RP-1 and JP-8 Thermal Stability Experiments

Sarah P. Brown,* Jessica M. Emens,† and. and Robert A. Frederick, Jr.‡

UAH Propulsion Research Center, Huntsville, Alabama, 35899

This work experimentally investigates the effect of fuel composition changes on jet and rocket fuel thermal stability. A High Reynolds Number Thermal Stability test device evaluated JP-8 and RP-1 fuels. The experiment consisted of an electrically heated, stainless steel capillary tube with a controlled fuel outlet temperature. An optical pyrometer monitored the increasing external temperature profiles of the capillary tube as deposits build inside during each test. Multiple runs of each fuel composition provided results on measurement repeatability. Testing at two different facilities provided data on measurement reproducibility. The technique is able to distinguish between thermally stable and unstable compositions of JP-8 and intermediate blends made by combining each composition. The technique is also able to distinguish among standard RP-1 rocket fuels and those having reduced sulfur levels. Carbon burn off analysis of residue in the capillary tubes on the RP-1 fuels correlates with the external temperature results.

Nomenclature

HN = HiReTS Number
r = Predicted repeatability
r_{act} = Measured repeatability
R = Predicted reproducibility
T_{Final} = Final external temperature of capillary tube at one station
T_{Min} = Minimum external temperature of capillary tube at one station
x = Average HiReTS Number

I. Introduction

A routine thermal stability specification for an aviation fuel involves the use of a flowing test known as the Jet Fuel Thermal Oxidation Test (JFTOT). The JFTOT rating criteria include a color comparison of the test section to a standard and the pressure drop across a filter following the test section. The color comparison is rated on a scale of 0-4 with 0 indicated no deposits and 4 indicating the maximum deposits visible by a brownish color on the heated aluminum tube from the test section. The specifications for JP-8 are a color rating of less than 3 with maximum pressure drop as 3.3kPa (MIL-DTL-83133E). The specifications for JP-7 (MIL-DTL-38219D) also include a JFTOT test though the test conditions and results are modified from the standard to account for the greater thermal stability of the JP-7. Currently, the specifications for kerosene-based rocket fuels do not contain a thermal stability requirement, although there is ongoing discussion about incorporating a thermal stability test in a new specification for rocket grade kerosene to include RP-1 and RP-2.

While the JFTOT is currently in use today, it operates in an unrealistic laminar flow regime, and also only provides a qualitative color comparison as a result.[1] It is important to develop a fuel testing rig that can accurately simulate the environment of the engine cooling tubes, has a low cost in both time and fuel consumption, and provides

---

* Graduate Research Assistant, UAH Propulsion Research Center, 5000 Technology Drive, and AIAA Student Member.

† Graduate Research Assistant, UAH Propulsion Research Center, 5000 Technology Drive, and AIAA Student Member.

‡ Associate Professor, UAH Propulsion Research Center, 5000 Technology Drive, and AIAA Associate Fellow.

This material is a work of the U.S. Government and is not subject to copyright protection in the United States.

enough measured data to adequately correspond with analytical or computational models.[2] With a properly designed test rig, it will be possible to analyze the tendency any particular fuel composition has to decomposition.

As new standards are being developed for RP-1 to help it meet the requirements of future engine systems, these new grades will have to be tested. A test needs to be developed that can quickly determine the potential of new fuel grades by testing at conditions that approximate real engine conditions. This test method needs to be economical in terms of time, fuel, or money, but also be something that can provide standard and verifiable results.

This research used a High Reynolds Number Thermal Stability (HiReTS) testing device. There are several factors that set the HiReTS machine apart from other thermal stability tests. First, unlike large-scale rigs, the HiReTS machine uses relatively little fuel and time. As opposed to taking 2000 L (528 gal) and 100 hours as in the case of the Single-Tube Heat Transfer Rig (STHTR), the HiReTS Machine only takes 5 L (1.32 gal) and 125 minutes. The HiReTS machine, unlike the commonly used JFTOT, which operates in the laminar regime, operates in the turbulent regime. This is a better simulation of actual engine conditions.[1] The HiReTS machine also provides a quantitative result, known as the HiReTS Number (HN), which a test such as the JFTOT does not. The JFTOT relies on the qualitative comparison of the color of deposition left on the heated tube to determine thermal stability.

The research presented in this paper has two major objectives. The first is to characterize and improve the repeatability and reproducibility of the HiReTS test device. The repeatability is the range of results for the same fuel, tested by the same machine, at the same location. The reproducibility is the range of results for the same fuel tested at different locations on different machines. This is necessary to define the minimum change in output reading required to verify a change in the result. The second research objective is to determine under what conditions the HiReTS approach will discern among RP rocket fuels having controlled levels of sulfur. The approach includes testing several compositions with known levels of sulfur. The test time and outlet temperatures were augmented to enhance the response of the HiReTS device.

