 13–17 Oct. 1997, Vol. 1, Pt. 4, pp. 271–352.

[15] Moses, C. A., Wilson, G. R., and Johnson, J. E., "Evaluation of Red-Dye Contamination in Jet Fuel and the Identification of Screen Method for Thermal Stability Issues," Southwest Research Institute, SwRI Project No. 03-02237, San Antonio, TX, Sept. 2002.

[16] ASTM D 6811-02, "Standard Test Method for Measurement of Thermal Stability of Aviation Turbine Fuels under Turbulent Flow Conditions (HiReTS Method)," ASTM International.

[17] Emens, J. M., Brown, S. P., and Frederick, R. A., Jr., "JP-8 and RP-1 Thermal Stability Experiments," AIAA Paper 2005-3850, July 2005.

[18] Emens, J. M., "Precision Analysis of the High Reynolds Number Thermal Stability Test Method," M.S. Thesis, Department of Mechanical and Aerospace Engineering, University of Alabama—Huntsville, Huntsville, AL, Aug. 2005.

[19] Edwards, T., "Liquid Fuels and Propellants for Aerospace Propulsion: 1903–2003," *Journal of Propulsion and Power*, Vol. 19, No. 6, Nov.–Dec. 2003, pp. 1089–1107.

C. Avedisian
Associate Editor