The results of this study show that the HiReTS method can clearly distinguish between a thermally stable and an unstable JP-8 fuel under ASTM standard operating conditions. The RP results indicate that the method can clearly distinguish between standard and reduced sulfur blends of RP-1. Augmenting the testing conditions using longer test durations and higher fuel outlet temperatures resulted in a clearer distinction among the various sulfur contents.

II. Approach

A. HiReTS Testing

The HiReTS machine works by pumping fuel through a heated stainless steel tube at a constant flow rate and measuring the temperature change on the outside of the tube. The fuel is pumped at a rate of 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 tube is electrically heated by two copper bus bars located at each end of the tube to maintain the fuel at a constant bulk exit temperature. The exit temperature can be set between 250 and 350 °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 (waste sample cooler) 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.

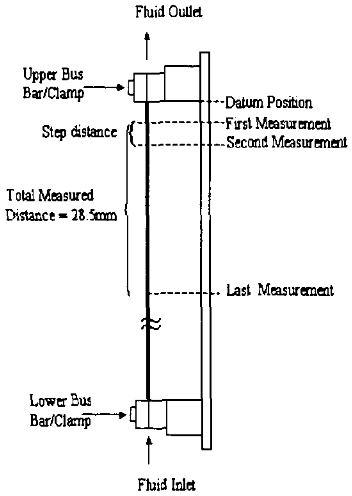

Figure 1. Diagram of Capillary Section.

The capillary tube assembly can be seen in Figure 1. 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 temperature on the outside of the tube is scanned by an optical pyrometer and black paint on the outside of the tube controls the emissivity of the tube for accurate temperature readings. This paint covers the entire length except for 20 mm (0.787 in) on each end. 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 twelve measurements scanning a total of 28.5 mm (1.1 in) of the capillary tube. It was assumed during the design of the HiReTS Machine that the vast majority of the deposit would accumulate at the outlet end of the tube, and thus it was unnecessary to scan further down the tube. All twelve 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 seconds and thus the time of a test can vary anywhere from around 10 minutes to close to 11 hours.

The quantitative result of the HiReTS machine, as mentioned earlier, is the HN. This value is calculated by the formula in Equation 1. The minimum temperature, $T_{\min}$, is subtracted from the final temperature, T_{final}, at each of the twelve measurement points. Those values are then summed over all twelve points to yield the overall HN for the test.

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

As deposit forms inside the tube, it causes a decrease in the thermal conductivity between the fuel and the heated tube wall because the deposit acts as an insulator. Thus, the external wall temperature must increase (driven by the electric heating) to maintain a constant overall energy flux to the fuel. The HiReTS machine measures this increase in wall temperature, and assumes that it is an indication of the amount of deposit within the tube. A higher temperature differential, and thus a higher HN, means more deposit, and thus more thermal instability in the fuel. Work with jet fuels has resulted in the assumption that a pass/fail HN of 1000 is reasonable, but this has not been standardized.[1] Fuels that have a HN higher than 1000 are not considered thermally stable enough to be reliably used in jet engine applications.

Table 1. Test Conditions

Parameter	ASTM Standard	UAH Test Conditions
Exit temperature [°C (°F)]	290 (554)	290 and 345 (554 and 653)
Flow Rate [mL/min (gal/min)]	35 (0.009)	35 (0.009)
Number of scans	13 or 25	25 or 39
Scanning Time [s]	300	300
Step distance[mm (in)]	2.5 (0.1)	2.5 (0.1)
Measurements per scan	12	12

Table 1 shows the range of settings possible for the HiReTS Machine. The standard operating conditions, as defined by ASTM standard D 6811, are shown in the first column. It should be noted that the easiest parameters to vary on the HiReTS machine are the exit temperature and the number of scans. Changing the flow rate requires a recalculation of the time needed to flush cleaning fluid and fuel through the various tube sections. Changing the step distance, measurements per scan, and the scanning time may either exceed the distance the pyrometer can travel, or require it to travel more quickly than it is capable causing the machine to function incorrectly.

B. Carbon Burn Off Analysis

The HiReTS machine indicates the amount of deposit left behind by a fuel by measuring the temperature of the tube wall. Another method, that can be used in the conjunction with the HiReTS machine is carbon burn-off testing. The carbon burn-off (CBO) testing was conducted by Wright Patterson Air Force Base using a LECO carbon determinator. The tubes that were tested were cut into four equal sections with each section being about 28mm (1 in) long. The entire portion of the tube measured by the pyrometer during a test is encompassed in roughly one of the four one-inch sections. The tubes were then placed inside the LECO carbon analyzer where they were combusted in an oxygen rich environment. The machine measured the amount of carbon dioxide produced, and from that measures the amount of carbon in the sample. This procedure was also performed on several untested or blank tubes to provide a baseline. Normally, the amount of carbon in the blank tubes is subtracted from the results of all the tested tubes as it is assumed that carbon came from the tube itself, not from deposition during the test. However, at the time of writing, the blank tube results are pending.

III. Results and Discussion

Table 2 summarizes the quantitative results for the tests. It first shows the fuels that were evaluated in this study and the HiReTS conditions under which they were tested. There were two compositions of JP-8. The first is designated JP-8-00 and is a fuel which is thermally stable. The second is another JP-8 which has been subject to a degraded environment and has poor thermal stability characteristics. Intermediate blends of these two stocks were made to produce intermediate compositions. The JP-8-20 contains 20% (by volume) of the JP-8-100 and 80% of the JP-8-00. The JP-8-40 contains 40% of the aged fuel. The matrix also includes a standard RP-1 rocket fuel, an ultra low sulfur blend of RP, and a 5 ppm sulfur RP. Standard RP has red dye. The ultra low formulations did not have red dye so one formulation was made with red dye to explore possible thermal stability changes. Table 3 shows the HiReTS test conditions used for each fuel formulation. The JP fuels were all evaluated at ASTM standard cooperating conditions. These tests were performed at the University of Alabama in Huntsville (UAH) and repeated at Southwest Research Institute (SWRI). The RP formulations were baselined at the ASTM standard conditions at UAH. The bulk of the testing employed a 39 scan, 345 C outlet condition to enhance the formation of deposits. At the time of writing, carbon burn off results have been completed for the RP tests. It also shows the test conditions, number of tests, *N*, the average HiReTS Numbers for 25 scans (HN25) and 39 scans (HN39) and the range (high minus low) of the results.

Table 3. Test Conditions and Results

		UAH Testing					SWRI Testing				
Fuel Designation	Description	N	HN 25	r_{act} 25	HN 39	r_{act} 39	N	HN 25	r_{act} 25	HN 39	r_{act} 39
JP-8 - 00	Stable JP-8 fuel	2	43	59	NA	NA	1	24	N/A	NA	NA
JP-8 - 20	20% Blend of JP-8-100/JP-8-00 (290 C)	7	370	166	NA	NA	5	262	271	NA	NA
JP-8 - 40	40% Blend of JP-8-100/JP-8-00 (290 C)	6	1209	213	NA	NA	N/A	N/A	N/A	NA	NA
JP-8 - 100	Aged JP-8 fuel (290 C) (*Extrapolated)	2	3025	7	NA	NA	2	2751	713	NA	NA
RP-1 - Standard	RP-1, 290 °C	2	72.6	40.5	192.4	93	0	NA	NA	NA	NA
RP-1 - Standard	RP-1, 345 °C	6	769.7	261.5	1270.4	466.6	3	436.2	225.8	694	226.5
RP-1 - UL	RP-1 with sulfur < 0.1 ppm (345 °C)	2	3	0.6	3.75	0.5	4	16.8	58.7	24.9	74
RP-1 - UL Red	RP-1 UL with Red Dye (345 °C)	4	48	66.8	93.7	35.4	0	NA	NA	NA	NA
RP-1 – TS - 5	RP-1 with sulfur < 5 ppm (345 °C)	2	8.8	9.3	11.4	0.7	0	NA	NA	NA	NA

A. JP-8 Results

Results of the JP-8-00 indicated results within the noise range of the machine, HN less than 100. Testing of the JP-8-100 yielded an incomplete test due to a temperature reading of the limit of 600°C on the outer walls of the tube. The results shown in Table 3 are extrapolated estimates of the HN if the test had completed. A first consideration of the data indicates the HiReTS tester is capable of differentiating between a thermally stable and unstable fuel. This is also indicative with comparison of the 40% blend compared the 20% blend, an increase of roughly 900 for the HN.

The ranges of the results are plotted versus the precision statement published in ASTM D 6811 to see if the results fall within the expected range. Equation 2 below is used to determine the curve, where *x* is the average of the two results considered. The average, *x*, is determined from using the minimum and maximum values from multiple tests. This function is defined for a 25 scan test with a 290 °C fuel outlet condition 2 The JP-8-100 is not considered since the results are out of the defined limit of the function, defined as 19002.

$$r = 1.322x^{0.9} \tag{2}$$

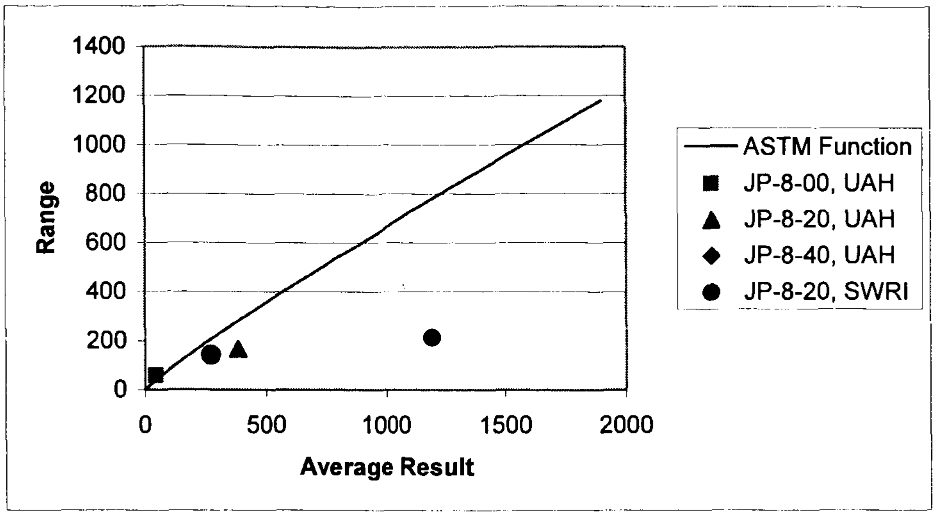

Figure 2. Repeatability of JP-8 Tests

From Figure 2, it is apparent that the JP-8-00 results do not comply with the defined repeatability for the HiReTS tester. As indicated, the results are within the noise level of the machine, so consideration of this data is not crucial. All other results fall within the expected range outlined in ASTM D 6811.

The reproducibility between the UAH and SWRI HiReTS machines are considered. The results in Table 3 show for JP-8-20 fuels, the UAH numbers are somewhat higher. The reproducibility results are compared to verify the two machines are operating with the defined ASTM precision statements. The range, difference between the high and low values, except in this case each value is taken from a different machine's results. The range is then compared to the ASTM function shown as Equation 3.

$$R = 1.667x^{0.9} \tag{3}$$

The function is plotted as the curve with the points representing the determined range. The results shown in Figure 3 indicate for these results, the machines are operating within the reproducibility range.

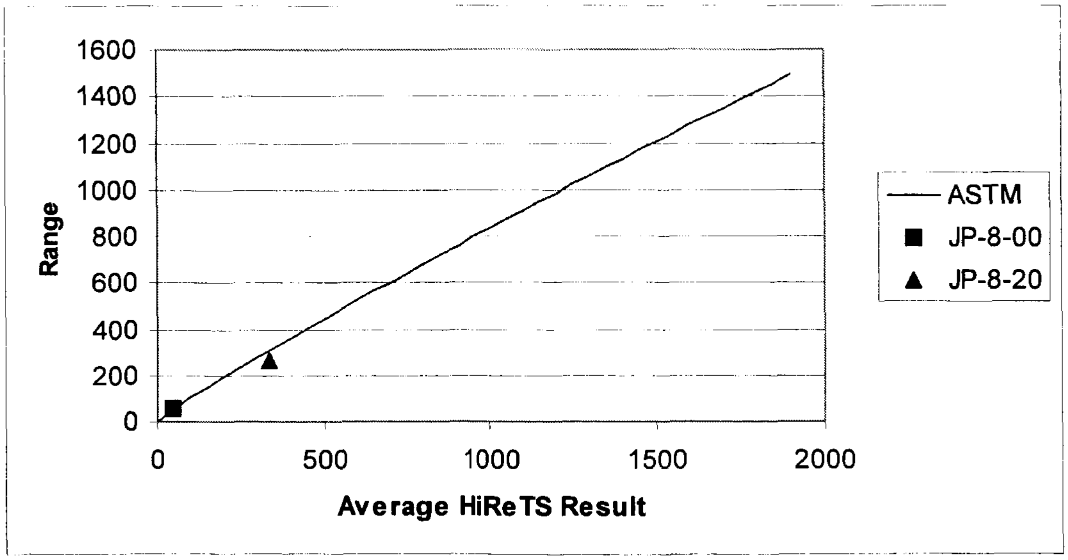

Figure 3. Reproducibility of JP-8 Tests

To provide further comparison of the machines to explain the higher results obtained at UAH, the temperature profiles along the length of the tube are compared at the beginning, 5 minutes, and end of each test, 125 minutes. For this comparison two tests with the lowest range were chosen, 1 from UAH and 1 from SWRI, with the HN indicated.

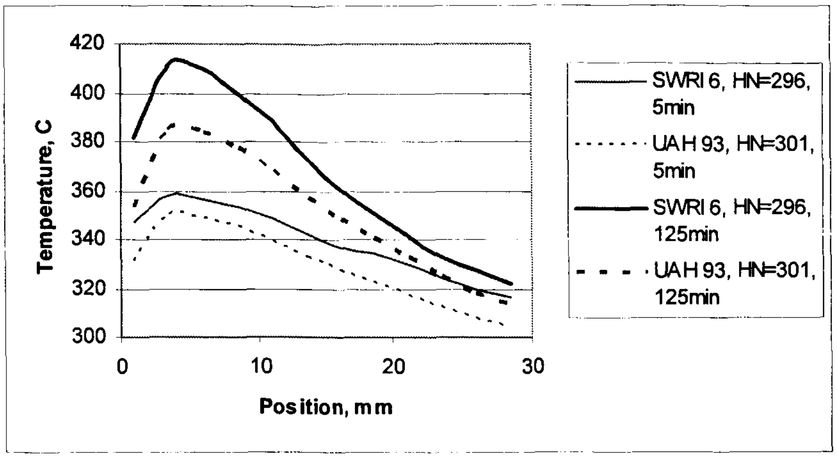

Figure 4. JP-8-20 Initial and Final Thermal Profiles for Different Laboratories

The temperature profiles shown above indicate the starting temperatures for SWRI's tester are somewhat higher than that of the UAH HiReTS. The final profiles indicate higher temperatures for the SWRI tester. Comparison of the difference of the trends of the curves indicates a higher increase on the positions located toward the fuel inlet side, roughly 20-30 mm on the graph. Further investigation of the data had indicated higher upper bus bar temperatures. The output of the HiReTS tester indicates this temperature at the start of each test. Comparison of the temperatures between the two testers indicates the SWRI HiReTS is higher by roughly 70 °C. This could be an indication of a variation of the heating methods between the two testers. Another output of the HiReTS tester is the minimum and maximum measured outlet temperature. Comparison of this range of the exit temperature indicates the UAH HiReTS tester has a tighter range, roughly 3 °C, compared to the 7 °C of the SWRI tester. The tester currently at SWRI is older and has been used significantly more.

The HNs are averaged for each sample to include all data from each laboratory. The average HN is plotted for the 4 samples considered with error bars shown to indicate the confidence interval. The confidence interval shown is the repeatability value given from the ASTM D 6811. The reported HNs for JP-8-100 are extrapolated values. Comparison of the data show the intervals do not overlap for the results considered.

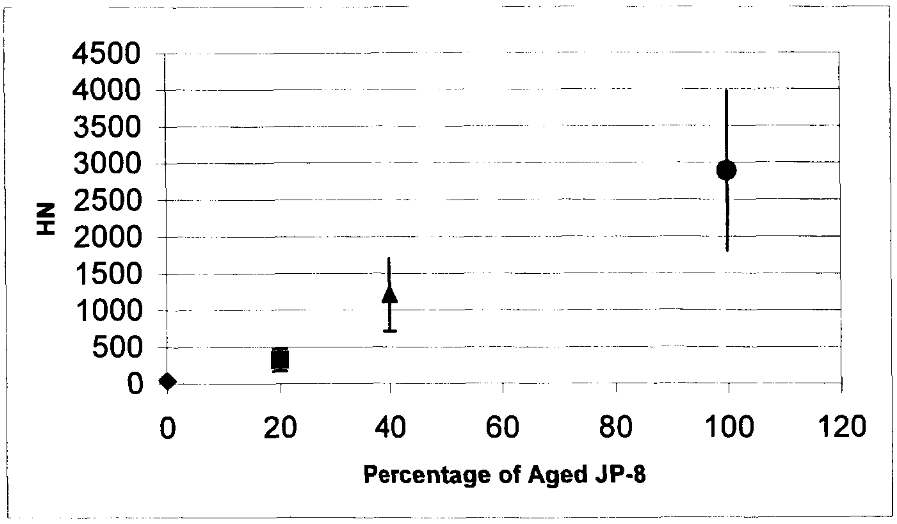

Figure 5. Summary of JP-8 Testing

B. RP-1 Results

Figure 6 shows the range in HN values for all the tests conducted as compared to the maximum value for the range given by the ASTM repeatability guidelines. The solid square represents the data for HN 25 and the hollow square represents the data for HN 39. Technically the HN 39 values violate the conditions for which the ASTM guidelines are designed to work. The graph indicates good reproducibility in the higher HN values, and poor reproducibility in the lower HN values.

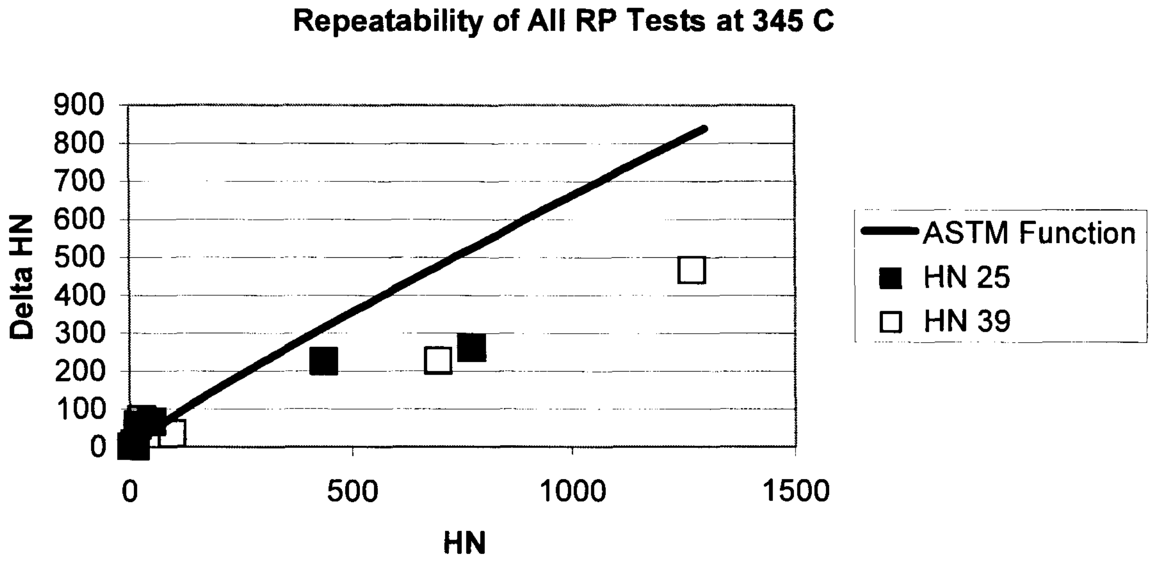

Figure 6. Repeatability Results for RP Fuels

Figure 7 shows the reproducibility for the standard grade RP-1 test series, which includes all tests done on the standard grade RP-1 at both UAH and SwRI, falls just below the line of the function in ASTM standard D 6811 that signifies the maximum expect value. This means that the results from this test series just barely meet the expected reproducibility. The results for the UL, which includes all UL tests run at both facilities, fall just above the ASTM standard D 6811 defined boundary. Therefore, the UL test series does not fall within ASTM standard D 6811 for reproducibility.

It is currently unknown as to why there is such a large variation in results between the UAH and SwRI facilities. One possible explanation was that the two facilities were using capillary tubes from difference batches and that differences between the batches could have been the cause of the varied results. However, two tubes from the batch used by SwRI were shipped to UAH and tested in the UAH HiReTS Machine. The tubes did not appear to cause significantly different results, and the results of the tests using the SwRI tubes were combined with the results using the original UAH tubes for the repeatability calculations shown in Figure 6. As already stated, the results still fall well within the guidelines in ASTM standard D 6811. Thus, it was deemed unlikely that a difference in tubes was the cause of the difference in results.

Other possible explanations include differences in fuel handling at the two facilities, but time and fuel constraints prevented further analysis of that hypothesis. It is also possible that differences in the HiReTS machines themselves could be a factor. In analyzing the test results, it was noted that the HiReTS machine records the temperature of the top bus bar at the beginning of each test. At SwRI, that temperature averaged 360 °C (680 °F) while it averaged only 270 °C (518 °F) at UAH. The range in exit temperature recorded for each test was also slightly larger at SwRI ranging from 340 °C (644 °F) to 346 °C (655 °F) while at UAH it only ranged from 343 °C (649 °F) to 346 °C (655 °F.) It is possible that these differences could have played a role in the discrepancies in the UAH and SwRI results.

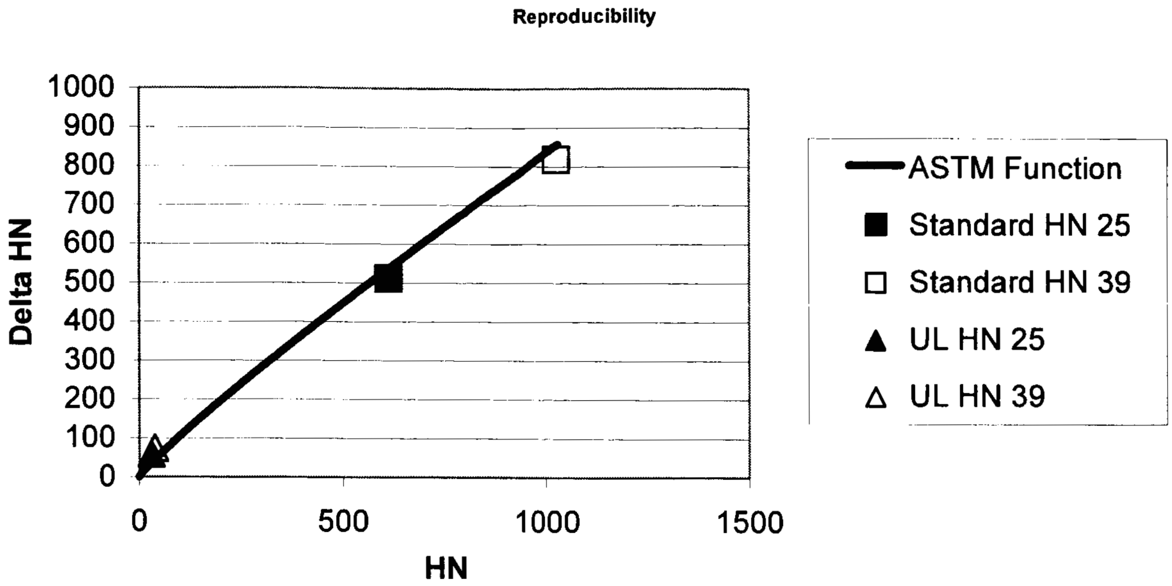

Figure 7. Reproducibility Results for RP Fuels

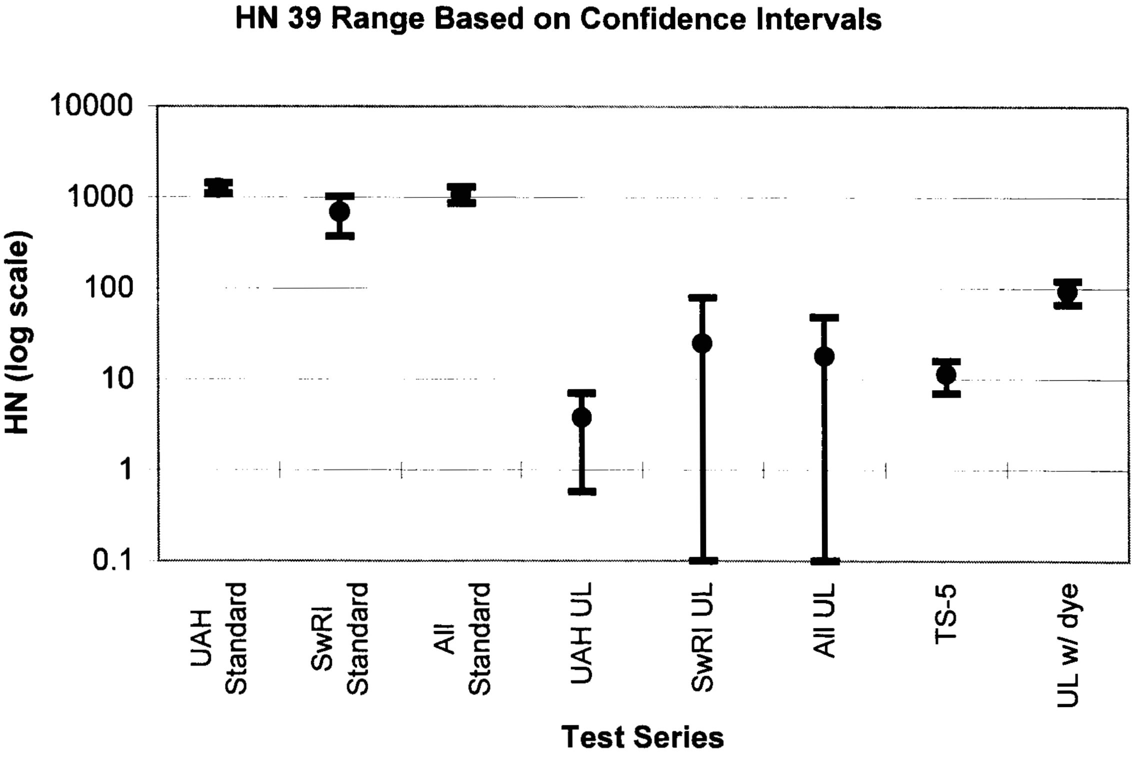

Figure 8. Summary of Results for RP Fuels

In Figure 8, The circles still represent the average HN 39 value for each series, and the uncertainty bars mark the ends of the intervals defined by a 95% statistical confidence level. The data was plotted on a logarithmic scale for easier comparison. Because of the wide intervals and low averages the minimum interval value for some test series went below zero. Since having a negative HN is not possible, those value were redefined as equal to zero. However, since a logarithmic plot cannot display values of zero, these values are represented as equal to 0.1 for the purposes of graphing. Based on these graphs, there is a distinct difference between not only the average HN 39s, but also the uncertainty bars between the standard grade RP-1 and the other grades. It is clear that the standard grade RP-1 has a higher HN, and is thus less thermally stable than the other grades. This is consistent with previous research. The results are not precise enough to differentiate between the thermal stability of the other grades because of the significant overlap in the uncertainty bars. There is a bit of overlap between the UL with dye and other series. However the noticeable difference indicates that the addition of the red dye did produce a measurable decrease in the thermal stability of the fuel. Enough difference was noticed to make this a possible topic for future study.

Figure 9 shows the correlation between the carbon deposition reported by the CBO analysis and the HN 39 result. It is invalid to compare the CBO results with the HN 25 result since the carbon present is a result of the full 39 scan test. The diamonds represent the amount of carbon in the section of the tube nearest the outlet. This is the section of the tube that is actually measured by the pyrometer. The squares represent the total amount of carbon in the tube.

There is a good correlation between HN 39 and carbon deposits for most of the tests. The tests plotted in black are all the tests from UAH for which carbon burn-off analysis was performed. For each set, both the outlet end only and the total tube, a linear regression was performed. The line from that analysis is displayed on the graph along with the coefficient of determination, shown as R^2. This R^2 value is very close to one showing that the data comes very close to fitting exactly along the line. This indicates the strong correlation between HN 39 and carbon deposition. It can also be seen that a correlation exists for both the amount of carbon in the outlet section of the tube, as well as the total amount of carbon in the tube. This indicates that the assumption made by the HiReTS machine that the important deposition occurs in the last quarter of the tube where the measurements are made is correct.

The data points which are offset and in grey are from tests done at SwRI on the standard grade RP-1. Since the discrepancy between HNs at the UAH and SwRI facilities was previously noted, it is not surprising that a discrepancy would be noted in the CBO data as well. However, the SwRI deposition results are lower for the corresponding HN result than the regression line suggests they would be had the tests been performed at UAH. This indicates that there may be additional differences in the two machines that cause different affects during tests

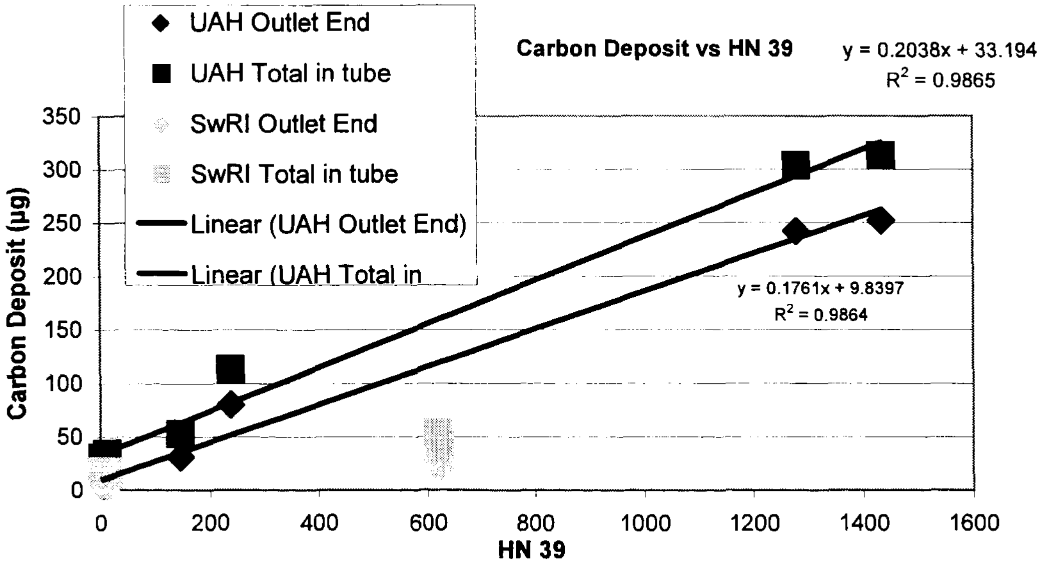

Figure 9. Carbon Burn off Correlation for RP Fuels

IV. Conclusions

The HiReTS method provides quantitative data on thermal stability characteristics of both JP-8 and RP-1 liquid hydrocarbon fuels. The results establish new estimates of repeatability and reproducibility confidence intervals for RP-1 fuels that were not available in previous rocket fuel thermal stability testing. The study uncovered potential items that can be further investigated to improve reproducibility among test facilities.

Testing with the JP-8 fuels and the blending of the fuels to provide a desired outcome indicate the HiReTS machine is operating properly and can differentiate between thermally stable and unstable fuels. The conducted study with the JP-8 fuels indicated the machine is operating within the defined repeatability outlined in ASTM D 6811. Comparison between the two testers indicated a difference of operation/procedure by comparison of the initial upper bus bar temperature and delta temperature measured by the exit PRT. Although this was the case, the two machines operated with the defined reproducibility limit. Further comparisons of the data indicate no overlap between the results obtained for the JP-8 fuels when considering reproducibility as the error interval.

For the RP-1 fuels, the HiReTS machine has shown the ability to make a distinction in thermal stability between the standard grade and UL RP at test conditions of 345 °C and 39 scans. Repeatability falls within ASTM guidelines for higher HN values, but not always for low HN values. Reproducibility shows the same trend although the results barely fall in line for higher HN values. This indicates there may be significant differences between equipment or testing procedures at the two facilities. The addition of red dye to UL RP has a measurable effect on thermal stability. CBO analysis shows good correlation with HN values.

Acknowledgments

This work was supported by NASA Grant NCC8-200 with NASA MSFC with Dr. 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 SwRI for HiReTS support and technical advice on thermal stability associated with red dyes. Dr. Hugh W. Coleman and Dr. D. Brian Landrum of UAH and James Urquhart of Pratt and Whitney provided essential technical advice. Mr. A. John Wood of Stanhope-Seta provided unprecedented technical assistance on HiReTS operations. Dr. Tim Edwards at Wright Pattern Air Force Base, Dr. 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 of support from Propulsion Research Center personnel at the University of Alabama in Huntsville. Tony Hall, Jordan Farina and Seth Tompson were helpful in preparing for and performing tests as well as solving technical problems.

References

---

[1] 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, Vancouver, B.C. Canada, October 13-17, 1997.

[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.